A window into hotter and drier futures:

phenological shifts and adaptive practices

Final Report to Grape and Wine

Research & Development Corporation

Project Number: SAR 0901

Reporting period: 1 July 2012 – 31 December 2012

Victor Sadras, Martin Moran, Paul Petrie & Marcos Bonada

February 2013

DISCLAIMER

The authors warrant that they have taken all reasonable care in producing this report. Although all reasonable efforts have been made to ensure quality, SARDI and the authors do not warrant that the information in this report is free from errors or omissions. SARDI and the authors do not accept any liability for the contents of this report or for any consequences arising from its use or any reliance placed upon it.

A window into hotter and drier futures: phenological shifts and adaptive practices

Project Number: SAR 0901

Abstract

Temperature is one of the main environmental factors influencing vine physiology, berry composition and wine attributes. However, much of our understanding on the effects of temperature on vine physiology and berry composition has been gained from experiments under controlled conditions. Almost all of our knowledge on temperature effects on wine is indirect, this means, it is based on comparisons between thermally contrasting locations or vintages. Controlled conditions often generate experimental artefacts and indirect methods are bound to be inconclusive.

This project measured the effects of elevated temperature on vine physiology, berry composition and wine attributes using open-top chambers to manipulate temperature under realistic vineyard conditions. Delayed pruning was identified as a potential tool to delay and decompress harvest, and to partially restore vine and berry balance under elevated temperature.

Here we report results of a single-season pilot study initiated to assess the value of delayed pruning, and to identify trade-offs with fruit yield and berry attributes in Shiraz and Cabernet Sauvignon. We also report wine sensory profiles of Shiraz in response to the combined effects of elevated temperature and water deficit over two seasons.

Executive Summary

Background and Objectives

This project belongs to Program 3 Grapes for Purpose, with a dominant element of Vine Performance and some elements of Berry Composition. The key strategy is "Collaborative investments in vine physiology" and the measure of success is "A better industry understanding of temperature, water and vine relationships". Against this background, three major R&D needs had been identified:

(i) Scaling-up to the 3-way interaction between heat, water and variety.
(ii) Variety-dependent tools for in-season prediction of ripening for logistic purposes, i.e. harvest, transport and winery scheduling, and irrigation planning.
(iii) Viticultural practices to reduce heat damage.

The main achievements of the project have been reported in the core document comprising the period 1 July 2009 – 30 June 2012, previously submitted to GWRDC. In this complementary report, we address the additional outputs and activities outlined in Table 1.

Table 1. Additional outputs and activities of project SAR 0901, period 1 July to 31 December 2012.

Year 4	Output	Due Date mm/yy	Activities	Update
a	Establish new time-of-pruning trials - A new trial will be established where conventional (winter) pruning will be compared with delayed pruning in early and late spring.	Dec 2012	Identify site/s and target varieties for new time-of-pruning trials in consultation with industry and GWRDC. Design experiment and establish treatments including conventional winter pruning and 2-3 late pruning treatments. Monitor vine phenological development and canopy micrometeorology (temperature, humidity profiles). Explore the application of a novel, non-destructive method to estimate vine growth based on sap-flow sensors to measure transpiration. These measurements will allow comparison of vine growth under the conventional and delayed pruning regimes.	Site has been identified in the with the guidance of Paul Petrie. Experiments were established at Waltons vineyard in the Barossa. Conventional (winter) and late pruning treatments were established. A total of five pruning dates were compared in both Cabernet Sauvignon and Shiraz. Phenological development was monitored regularly during the growing season. This is reported in Chapter 1. Sapflow sensors were damaged in the process of transferring them from SARDI's trial to the pilot trials in commercial farms. A new set of sensors is going to be used in the new GWRDC project.

b	Assess time-of-pruning trials (pilot study carried out in 2011-12) - Assessment of the potential to restore anthocyanins-sugar balance with late pruning, and evaluation of yield consequences.	Dec 2012	Measurement of anthocyanins in frozen samples from fully replicated trial. Weekly samples from three replicates per treatment were taken at Waltons vineyard in the Barossa. Treatments included Cabernet Sauvignon and Shiraz pruned on 26th May, 4th August, 1st September, 22nd September and 13th November 2011. Analyse the data to explore the potential of restoring anthocyanin-sugar balance with late pruning. Analyse the impact of late pruning on yield and explore the trade-off between restoring anthocyanin-sugar balance and yield reduction. Preliminary findings communicated to and feedback sought from industry.	Analysis of anthocyanins has been completed. In addition, we completed analysis of tannins. Relationships between sugar and anthocyanins were analysed. Yield analysis was completed. Yield, pruning weights and berry traits are summarised in **Chapter 1**. Results were discussed with growers and winemakers. Positive feedback pointed out the potential to use late pruning to improve vine balance. Owing to the preliminary nature of results, however, we avoided a wider communication of results.
c	Assess wines from temperature x irrigation trial - Assessing Shiraz wine attributes in response to elevated temperature, water deficit and their interaction.	Dec 2012	Wine sensory assessment, with the input of Treasury Wine Estates winemakers. Analyse berry traits including: sensory profile, cell death, berry compression, skin thickness and hardness, seed compression, peduncle detachment force. Explore correlations between wine and berry traits. Findings communicated to and feedback sought from industry.	Wines were bottled late August 2012. Sensory analyses were completed in February 2013 and results are presented in **Chapter 2.**
d	Maintain the regime of elevated temperature in Shiraz trial - Capacity to measure the long-term effect of elevated temperature. This is important to capture the capacity of vines for acclimation and therefore provide a more realistic view of the long-term effects of warming.	Dec 2012	Maintenance of elevated temperature trial and monitoring of vine phenology.	The trial was maintained during the 2012-13 season. Phenology was monitored during the season using the EL scale from budburst to veraison, and berry sugar concentration from veraison to harvest. This trial will be maintained over the next 3 years, returning a total of 6 seasons of warming. This is a valuable resource to capture the long term effects of temperature on vine development.

Chapter 1

Effects of late pruning on the phenology, yield and berry attributes of Cabernet Sauvignon and Shiraz

MA Moran, PR Petrie and VO Sadras

Introduction

Early and compressed harvests are creating logistic problems to the Australian wine industry. We are interested in exploring the potential of late pruning to delay and decompress harvest. Delayed pruning has attracted some attention in viticulture as a tool to manipulate yield and vine balance, and reducing risk of frost but has not been approached from the perspective of global warming. Here we report the effect of pruning date on the phenology, yield and pruning weight of Shiraz and Cabernet Sauvignon. We also discuss effects of pruning time on berry TSS, TA, pH, malic acid and polyphenols.

Methods

Five pruning treatments were established: 26 May, 4 August, 5 September, 22 September and 18 October. Treatments were applied to Shiraz and Cabernet Sauvignon at the Seppeltsfield Treasury Wine State vineyard in the Barossa Valley. Each treatment was replicated six times. Phenology was monitored regularly; late pruning treatments from September to October corresponded to E-L 1.5, 5 and 12 for Cabernet Sauvignon and E-L 3, 10 and 6 for Shiraz. Berry samples were taken to determine total soluble solids, titratable acidity, malic acid and pH. Anthocyanins and tannins were measured in frozen berries (Iland et. al. 2000).

Results

Phenology

Pruning date had significant effects on the phenology of both Cabernet Sauvignon and Shiraz as characterised with E-L scale (Figure 1) and berry TSS (Figure 2). The last pruning date (applied on E-L 12 in Cab. Sauvignon and E-L 16 in Shiraz) reduced canopy size, quality and yield substantially; this treatment is therefore taken as an upper limit for late pruning in future trials. Maturity was delayed up to 13-16 days in relation to winter pruned controls (Fig. 2).

Yield Components and pruning weight

Table 1 shows the analysis of variance for yield, its components, pruning weights and berry attributes. The second and third pruning dates increased the yield of Cabernet Sauvignon in relation to winter pruning control, and had no effect on Shiraz (Table 1, Figure 3). Reductions in pruning weight did not reach statistical significance despite the removal of growing shoots in the late pruning treatments (Table 1, Figure 4).

Berry attributes

Harvest was targeted at 14 ºBé in Cabernet Sauvignon and 15 ºBé in Shiraz. Figures 5 and 6 show berry attributes, and Table 1 the analysis of variance. Berry size was smaller in Cabernet Sauvignon pruned at E-L 1.5 and E-L 3 and it was negatively correlated with bunch weight ($r^2 = 0.29$, $p = 0.020$), anthocyanin ($r^2 = 0.44$, $p < 0.0001$) and tannin contents ($r^2 = 0.48$, $p < 0.0001$). Berry size of Shiraz did not respond to pruning weight and polyphenols were unrelated to berry size. Late pruning did not affect pH in Cabernet Sauvignon, but it did for Shiraz. Conversely, Cabernet Sauvignon had higher titratable acidity and malic acid for the E-L 12 pruning treatment.

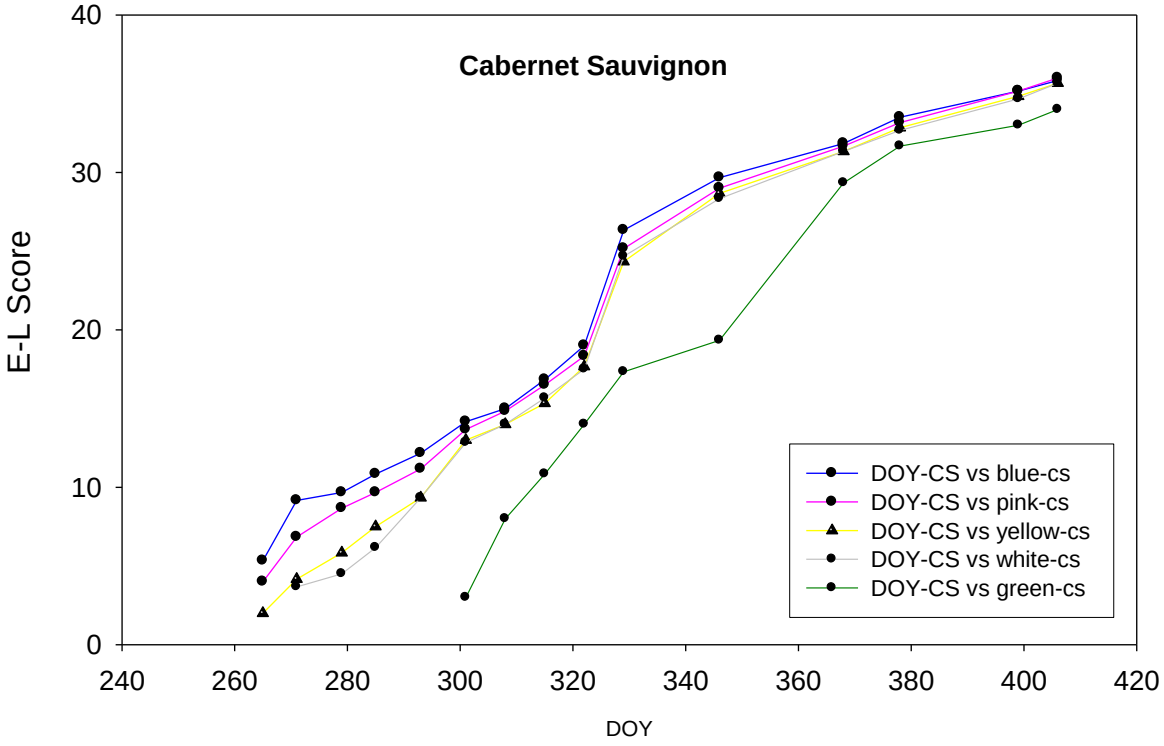
Concluding remarks

Grapevine yield and berry attributes are strongly influenced by environmental conditions. Thus, a single season of experiments precludes meaningful conclusions. Encouragingly, late

pruning effectively delayed maturity by about two weeks in both varieties. Not surprisingly, late pruning triggered a mix of positive and negative effects on yield and berry attributes. Continuity in this line of research will allow reaching industry relevant conclusions on the role of late pruning to delay and decompress harvest. In a context of risk management, we envisage late pruning could be used on a rotational basis, rather than as a blanket practice.

Table 1. Significance in variables measured at harvest for Cabernet Sauvignon and Shiraz. Last pruning treatment in Shiraz was excluded for the analysis.

Cabernet Sauvignon		**Shiraz**	
Trait	Effect of pruning date	Trait	Effect of pruning date
Yield	0.0006	Yield	0.1055
Bunch nº	0.1155	Bunch nº	0.0005
Bunch Weight	<.0001	Bunch Weight	0.1815
Berry size (g)	0.0112	Berry size (g)	0.1364
Shoot nº	0.6739	Shoot nº	0.4916
Shoot (g)	0.5165	Shoot (g)	0.256
Total Acids	0.0052	Total Acids	0.0219
Malic Acid	0.0232	Malic Acid	0.5453
pH	0.8657	pH	0.0088
TSS	0.0218	TSS	0.0002
Anthocyanin	0.127	Anthocyanin	0.0046
Tannin	0.0256	Tannin	0.1289



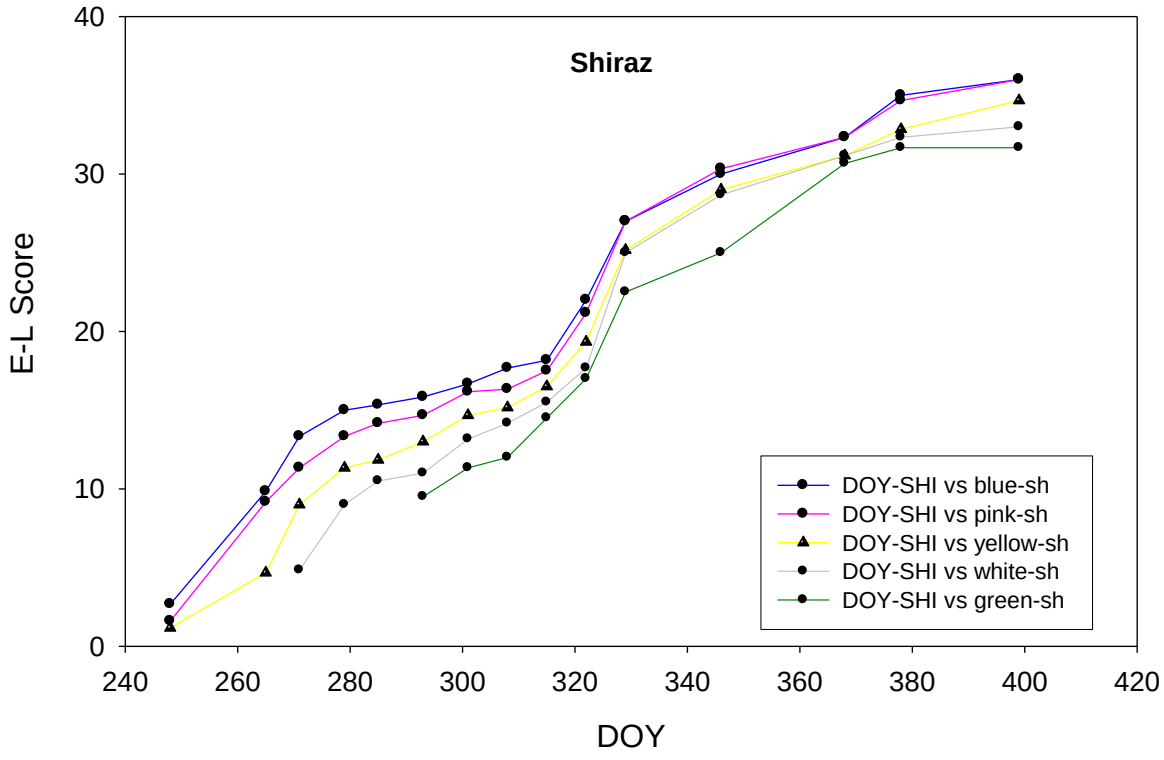


Figure 1 Phenology of Cabernet Sauvignon and Shiraz under five pruning dates. Code: 26 May (blue), 4 August (pink), 5 September (yellow), 22 September (grey) and 18 October (green). DOY: day of year.

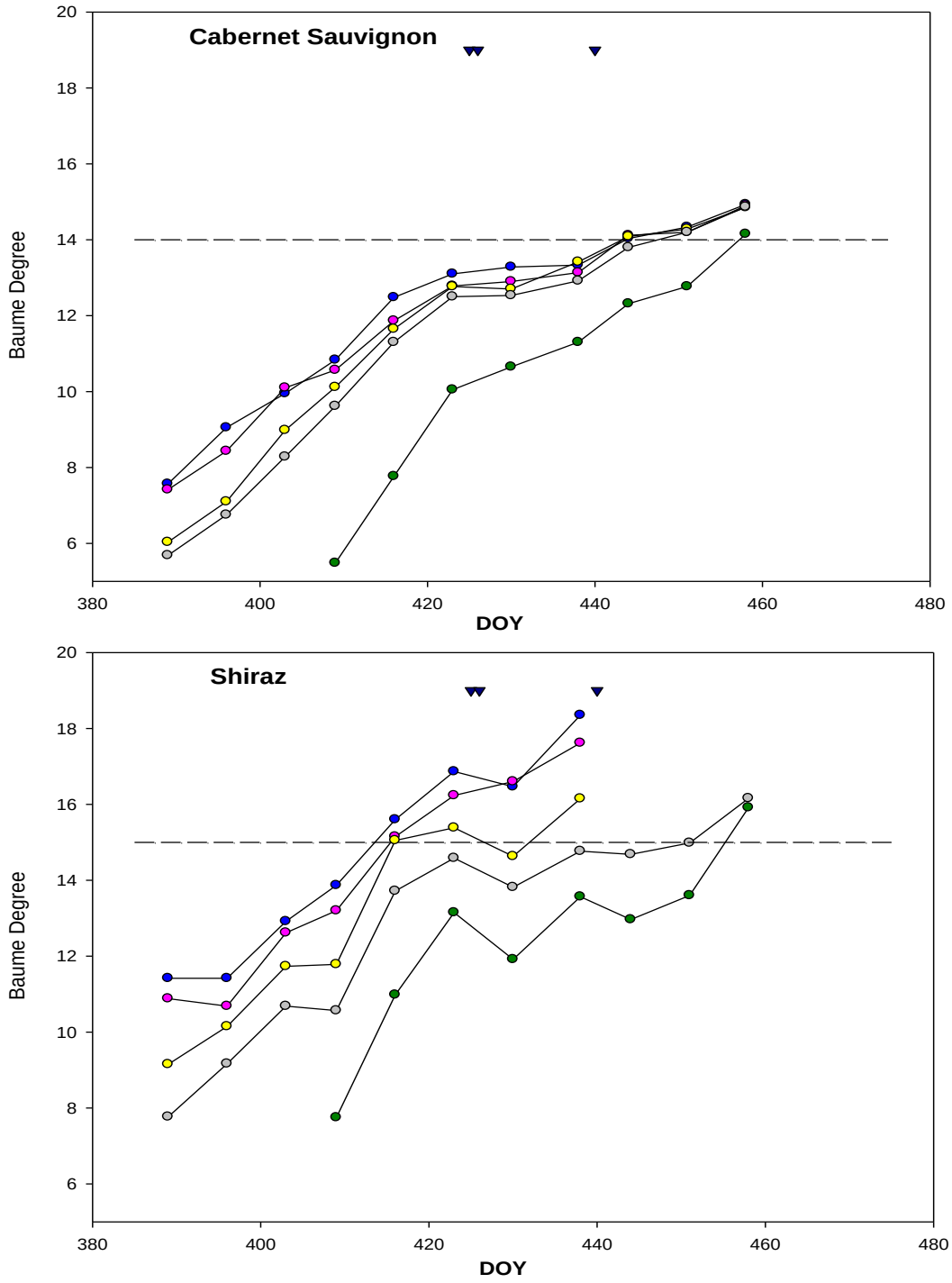


Figure 2 Dynamics of total soluble solids in berries of Cabernet Sauvignon and Shiraz under five pruning dates. Code: 26 May (blue), 4 August (pink), 5 September (yellow), 22 September (grey) and 18 October (green). Triangles indicate a significant rain event (>10mm). DOY: day of year.

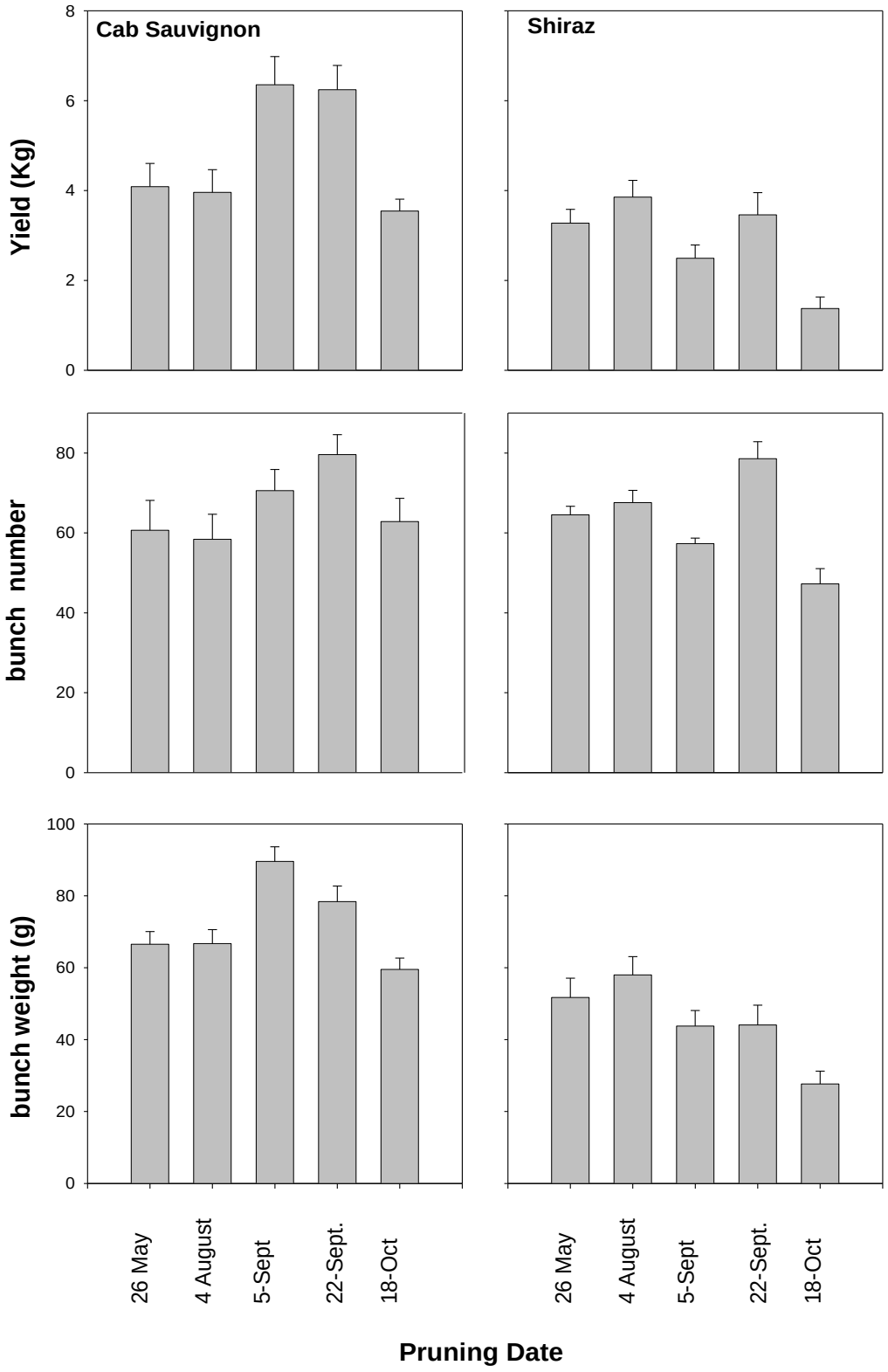


Figure 3. Yield components of Cabernet Sauvignon and Shiraz in response to pruning date. Error bars are one standard error of the mean.

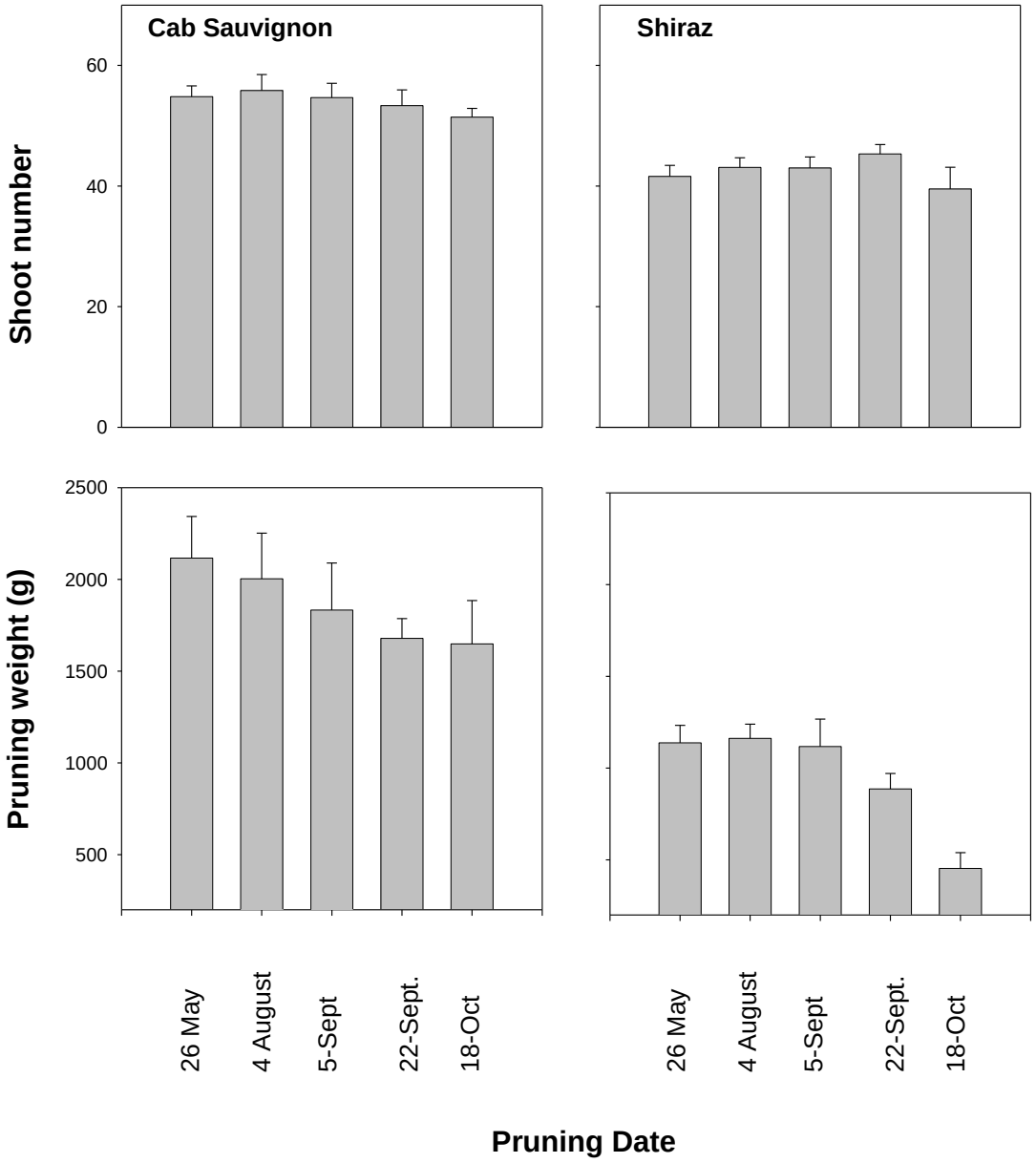


Figure 4 Shoot number and pruning weight of Cabernet Sauvignon and Shiraz in response to pruning date. Error bars are one standard error of the mean.

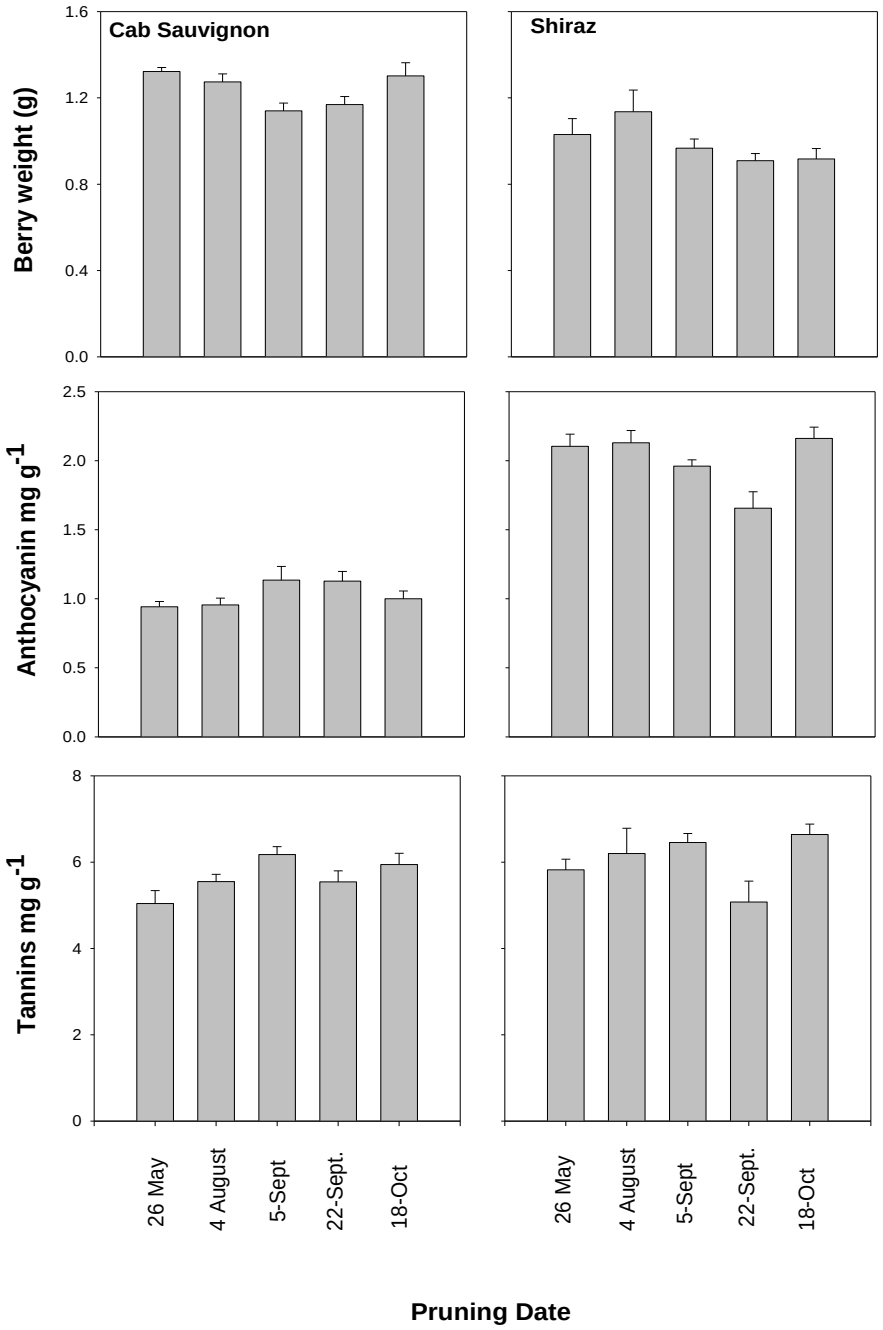


Figure 5 Berry size, anthocyanin and tannin contents in berries of Cabernet Sauvignon and Shiraz in response to pruning date. Error bars are one standard error of the mean.

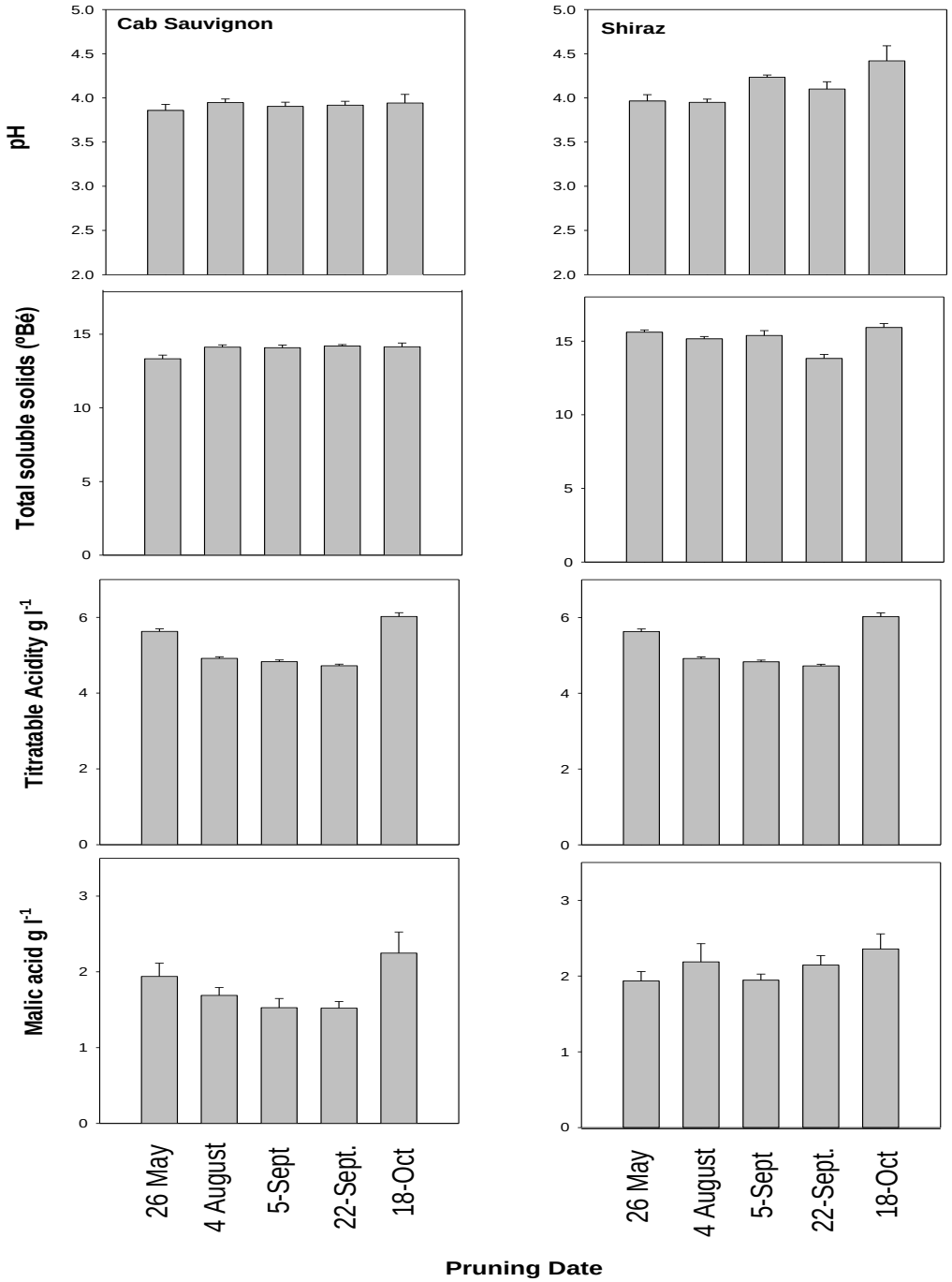


Figure 6 Chemistry juice analysis at harvest of Cabernet Sauvignon and Shiraz in response to pruning date. Error bars are one standard error of the mean.

Chapter 2

Effects of elevated temperature and water stress on Shiraz wines

M Bonada[1], VO Sadras, MA Moran, P Petrie

Introduction

Irrigation strategies that maximise profitability in viticulture need to deal with the dual objectives of production volume and quality (Sadras and Schultz 2012). Moderated water deficit during ripening is considered beneficial for production of quality grapes in red wine cultivars (Kennedy et al. 2002, Roby and Matthews 2004, Iland et al. 2011, Basile et al. 2011, Intrigliolo et al. 2012). However, water deficit during sensitive periods, e.g. flowering, may constrain production and affect grape quality (Ojeda et al. 2002).

Indirect studies with time series have related wine attributes and temperature (Jones et al. 2005, Duchene and Schneider 2005, Sadras et al. 2007). However, temperature varies alongside other sources of variation, and like all indirect methods, caution is needed in drawing conclusions from time series studies or comparisons between vintages or regions. Direct experimental evidence supports the negative effect of elevated temperature on aspects of berry and wine quality. Advanced berry development, as driven by warming, accelerates shrivelling and decouples berry sensory traits (Bonada et al. 2013a, Sadras et al. 2013). Furthermore, temperature effects on wine sensory profiles depend on the cultivar (Sadras et al. 2012c). In the light of these results, developing winemaking strategies aiming to warming adaptation should integrate findings from direct evaluations combining factors, temperature and water, in realistic field conditions. Here we report the effects of elevated temperature combined with water deficit on Shiraz wine attributes.

[1] This section is part of Marcos Bonada Ph D thesis, University of Adelaide.

Methods

Experiments

The experimental vineyard is located in the Nuriootpa Research Station in the Barossa Valley of South Australia (34◦S, 139◦E). Own-rooted Shiraz vines (clone 1654) were planted in 2004 on a red brown earth (Northcote 1979). Row orientation is north-south and vines are planted at 2.25 m between vines and 3.0 m between rows. Vines are spur-pruned to 40-50 buds per vine and trained to a single-wire trellis.

The factorial experiment was established on October 2010; it combines two temperatures and two irrigation regimes. Treatments were laid out in a split-plot design with three replicates; temperature was assigned to main plot and water regimen to subplots. The vineyard has received the same management since the treatments were established. Each replicate included nine vines; sampling was constrained to the seven central vines of each replicate, leaving the two external vines as buffers. To avoid interference between treatments, one guard row was left on both sides of the experimental row and replicates were separated by a buffer zone ~ 13.5 m.

Heated plants were compared with control vines at ambient temperature. To increase temperature under realistic field conditions we use open-top chambers. Full construction details, performance and limitation are in Sadras et al. (2012a). Briefly, these automated chambers combine passive heating during clear-sky day's hours and active heating, with pressured hot water, during cloudy or night's hours. Automated open-close panels allow for dissipation of heat when temperature exceeds the target and heat irradiates through hot water circulating through polyethylene pipes at soil level when passive heating is insufficient.

Water regimens were imposed in two consecutive seasons (2010/11 and 2011/12) based on calendar applications. Control vines were watered weekly at a flow rate of ~ 4.4L h^{-1}, during ~ 8 hours per irrigation event. Each row had one lateral with pressure compensated button drippers spaced at one meter intervals. During the season 2010-11, well watered plants were watered seven times from 24 January and 07 March, while water deficit vines were irrigated only twice on 21st and 28th February. In the drier season 2011/12 irrigation scheduling started earlier and control plants received 13 irrigations from 26 November to 24 February in comparison with their water deficit counterparts that were irrigated only twice on 24 January and 17 February.

The approach used for characterising thermal and water regime in this experiment have been reported elsewhere (Sadras and Moran 2012b, Sadras et al. 2012b). Briefly, temperature and relative humidity at mid canopy level from each replicate was continuously monitored during both growing seasons and the intervening dormant period using Tinytag Ultra2 temperature and humidity loggers (Hastings Dataloggers, Port Macquarie, Australia). Vine water status during the season was assessed using the procedures of Hsiao (1990); during both seasons we measured pre-dawn water potential as previously reported in Sadras and Moran (2012a). In 2011-12, we also measured stem water potential at mid-day (Bonada et al. 2013b).

Micro-vinification

Microvinification was carried out following the procedures previously described in Sadras et al. (2012c) and Imre et al. (2012). Grapes were hand harvested targeting a similar concentration of total soluble solids between treatments. Field replicate identity was maintained during the vinification process to avoid confounded field and fermentation effects (Sadras et al. 2012c); fruit was separately crushed and destemmed using hand operated equipment. Potassium metabisulfite was added on the resulting must at a rate of 0.1 g/kg fruit. Standard juice analyses were undertaken immediately after crushing following the guidelines of Iland et al. (2000); including total soluble solids (digital refractometer; HI 96801, HANNA, Woonsocket, Rhode Island, USA), titratable acidity and pH (autotitrator; CRISON, Barcelona, Spain). Must was inoculated with dry yeast (*Saccharomyces cerevisiae* Lalvin EC-1118, Lallemand Inc., Montreal, Quebec, Canada) and yeast nutrient (0.3 g/L) following the manufacturer's instructions. The fermentation was carried out on skins in 75 L plastic bins at temperature controlled room (~ 22^{o}C), with the ferment being plunged twice a day. When fermentation was completed (reducing sugars < 2g/L), the wine was pressed and racked into 10 L demijohns and inoculated with malolactic bacteria (*Oenococcus oeni* Lalvin VP 41, Lallemand Inc., Montreal, Quebec, Canada). After malolactic fermentation (< 0.1 g/L malic acid), wine was treated with potassium metabisulfite and tartaric acid as required. The wine was racked clean from the lees, bottled and sealed with screw-caps and stored at temperature controlled room (~17^{o}C) until sensory assessment.

Sensory assessment

Wine sensory assessment was undertaken by a tasting panel of 15 (2011) and 20 (2012) professional winemakers from Treasury Wine Estates. Prior to the formal tasting in 2011, winemakers defined the most contrasting attributes between treatments; by consensus four attributes were chosen (berry flavours, floral aromas, cooked fruit flavours and tannin structure). The ranking test procedure was used to assess sensory intensity of each single attribute across treatments (Lawless and Heymann 2010). Sample wines of each treatment were presented in random order to panellists who were asked to rearrange for each attribute in a rank order from least intense (1) to more intense (4). Wines were presented in coded, black, tulip-shaped wine glasses (~ 25 mL at ambient temperature) covered by glass Petri dishes. In both seasons wines testing included three replicates and all samples were tested in a single 2-h session.

Statistical analyses

The effects of temperature, water and their interaction on berry total soluble solids (TSS), titratable acidity (TA) and pH was assessed at harvest with the analysis of the variance. Both non-parametric (Friedman test) and parametric (ANOVA) methods were used to analyse the ranking data for each sensory attribute (Juanola et al. 2004). To test for significance of treatment effects, Friedman's statistic (F) was calculated and compared with the χ^2 distribution for three degrees of freedom at a 5% level of significance (Lawless and Heymann 2010). Assuming that the ranks were quantitatively related to the intensity of the attribute, the analysis of the variance was done testing for the effect of temperature, water and the temperature x water interaction for each season.

Results

Growing conditions

Background climate conditions were different between seasons; 2011-12 was warmer and drier than 2010-11. During the growing period September to March, differences in mean minimum temperatures were negligible between seasons (< 0.02^{o}C), mean maximum temperature, however, was ~ 1.5^{o}C higher in 2011-12. The accumulated rainfall during the season 2010-11 (September to March) was 509 mm, which compares with the 257 mm in the same period during 2011-12.

Performance of the heating system, including potential artefacts, and thermal regimes during the experiments have been fully described (Sadras et al. 2012b, Sadras and Moran 2012b). Across two growing seasons and the intervening winter, from September 2010 to March 2012, mean daily temperature at canopy level in the heated treatments was 1.31^{o}C (SD = 0.63) higher than in controls (Sadras and Moran 2012a).

Temperature treatments did not affect pre-dawn leaf water potential; the data pooled across temperature regimes showed significant differences in pre-dawn leaf water potential between irrigated and deficit treatments in both seasons (Supplementary Figure 1 in Sadras and Moran 2012a). Briefly, differences started to develop shortly before veraison and lasted for 3 weeks in 2010-2011 and extended too shortly before harvest in 2011-12. Measurements of mid-day stem water potential in 2011-12 showed that control treatments were maintained at or above -1.0 MPa from pea size to harvest (Bonada et al. 2013b). Severe stress developed in the water deficit treatments from veraison to harvest (> -1.2 MPa). Heated vines had lower stem water potential (more negative) compared to vines at ambient temperature (P = 0.02).

Total soluble solids, TA, TSS:TA ratio and pH in berry juice

We targeted to harvest grapes at the same sugar concentration between treatments; this was achieved on both seasons for all treatments. There was a highly significant season effect (P < 0.0001) on TSS content, whereby concentrations were higher in 2011-12 (~ 26.6) than in 2010-11 (~ 23.2). Differences were undetectable between water and temperature treatments, however, when data was split by seasons (Table 1, Figure 1a and b).

The remaining berry traits (TA, pH and TSS:TA ratio) responded to temperature ($P < 0.0001$) and temperature x season interaction ($P < 0.01$). The higher titratable acidity of berries in 2011-12 (Figure 2c and d) was reflected on the significant seasonal effect found on TA ($P < 0.0001$). To interpret the high order effects, we split data by seasons; only temperature on 2010-11 accounted by variations in these traits (Table 2). Irrespective of water regime, berries from heated treatments had lower TA and higher pH and TSS:TA ratio compared with controls (Figure 2c, e and g).

Wine sensory

We analysed sensory results using both parametric and non-parametric statistics. Both methods returned consistent results; non-parametric analysis, however, preclude discriminating single effects. Table 1 and Figure 1 summarise the single and combined effects of temperature and water on berry sensory attributes assessed during both seasons. Only two attributes were affected by treatments during 2010-11. Elevated temperature increased berry floral aromas for both irrigated and water deficit treatments, and increase cooked fruit flavours in deficit but not in control treatments.

In 2011-12 the four tested attributes were affected by temperature, water and/or by their interaction. Water deficit enhanced floral aromas in berries from both control and heated treatments. There was an interaction between temperature and water in berry floral aromas whereby this trait was enhanced by warming in water deficit berries but was reduced in control berries. Similar effects were found in cooked fruit flavours and tannin structure attributes; warming slightly increased these attributes in irrigated treatments but strongly reduced these characters in water deficit treatments.

Concluding remarks

The effect of water deficit on wine attributes is well established, as experiments with variable water regimes are straightforward. In contrast, there were no previous reports where the thermal regime of the vineyard was manipulated; our understanding of temperature effects on wines is mostly indirect, from comparisons between vintages and regions. Here we report, for

the first time, the combined effects of water deficit and elevated temperature. Berry flavours, floral aromas, cooked fruit flavours and tannin structure responded to the interaction between water and temperature, particularly in 2012.

Table 1: *P* values from the analysis of variance assessing the effects of temperature, water and their interaction on traits of Shiraz berries during two seasons in the Barossa Valley.

Vintage	Source of variation	*P*			
		TSS (^{o}Brix)	**TA (g/L)**	**pH**	**TSS/TA (^{o}Brix/g/L)**
2010-11	Temperature (T)	0.2426	**<0.0001**	**<0.0001**	**<0.0001**
	Water (W)	0.2426	0.9835	0.1482	0.6398
	T x W	0.4572	0.7261	0.1901	0.9565
2011-12	Temperature (T)	0.6953	0.2099	0.2381	0.3080
	Water (W)	0.0560	0.1533	0.2819	0.0991
	T x W	0.4974	0.7790	0.6402	0.9327

Table 2: Effect of temperature, water regime and their interaction on Shiraz wines sensory traits during two seasons in the Barossa Valley. *P* values are from the analysis of the variance and Friedman's test (df = 3).

Vintage	Descriptor	*P* values (ANOVA)			Friedman	
		Water	Temperature	Interaction	F	*P*
2010-11	Berry flavours	0.0953	0.1247	0.3157	4.78	0.1889
	Floral aromas	0.6877	**0.0331**	0.2287	4.89	0.1813
	Cooked fruit flavours	0.7384	0.6402	**0.0286**	3.93	0.2695
	Tannin structure	0.1820	0.5038	0.0623	4.58	0.2052
2011-12	Berry flavours	**0.0102**	0.0654	0.3206	9.13	**0.0276**
	Floral aromas	0.5955	0.6796	**0.0002**	10.62	**0.0140**
	Cooked fruit flavours	**0.0094**	**0.0181**	**0.0132**	13.66	**0.0032**
	Tannin structure	0.0607	**0.0186**	**0.0149**	11.75	**0.0083**

Caption of Figures

Fig. 1: Total soluble solids (TSS), titratable acidity (TA), pH and TSS:TA ratio of grape juice at harvest for Shiraz berries grown in a factorial (2 x 2) temperature (control and heated) by water (deficit and irrigated) experiment. Data are from two consecutive seasons, 2010-11 (left) and 2011-12 (right), in the Barossa Valley. Values are mean ± standard error.

Figure 2: Sensory attributes of wines from Shiraz grapes grown under two temperature (control and heated) and water (deficit and irrigated) regime. Values are mean ± standard error for two consecutive seasons, 2010-11 (left) and 2011-12 (right), in the Barossa Valley.

Figure 1

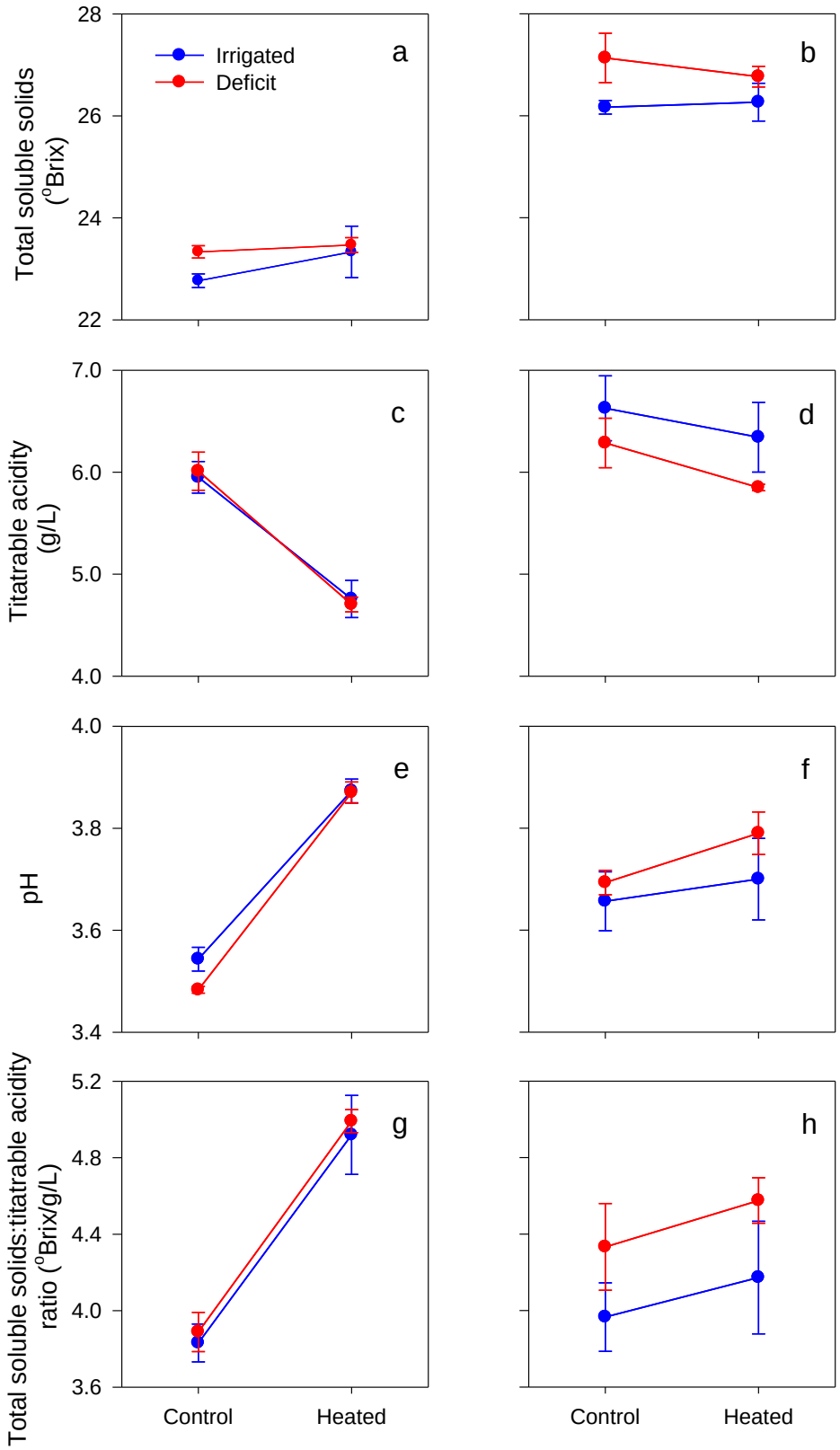
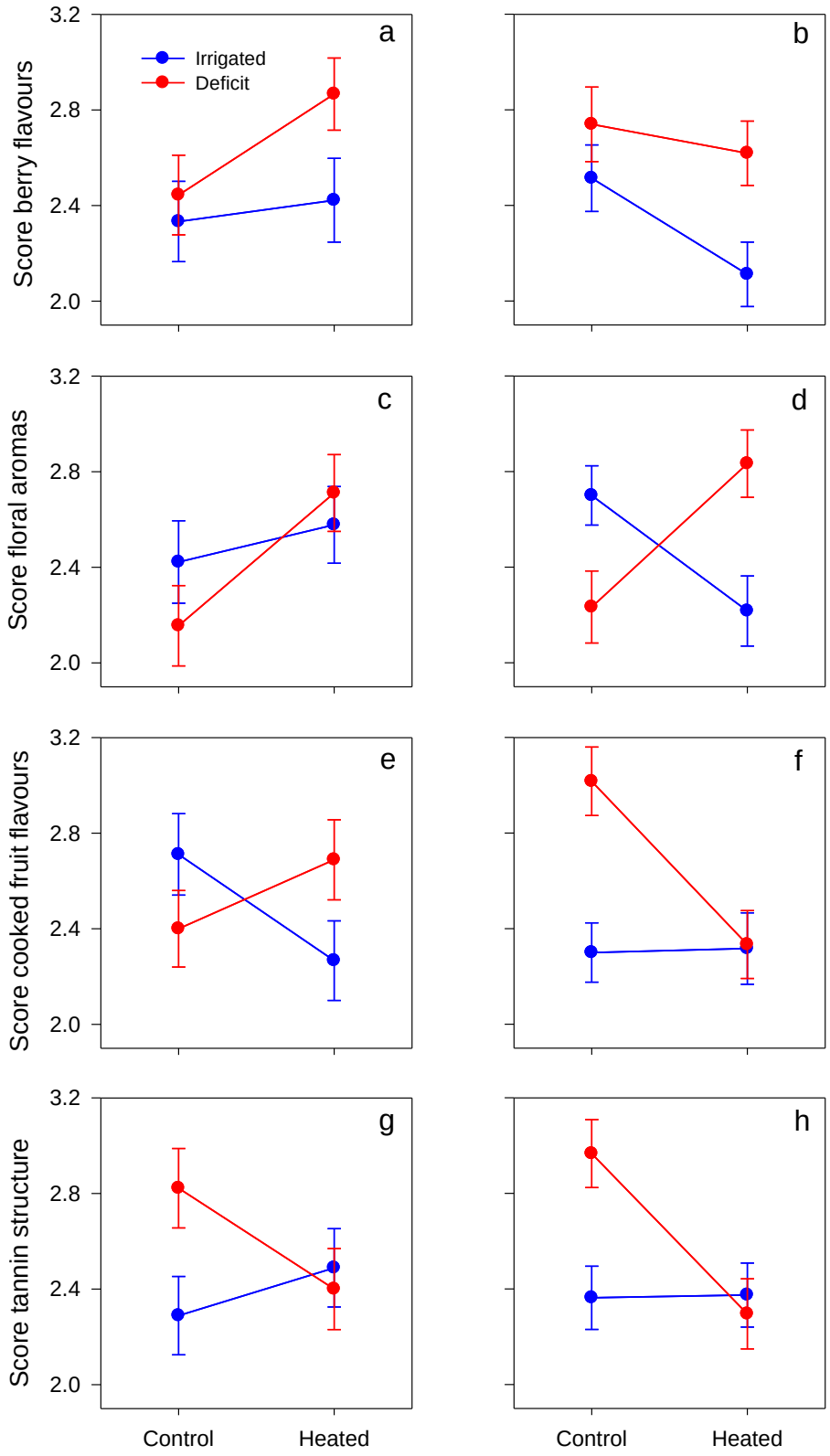

Irrigated
Deficit
a
b
c
d
e
f
g
h
Total soluble solids (°Brix)
Titatrable acidity (g/L)
pH
Total soluble solids:titatrable acidity ratio (°Brix/g/L)
28
26
24
22
7.0
6.0
5.0
4.0
4.0
3.8
3.6
3.4
5.2
4.8
4.4
4.0
3.6
Control
Heated
Control
Heated

Figure 2


a
b
c
d
e
f
g
h
Irrigated
Deficit
Score berry flavours
Score floral aromas
Score cooked fruit flavours
Score tannin structure
3.2
2.8
2.4
2.0
Control
Heated

References

Basile, B., Marsal, J., Mata, M., Vallverdu, X., Bellvert, J., and Girona, J. (2011) Phenological sensitivity of Cabernet Sauvignon to water stress: vine physiology and berry composition. American Journal of Enology and Viticulture **62**, 452-461.

Bonada, M., Sadras, V.O., and Fuentes, S. (2013a) Effect of elevated temperature on the onset and rate of mesocarp cell death in berries of Shiraz and Chardonnay and its relationship with berry shrivel. Australian Journal of Grape and Wine Research **19**, 87-94.

Bonada, M., Sadras, V.O., Moran, A.M., and Fuentes, S. (2013b) Elevated temperature and water stress accelerate mesocarp cell death, shrivelling and accelerate and decouple sensory traits in Shiraz berries. Irrigation Science **Submitted**.

Brunetti, M., Maugeri, M., and Nanni, T. (2000) Variations of temperature and precipitation in Italy from 1866 to 1995. Theoretical and Applied Climatology **65**, 165-174.

Duchene, E. and Schneider, C. (2005) Grapevine and climatic changes: a glance at the situation in Alsace. Agronomy for Sustainable Development **25**, 93–99.

Giorgi, F. and Lionello, P. (2008) Climate change projections for the Mediterranean region. Global and Planetary Change **63**, 90-104.

Hsiao, T.C. (1990) Measurements of plant water status. In: Irrigation of agricultural crops, Eds. Stewart, B.A. and Nielsen, D.R. (ASA, CSSA, SSSA: Madison) pp. 243–279.

Iland, P., Dry, P., Proffitt, T., and Tyerman, S. (2011) Water, soil and the vine. In: The grapevine from the science to the practice of growing vines for wine (Patrick Iland Wine Promotions Pty Ltd: Adelaide, South Australia, Australia) pp. 184-232.

Iland, P., Ewart, A., Sitters, J., Markides, A., and Bruer, N. (2000) Techniques for chemical analysis and quality monitoring during winemaking. (Patrick Iland Wine Promotions: Adelaide, South Australia).

Imre, S., Kilmartin, A., Rutan, T., Mauk, L., and Nicolau, L. (2012) Influence of soil geochemistry on the chemical and aroma profiles of Pinot noir wines. Journal of Agriculture & Environment **10**, 280-288.

Intrigliolo, D.S., Perez, D., Risco, D., Yeves, A., and Castel, J.R. (2012) Yield components and grape composition responses to seasonal water deficits in Tempranillo grapevines. Irrigation Science **30**, 339-349.

Jones, G., White, M., Cooper, O., and Storchmann, K. (2005) Climate change and global wine quality. Climatic Change **73**, 319–343.

Juanola, R., Guerrero, L., Subirà, D., Salvadó, V., Insa, S., Garcia Regueiro, J.A., and Anticó, E. (2004) Relationship between sensory and instrumental analysis of 2,4,6-trichloroanisole in wine and cork stoppers. Analytica Chimica Acta **513**, 291-297.

Kennedy, J.A., Matthews, M.A., and Waterhouse, A.L. (2002) Effect of maturity and vine water status on grape skin and wine flavonoids. American Journal of Enology and Viticulture **53**, 268-274.

Lawless, H.T. and Heymann, H. (2010) Sensory evaluation of food. Principles and practices. (New York).

Northcote, K.H. (1979) A factual key for the recognition of Australian soils. (Rellim Technical Publications: Glenside, S.A., Australia).

Ojeda, H., Andary, C., Kraeva, E., Carbonneau, A., and Deloire, A. (2002) Influence of pre- and postveraison water deficit on synthesis and concentration of skin phenolic compounds during berry growth of *Vitis vinifera* cv. Shiraz. American Journal of Enology and Viticulture **53**, 261-267.

Roby, G. and Matthews, M.A. (2004) Relative proportions of seed, skin and flesh, in ripe berries from Cabernet Sauvignon grapevines grown in a vineyard either well irrigated or under water deficit. Australian Journal of Grape and Wine Research **10**, 74-82.

Sadras, V.O., Bubner, R., and Moran, M.A. (2012a) A large-scale, open-top system to increase temperature in realistic vineyard conditions. Agricultural and Forest Meteorology **154–155**, 187–194.

Sadras, V.O., Montoro, A., Moran, M.A., and Aphalo, P.J. (2012b) Elevated temperature altered the reaction norms of stomatal conductance in field-grown grapevine. Agricultural and Forest Meteorology **165**, 35-42.

Sadras, V.O. and Moran, A.M. (2012a) Nonlinear effects of elevated temperature on grapevine phenology Agricultural and Forest Meteorology http://dx.doi.org/10.1016/j.agrformet.2012.10.003.

Sadras, V.O. and Moran, M.A. (2012b) Elevated temperature decouples anthocyanins and sugars in berries of Shiraz and Cabernet Franc. Australian Journal of Grape and Wine Research **18**, 115-122.

Sadras, V.O., Moran, M.A., and Bonada, M. (2013) Effects of elevated temperature in grapevine. I Berry sensory traits. Australian Journal of Grape and Wine Research **19**, 95-106.

Sadras, V.O., Petrie, P.R., and Moran, A.M. (2012c) Effects of elevated temperature in grapevine. II Juice pH, titratable acidity and wine sensory attributes Australian Journal of Grape and Wine Research **In press**.

Sadras, V.O. and Schultz, H., "Crop yiel response to water", in *FAO irrigation and drainage paper # 66*, edited by Steduto, P., Hsiao, T.C., Fereres, E., and Raes, D. (Food and Agriculture Organization of the United Nations, via delle Terme di Caracalla, Roma, Italy, 2012).

Sadras, V.O., Soar, C.J., and Petrie, P.R. (2007) Quantification of time trends in vintage scores and their variability for major wine regions of Australia. Australian Journal of Grape and Wine Research **13**, 117-123.

Webb, L.B., Whetton, P.H., and Barlow, E.W.R. (2007) Modelled impact of future climate change on the phenology of winegrapes in Australia. Australian Journal of Grape and Wine Research **13**, 165–175.