Managing grapevines in variable climates: The impact of temperature



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Managing grapevines in variable climates: The impact of temperature

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Executive Summary

This project had two objectives:

1. Summarise the effects of weather events on yield and quality components in grape production in Australia. Emphasis is placed on temperature, and its quantitative effects on crop phenology, flower and fruit development, berry growth and ripening.

2. Develop and deliver the synthesis of information in a risk management framework.

Working with 1.5 full time equivalents, the project delivered 8 industry publications, 10 scientific publications, 29 presentations in industry and scientific meetings, and a website summary:
http://www.scitopics.com/Temperature_vines_and_wines.html.

Achievements in relation to objective 1 include:

1. State-of-the-art, novel techniques to simulate (i) short, extreme heat waves, (ii) milder, longer increases in whole-canopy temperature, and (iii) refined control of bunch temperature. An important feature of all these systems is that they were devised for application in realistic field conditions, as opposed to controlled environments where experimental artefacts are more likely.

2. Field studies demonstrated the capacity of irrigated Shiraz to withstand three consecutive days of daytime temperature around or over 40 ^{o}C. Important corollaries from these findings are: (i) the importance of irrigation to maintain canopy functioning and berry growth and development, and (ii) indirect evidence on the importance of night temperature. The up regulation of stomatal conductance in Shiraz was possibly involved in this response. If so, cultivars with different stomatal behaviour and water-stressed vines may have a different sensitivity to heat episodes. The three-way interaction between heat, variety and water supply was thus identified as critical, and will be the focus of SARDI's next project (GWRDC project SAR 0901).

3. An open-system to heat vines in the field was used to increase maximum temperature by 2-4 ^{o}C during 2-3 week phenological windows from budburst to few days before harvest. None of the treatments affected yield or yield components. This reinforced the conclusion that irrigated Shiraz has a considerable capacity to maintain its performance under this range of temperature increase.

4. Irrigated Shiraz under typical Barossa conditions maintained berry anthocyanins at harvest in response to discrete episodes of high temperature during ripening, including (a) 3-day periods of elevated maximum temperature (> 40 ^{o}C), (b) 2-week periods of elevated maximum temperature (2-4 ^{o}C above controls), and (c) 10-day periods with day temperature, night temperature or both elevated by about 6^{o}C in relation to controls.

5. The first Australian-wide report of actual advancement in grapevine maturity for Shiraz, Chardonnay, and Cabernet Sauvignon associated with recent warming. Using records from commercial vineyards across Australia, we showed an average change in time of maturity of 7 days per ^{o}C change in November temperature. The original database used in this study will be explored further in the next GWRDC project (SAR 0901) with the aim of improving methods to predict maturity with logistic applications in vineyard and winery.

6. The first Australian-wide report of measured changes in vintage quality over the last three decades. Despite warming trends, water shortages and financial pressure, this quantitative study clearly showed a sustained increase in both vintage quality and wine reliability attributable to technological improvement in vineyards and wineries.

7. A new statistical method to quantify the association between climate drivers and red wine quality. This was applied to the Hunter Valley, Margaret River, Coonawarra and Barossa Valley; critical phenological windows were identified and temperature, radiation and humidity conditions conducive to better vintages were identified for each region.

8. Quantitative characterisation of phenological plasticity of seven grapevine varieties in South Australia. We show that plasticity of development before flowering is adaptive in terms of high yield potential. This is a new angle to the increasingly important issue of matching variety and environment.

9. New quantitative model of the dynamics of sugar concentration in Shiraz berries using allometric analysis. This model allows for both irrigation and seasonal effects on size-mediated changes in sugar concentration, and accounts for the typical shrinkage of Shiraz at late ripening stages.

10. An allometric approach to model accumulation of anthocyanins and sugars in berries of Cabernet Sauvignon accounting for irrigation and bunch thinning. We propose that irrigation management can partially compensate for putative decoupling of colour and sugar maturity caused by high temperature.

11. A comparative analysis of accumulation of sugar in berries and physiology of 12 grape varieties. This revealed the importance of stomatal conductance and its modulation by source:sink ratio (canopy:yield) in determining time of maturity. This opens opportunities to model and manage maturity that will be explored in the next GWRDC project (SAR 0901).

Achievements in relation to objective 2 include:

12. We addressed the question “Can we define dangerous climate change for Australian Viticulture”. While recognising the vulnerability to climate change, especially warming beyond 2-3 ^{o}C, we focused on the adaptive capacity at the level of the vine, vineyard and winery and the significant year to year variability in mean January and growing season temperature that is currently being managed.

13. Compilation of information on the meteorology of heatwaves. We characterised the weather patterns that lead to a hot day and the blocking process that leads to a run of hot days. This was applied to the recent heatwaves of February 2004, March 2008 and January 2009.

14. New insights in the climatology of heat waves. We developed a model that outlines a relationship between the frequency of a heatwave (number of times per year), the temperature (e.g. > 37 ^{o}C) and duration (number of days). This relationship is modified by location across the South East Australian wine regions.

15. The development of a simple method to determine, for any region in SE Australia, the likelihood of a heatwave of a given temperature and run of days for summer as a whole and every fortnight from September to April. This robust method could be used to examine the impact of climate change.

16. The application of a risk management framework to information from a weather forecast of a heatwave in the coming week or the climatological odds of a heatwave for a given location over the season. This risk management framework considers the accuracy of the information from weather and climate science and the benefits and costs of different decisions a grape grower or winery manager might make.

Introduction

Season-to-season variation in weather, chiefly temperature, affects grapevine phenology, and key yield and quality components. For example in the period 1950-1998, the date of Chardonnay budburst at Mildura ranged from August 19 (1962) to September 14 (1958)[1]. This variation in budburst date, estimated with VineLOGIC, reflects the variability in temperature in a single location. Early budburst might increase frost risk, whereas later budburst may shift subsequent processes of flower development, fruit set, berry growth and ripening into warmer conditions. All these shifts in phenology are likely to have important consequences for yield and berry attributes. For instance, the experiments of Petrie and Clingeleffer[1], where they exposed single buds to a range of temperatures under field conditions, indicated flower number declined at a rate of 24 (apical inflorescence) or 33 (basal inflorescence) flowers per ^{o}C increase in temperature in the 2 weeks previous to budburst. This decline was found for a relatively narrow range of temperature, about 3 ^{o}C. From long-term records at Mildura, the calculated range in average temperature 2 weeks before budburst was 4.2 ^{o}C and the estimated number of flowers per inflorescence varied over a range of at least 100. Studies with a similar level of detail that focus on the effect of high temperature at other phenological windows are scarce and highlight important knowledge gaps. Importantly, the widespread notion that vine "shutdown" in response to heat stress is widespread is inconclusive in the absence of studies where heated and control vines are compared.

Against the background of a partial understanding of the effects of temperature on grapevine physiology and berry and wine attributes, and the relevance of these questions for industry, Project SAR 05-01 had two objectives:

1. Summarise the effects of weather events on yield and quality components in grape production in Australia. Emphasis is placed on temperature, and its quantitative effects on crop phenology, flower and fruit development, berry growth and ripening.

2. Develop and deliver the synthesis of information in a risk management framework.

This publication is organised in three parts. Part 1 deals with objective 1 and reports the results of field experiments, literature reviews and novel statistical and modelling analysis on the reponses of vines and wines to climate, with emphasis on temperature. Part 2 addresses objective 2 and covers the weather patterns and the mathematical odds of heatwaves in SE Australia and considers how these might be managed. Part 3 summarises the communication activities associated with the project and outlines future research lines.

[1] Petrie PR, Clingeleffer PR (2005) Australian J. Grape and Wine Research 11, 59-65.

Part 1

Vine physiology and wine quality: effects of climate and interactions with technology

Indirect and direct methods have been used to investigate the effects of temperature on vines and wines. Indirect methods have compared seasons, regions and analysed long-term data series using a range of statistical tools to infer the putative effects of temperature. Results from this indirect approach are valuable, but are bound to remain inconclusive because temperature is correlated with other factors such as radiation, vapour pressure deficit and rainfall and the confounding effects of technological change. Unequivocal results require direct comparisons where vines are exposed to different temperatures. Manipulation of temperature in controlled environments is straightforward and this has been the favoured method, but growing vines in pots in chambers or glasshouses often bears little relation to vineyard conditions. We thus developed, tested and deployed three novel systems to control temperature in the field (Chapter 1). Field studies showed higher than expected tolerance to high temperature in irrigated Shiraz, and some of the physiological mechanisms have been unveiled (Chapters 2-3). Yield, yield components, berry growth, sugar accumulation were largely unaffected by discrete events of high temperature.

We assessed long-term records of vine phenology to quantify the advancement in maturity associated with recent warming (Chapter 4), the improvements in wine quality driven by technological developments during the last three decades (Chapter 5) and associations between climate drivers and red wine quality (Chapter 6). Chapter 7 presents new physiological insights on the adaptive value of phenological development in grapevine varieties that is relevant to the key question of how to match variety and environment. Allometric analysis is used to develop new models of berry development and growth (Chapters 8-10). These models account for effects of berry size and shed new light on the opportunities to manipulate berry composition, for example the relative rate of accumulation of pigments and sugars, using irrigation as a management tool.

Chapter 1

Development of methods for heating canopies and bunches under realistic vineyard conditions

CJ Soar, VO Sadras

Summary

We describe three heating systems that were developed, tested and applied over the experimental seasons of the project. Two whole-canopy systems and one bunch heating system were developed and all three systems were found to have distinct but useful applications in the context of this project. The systems can be used in combination (eg. chamber and bunch blower), upgraded (e.g. open system upgraded to increase night time temperature) and combined with other facilieties, e.g. our open heating system could be combined with Free Air CO_2 Enrichment (FACE) facilities to investigate temperature by CO_2 interactions.

Scope

One component of objective 1 in this project is the development and use of whole-of-vine and bunch heating systems to directly measure the effects of elevated temperature on grapevine phenology and fruit growth and composition. Our targets were

1. To devise a range of experimental systems to control ambient temperature in vineyards.

2. To test prototype systems for strengths and weaknesses to define potential applications and required modifications ready for construction of full-scale systems.

Two prototypes for heating entire canopies (closed chamber and undervine tent, UVT) and one for modifying bunch temperature alone (bunch blower) were constructed and tested during the 2006/2007 season and improved and deployed in subsequent seasons.

Overview of heating devices

Chamber

Constructed in collaboration with CSIRO, the chamber enclosed a single panel of three vines and comprised a 6 x 2 x 2 m (L x W x H) steel tubular frame covered with soft PVC sheeting in 2006/07 and solid Standard-Clear-Greca polycarbonate sheeting (Suntuf, Australia) afterwards (Fig. 1). This material blocks most UV radiation (200 to 400 nm) and has a very high (90 %) and uniform transmittance between 400 and 1600 nm. Maximum temperature was thermostatically controlled by

ventilation with outside cooler air circulated by four fixed fans (Nicotra DD9-9T 315W, Australia). Air was distributed through 300 mm PVC ducts with holes (100 mm diameter) at 30 cm intervals (Fig. 1). The thermostats were set to start the fans on the low setting when the temperature in the chamber reached 42ºC. The fan speed was automatically increased if necessary in the event that the temperature continued to rise above the set point. Temperature and humidity both inside and outside the chambers were recorded at 15 min intervals using TinyTag Ultra2 temperature and humidity loggers (Hastings Dataloggers, Port Macquarie, Australia) which where shielded in Stevenson type screens. During normal operation two fans were run on 2x speed and two on 3x speed which based on the average flows of all fans meant that the full chamber volume was being replaced approximately once every 13 seconds.



Figure 1. Heating chamber showing detail of fans and perforated pipe for air distribution.

Under Vine Tent

Two support wires, one each side of the vine row, were mounted on steel brackets immediately below the bunch zone 45cm either side of the row. This created a 90cm wide opening along the top of the tent after the walls were installed. The prototypes were approximately 20 m long and spanned 3 panels or 9 vines. Plastic sheeting was attached to this supporting wire using 2m long aluminium V-Grip™ shade-cloth fasteners (V-Grip Australia). The bottom edge of the plastic was then pulled out towards the mid-row to form an angled face similar to that of an A-frame tent. The bottom edge of the plastic was fastened to the ground using Holdon™ Midi clips (Amicus-trade AB Sweden) and tent pegs. In the first season, we tested black and clear plastic (200 µm PVC), and found clear gave better results. In subsequent seasons, the system was improved in two aspects (a) a solid frame (rather than wire) and (b) solid Standard-Clear-Greca polycarbonate sheeting (Suntuf, Australia) were used (Fig. 2).



Figure 2. Undervine tent with solid polycarbonate walls.

Bunch blowers

Bunch blowers were designed and built by Measurement Engineering Australia based on a modified concept of Tarara et al[2]. Blowers were constructed from 150mm PVC plastic piping and were fitted internally with 200W heating elements complete with a heat sink and a 240V fan mounted on the inlet end that delivered a flow of approx 25 L/s at the outlet (Fig. 3).

The control of the blowers was via a software feedback based on temperatures measured by a bead thermistor that could be positioned within the bunch cluster. Maximum and minimum set points could be programmed within the software such that the blowers were on when the temperature of the control thermistors were below the set minimum temperature and then switched off when the maximum temperature was exceeded. Control blowers with no heating elements were also designed that accounted for air flux.

[2] Tarara JM, Ferguson JC, Spayd SE (2000) A chamber-free method of heating and cooling grape clusters in the vineyard. Am. J. Enol. Vitic. 51, 182-188.



Figure 3. Bunch blowers

Performance of heating systems

Chamber

Figure 4 shows the temperature traces for both the control and treated vines for each of the four 3-day heating windows. For each time window the set temperature for the chamber was 42ºC. The actual temperatures in the chamber exceeded the set point in window 1 (day 1 and 3), window 2 (day 2 and 3) and window 4 (day 2), with the maximum temperature reached in any single window approximately 46 ºC on day 3 in window 2. Hot air passing through the cooling fans, either as a result of high ambient temperatures or recycling of hot air from inside the chamber was the more likely factor underlying the failure to control temperatures below the set point. The later issue arose because the circulation fans were mounted directly on the side walls of the chamber such that the billowing side walls of the chamber partially covered the fan inlets. The temperatures achieved in window 3 were noticeably lower than in any other window. Climate records showed that these three days were not significantly cloudier than during the other three windows. However, a heavy rainfall event (60 mm) in the four days prior to window 3, increased the humidity and resulted in heavy condensation on the interior of the chamber throughout the treatment period. It is believed that this condensation greatly reduced the heating efficiency of the chamber. An important feature of the chambers is that they altered vapour pressure deficit, rather than relative humidity (Fig. 5); this is a desirable attribute of methods to simulate heat stress as explained by Hall and Sadras.[3]

[3] Hall AJ, Sadras VO (2009) Whither crop physiology? . In 'Crop physiology: applications for genetic improvement and agronomy'. (Eds VO Sadras and DF Calderini) pp. 545-570. (Academic Press: San Diego)

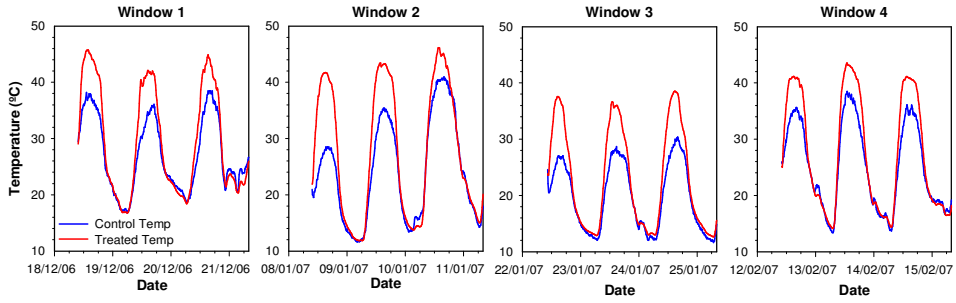


Figure 4. Temperature traces inside (red) and outside (blue) heating chambers at four 3-day windows of treatment in a vineyard at Nuriootpa.

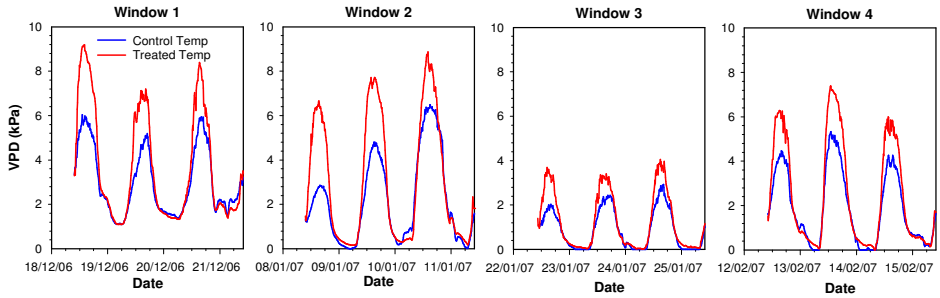


Figure 5. Vapour pressure deficit inside (red) and outside (blue) prototype heating chambers at four 3-day windows of treatment in a vineyard at Nuriootpa.

The issues with hot air intake by the fans and potential condensation after rain were largely overcome in the updated model of the chamber by (a) relocation of the fans away from the chamber into the shade of neighbouring rows, (b) an improved system to distribute air within the chamber using perforated pipes and (c) remodelling of the roof to a solid structure with the capacity for adjustable venting (Fig. 1). In the next section ("Irrigated Vitis vinifera L. Shiraz up-regulates gas exchange…") we present a critical and detailed analysis of the performance of the final chamber model, and its application to study the effect of short episodes of high temperature on Shiraz physiology and berry dynamics.

Under vine tent

Figure 6 shows the difference in ambient temperature between the prototype undervine tents and untreated controls. Clear single layer plastic provided the best overall heating with maximum day temperatures elevated 4 ºC above ambient with some days spiking to 5 or 6 ºC above control and no change in night temperature. Black plastic was less effective and also reduced ambient temperature at night. The final version of the system therefore used clear material and more robust and practical modular structure (Fig. 2).

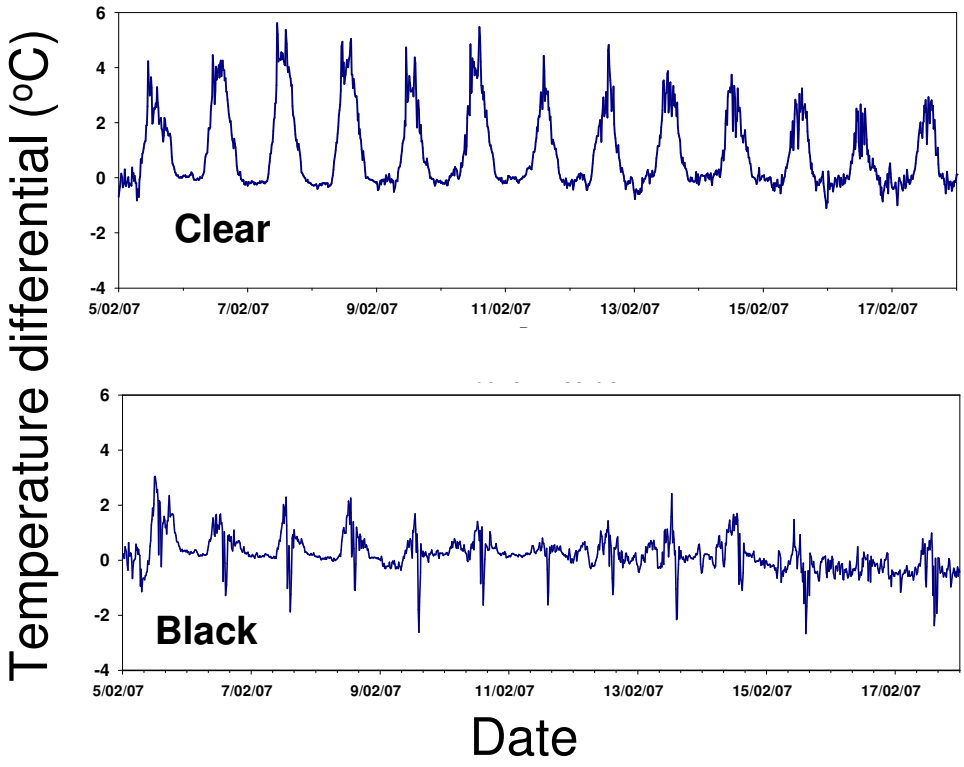


Figure 6. Difference in ambient temperature measured at bunch-level between undervine tents and untreated controls. Undervine tents used either clear or black plastic.

Owing to edge effects, heating was more effective in the central area of the tent. This highlights the need to have the UVT of sufficient length to provide adequate numbers of treated vines and detailed monitoring of temperature along the row. It was also observed that vines immediately adjacent to a UVT in the same row had elevated temperatures compared to ambient. This was likely due to wind displacing hot air from the UVT to non-target vines and highlights the need of proper buffers between treatments.

In comparison to the enclosed canopy in the chambers, the under vine tents maintained normal canopy exposure with minimum secondary effects on important environmental variables such as the light and air profiles, air flux and boundary layer. The under vine tents have the potential to be used to generate a smaller but sustained elevation in average day temperature over a longer period, possibly even an entire growing season. Another advantage of the undervine tent is that it is a relatively cheap structure that does not require mains power. Therefore the undervine tent can be erected in any vineyard and can be used to treat large numbers of vines. It therefore is a viable treatment method to investigate the effects of elevated temperature on quality components on small batch wines.

Bunch blowers

The bunch blowers were capable of increasing day and night time temperatures by up to approximately 5 ºC. The oscillation in night- time temperature increased as the differential between set temperature and ambient became greater. To counter this, it is important to set the control range for the software (i.e switch on/off temperatures) as narrowly as possible (1 ºC). The main deficiency in this system was related to the attachment of the control thermistor to the bunch. On many occasions the controlling thermistor became dislodged from its position in the bunch thus ruining temperature control and causing almost continuous heating without monitoring. This problem was easily overcome by developing a more reliable method of holding the thermistors in place relative to the bunch. Maximum temperatures attainable with these blowers could be elevated by substituting the heating elements for ones with higher power ratings.

Conclusion

All three heating systems provide a sound platform for manipulating temperature in realistic field conditions. Table 1 compares the features of the three systems discussed in this report highlighting their advantages and disadvantages. Most of the items on the list are inherent properties of each of the systems and cannot be modified. All three systems have unique and useful attributes that make them suitable to answer different questions. For example the chamber is the best system to look at short-term (3-5 days) well controlled extreme episodes of heat stress. However, owing to its non-target effects on light and air movement it is not well suited for long-term treatments. In contrast, the undervine tent is an open system that does not suffer from these non-target effects and can therefore be used for longer periods (weeks). However the under vine tent is only capable of modest, less controllable heating and so is not useful for looking at extreme temperatures but rather the effects of long term small increases in temperature. The applications for the bunch blowers are clearly distinct from the whole-of vine techniques. They allow for separation of temperature effects directly on the biochemistry/physiology of the bunch rather than the coupled effects of temperature on the canopy and the bunch. The bunch blowers also provide an easy means of looking at the effects of elevated night temperature versus day temperature and could be used in combination with either chambers or undervine tents.

Table 1. Comparison of characteristics, advantages and limitations of three experimental heating systems developed by SARDI.

Attribute	System		
	chamber	under vine tent	bunch blower
canopy heating	yes	yes	no
bunch heating	yes	yes	yes
programable max temperature	yes	no	partial
extreme daytime temperature (10 °C above ambient)	yes	no	no
night temperature	potentially	potentially	yes
cost	moderate	low	high
scalability	low	high	moderate
mobility	moderate	moderate	high
power requirement (24 OV)	yes	no	yes
effects on radiation	moderate	negligible	none
effects on humidity	moderate	negligible	none
effects on air movement	high	nil to moderate	moderate

Chapter 2

Irrigated *Vitis vinifera* L. Shiraz up-regulates gas exchange and maintains berry growth under short spells of high maximum temperature in the field

CJ Soar, MJ Collins, VO Sadras

Summary

We tested the hypotheses that (i) a short period of high maximum temperature disrupts gas exchange and arrests berry growth and sugar accumulation in established, well-watered Shiraz vines, and (ii) the magnitude of these effects depend on the phenological window when stress occur.

Using a system combining passive heating (greenhouse effect) and active cooling (fans) to control daytime temperature, we compared vines heated to a nominal maximum of 40 ^{o}C for three consecutive days and untreated controls. Maximum air temperature in heated treatments was 7.3 ^{o}C (2006/07) and 6.5 ^{o}C (2007/08) above ambient. Heat episodes were aligned with the beginning of a weekly irrigation cycle and applied in one of four phenological windows, namely post-fruit set, pre-veraison, veraison and pre-harvest. Heating systems did not affect relative humidity, hence vapour pressure deficit (VPD) in the heated treatments tracked the daily cycle of temperature.

Heat did not affect the dynamics of berry growth and sugar accumulation, except for a 16% reduction in berry size and sugar content in vines heated shortly after fruit set in 2006/07. Vines up-regulated stomatal conductance and gas exchange in response to heat. Stomatal conductance, photosynthesis and transpiration at a common VPD were consistently higher in heated vines than in controls. We propose that stomatal behaviour previously described as part of Shiraz anisohydric syndrome may be adaptive in terms of heat tolerance at the expense of short-term transpiration efficiency.

Introduction

Extreme events are not unprecedented but are uncommon, and play a disproportionate role in shaping the physiology, ecology and evolution of terrestrial plants (Gutschick and BassiriRad 2003). In addition to their biological significance, extreme events including heat waves are highly relevant for the wine industry. Indirect evidence indicates that high temperature may disrupt photosynthesis and berry sugar accumulation in commercial vineyards (AWBC 2008; Retallick and Schofield 2008) and phenological windows when high temperature correlates with low wine quality have been identified (Soar *et al.* 2008). However, these interpretations are speculative in the absence of experiments where heated vines and their products are compared with unheated controls under realistic field conditions.

Many studies of heat stress in vines have been carried out in controlled environments with a dominant focus on low levels of organisation and short-time responses (Kadir 2006; Kadir *et al.* 2007; Liu *et al.* 2008; Wang *et al.* 2004; Wang *et al.* 2005; Wang and Li 2006a; Wang and Li 2006b; Wen *et al.* 2008; Zhang *et al.* 2008). The focus of these studies included, for instance, subcellular localization of heat shock proteins (Zhang *et al.* 2008) and short-term (≤ 24 h) thermotolerance and related antioxidant enzyme activities (Wang and Li 2006b). The viticultural relevance of these studies is restricted by one or more factors including:

(a) the difficulties in scaling up from low (e.g. molecular or cellular) to the crop level of organisation and from short (hours) to seasonal (months) time scales (Sadras *et al.* 2009; Struik *et al.* 2007),
(b) unrealistic growing conditions, e.g. 40/35 ^{o}C day/night temperature for four weeks (Kadir 2006),
(c) artefacts typical of pot-grown plants (Ben-Porath and Baker 1990; McConnaughay and Bazzaz 1991; Passioura 2006; Sachs 2006; Sadras *et al.* 1993a; Sadras *et al.* 1993b; Wise *et al.* 1990), and
(d) other experimental manipulations, e.g. use of detached berries (Wen *et al.* 2008).

Less often, heat stress has been investigated under more realistic field conditions. Tarara et al. (2002; 2000) used ingenious devices to heat individual bunches, Bowen et al. (2004a; 2004b) used clear polyethylene enclosures around canes or cordons and Petrie and Clingeleffer (2005) used small plastic chambers to increase bud temperature. All these studies targeted specific questions, such as the separation of temperature and radiation effects, but none of them aimed at the heating of the whole canopy that is typical of heat wave conditions.

In this study we used closed chambers to simulate short heat episodes in established Shiraz vines. We tested the hypotheses that (i) three consecutive days of high maximum temperature (~ 40 ^{o}C) disrupt leaf gas exchange and arrest berry growth and sugar accumulation, and (ii) the magnitude of these effects depend on the phenological window when stress occur.

Methods

Experiments were carried out over two seasons. In 2006/07, an unreplicated trial aimed at refining heating systems and collecting preliminary data on vine responses. In 2007/08, a fully replicated experiment was carried out to test our working hypotheses.

Site and vines

Experiments were established on a red brown earth (Northcote 1979) at SARDI's Nuriootpa Research Station in the Barossa Valley of South Australia (34 ^{o}S, 139 ^{o}E). Gladstones (1992) and Dry and Coombe (2004) described the climate, soils and viticultural practices of the region. We used 10-year old Shiraz vines top-worked on Sauvignon Blanc roots (2006/07) and 3-year old own-rooted Shiraz (2007/08). Vines were spur pruned to 40-50 buds per vine and trained to a single-wire trellis; row spacing was 3.0 m and vine spacing 2.25 m. Vines were drip-irrigated weekly from mid December at a rate of ~ 21 L vine^{-1} per irrigation.

Heating system

The system combined passive heating (greenhouse effect) and active cooling (fans) to control daytime temperature (Fig. 1). Each chamber enclosed a single panel of three vines and comprised a 6 x 2 x 2 m (L x W x H) steel tubular frame covered with soft PVC sheeting in 2006/07 and solid Standard-Clear-Greca polycarbonate sheeting (Suntuf, Australia) in 2007/08. This material blocks most UV radiation (200 to 400 nm) and has a very high (90 %) and uniform transmittance between 400 and 1600 nm. Maximum temperature was thermostatically controlled by ventilation with outside cooler air circulated by four fixed fans (Nicotra DD9-9T 315W, Australia). Air was distributed through 300 mm PVC ducts with holes (100 mm diameter) at 30 cm intervals (Fig. 1). The thermostats were set to start the fans on the low setting when the temperature in the chamber reached 42ºC. The fan speed was automatically increased if necessary in the event that the temperature continued to rise above the set point. Temperature and humidity both inside and outside the chambers were recorded at 15 min intervals using TinyTag Ultra2 temperature and humidity loggers (Hastings Dataloggers, Port Macquarie, Australia) which where shielded in Stevenson type screens.



Figure 1. Heat chamber combining passive heating (greenhouse effect) and active cooling (fans) to control daytime temperature.

Treatments and experimental design

In both seasons, untreated (open air) controls were compared with vines heated to a nominal maximum of 40 ºC for three consecutive days. Comparison with long-term temperature records indicated this represents a rare (5.6 % chance) but realistic event in Nuriootpa (Fig. 2). Heat episodes were aligned with the beginning of the weekly irrigation cycle and applied in one of four phenological windows (Tables 1 and 2).

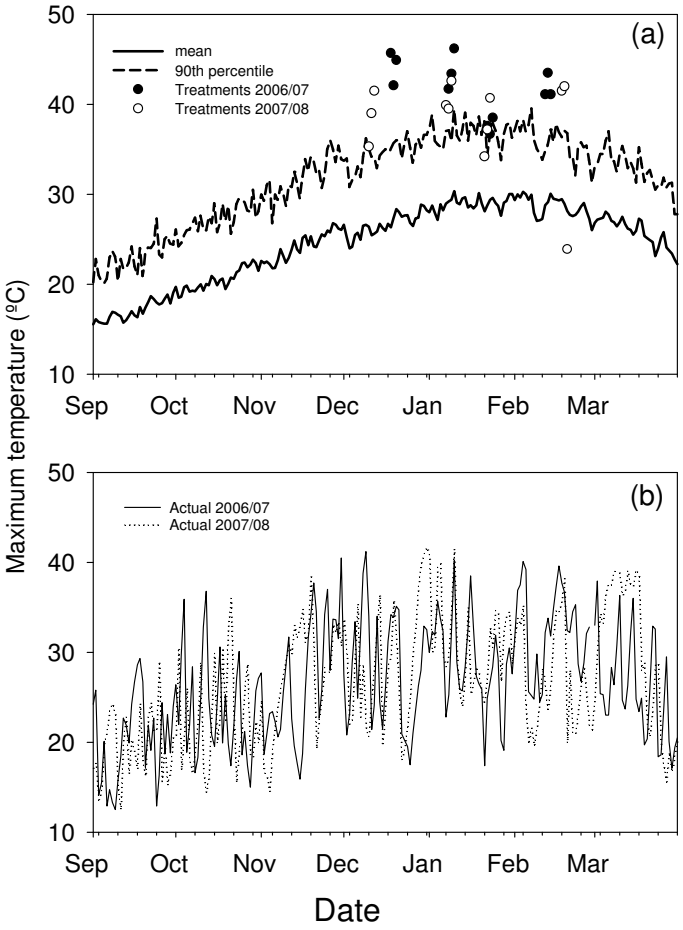


Figure 2. Heat chamber combining passive heating (greenhouse effect) and active cooling (fans) to control daytime temperature.

Table 1. Comparison of maximum temperature, minimum relative humidity and maximum vapour pressure deficit (VPD) in control and heated treatments applied at four phenological windows in 2006-07. Each heating episode lasted 3 days.

Heating window	Day	Maximum Temperature (ºC)			Minimum Relative Humidity			Maximum VPD (kPa)		
		Control	Heated	Diff.	Control	Heated	Diff.	Control	Heated	Diff.
18 to 20 Dec	1	38.2	45.7	7.5	9.0	7.2	-1.8	6.05	9.18	3.13
post-set	2	36.1	42.1	6.0	13.0	12.7	-0.3	5.19	7.20	2.01
E-L 31*	3	38.5	44.9	6.5	12.8	11.3	-1.5	5.94	8.40	2.46
8 to 10 Jan	1	28.5	41.7	13.2	25.3	17.8	-7.5	2.85	6.66	3.80
pre-veraison	2	35.4	43.4	8.0	16.3	12.3	-4.0	4.80	7.72	2.92
E-L 33	3	41.0	46.2	5.2	14.4	12.7	-1.7	6.49	8.87	2.39
22 to 24 Jan	1	28.4	37.6	9.2	38.2	40.9	2.7	2.37	3.70	1.33
veraison	2	28.7	36.7	8.0	30.2	36.4	6.1	2.44	3.40	0.95
E-L 35	3	30.4	38.5	8.1	31.5	38.5	6.9	2.93	4.05	1.12
12 to 14 Feb	1	35.7	41.1	5.5	23.5	19.6	-4.0	4.46	6.29	1.83
pre-harvest	2	38.5	43.5	5.1	21.2	17.2	-4.0	5.34	7.39	2.05
2 wk before E-L 37	3	36.1	41.1	5.0	28.5	23.9	-4.6	4.26	5.99	1.73

* E-L scale (Coombe 1995).

Table 2. Comparison of maximum temperature, minimum relative humidity and maximum vapour pressure deficit (VPD) in control and heated treatments applied at four phenological windows in 2007-08. Each heating episode lasted 3 days; the days before and after establishment of treatments are also shown. Night differences (heated – control) are shown for minimum temperature and maximum relative humidity.

Heating window	Day	Maximum temperature (ºC)			Minimum relative humidity (%)			Maximum VPD (kPa)			Night difference	
		Control	Heated	Diff.	Control	Heated	Diff.	Control	Heated	Diff.	Min Temp (ºC)	Max RH (%)
10 to 12 Dec	Before	24.3	24.4	0.1	33.5	32.4	-1.1	1.99	2.00	0.02	-0.1	-1.5
post-set	1	24.5	35.3	10.8	25.4	20.9	-4.5	2.21	4.40	2.19	-0.3	0.7
E-L 31*	2	28.8	39.0	10.2	27.4	23.0	-4.4	2.85	5.35	2.50	1.5	-3.8
	3	32.4	41.5	9.2	18.6	18.2	-0.4	3.94	6.58	2.63	0.4	-2.6
	After	37.1	37.0	-0.1	14.6	14.2	-0.4	5.38	5.40	0.02	-0.1	5.1
7 to 9 Jan	Before	33.9	33.5	-0.3	20.5	20.7	0.3	4.14	4.10	-0.05	0.0	-3.7
pre-veraison	1	32.4	39.9	7.5	21.6	21.3	-0.3	3.77	5.72	1.96	0.0	-1.1
E-L 33	2	32.8	39.5	6.7	24.4	24.1	-0.3	3.72	5.33	1.61	0.3	-2.6
	3	37.8	42.6	4.8	15.3	18.5	3.2	5.53	6.84	1.32	0.1	-1.3
	After	44.4	45.0	0.5	9.9	9.8	-0.1	8.39	8.55	0.17	0.9	4.2
21 to 23 Jan	Before	28.6	28.2	-0.4	36.4	36.8	0.5	2.47	2.39	-0.08	0.0	-1.9
veraison	1	27.1	34.2	7.1	25.8	27.0	1.3	2.57	3.81	1.24	-0.1	-1.1
E-L 35	2	29.9	37.2	7.4	26.1	25.9	-0.1	3.07	4.49	1.42	0.3	-2.7
	3	34.7	40.7	6.0	12.0	16.9	4.9	4.64	5.92	1.28	0.2	-0.9
	After	32.4	32.5	0.1	27.2	27.1	0.0	3.53	3.55	0.01	1.1	-6.9
18 to 20 Feb	Before	37.3	37.3	-0.1	13.6	14.4	0.9	5.43	5.40	-0.03	-0.1	-1.5
pre-harvest	1	38.1	41.5	3.4	14.2	17.2	3.0	5.70	6.52	0.83	0.9	-1.1
2 wk before E-L 37	2	39.8	42.0	2.2	15.1	16.5	1.4	6.23	6.77	0.54	0.7	4.8
	3	20.7	23.9	3.2	65.9	56.7	-9.2	0.82	1.26	0.44	0.0	-3.4
	After	30.3	29.6	-0.8	30.8	32.8	2.0	2.98	2.77	-0.21	0.4	0.4

* E-L scale (Coombe 1995).

A single chamber was used in 2006/07; replication of heating treatment was therefore limited to the three within-chamber vine replicates rather than actual treatment replicates. However to increase the confidence in the comparison, four control panels, each of three vines, were included. In 2007/08 the treatments were arranged within a randomised block design with three blocks. Each block contained one timing of each heat treatment (a single panel or three vines), and two controls (two panels). Treatment and control plots were arranged to allow for a minimum of one untreated buffer panel or one row between neighbouring plots.

Vine measurements

Phenological development was assessed visually using the E-L scale (Coombe 1995). Foliar and bunch temperatures were measured using an Agri-therm 2 infrared thermometer (Everest Interscience; Tucson, Arizona, USA). Measurements were taken in the morning (commencing 10:00) and afternoon (commencing 13:30) on days 2 and 3 of the heating treatments. In 2006/07, temperature was measured on 15 leaves of treated and control vines. In 2007/08, temperature was measured in two sections of the canopy per replicate at 1 m from the canopy surface at 45º and 135º to the northern face. With the infrared thermometer's variable focal length set to maximum this generated a measurement spot size ~ 40 cm diameter. Bunch surface temperatures were measured on 20 randomly selected bunches per replicate at each measurement time in both seasons. The thermometer was held approximately 5-7 cm from the bunch, which at the maximum spot size measured a field ~ 3.5 cm diameter.

In 2007/08, we measured stomatal conductance and gas exchange in the morning (0900 to 1030) and afternoon (1230 to 1400) of the second and/or third day of the post set, pre-veraison, and veraison treatments. Stomatal conductance, transpiration and photosynthesis were measured using a LiCor 6400 photosynthesis system with a red-blue LED light source (LiCor Environmental Sciences, Lincoln, Nebraska, USA). Transpiration efficiency was calculated as the ratio of photosynthesis and transpiration. For each replicate we measured nine sun-exposed leaves at the top of the canopy; measurement conditions included: chamber temperature set at ambient temperature, saturating PAR (2000 μmol m^{-2} s^{-1}), air flow set to 500 μmol s^{-1} and chamber CO_2 flux concentration set to 380 μmol mol^{-1} using an external CO_2 injector. Airflow into LiCor 6400 was not scrubbed for humidity. Matching of the sample and reference chambers was performed at the beginning of each treatment replicate (every 9 leaves). Stomatal conductance was also measured using an AP4 diffusion porometer (DeltaT devices, Cambridge, UK) in twelve sun-exposed leaves per replicate. The porometer was calibrated according to the instructions in the AP4 manual using the supplied calibration plate. Calibration was repeated in the morning and afternoon and when changing from control to heat chamber readings.

Periodically throughout the season leaf chlorophyll was measured using a SPAD-502 (Minolta, Plainfield, Illinois, USA). Measurements included three spots per leaf x five mature leaves per vine x three vines per replicate.

Berry growth and sugar accumulation

Berries were sampled to determine fresh weight and total soluble solids (TSS) as explained in Sadras et al. (2008). Briefly, weekly samples were taken between 8 and 11 a.m. in the period between five weeks after full bloom and harvest. Each sample comprised 50 berries/replicate cut with scissors through the pedicel as close as possible to their point of attachment. For the entire 2006/07 season and prior to veraison in 2007/08, each complete sample was crushed using moderate hand pressure in a zip-lock resealable bag from which the juice fraction was recovered and centrifuged at 3000 g for 10 minutes. Total soluble solids were then measured using a constant temperature bench refractometer. After berry softening in 2007/08 (commencing January 5th) juice + pulp and skins were separated for other analyses (not reported here). A 1 mL aliquot of juice taken from the mixed juice/pulp sample was spun at 5000 g in a bench top micro-centrifuge and measurement of TSS was made as previously described.

Statistical analysis

Differences between treatments in canopy and bunch temperature, stomatal conductance, photosynthesis and transpiration were tested with ANOVA (Genstat version 11). Associations between pairs of variables (e.g. stomatal conductance and VPD) were explored with regression analysis; statistical significance of quadratic terms was used to test departures from linearity.

Potvin et al. (1990) outlined statistical methods to compare response curves involving repeated measures. Here we assessed the effect of temperature by comparison of the functions describing the time course of berry weight (*BW*) and total soluble solids (*TSS*):

$$BW = a + \frac{BW\max}{1 + e^{-(\frac{t - t_0}{b})}} \qquad \text{eq 1a}$$

$$TSS = a' + \frac{TSS\max}{1 + e^{-(\frac{t - t_0'}{b'})}} \qquad \text{eq 1b}$$

where *a, a'* are constants, subscript max indicates maximum; t_0 *and* t_0' are the transition centres, i.e. the time when berry weight or total soluble solids are half-way from the minimum (*a* or *a'*) to the maximum, and *b and b'* are the transition width * 2.197^{-1} (SYSTAT 2002). The transition width is the time (days) it takes for berry weight or soluble solids to raise from 0.25 to 0.75 of maximum (Sadras *et al.* 2008).

Results

Control of temperature in the field

Fig. 2 compares maximum temperatures in the heated treatments with climate records, Fig. 3 illustrates the quarter-hourly course of temperature, relative humidity and vapour pressure deficit in heated and untreated controls and Tables 1 and 2 summarise the treatments during the two seasons. Maximum ambient temperature rarely exceeded 40 ^{o}C. Of the 12 treatment days in each season, all except one in 2007/08 were close to or above the 90th percentile for the time of year. Our target temperature was therefore a realistic representation of extreme heat events in the Barossa Valley. As expected from a passive system relying on greenhouse effect, heating was less effective on overcast days, but these were infrequent (e.g. February 20, 2008 in Table 2). Occasionally, the target temperature was surpassed when ambient temperature was over 38 ºC in the first season (Table 1); improvements in ventilation prevented this problem in the second season (Table 2). Chambers had negligible effects on relative humidity, and therefore vapour pressure deficit tracked temperature. Chamber air flux was high while the fans were in operation with volume turnover occurring once every 13-16 seconds depending on fan speed. However, even when the fans were not operating (e.g. at night) relative humidity inside the chamber was not significantly different to ambient.

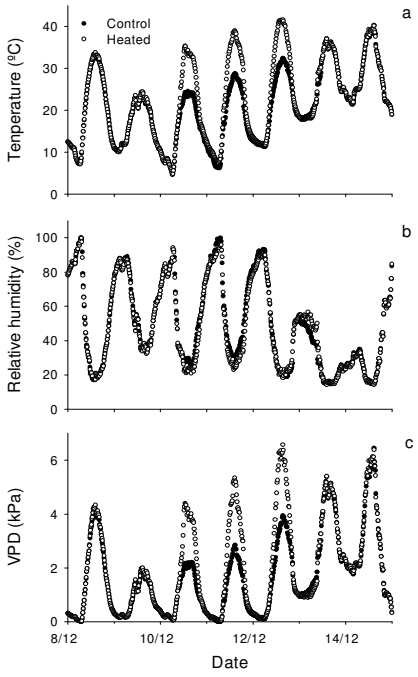


Figure 3. Temperature, relative humidity and vapour pressure deficit inside (open symbole) and outside (closed symbols) the heating chambers during the post-set treatment in 2007. The treatment was applied from the 10th to the 12th of December inclusive. As background, trajectories are expanded by two days both sides of the treatment period.

Canopy and bunch temperature

Inter- and intra-seasonal variation generated a range of maximum ambient temperature from 20.7 to 41.0 ºC during the treatment periods. Over this two-fold range, the heating treatments consistently increased foliar and bunch temperature relative to controls (Fig. 4, Tables 1, 2).

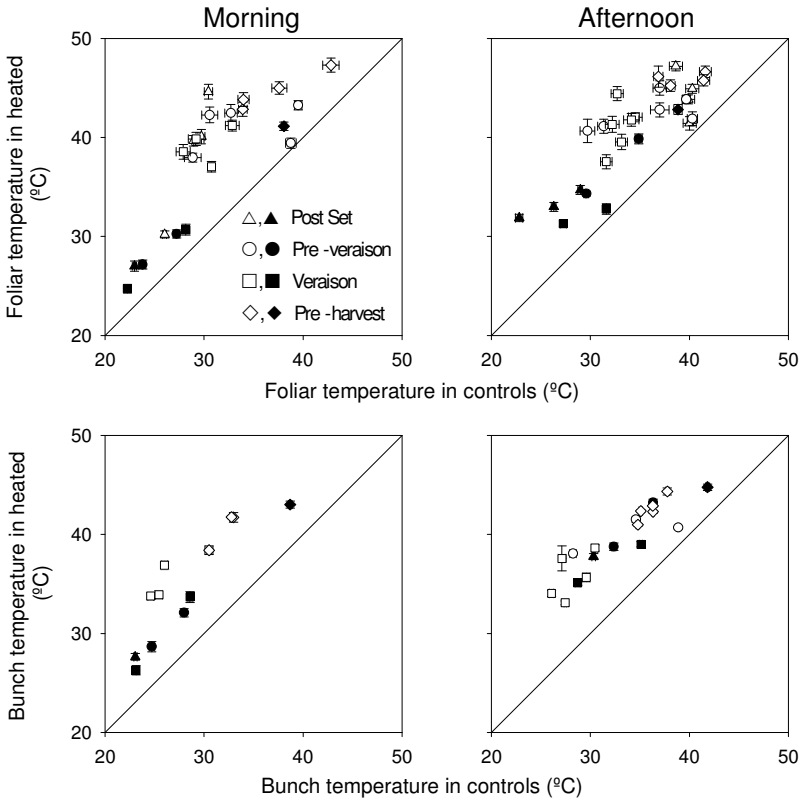


Figure 4. Comparison of foliar temperature and bunch temperature in heated and controls vines in 2006/07 (open symbols) and 2007/08 (closed symbols). Foliar temperature is single leaf (2006/07) or canopy (2007/08). The solid line is y=x and error bars are standard errors of the means.

Stomatal conductance and gas exchange

Heating increased stomatal conductance, leaf transpiration and leaf photosynthesis with more marked effects in the morning than in the afternoon (Fig. 5). For the pooled data, stomatal conductance accounted for 69% of the variation in leaf photosynthesis (inset Fig. 5). Heating had no detectable effect on leaf chlorophyll as measured with SPAD (not shown).

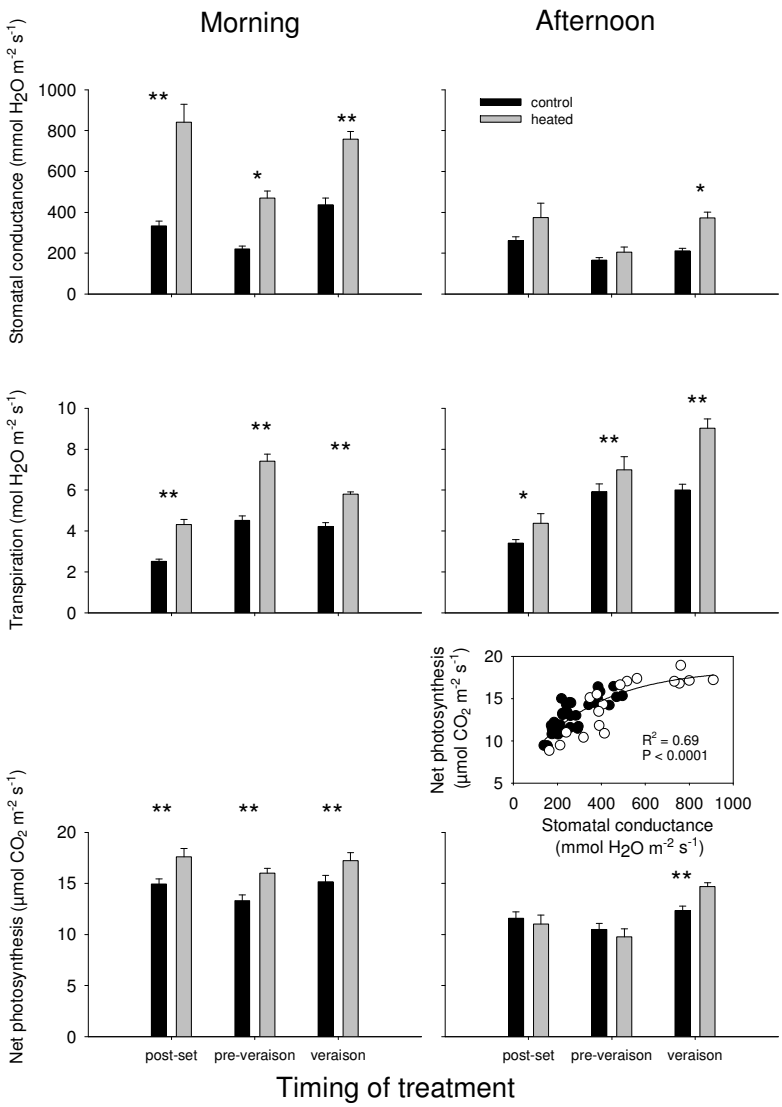


Figure 5. Stomatal conductance, leaf transpiration and net photosynthesis of heated and control vines in the morning and afternoon of the second day of heating for the post-set, pre-veraison and veraison treatments. Error bars are standard errors of the means and asterisks indicate significant differences between heated and control vines as tested by ANOVA (* $p < 0.05$, ** $p < 0.01$). Inset shows the relationship between net photosynthesis and stomatal conductance for the pooled data from control (closed symbols) and heated (open symbols) treatments. Data from 2007/08.

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The results obtained with the LiCor 6400 in Fig. 5 are a true reflection of the treatments only to the extent that the conditions in the chamber enclosing the leaf during measurements reflected the environmental conditions of the corresponding treatment; this is particularly relevant for the heated treatments. Vapour pressure deficit inside the LiCor leaf chamber correlated well with ambient VPD (r^2 = 0.80 for controls and 0.77 for heated treatments, both P <0.0001). Furthermore, measurements with a diffusion porometer also showed that high temperature increased stomatal conductance in comparison to controls (Fig. 6).

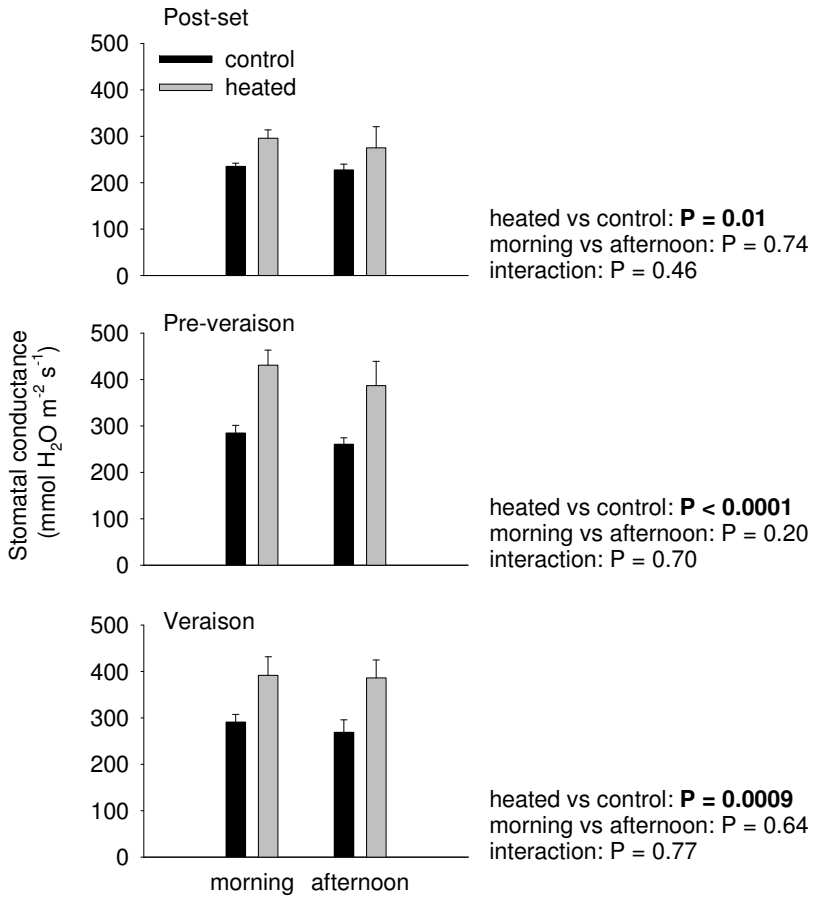


Figure 6. Stomatal conductance measured with diffusion porometer in heated and control vines in the morning and afternoon of the second and/or third day of heating for the post-set, pre-veraison and veraison treatments. Error bars are standard errors of the means. P values are from ANOVA. Data from 2007/08.

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Effects of temperature at a common VPD

We analysed the effects of temperature at a common VPD on stomatal conductance, leaf photosynthesis and leaf transpiration (Fig. 7). Our experimental design (see Methods) included two control replicates per block to increase the degrees of freedom for comparisons, and this involved a trade-off in terms of higher density of measurements in controls compared to heated treatments. Stomatal conductance and gas exchange were therefore uniformly distributed in the range of VPD from ~1.1 to 5.1 kPa in controls, whereas measurements in heated leaves were more clustered at the extremes of the range with a gap between ~3 and 4 kPa. The clustering of data in the heated treatment was, however, unrelated to morning vs afternoon measurements (Fig. 7).

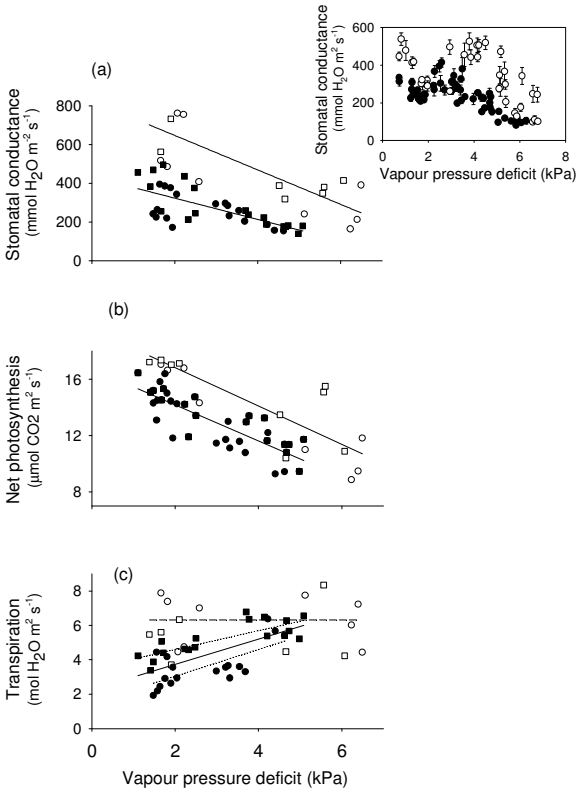


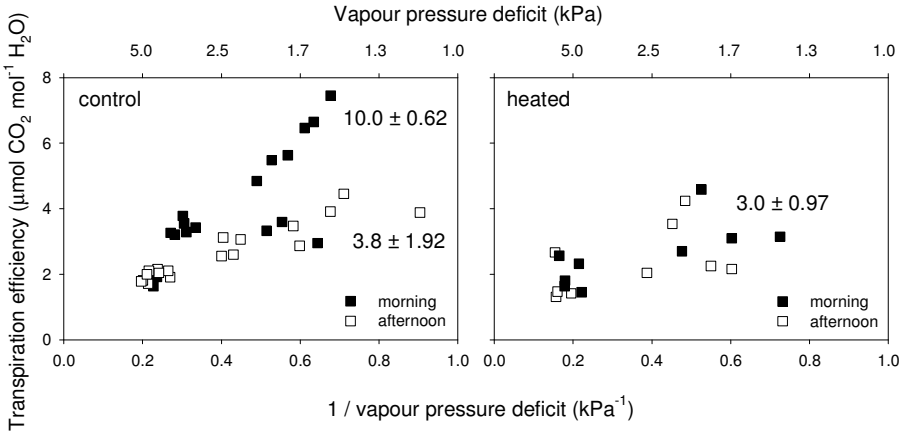
Figure 7. Relationships between (a) stomatal conductance, (b) transpiration, and (c) net photosynthesis and vapour pressure deficit for heated (open symbols) and control (closed symbols) vines. Measurements were taken in the morning (circles) and afternoon (squares) of the second day of heating applied at post-set, pre-veraison and veraison; each point is the average of nine leaves. Solid lines are linear regressions for the pooled morning and afternoon data ($0.46 \leq r^2 \leq 0.71$, $P < 0.0001$). In (c) the dashed line represents the average transpiration of heated leaves across VPD (regression not significant, $P > 0.45$) and the dotted lines are separate regressions for morning and afternoon measurements. Inset shows the relationship between stomatal conductance measured with porometer and VPD for heated (open symbols) and control (closed symbols) vines. Data from 2007/08.

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Stomatal conductance at a common VPD was consistently higher in heated vines than in controls (Fig. 7a). Non-linear terms in the response of stomatal conductance to VPD were not significant, i.e. $P > 0.91$ in controls and $P > 0.31$ in heated vines. The lineal rate of change in stomatal conductance with VPD was 62% higher in heated vines than in controls (-89 ± 16.5 vs. -55 ± 9.6 mmol H_20 m^{-2} s^{-1} kPa^{-1}) but this difference was not significant ($P > 0.05$). Measurements with diffusion porometer reinforced the conclusion that heating increased stomatal conductance at a common VPD (inset Fig. 7a).

Photosynthetic rate at a common VPD was consistently higher in heated vines than in controls (Fig. 7b). Non-linear terms in the response of net photosynthesis to VPD were not significant, i.e. $P > 0.27$ in controls and $P > 0.86$ in heated vines. The linear rate of change in photosynthesis with VPD was similar in both treatments, i.e. -1.27 ± 0.154 in controls and -1.36 ± 0.215 µmol CO_2 m^{-2} s^{-1} kPa^{-1} in heated vines.

Leaf transpiration rate of controls increased with VPD at an average rate of 0.73 ± 0.138 mol H_2O m^{-2} s^{-1} kPa^{-1} (non linear term: P > 0.35) and was unrelated to VPD (P > 0.45) in heated vines (Fig. 7c). Transpiration of control leaves at a common VPD was higher in the afternoon than in the morning (dotted lines in Fig. 7c). Consistent with this response of transpiration and the lack of hysteresis in photosynthesis (Fig. 7b), the plot of transpiration efficiency as a function of VPD^{-1} revealed a strong diurnal hysteresis in controls (Fig. 8). In controls, transpiration efficiency at low VPD was higher in the morning than in the afternoon, and morning and afternoon efficiencies converged with high VPD. The response of transpiration efficiency to VPD in heated leaves was similar to that of controls in the afternoon.



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Figure 8. Transpiration efficiency as a function of the inverse of vapour pressure deficit in leaves from control and heated vines. Measurements were taken in the morning and afternoon of the second day of heating applied at either post-set, pre-veraison and veraison; each point is the average of nine leaves. Numbers are slopes (± s.e.) of linear regressions for measurements in the morning and afternoon for controls and for the pooled data in heated leaves, as morning and afternoon responses were statistically undistinguishable (P > 0.05). The top x-axis indicates vapour pressure deficit to facilitate interpretation, but note this scale is not linear. Data from 2007/08.

Berry growth and sugar accumulation

The use of different plant material in the two seasons (see Method) did not seem to generate differences in berry responses to temperature (Fig. 9). A single model (eq. 1a) with common parameters for all treatments accounted for 96.4% of the variance in berry weight in 2006/07 and 96.5% of the variance in 2007/08 (both P < 0.001). Adding a separate constant a for each treatment but maintaining a common value for BWmax and b improved the model significantly (P < 0.001). This improvement is related to the smaller berry weight for pea-size treatment in 2006/07 and the veraison treatment in 2007/08. Further tests directly comparing these two treatments and their respective controls indicated significant differences (P < 0.05), i.e. the slopes of the regressions between berry weight in heated and control berries were lower than 1, i.e. 0.79 ± 0.059 g g-1 for pea-size treatment in 2006/07 and 0.90 ±

0.032 g g-1 for the veraison treatment in 2007/08 (insets in Fig. 9). A single model (eq. 1b) with a common set of parameters accounted for 99% of the variation in accumulation of total soluble solids ($P<0.001$) indicating no difference between treatments in 2007/08 (Fig. 9). In 2006/07, the best model included a different constant term (a') for each treatment ($P<0.001$, $R^2 = 0.99$), allowing for a slightly lower TSS in the pea-size treatment. Direct comparison of pos-set and control treatments, however, indicated no significant difference in TSS ($P > 0.05$) and, associated with differences in berry weight, a 16% reduction in the amount of sugar per berry ($P < 0.05$).

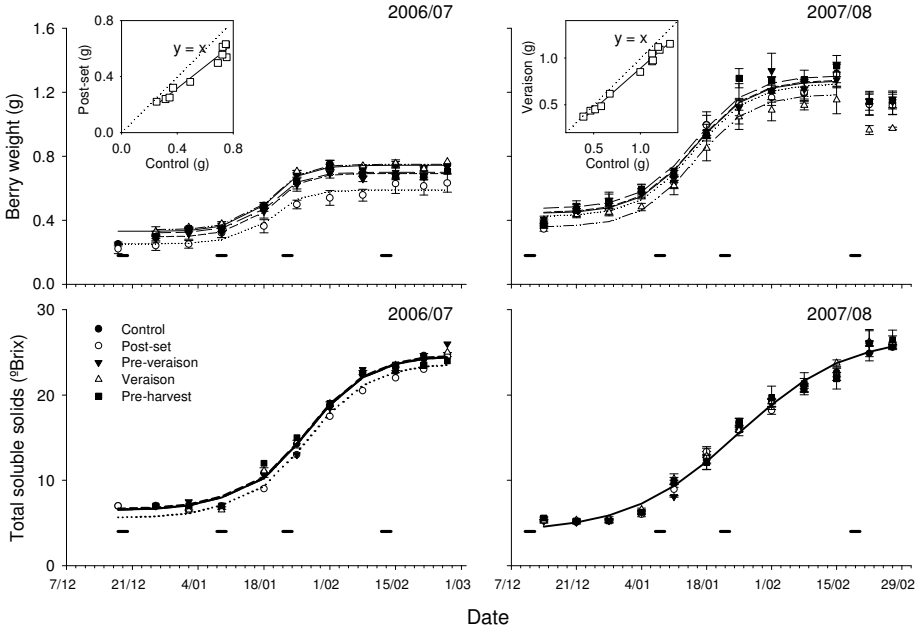


Figure 9. Dynamics of berry growth and total soluble solids in berries from controls, and from vines heated during three days at one of four phenological stages (horizontal bars). Error bars represent standard errors of the means. Fitted curves are eq. 1. In 2007/08, measurements of berry weight during the shrinkage period (Sadras and McCarthy 2007) were not used to fit the curves (2 last dates).

Discussion

Heating treatments: realism, limitations and potential artefacts

Our heating treatments generated extreme but realistic maximum temperatures (Fig. 2). To avoid unrealistic interactions between temperature and vapour pressure deficit in experiments where temperature is manipulated, vapour pressure deficit rather than relative humidity needs to be controlled (Hall and Sadras 2009). An important feature of our treatments was therefore the realistic time courses of vapour pressure deficit (Fig. 3). Similarly important, a high turnover rate, i.e. up to 1 chamber volume replaced every 13 seconds, prevented air stratification in the chamber.

The main aspect where treatments departed from real heat wave conditions is that we did not manipulate night temperature, which is normally above average during heat waves (W. Grace, pers. comm. 2008). Night temperature can affect plant processes with consequences for crop yield and quality (Aguirrezábal *et al.* 2009; Koshita *et al.* 2007; Mori *et al.* 2005; Mutters and Hall 1992; Thomas and Raper 1981; Warrag and Hall 1984).

Other secondary effects included a slight reduction in PAR (10%), increased diffuse radiation and reduced UV radiation. Measurements and modelling support the notion that canopy and ecosystem photosynthesis increase with increased diffuse radiation (Roderick *et al.* 2001; Rodriguez and Sadras 2007; Sinclair *et al.* 1992; Urban *et al.* 2007; Wohlfahrt *et al.* 2008). Where diffuse radiation increased in association with cloudiness and atmospheric particles, three mechanisms accounted for enhancement of photosynthesis: (i) canopy changes, i.e. improved distribution of light in the canopy profile (ii) microclimatic changes, i.e. reduction in temperature and VPD, and (iii) leaf changes, i.e. stimulation of photochemical reactions and stomatal opening via an increase of blue/red light ratio (Urban *et al.* 2007). The first mechanism is quantitatively the most important (Roderick *et al.* 2001; Urban *et al.* 2007; Wohlfahrt *et al.* 2008) but is not relevant to our measurements of individual leaf photosynthesis using a red-blue LED light source under saturating light. Likewise, microclimatic changes were not relevant, as high diffuse radiation in the chambers was paralleled with high temperature and high VPD. Changes in leaf-level photosynthesis associated with changes in blue/red ratio of light were unlikely, as the chamber has a high and uniform transmittance between 400 and 1600 nm. Long-term exclusion or enhancement of UV-B alters leaf traits including photosynthetic pigment composition, specific leaf mass and UV-B absorbing flavonoids (Láposi *et al.* 2009). To minimise the impact of these and other secondary factors, we established treatments for only three days.

Canopy temperature, stomatal conductance and gas exchange

Studies with grapevine in controlled environments showed that heat stress can trigger the production and accumulation of heat-shock proteins in young leaves, reduce stomatal conductance, disrupt the photosynthetic apparatus and reduce CO_2 assimilation (Kadir 2006; Kadir *et al.* 2007; Sepulveda and Kliewer 1986; Zhang *et al.* 2008). Growing conditions in most of these studies, however, are unrepresentative of vineyard situations (see Introduction).

Our aim was to measure vine responses in realistic field conditions, while minimising secondary effects from heat chambers. We found that recently irrigated Shiraz vines responded to short duration heat shock with an increase in stomatal conductance, a corresponding increase in transpiration, a small to moderate increase in photosynthesis and no evident degradation of leaf chlorophyll in young leaves.

Bowen et al. (2004a; 2004b) used clear polyethylene enclosures around Merlot canes or cordons which increased maximum temperatures by 5-8 °C and enhanced photosynthetic rate in association with increased mesophyll and stomatal conductance in relation to controls. Our data indicated stomatal conductance was the dominant source of variation in photosynthesis (inset of Fig. 5). Diffuse radiation inside the chamber might have contributed to the enhancement of photosynthesis in

heated leaves, but this was unlikely, as discussed in the previous section. In our study relative humidity in the chambers was not significantly different from ambient and vapour pressure deficit was dramatically and realistically increased (Hall and Sadras 2009). We propose therefore that the increased stomatal conductance, verified with both diffusion porometer and gas exchange measurements, and enhanced gas exchange in our heated vines was a likely response to high temperature rather than an artefact of growing conditions.

Generally, stomatal responses partially counteract shifts in the balance between supply and demand of water, e.g. increased VPD shifts the hydraulic balance towards demand, and stomata respond to increased transpiration rate by reducing their apertures (Buckley 2005; Fredeen and Sage 1999; Mott and Parkhurst 1991). The coordination between stomatal conductance and water balance is generally accepted, but the underlying mechanisms are still controversial (Buckley 2005). In this context, the responses of stomatal conductance and gas exchange to increasing VPD in controls were typical (Brodribb and Jordan 2008; Pou *et al.* 2008): stomatal conductance, photosynthesis and water use efficiency decreased and transpiration increased. Against this pattern, heated vines showed qualitative and quantitative differences (Fig. 7).

Fredeen and Sage (1999) concluded that VPD and leaf temperature have independent effects on stomatal conductance of *Picea glauca*., and consolidated this notion in a two-phase model of transpiration vs VPD (their Figure 4). In the first phase, transpiration increased linearly with VPD up to a temperature-dependent threshold, e.g. ~ 2 kPa at leaf temperature of 35 ^{o}C. In the second phase transpiration was stable. In the context of stomata responses to supply and demand of water, they proposed this pattern was mediated by (a) a reduction in water viscosity and increase in plant membrane permeability with increasing temperature leading to (b) a linear increase in water supply to guard cells, and (c) an exponential increase in VPD with temperature eventually leading to (d) a decline in stomatal conductance restricting transpiration (Fredeen and Sage 1999). We suggest that the lack of net response of transpiration to VPD in our heated vines (Fig. 7c) corresponded to the second phase in the model of Fredeen and Sage (1999) where non-stomatal limitations were impacting on water loss from the leaf surface. We speculate that the first phase was not evident because of the scarcity of data for VPD < 2 kPa under our experimental conditions.

Irrespective of the physiological mechanism, stomatal regulation allowed for heated, well-watered Shiraz to maintain a relatively high and steady transpiration flux independent of VPD (dashed line in Fig. 7c). The lack of relationship between leaf transpiration and VPD, and the maintenance of a relatively high transpiration rate in our heated vines compares with the decoupling and maintenance of a relatively low rate of transpiration in water-stressed grapevine (Pou *et al.* 2008) and olive (Fig. 5 in Moriana *et al.* 2002). Stomatal regulation has been often interpreted in terms of optimisation of transpiration efficiency and prevention of xylem cavitation (Buckley 2005; Kramer and Boyer 1995). We suggest that stomatal responses previously described as part of Shiraz anisohydric behaviour (Schultz 2003; Soar *et al.* 2006) may play a role in terms of heat stress tolerance. In common with previous reports (Amani *et al.* 1996; Lu 1994; Radin *et al.* 1994), our study indicates that stomatal regulation in heat-stressed Shiraz may have favoured evaporative cooling at the

expense of short-term transpiration efficiency. A corollary of this is that timely pulses of water prior to heat waves could help mitigate the otherwise damaging effects of high daytime ambient temperature on the photosynthetic capacity of plants with anisohydric stomatal regulation. Specific studies on the interaction between water supply, heat stress and cultivar are required for a direct test of this hypothesis; viticultural implications are discussed below.

Berry growth and sugar accumulation

We characterised the dynamics of berry growth and sugar accumulation to test the hypothesis that high maximum temperature alone can disrupt berry development and ripening, and to determine whether there are phenological stages that are more vulnerable to high temperature. We found significant reductions in berry size for the post-set treatment in 2006/07 and the veraison treatment in 2007/08 (Fig. 8). A reduction in berry size associated with high temperature shortly after fruit set is consistent with the active process of cell division in fruit tissues at this developmental stage (Coombe and Iland 2004). Heating in the post-set stage raised maximum temperatures up to 42.1-45.7 ^{o}C in 2006/07 whereas the corresponding treatment in 2007/08 reached 35.3-41.5 ^{o}C (Tables 1 and 2). These differences may account for the measurable effect in 2006/07 (i.e. 16% reduction in berry size and sugar per berry) and the lack of response in 2007/08. The reduction of berry size in the veraison treatment in 2007/08 was clearly associated with differences in berry size before the imposition of the treatment, so we can safely conclude this difference was related to vine-to-vine variability rather than to the treatment. The dynamics of TSS in berries were largely unaffected by heating.

Some studies supported the notion that high temperature could reduce berry growth in a process mediated by reductions in stomatal conductance and net carbon assimilation (Matsui *et al.* 1986; Sepulveda and Kliewer 1986). Kliewer (1977) reported variety-dependent reductions in berry size when vines were exposed to high temperature (32 to 40 ºC) from bloom to fruit set in controlled environments. Some controlled-environment experiments indicated that sugar accumulation is sensitive to temperature at early berry growth stages (Buttrose *et al.* 1971; Hale and Buttrose 1974), others pointed to post-veraison as a vulnerable stage (Jackson and Lombard 1993) and many found no effects (Kliewer 1970; Radler 1965; Spayd *et al.* 2002). Differences in duration and intensity of heat stress, interactions with other factors (chiefly water supply and radiation), artefacts from controlled environments or a combination of these may account for the differences with our study where we found little or no alteration of berry growth in vines exposed to short episodes of heat stress at several phenological stages.

Viticultural implications

The short, extreme heat treatments imposed to field-grown irrigated Shiraz did not affect berry growth or sugar accumulation, except for the post-set treatment in 2006/07 when maximum temperature was maintained above 42 ^{o}C for three

consecutive days. Consistent with the ability of irrigated Shiraz to maintain berry growth and sugar accumulation, stomatal conductance and gas exchange were either maintained at the levels of controls or enhanced. In addition to the duration of heat stress, three main factors could account for the discrepancy between this response and the apparent arrest of berry growth commonly attributed to heat waves in the Australian wine industry: night temperature, wind and water supply. Heat waves in south-eastern Australia increase not only maximum but also night temperature and are associated with northerly hot and dry winds (Grace and Curran 1993). For some plant processes such as seed set and seed composition, the influence of temperature may be more prominent during the night than during the day (Aguirrezábal *et al.* 2009; Mutters and Hall 1992; Warrag and Hall 1984). In grapevine, high night temperature may alter berry composition (Kliewer 1973; Koshita *et al.* 2007). Under the experimental conditions of Greenspan et al. (1996), Cabernet Sauvignon berries showed marked day-night fluctuations, i.e. day-time reduction and night-time increase in diameter, that were more noticeable before veraison and under water deficit. Wind speed alters the boundary layer of the canopy and therefore influences the response of transpiration to temperature, vapour pressure deficit and stomatal conductance (Aphalo and Jarvis 1993; Jarvis and McNaughton 1986). Heating in this study was applied at the beginning of an irrigation cycle, therefore the chances of water deficit arising during treatment were reduced and the capacity for evaporative cooling was maintained. However, water deficit and heat stress often co-occur, particularly in rainfed systems or production systems with limited irrigation. Both stresses interact in complex ways at scales from molecular to whole-crop and regional (Barnabas *et al.* 2008; Dalla-Salda *et al.* 2009; Warrag and Hall 1984). The generally non-additive effect of water and heat stress has potentially damaging consequences. Crown necrosis and death of individual trees, for example, were reported following the heat and drought wave of 2003 in France (Dalla-Salda *et al.* 2009).

Extrapolation of these results to other grapevine species or varieties needs to account for genotype-dependent thermotolerance and water relations (Kadir 2006; Kadir *et al.* 2007; Schultz 1997; Soar *et al.* 2006). In the study of Kadir (2006), the reduction in quantum efficiency of photosystem II after exposure to 40/35 ^{o}C (day/night) ranked Cabernet Sauvignon > Semillon > Pinot Noir. Differences between anisohydric (e.g. Shiraz) and isohydric (e.g. Grenache) types in stomatal response to VPD and soil drying (Schultz 2003; Soar *et al.* 2006) may be relevant for heat stress tolerance. In comparison to Grenache, Shiraz maintained high stomatal conductance and transpiration in dry soil, i.e. predawn leaf water potential up to –1.4 MPa (Schultz 2003) and high VPD, i.e. up to 5 kPa (Soar *et al.* 2006). Anisohydric behaviour may contribute to heat dissipation, provided soil water content is sufficient to maintain transpiration, whereas reduction in stomatal conductance in isohydric plant types might enhance the damaging effects of high ambient temperature. Up-regulation of stomatal conductance improved the tolerance to heat stress in some combinations of plants and environments (Banowetz *et al.* 2008; Natarajan and Kuehny 2008; Radin 1994) but direct comparisons among grape varieties are required, including the probing for trade-offs between up-regulation of stomatal conductance and other attributes with putative value for heat tolerance, e.g. membrane thermostability (Blum *et al.* 2001; Hong *et al.* 2003).

Depending on the relative importance of day and night temperature, wind, and the interaction between heat, water supply and cultivar, different practices may have different effectiveness in dealing with heat waves. For example, shading is likely to be less effective for physiological disruption caused by high night temperature and irrigation is less likely to be effective in isohydric plant types. Thus, disentangling the main components of heat waves and accounting for variety-dependent interactions between temperature and water are critical to devise management strategies to deal with heat stress in vineyards. Irrigated Shiraz in our study, however, showed a larger than expected capacity to cope with three consecutive days of extreme heat, partially accounted by physiological up regulation of gas exchange.

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Chapter 3

Shiraz vines maintain yield in response to 2-4 °C increase in maximum temperature at key phenostages

VO Sadras and CJ Soar

Summary

We measured the effects of increased daytime temperature during 2- (2007/08) or 3-week periods (2008/09) on the yield and yield components of irrigated Shiraz vines in the Barossa Valley of Australia. A simple and inexpensive open system was used to elevate temperature during a single phenological window, either bracketing budburst (E-L stage 4), shortly after flowering (E-L stage 23), bracketing pea-size (E-L stage 31), around veraison (E-L stage 35) or shortly before harvest (E-L stage 38). In comparison to controls, maximum ambient temperature was increased between 1.8 and 4.1 °C in treated plots; treatments did not affect minimum temperature. Two important features of the heating systems were: tracking of diurnal temperature dynamics, and maintaining relative humidity, hence avoiding the interaction between temperature and vapour pressure deficit. Increasing temperature around budburst accelerated development in comparison to controls; no phenological changes were detected for other timings of treatment. Yield averaged 4.3 kg vine^{-1} in 2007-08 and 6.1 kg vine^{-1} in 2008-09. In both seasons and for all timings of treatment, increasing temperature did not affect yield or its components; lack of yield response did not result, therefore, from compensatory mechanisms, e.g. heavier berries compensating for fewer fruit. The dynamics of berry growth and total soluble solids were largely unaffected by temperature.

Introduction

The direct effects of temperature on viticulture are manifold. On the one hand, maximum, minimum and mean temperatures vary in annual, decadal and long-term scales (Salinger, 2005) and temperature varies spatially at macro-, meso- and micro-scales relevant to viticulture (Tonietto and Carbonneau, 2004; Gladstones, 2005). On the other hand, temperature modulates many biological processes including vine phenological development, vegetative and reproductive growth, yield and berry attributes. In the period 1950-1998, the modelled date of budburst for Chardonnay at Mildura, Australia (34 °S) ranged from August 19 to September 14 (Petrie and Clingeleffer, 2005); this variation reflects the annual variability in temperature in a single location. Long-term increase in mean temperature has been associated with accelerated phenological development and altered berry composition in Europe, North America and Australia (Jones and Davis, 2000; Duchene and Schneider, 2005; Wolfe et al., 2005; Petrie and Sadras, 2008). The review of Dunn (2005) illustrates reproductive responses that are dependent on both temperature range and cultivar: the number of bunch primordia per bud increased linearly with temperature between 15 and 25 °C in both Shiraz and Riesling, the rate of response was higher for Riesling, and the responses of the two varieties diverged for temperature between 25 and 35 °C. Associations between red wine quality and maximum and minimum temperature at critical phenological windows have been

reported for the Barossa Valley, Coonawarra, Margaret River and Hunter Valley (Soar et al., 2008). Indirect effects of temperature on vines and wines, e.g. mediated by changes in population dynamics of pests and pathogens (Seem, 2004; Salinari et al., 2006) or oak wood traits (Tate, 2001) are likely to be important but are harder to detect and predict.

Indirect and direct methods have been used to investigate the effects of temperature on vines and wines. Indirect methods compare seasons or regions using a range of statistical tools to infer the putative effects of temperature (Duchene and Schneider, 2005; Jones et al., 2005; Soar et al., 2008). Results from this indirect approach are bound to remain inconclusive because temperature is confounded with other climatic factors, management practices and soils (Calviño and Sadras, 1999; Soar et al., 2008). Unequivocal results require direct comparisons where vines are exposed to different temperatures. Manipulation of temperature in controlled environments is straightforward and this has been the favoured method (Wang et al., 2004; Mori et al., 2005; Wang et al., 2005; Kadir, 2006; Wang and Li, 2006b; Wang and Li, 2006a; Kadir et al., 2007; Liu et al., 2008; Wen et al., 2008; Zhang et al., 2008). Soar et al. (2009) and Tarara et al. (2000) discussed artefacts from controlled environments and their relevance for vineyard conditions. To overcome these problems, a number of researchers manipulated the temperature of vines or vine parts in the field. Tarara and co-workers (2000; 2008) developed and applied a chamber-free system whereby heated or cooled air was blown across bunches to achieve up to 10 °C temperature differential. Petrie and Clingeleffer (2005) used mini-chambers combined with shade cloth and reflective foil to change the temperature and irradiance of individual buds. Bowen et al. (2004a; 2004b) enclosed cordons or canes in polyethylene “sleeves” which increased maximum temperature by 5-8°C and decreased minimum temperature by 1-2°C. All these studies targeted specific plant parts to address particular issues, such as the separation of temperature and radiation effects on berry composition, but none of them aimed at the heating of the whole canopy. Plastic enclosures have been used to increase temperature of whole vines (Ezzahouani, 2003; Soar et al., 2009). These closed systems reduce total radiation, increase diffuse radiation and alter the boundary layer of the canopy; collectively, these secondary effects constrain the usefulness of closed systems as research tools (Tarara et al., 2000; Soar et al., 2009). To overcome the limitations of both controlled environments and closed systems in the field, we devised a simple and inexpensive open system to increase maximum temperature in realistic vineyard conditions. This paper describes this system and its performance over two growing seasons involving irrigated Shiraz vines in the Barossa Valley of South Australia. Our focus was the response of yield and its components to elevated maximum temperature during discrete phenological windows.

Methods

Site and vines

We used own-rooted Shiraz vines planted in 2004 on a red brown earth (Northcote, 1979) at SARDI’s Nuriootpa Research Station in the Barossa Valley of South Australia (34 °S, 139 °E). Gladstones (1992) and Dry and Coombe (2004) described the climate and viticultural practices of the region. Vines were spur pruned to 40-50 buds per vine and trained to a single-wire trellis; row spacing was 3.0 m and vine

spacing 2.25 m. Vines were drip-irrigated weekly from mid December at a rate of ~ 21 L vine^{-1} per irrigation.

Heating system

Fig. 1 shows the open heating system. The system consists of modular rectangular units (1580 mm high x 1510 mm wide) each supported by a pair of fold-out legs (870 mm tall) hinged 125 mm below the top of the panel face. The frame was made from 25 mm square tube steel (Stratco, Australia) and the unit face was made from solid Standard-Clear-Greca polycarbonate sheeting fastened to the steel frame (Suntuf, Australia). The polycarbonate material blocks most UV radiation (200 to 400 nm) and has a very high (90%) and uniform transmittance between 400 and 1600 nm. Consecutive units were fastened together during vineyard installation using plastic "zip" cable ties and each unit was independently anchored to the ground using 300 mm tent pegs.



Figure 1. Open-system for increasing daytime temperature in vineyards.

Treatments and experimental design

We compared untreated controls and vines exposed to increased daytime temperature during 2- (2007/08) or 3-week (2008/09) periods. Increased temperature treatments were applied at one of four (2007/08) or five (2008/09) phenological windows lasting two weeks in 2007/08 and three weeks in 2008-09. The extended treatment in 2008/09 was motivated by lack of significant yield effects in 2007/08. Phenological development was assessed visually using the E-L scale (Coombe, 1995); the windows of treatments common to both seasons were: shortly after flowering (E-L stage 23), bracketing pea-size (E-L stage 31), around veraison (E-L stage 35) and shortly before harvest (E-L stage 38). An additional treatment bracketing budburst (E-L stage 4) was included in 2008-09. Treatments were laid out in a block design with three replicates. Each individual replicate included nine vines, i.e. three panels of three vines per panel. To allow for edge effects, measurements were made in the central seven vines within each treatment and we used a buffer of at least two panels between treatments within a row and a single-row buffer between rows.

Measurements

Canopy and bunch temperatures were measured using an Agri-therm 2 infrared thermometer (Everest Interscience; Tucson, Arizona, USA). Measurements were taken in the morning (commencing 10:00) and afternoon (commencing 13:30) on several days during each treatment period. Foliar temperatures were measured on the north side of the central vine in each panel in 2007/2008, and from both the north and south in 2008/2009. For each vine, temperature was measured at 45º and 135º to the canopy with the thermometer lens held 1 m from the canopy surface. With the infrared thermometer's variable focal length set to maximum this generated a measurement spot size ~ 40 cm diameter. Bunch surface temperatures were measured on 20 randomly selected shaded bunches per replicate on both the north and south sides of the vine row at each measurement time in both seasons. For bunch temperature the thermometer was held approximately 5-7 cm from the bunch, which at the maximum spot size measured a field ~ 3.5 cm diameter.

Berries were sampled to characterise the dynamics of fresh weight and total soluble solids as explained in Sadras et al. (2008). Briefly, weekly samples were taken between 6 and 9 a.m. in the period between five weeks after full bloom and harvest. Each sample comprised 50 berries per replicate cut with scissors through the pedicel as close as possible to their point of attachment. Before veraison, each complete sample was crushed using moderate hand pressure in a zip-lock resealable bag from which the juice fraction was recovered and centrifuged at 5000 g for 5 minutes in a bench top micro-centrifuge. Total soluble solids were measured using a constant temperature bench refractometer. After veraison, juice + pulp and skins were separated for other analyses (not reported here). A 1 mL aliquot of juice taken from the mixed juice + pulp sample was spun at 5000 g for 5 minutes and measurement of total soluble solids was made as previously described.

All experimental plots were harvested when the average concentration of soluble solids reached 26 ºBrix. We counted and weighted all bunches in all treated and control vines, and measured berry size in samples comprising 50 berries per replicate. In 2007-08, the total acidity and pH in juice from berries at harvest was measured using the procedures described in Iland et al. (2000).

Statistical analysis

The effect of temperature was primarily tested with analysis of variance. A complementary analysis for some variables (minimum temperature, phenological development, berry weight and berry soluble solids) involved regressions between heated and control treatments and tests for departure from the $y = x$ line, i.e. the null hypotheses were intercept = 0 and slope = 1, which correspond to lack of temperature effect. Model II regression was used to account for errors in both y- and x-axis (Niklas, 1994).

The effect of temperature on the dynamics of berry weight (BW) and total soluble solids (TSS) was tested by comparison of parameters of the models:

$$BW = y_o + \frac{a}{1 + e^{-(\frac{t - t_0}{b})}} \qquad \text{eq 1a}$$

$$TSS = y_o' + \frac{a'}{1 + e^{-(\frac{t - t_0'}{b'})}} \qquad \text{eq 1b}$$

where a, a', y_o and y_o' are constants related to initial and final values of berry weight or total soluble solids, t_0 and t_0' are the transition centres, i.e. the time when berry weight or total soluble solids are half the maximum increase from y_o or y_o', and b and b' are the transition width * 2.197^{-1} (SYSTAT, 2002). The transition width is the time (days) it takes for berry weight or soluble solids to raise from 0.25 to 0.75 of maximum (Sadras et al., 2008). Shiraz berries often shrink during late development (McCarthy, 1999; Sadras and McCarthy, 2007). In 2007-08, berries shrank in the last two sampling dates and these data were excluded in fitting eq. 1. No shrinkage was observed in 2008-09.

To account for size effect on total soluble solids, allometric analysis was used as described in Sadras and McCarthy (2007). Briefly, we fitted linear regressions between mass of sugar per berry and berry weight in a log-log scale. The slope for each individual treatment, i.e. the scaling exponent, represents the relative rate of change in sugar per unit change in relative rate of berry weight (Niklas, 1994; Sadras and McCarthy, 2007). Scaling exponents were derived from linear regressions fitted to data between veraison and maximum berry weight (Sadras and McCarthy, 2007).

Results

Treatment windows and control of maximum temperature in the field

Figure 2 shows the enhancement of temperature in treated vines in relation to key phenostages and the maximum and minimum temperatures in controls. We targeted four nominal phenological windows in both seasons: flowering, pea size, veraison and pre-harvest, and an additional treatment close to budburst in 2008-09. The timing of treatment windows was consistent in both seasons except for veraison, which was established a few days after veraison in 2007-08 and bracketed veraison in 2008-09.

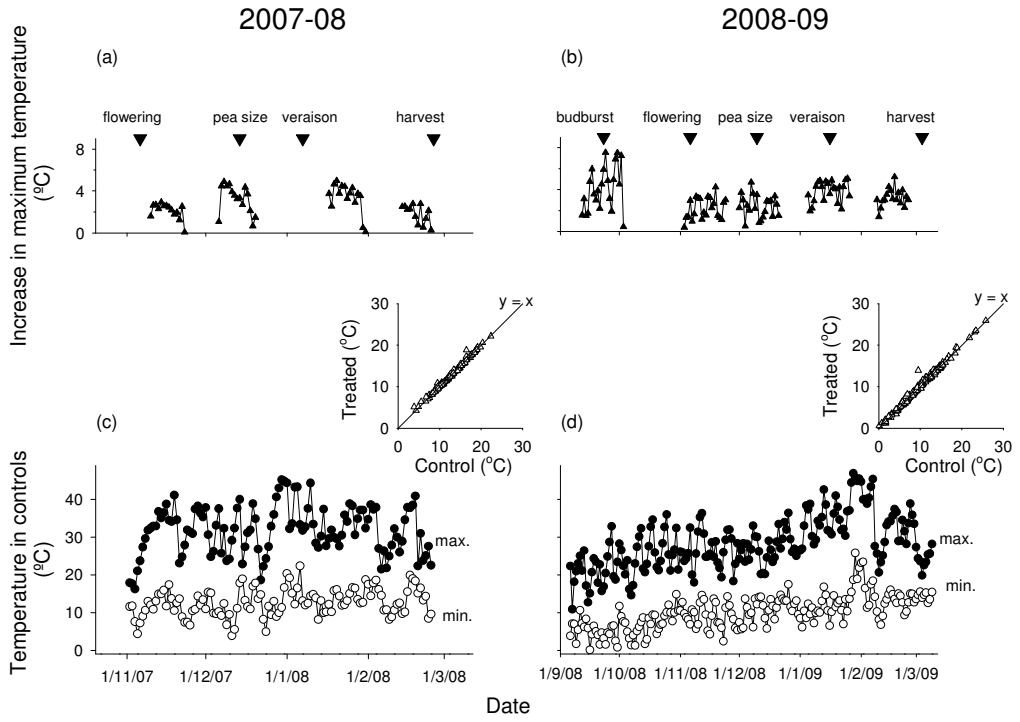


Figure 2. (a, b) Increase in maximum temperature, i.e. difference between treated and control vines and (c, d) seasonal dynamics of maximum and minimum temperature in controls. Arrowheads indicate the timing of key phenostages. Insets show minimum temperatures in treated and control vines; lines are y = x. All temperatures were measured at bunch height.

In 2007-08, elevation of maximum temperature in treated vines averaged 2.0 ± 0.23 °C for the flowering treatment, 3.2 ± 0.35 °C for pea size, 3.4 ± 0.36 °C for veraison, and 1.8 ± 0.23 °C for pre-harvest. In 2008-09, elevation of maximum temperature in treated vines was 4.1 ± 0.45 °C for the budburst treatment, 2.2 ± 0.22 °C for flowering, 2.4 ± 0.23 °C for pea size, 3.8 ± 0.21 °C for veraison, and 3.2 ± 0.21 °C for pre-harvest. The heating system did not affect minimum temperature; model II regression showed the fitted line between treated and control minimum temperature was statistically undistinguishable from the y = x line (insets Fig. 2).

Figure 3 illustrates the 15-minute trajectories of temperature, relative humidity and vapour pressure deficit in treated and control plots. Under the prevailing conditions of these experiments, the heating system maintained the daily cycle of temperature (Fig. 3a) with little effect on relative humidity (Fig. 3b), resulting in the natural daily tracking of vapour pressure deficit (Fig. 3c). For the pooled data, relative humidity varied in a ± 14% range.

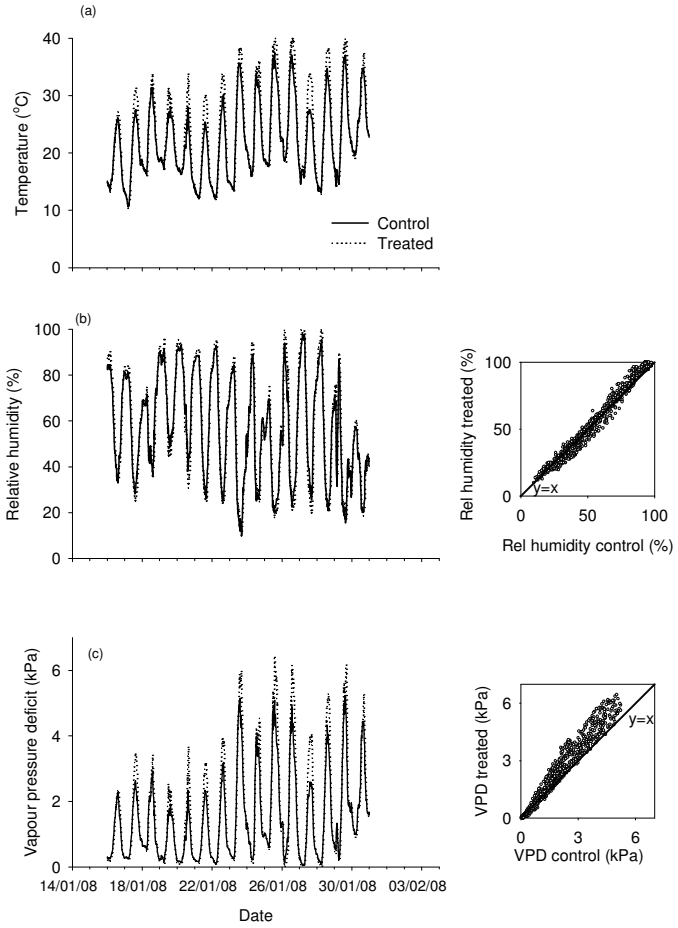


Figure 3. Dynamics of (a) ambient temperature, (b) relative humidity and (c) vapour pressure deficit measured at 15-minute intervals in treated and control plots during the veraison treatment in 2007-08. Insets compare treated vs control.

Averaged across timing of treatments, canopy temperature of treated vines was 1.1 °C (2007-08) and 0.9 °C (2008-09) higher than in the untreated vines. Treatment effects were stronger and more consistent for bunches, i.e. average elevation of bunch temperature was 3.2 °C in 2007-08 and 2.3 °C in 2008-09 (Fig. 4).

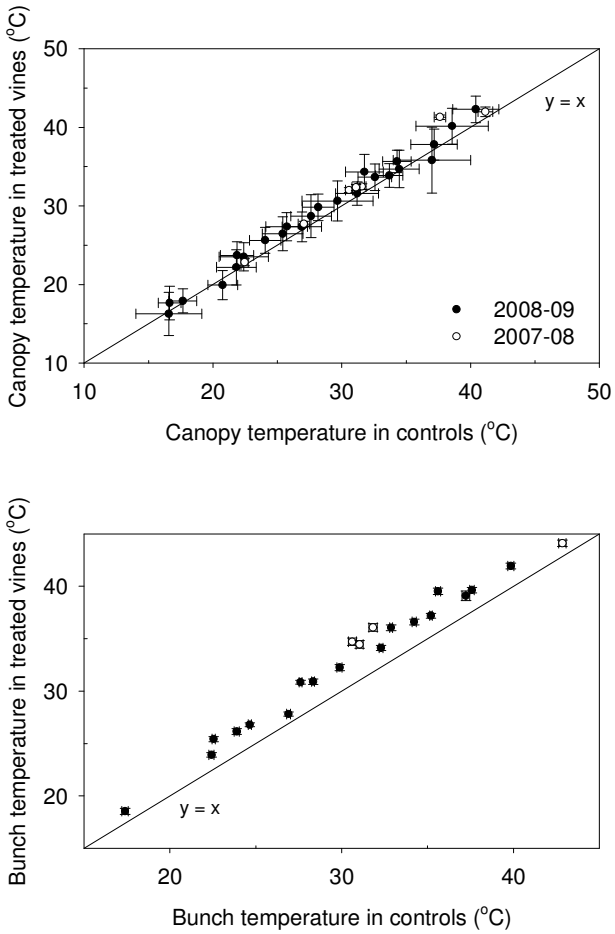


Figure 4. Comparison of canopy and bunch temperature in treated and control Shiraz vines. Error bars are two standard errors of the mean.

Phenology

Figure 2 shows the timing of key phenological stages in control vines. Increasing temperature around budburst accelerated development in comparison to controls in 2008-09 (Fig. 5). Increasing temperature did not affect phenological development in vines treated around flowering, pea size, veraison or pre-harvest in 2007-08 (not shown) or 2008-09 (Fig. 5).

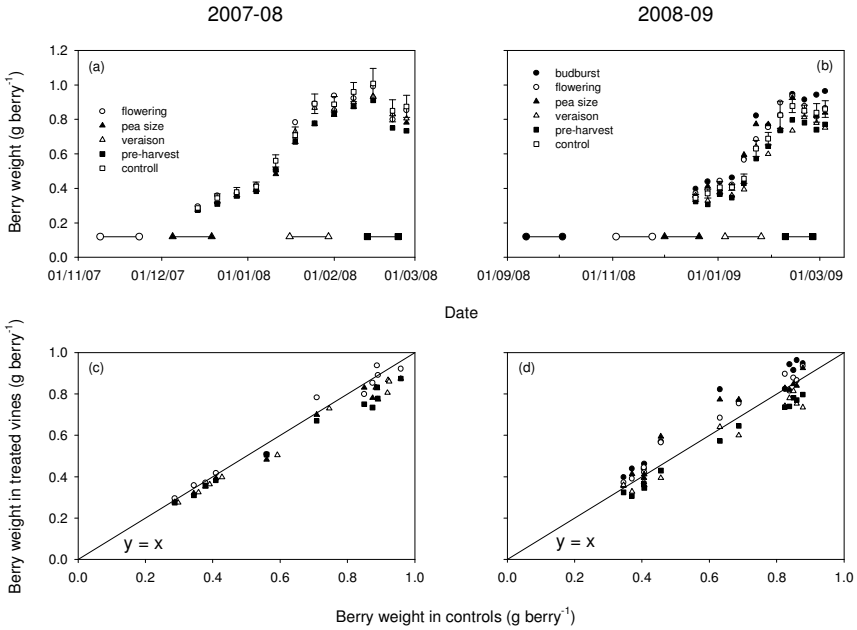


Figure 5. Comparison of phenological development between treated and control Shiraz vines in 2008-09. Development was scored using the E-L system (Coombe, 1995). Asterisks indicate significant differences ($P < 0.01$), which were only detected in the budburst treatment.

Yield and its components

Yield averaged 4.3 kg vine^{-1} in 2007-08 and 6.1 kg vine^{-1} in 2008-09. In both seasons and for all timings of treatment, increasing temperature did not affect yield or its components (Table 1).

Table 1 Yield components (± s.e.) of irrigated Shiraz in response to elevation of temperature at four (2007-08) or five (2008-09) phenological windows. P is the treatment effect from ANOVA.

Treatment	Yield (kg vine^{-1})	Bunch number (vine^{-1})	Bunch weight (g bunch^{-1})	Berry number (bunch^{-1})	Berry weight (g berry^{-1})
2007-08					
control	4.3 ± 0.49	63 ± 2.8	68.0 ± 8.74	76 ± 6.0	0.87 ± 0.059
flowering	4.2 ± 0.70	66 ± 4.3	64.5 ± 12.90	74 ± 8.5	0.85 ± 0.075
pea size	4.6 ± 0.38	75 ± 8.0	62.1 ± 1.79	80 ± 3.7	0.78 ± 0.038
veraison	4.2 ± 0.54	72 ± 4.9	57.6 ± 3.83	72 ± 3.9	0.81 ± 0.034
pre-harvest	4.3 ± 1.42	72 ± 2.4	59.5 ± 17.60	78 ± 11.4	0.73 ± 0.112
P	0.99	0.46	0.96	0.93	0.63
2008-09					
control	5.8 ± 0.56	85 ± 4.0	67.6 ± 5.12	79 ± 3.1	0.86 ± 0.048
budburst	6.2 ± 0.77	85 ± 6.4	71.2 ± 4.54	74 ± 4.9	0.96 ± 0.022
flowering	6.3 ± 1.12	85 ± 3.9	75.9 ± 15.33	86 ± 9.1	0.86 ± 0.098
pea size	7.1 ± 1.15	91 ± 4.0	77.3 ± 12.29	91 ± 4.9	0.84 ± 0.087
veraison	5.4 ± 0.49	90 ± 5.3	61.3 ± 5.03	82 ± 6.9	0.75 ± 0.045
pre-harvest	5.9 ± 0.56	86 ± 0.4	68.3 ± 6.80	88 ± 6.5	0.77 ± 0.020
P	0.77	0.89	0.81	0.34	0.28

Dynamics of berry growth and sugar accumulation

Analysis of variance did not detect treatment effects on berry weight at harvest (Table 1). To explore for transient effects of temperature, we fitted eq. 1 to the trajectories of berry weight (Fig. 6ab, Table 2). The sigmoidal model (eq. 1a) provided a statistically close description of the data ($R^2 \geq 0.95$, $P < 0.0001$). Lack of significant difference in parameters ($P > 0.05$) reinforced the conclusion of undetectable temperature effects. Model II regression comparing treated vs control (Fig. 6cd), however, indicated that the slopes departed from 1 in the post-set and pre-harvest treatments in 2007-08 and the veraison and pre-harvest treatments in 2008-09 (last column of Table 2). Slopes were ≈ 0.9, which is consistent with ≈ 10% smaller berries in these treatments (Table 1).

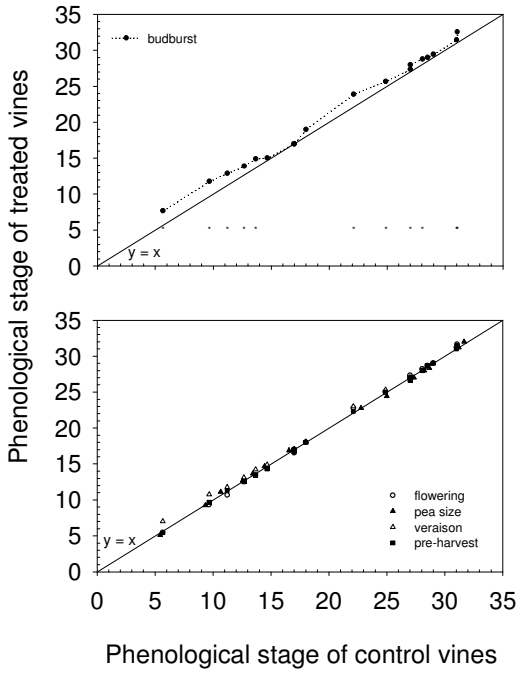


Figure 6. (a, b) Dynamics of berry growth and (c,d) comparison of treated and control berries. Table 2 shows parameters of the sigmoidal models fitted to the data in (a, b), and statistical analysis of the departures from the y=x line for the data in (c,d). In (a,b) horizontal segments indicate timing of treatments and error bars (2 s.e.) are illustrated only for controls to avoid clustering of symbols.

Table 2. Parameters (± s.e.) of the sigmoidal model of berry growth (eq. 1) and parameters of model II linear regression comparing berry weight in treated and control vines.

Season	Treatment	Parameters of equation (1)					Parameters of linear regression	
		R^2	a	b	x_0	y_o	intercept[a]	slope
2007-08	control	0.99	0.70 ± 0.048	7.5 ± 1.30	32.9 ± 1.30	0.30 ± 0.028		
	flowering	0.99	0.62 ± 0.032	4.6 ± 0.85	32.4 ± 0.96	0.34 ± 0.021	0.00	1.00[b]
	pea size	0.99	0.64 ± 0.048	7.7 ± 1.42	33.2 ± 1.41	0.28 ± 0.028	0.01	0.91[c]
	veraison	0.99	0.61 ± 0.031	5.3 ± 0.88	32.0 ± 0.97	0.30 ± 0.020	0.00	0.95[b]
	pre-harvest	0.99	0.63 ± 0.027	7.7 ± 0.81	32.9 ± 0.81	0.28 ± 0.016	0.01	0.90[c]
2008-09	control	0.98	0.50 ± 0.027	6.3 ± 1.12	36.7 ± 1.23	0.36 ± 0.019		
	budburst	0.96	0.55 ± 0.069	8.1 ± 2.64	32.9 ± 2.79	0.39 ± 0.050	0.05	1.04[b]
	flowering	0.97	0.49 ± 0.042	5.9 ± 1.68	33.4 ± 1.87	0.39 ± 0.031	0.04	1.00[b]
	pea size	0.97	0.47 ± 0.033	4.0 ± 1.20	29.9 ± 1.35	0.38 ± 0.025	0.05	0.98[b]
	veraison	0.95	0.44 ± 0.047	6.3 ± 2.23	36.1 ± 2.46	0.34 ± 0.033	0.01	0.89[c]
	pre-harvest	0.98	0.45 ± 0.024	6.0 ± 1.07	35.7 ± 1.18	0.32 ± 0.017	-0.01	0.91[c]

[a] Intercepts were not different from zero at $P > 0.86$ in 2007-08 and $P > 0.82$ in 2008-09.

[b] Not different from one at $P > 0.09$ in 2007-08 and $P > 0.79$ in 2008-09.

[c] Different from one at $P < 0.05$.

The dynamics of total soluble solids was largely unaffected by temperature as indicated by three complementary statistical tests (Fig. 7ab). First, eq. 1b provided a sound characterisation of the dynamics of soluble solids ($R^2 \geq 0.96$, $P < 0.0001$) with statistically undistinguishable parameters for all the treatments (not shown). Second, model II regression comparing treated vs control (insets in Fig 7ab) indicated that intercepts did not differ from zero ($P > 0.43$) and slopes did not differ from 1 in 7 out of 9 cases ($P > 0.05$). The exceptions were slopes different from 1 ($P < 0.01$) in the flowering (slope = 1.03) and veraison (slope = 0.93) treatments in 2008-09. Third, allometric analysis returned statistically similar scaling exponents of berry soluble solids, i.e. the relative rate of accumulation of soluble solids was maintained relative to the relative rate of change in berry weight (inset of Fig. 7cd).

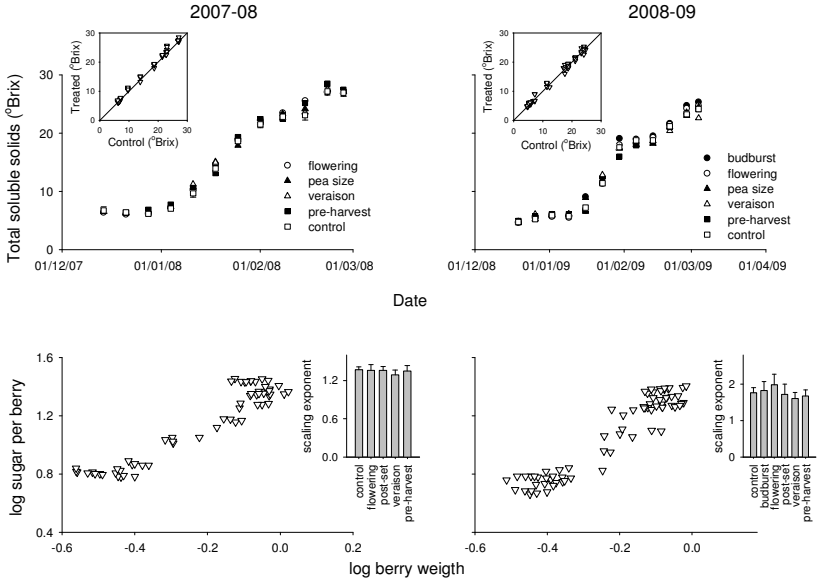


Figure 7. (a, b) Dynamics of total soluble solids and (c,d) allometric relationship between total soluble solids (g) and berry weight (g). Insets in (a,b) compare total soluble solids in berries of control and treated vines. Insets in (c,d) are the scaling exponents, i.e. the slopes of the regression log sugar vs log berry weight for each treatment.

Berry acidity and pH

Temperature treatments did not affect total acidity ($P > 0.99$; grand mean = 3.54 g/l, s.e. = 0.052) or pH ($P > 0.30$; grand mean = 3.88, s.e. = 0.016) in 2007-08.

Discussion

The worst-case scenario for projected mean temperature over the next four decades in south-eastern Australia is an increase of about 2 °C with respect to the 1961-1990 baseline (Webb et al., 2007). Assessing the impact of this projected warming requires active heating systems to elevate day and night temperature continuously over the dormant and growing parts of the vine annual cycle, and applying treatments for several seasons to allow for acclimation. As a first step towards this estimate, we devised and tested an open system to manipulate daytime temperature under realistic vineyard conditions; we are currently incorporating active heating and more refined temperature control while maintaining the benefits of an open system. Three outcomes were achieved (i) increased daytime temperature commensurate with worst-case scenario projections, (ii) tracked diurnal temperature cycle, and (iii) affected vapour pressure deficit, rather than relative humidity. The nature of our open system to increase temperature makes it primarily compatible with free-air carbon dioxide enrichment facilities (Bindi et al., 2001) and the possibility to investigate the interaction between temperature by ambient CO_2 concentration in vineyard conditions. Daytime warming during discrete phenological windows did not alter the yield components of Shiraz vines grown with standard practice in the Barossa Valley. None of the critical phenological stages probed in this study showed particular sensitivity to this magnitude and duration of daytime warming.

Increasing ambient temperature by 2-4 °C during 2 weeks in 2007-08 or 3 weeks in 2008-09 had no detectable effect on phenological development for treatments applied from flowering onwards. The budburst treatment in 2008-09 accelerated development in two "waves", i.e. between E-L 4 (budburst, leaf tip visible) and E-L 12/13 (5/6 leaves separated) and later around E-L 23 (50% caps off). Differences between treated and control vines disappeared in the intervening period. The phenological response to heating for the budburst treatment in contrast to the lack of response for other treatments maybe related to an intrinsically greater sensitivity of this stage, the greater temperature differential created by this treatment, or a combination of both. In grapevine, phenology is often modelled assuming that the base temperature is constant throughout the annual developmental cycle (Gutierrez et al., 1985; Williams et al., 1985; Jones and Davis, 2000). Detailed studies in annual species indicate, however, a clear seasonal pattern: base temperature for development declines with ontogeny in crops with a spring-summer cycle (Slafer et al., 2009). If this applies to grapevine, then it could be expected a greater responsiveness to increased temperature at early developmental stages, as we found in the budburst treatment. Bowen et al. (2004b) suggested a base temperature ≈ 0 °C for budburst and ≈ 10 °C for bunch development in Merlot. There is clear need for direct re-assessment of cardinal temperatures for development in grapevine. Working with Chardonnay, Petrie and Clingeleffer (2005) found no acceleration of development with increasing temperature before budburst and a significant acceleration of phenology in buds enclosed in mini-chambers where maximum temperature was increased by 5.7 °C after budburst. Experimental differences between their study and ours include: (i) heating individual buds vs whole plants, (ii) duration of treatment (iii) timing of treatment, i.e. pre- and post-budburst vs treatments bracketing budburst, (iv) moderate differences in the intensity of heating and (v) secondary effects such as accumulation of ethylene in their closed systems which were less likely in our open system. Importantly, the effect of temperature may involve a direct component on developing buds, and an indirect component related to mobilisation of carbon reserves, which was only captured in our whole-vine treatments. Further research to separate the putative indirect and direct effects of temperature on early bud development is important to capture relevant interactions, e.g. long-term effect of temperature that might reduce carbon reserves and partially cancel the direct accelerating effect of temperature on bud development.

Increasing temperature by 2-4 °C over 2 or 3 week periods on critical phenostages did not affect any yield component of weekly irrigated Shiraz. Lack of yield response did not result, therefore, from compensatory mechanisms; the only important compensatory pathway not tested in this paper is the one between flower number and fruit set. In the experiment of Ezzahouani (2003) in Morocco, the yield of Danlas grapevine grown under plastic cover was similar to that of untreated controls as a result of a reduction in berry number fully compensated by an increase in berry weight. In two out of three vineyards in the Okanagan Valley of British Columbia, Merlot yield was unaffected by sleeves that increased temperature of canes or cordons during 7 weeks in spring; smaller berries fully compensated by greater number of berries per bunch in response to elevated temperature (Bowen et al., 2004b). In the third vineyard, berry number decreased and was not compensated by heavier berries, leading to a significant yield reduction in response to heating (Bowen et al., 2004b). In Chardonnay, Petrie and Clingeleffer (2005) found that manipulation of single-bud temperature using closed mini-chambers before and after budburst had

significant effect on flower number; flower number per inflorescence decreased linearly with mean temperature between 14 and 18 ^{o}C at a rate between 24 and 33 flowers $^{o}C^{-1}$ but fruit set was not reported. Spayd et al. (2002) targeted individual bunches during the period from bunch closure to harvest and found no effect of temperature, or interaction between temperature and radiation on Merlot berry size.

The stability of yield components and the largely unaltered trajectories of berry weight and total soluble solids of Shiraz in response to increased temperature in our study may involve a variety-specific component. There is fragmented evidence to support this proposition. For an increase in temperature from 20 to 30 ^{o}C, the weight of bunch primordia increased 4-fold in Riesling, and was largely unaffected in Shiraz (Dunn, 2005). In a comparison of seven grapevine varieties in diverse environments of South Australia, Shiraz had the lowest phenotypic plasticity for budburst that indicates a comparatively low responsiveness to environmental variation (Sadras et al., 2009). Under short spells of high maximum temperature (> 40 ^{o}C) field-grown Shiraz up regulated stomatal conductance and gas exchange; this response was thought to contribute to heat dissipation and maintenance of physiological function under thermal stress (Soar et al., 2009). Consistent with this concept, we found that increased ambient maximum temperature by 2-4 ^{o}C only increased afternoon canopy temperature by 1.1-0.9 ^{o}C; Shiraz canopies effectively buffered the increase in ambient temperature (Fig. 4). This highlights the importance of water supply as a major factor modulating vine responses to temperature in anisohydric type plants such as Shiraz (Schultz, 2003; Soar et al., 2006).

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Chapter 4

Advancement of grapevine maturity in Australia between 1993 and 2006: putative causes, magnitude of trends and viticultural consequences

PR Petrie, VO Sadras

Summary

The magnitude of crop phenological responses to recent warming trends depends on the species and the cultivar, the phenophase, the magnitude of temperature changes, and the interactions among these factors. Given the importance of phenological development in viticulture, and the otherwise intractable interactions behind the actual responses to warming trends, we empirically determined the rate of change in phenological development of Chardonnay, Cabernet Sauvignon and Shiraz from commercial crops across Australia between 1993 and 2006. Data availability constrained the analysis to a short time series, but the analysis is nonetheless relevant to industry, quantifies the time-trends of phenological events under Australian conditions, and allows for comparison with other wine growing regions of the world.

Using linear regression with vintage year as independent variable, we calculated rates of change in (i) date of designated maturity (21.8 ^{o}Brix), (ii) date of harvest, (iii) sugar concentration of berries at harvest, and (iv) daily average temperature on a monthly basis.

We found (a) an advancement in the date of designated maturity in all region-cultivar combinations, with rates between –0.5 and –3.1 days per year and statistical significance in 24 out of 44 cases ($P < 0.05$); (b) no apparent association between trends in the date of designated maturity and trends in crop yield, (c) region-dependent temperature trends ranging from negligible up to 0.19 ^{o}C per year, with a clear seasonal pattern, i.e. more consistent warming in March, June and October-November, (d) correlations between temperature trends at different times of the year, including correlations between winter and spring trends, and (e) correlations between rate of change in date of designated maturity and rate of change in temperature which were strong for Chardonnay and Cabernet Sauvignon, and tenuous for Shiraz. For the pooled data, the rate of change in time of designated maturity per unit change in November temperature was -9.3 ± 2.67 days per ^{o}C. Collectively, these findings strongly support, but do not prove, a link between advancement in maturity and increasing temperature.

Harvest is a “false phenostage” as its timing is partially determined by the biological responses of the crop to the environment, and strongly influenced by winemaking decisions. Harvest was anticipated at a rate between –0.4 and –2.4 days per year. For Chardonnay, the rate of advancement in harvest was commensurate with the rate of change in maturity; hence berry sugar concentration at harvest remained stable in the investigated time period. In contrast, the advancement of harvest of

Cabernet Sauvignon and Shiraz only partially offset the advancements in maturity, with the result of a systematic increase in the concentration of berry sugar at harvest, up to ≈ 0.3 ^{o}Brix per year consistent with the trend for increasing alcohol previously reported for this period.

Introduction

Phenology is the most important attribute involved in the environmental adaptation of crops, and the timing of key phenostages, including flowering and harvest maturity, are strongly driven by temperature (Passioura et al. 1993, Pearce and Coombe 2004, Sadras and Trápani 1999). For grapevine, the timing of maturity also has logistic and winemaking implications.

Principles of crop physiology and empirical evidence both support the faster developmental rates associated with recent warming trends. For instance, Wolfe et al. (2005) reported flowering time of grapevine in northern North America had advanced at 0.15 d yr^{-1} between 1960 and 2001, whereas the rate of advancement for flowering of apple in the same environment and time interval was 0.20 d yr^{-1}. Sparks et al. (2005) reported consistently faster rates of advancement for perennials in the UK between 1980 and 2000, i.e. 0.47 d yr^{-1} for plum, 0.31 d yr^{-1} for pear, and 0.50 d yr^{-1} for cherry. The difference between these two studies is partially associated with the greater rate of increase in temperature during the last two decades (IPCC 2007), which was the time interval of the UK study, compared to the last four decades in the North American report. Also reflecting the sharper warming in the last two decades, time-trajectories of date of budburst, flowering and veraison of Riesling in Alsace showed a distinct two-line pattern, with no clear trend between 1960 and the mid 1980s, and a consistent linear advancement afterwards (Duchene and Schneider 2005).

Importantly, the responsiveness of plant development to temperature varies with phenophase (Sadras and Hall 1988, Slafer and Rawson 1994) and the dynamic nature of crop development adds a layer of complexity that makes assumptions based on linearity of responses unrealistic. For instance, modelled time from sowing to maturity of wheat in eastern Australia was reduced by up to ~ 0.3 d yr^{-1} in the last five decades, with time to flowering accounting for most of the variation in time to maturity (Sadras and Monzon 2006). The duration of the post-flowering phase was largely unchanged in association with either lack of detectable change in temperature in some locations, or where temperature increased, earlier flowering that shifted post-flowering development to relatively cooler conditions, thus neutralising the trend of increasing temperature. Budburst and flowering of Riesling in Alsace were about 15 days earlier in 2003 than in 1965 whereas veraison was advanced about 23 days in the same period (Duchene and Schneider 2005). The greater response of veraison was attributed to the combined effects of earlier budburst and a reduction of 8 days in the flowering-to-veraison period (Duchene and Schneider 2005).

Thus, principles of crop physiology and actual data both justify the expectation of faster development with increasing temperature. The actual rate of response, however, varies with the particular phenophase under consideration, the species and the cultivar, and the actual magnitude of temperature changes. Importantly, all these

factors often interact in largely unpredictable ways. Given the importance of phenological development in viticulture, and the interactions behind the actual response to warming trends, in this paper we empirically determined the rate of change in phenological development of three key varieties, i.e. Cabernet Sauvignon, Chardonnay and Shiraz, grown in major wine regions of Australia. In contrast to European long-term records (Chuine et al. 2004, Jones and Davis 2000), consistent and reliable records of phenology for the Australian industry are limited to shorter time periods, since 1993 in this case study. The analysis in this paper is therefore constrained to a short time series, but it is nonetheless relevant to industry, quantifies the time-trends of relevant phenological events under Australian conditions, and allows for comparison with other wine growing regions of the world. With cautious interpretation of results, analysis of short-term, i.e. decadal, time trends may yield valuable information (Wild et al. 2005).

Method

We used a commercial data set comprising samples from major grape growing regions in Australia between the 1993 and 2006 vintages (Table 1). The key variables derived from this data set were (i) date when fruit reached 21.8 ^{o}Brix (12 ^{o}Baume), from sequential maturity samples, and (ii) date of harvest and (iii) sugar concentration at harvest, from harvest samples. Hereafter, the date when fruit reached 21.8 ^{o}Brix will be referred to as date of designated maturity.

Sequential maturity samples

Company representatives or vineyard staff collected maturity samples at approximately weekly intervals in the period leading up until harvest. Samples were taken from both exposed and shaded fruit from both sides of the canopy across the block (Anon. 2006). Approximately 30 bunches per block were sampled to account for a coefficient of variation around 3 to 7% typical of a vineyard block (Bramley 2005, Krstic et al. 2003).

Sugar concentration of fruit was measured either on site by the vineyard staff or in the winery laboratory. If analysis was completed at the vineyard, the fruit was usually macerated in the plastic bag used for collection, and a sample decanted for sugar analysis using an analogue refractometer or hydrometer, normally not compensated for temperature. At the winery laboratories, juice was normally extracted using a small pneumatic press and analysis completed using a temperature compensating digital refractometer.

Company regulations currently target the collection of a minimum of four maturity samples per individual block prior to harvest; this means that sampling would normally start approximately a month before the block was harvested (Anon. 2006). However the number of samples entered into the database varied greatly depending on the maturity of the fruit when the first sample was taken, that rate at which the block ripened, the product that the fruit was processed into, and the enthusiasm of the person responsible for sampling the fruit.
Vineyard staff had a further incentive to avoid sample bias as the delivery of fruit to the winery that is different from the sample maturity may result in a financial penalty (Anon. 2006).

Table 1. Wine regions, time-series interval and number of samples used in the analysis of crop phenology for three grapevine varieties in Australia

Wine Region	Location[a]	Temp.[b] (°C)	Time-series interval			Number of samples[c]		
			Chardonnay	Cab Sauv	Shiraz	Chardonnay	Cab Sauv	Shiraz
Adelaide Hills	Stirling	18.7	1993-2006	1993-2006	1995-2006	203	163	104
Grampians	Ararat	19.1	1993-2006	1993-2006	1993-2006	45	51	164
Yarra Valley	Scoreby	19.2	1994-2006	1997-2006		150	54	
Coonawarra	Coonawarra	19.5	1994-2006	1994-2006	1994-2006	155	476	263
Padthaway	Padthaway	20.3	1994-2006	1994-2006	1994-2006	225	151	167
Lang. Creek	Strathalbyn	20.5	1993-2006	1993-2006	1993-2006	83	404	408
Goulburn Valley	Shepparton	21.1			1996-2006			51
Barossa Valley	Nuriootpa	21.2	1993-2006	1993-2006	1993-2006	483	597	2600
Alpine Valleys	Bright	21.3		1994-2005				
McLaren Vale	Strathalbyn	21.4	1993-2006	1993-2006	1993-2006	385	514	1059
Clare Valley	Clare	21.5	1993-2006	1993-2006	1993-2006	174	258	440
Adelaide Plains	Parafield	22.4	1993-2006	1993-2006	1997-2006	33	26	78
Hilltops	Young	22.6		1996-2006	1996-2006		44	42
Riverland	Berri	23.2	1993-2006	1993-2006	1993-2006	1097	108	1389
Mudgee	Mudgee	23.3		1996-2006			135	
Swan Hill	Swan Hill	23.4	1993-2006	1997-2006	1997-2006	65	54	134
Cowra	Cowra	23.5	1997-2006	1997-2006		93	42	
Murray Darling	Mildura	23.6	1993-2006	1995-2006	1996-2006	964	597	767

a. Reference locations for climate data from SILO (http://www.bom.gov.au/silo/)
b. Mean temperature of the warmest month, from Gladstones (1992)
c. Number of samples for maturity date (21.8 °Brix). The number of samples for harvest date and sugar concentration at harvest was 1.4 to 8.8 larger.

Harvest samples

Harvest samples were collected at the weighbridge. Prior to 1998 most sites collected samples from bins of machine harvested fruit using a manual probe, and sufficient juice was collected to allow sugar measurement using a hydrometer, although a refractometer was also used on some sites. Hand harvested fruit was taken from the top of bins and pressed using a small pneumatic press. More recently an automated sampling system (Maselli Misure, Parma, Italy) has been used for hand and machine harvested fruit at most sites.

Data management and analysis

Data were collected and held in a vineyard and winery management software (Total Systems for Management Pty Ltd, Australia). Reports were extracted from the database containing information on the location of the vineyard blocks and the grape variety, the sample date and sugar concentration from sequential maturity samples, the date that the fruit was delivered to the winery, and the sugar concentration of the fruit at delivery. Multiple maturity samples from a block on a given date were averaged. If a block was harvested in two dates, these events were recorded separately, and both contributed to the calculated average harvest date and sugar concentration at harvest.

The date of designated maturity for each individual block was calculated from linear interpolation of sequential samples. Rates of change of the three dependent variables, i.e. date of designated maturity, date of harvest and sugar concentration at harvest, were calculated using linear regression against the independent variable, vintage year. Likewise, we used regression analysis to calculate the rate of change in average temperature for each location and for each period corresponding to the actual records of crop observations (Table 1). Daily average temperature for a reference location in each region (Gladstones 1992) was obtained from the Australian Bureau of Meteorology (http://www.bom.gov.au/silo/). The relationships between crop responses and temperature were explored with regression analysis.

Results

Spatial variation in date of designated maturity (21.8 ^{o}Brix)

Regression between the date of designated maturity and average temperature in November for the data pooled across seasons and cultivars, yielded a rate of –6.6 d $^{o}C^{-1}$, which accounts for the spatial variation across the wine regions under study (Figure 1). This rate is considered robust, as it accounts for well-defined regional differences, and provides a benchmark for the rate of change in date of designated maturity with time, which is likely to be less reliable owing to the short time series used in this analysis (next section).

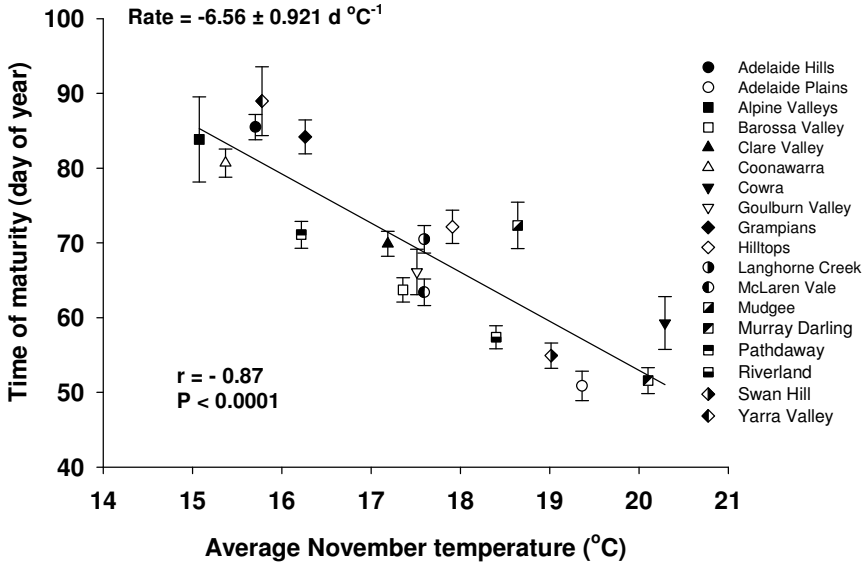


Figure 1. Date of designated maturity (21.8 °Brix) as a function of average November temperature across Australian wine regions. Data were pooled across seasons and varieties, as indicated in Table 1. Error bars are two standard errors of the mean.

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Time trends in date of designated maturity and temperature

The date of designated maturity advanced, i.e. the rate of change with time was negative, in all region- cultivar combinations (Table 2). This rate ranged from –0.5 to –3.1 d yr^{-1}, and was significant in 24 out of 44 cases.

Table 2. Time-trends of designated maturity date (21.8 °Brix, y_1), harvest date (y_2) and sugar concentration at harvest (y_3) for three varieties in major wine regions of Australia. Values are the slope ± standard error of linear regressions between the independent variables (y_1, y_2, y_3) and vintage year (x) for the periods indicated in Table 1. Rates in bold indicate $P < 0.05$. Regions are in order of increasing temperature (cf. Table 1)

Region	Maturity	(d yr^{-1})		Harvest	(d yr^{-1})		Sugar at harvest	(°Brix yr^{-1})	
	Chardonnay	Cab. Sauv.	Shiraz	Chardonnay	Cab. Sauv.	Shiraz	Chardonnay	Cab. Sauv.	Shiraz
Adelaide Hills	-0.89 ± 0.606	-0.48 ± 0.607	-0.92 ± 0.949	-0.34 ± 0.616	-0.89 ± 0.432	**-1.49 ± 0.597***	0.00 ± 0.024	0.11 ± 0.052	**0.16 ± 0.044****
Grampians	-1.05 ± 0.582	-1.62 ± 1.092	**-2.07 ± 0.740***	-1.05 ±0.619	**-1.74 ± 0.646***	**-2.01 ± 0.724***	0.07 ± 0.054	0.08 ± 0.064	012. ± 0.063
Yarra Valley	**-1.96 ± 0.572****	-2.79 ± 1.338		**-2.36 ± 0.481*****	**-1.76 ± 0.494****		0.09 ± 0.042	**0.29 ± 0.030*****	
Coonawarra	-1.18 ± 0.569	**-2.18 ± 0.523****	-1.06 ± 0.767	**-1.49 ± 0.628***	**-1.09 ± 0.429***	-0.49 ± 0.592	0.06 ± 0.045	0.10 ± 0.068	**0.19 ± 0.059****
Padthaway	**-1.20 ± 0.538***	**-1.66 ± 0.629***	-1.49 ± 0.763	**-1.87 ± 0.596****	-1.10 ± 0.531	-1.25 ± 0.642	0.03 ± 0.048	0.15 ± 0.071	**0.23 ± 0.041*****
Langhorne Creek	-0.69 ± 0.580	**-2.05 ± 0.396*****	**-1.98 ± 0.318*****	-1.11 ± 0.534	**-1.36 ± 0.409****	**-1.53 ± 0.416****	0.02 ± 0.016	**0.12 ± 0.047***	**0.16 ± 0.052****
Goulburn Valley			**-2.12 ± 0.729***			**-2.04 ± 0.505****			**0.05 ± 0.069**
Barossa Valley	-0.93 ± 0.563	**-1.16 ± 0.438***	**-1.30 ± 0.466***	-1.37 ± 0.659	-0.91 ± 0.526	**-1.49 ± 0.494***	-0.03 ± 0.02	**0.13 ± 0.040****	**0.09 ± 0.029***
Alpine Valleys		-1.12 ± 1.714			-2.03 ± 1.263			**0.15 ± 0.070***	
McLaren Vale	-0.93 ± 0.611	**-1.61 ± 0.390*****	**-1.78 ± 0.413*****	**-1.54 ± 0.615***	**-1.51 ± 0.483****	**-1.50 ± 0.468****	-0.02 ± 0.043	**0.11 ± 0.045***	**0.11 ± 0.025*****
Clare Valley	-0.86 ± 0.596	**-1.40 ± 0.428****	**-1.40 ± 0.383****	**-1.55 ± 0.579***	**-1.18 ± 0.505***	**-1.30 ± 0.534***	-0.02 ± 0.039	**0.13 ± 0.060***	**0.19 ± 0.050****
Adelaide Plains	**-1.30 ± 0.495***	**-1.23 ± 0.503***	-1.47 ± 0.829	**-1.13 ± 0.471***	-0.69 ± 0.616	**-1.51 ± 0.458****	-0.01 ± 0.092	**0.20 ± 0.077***	0.03 ± 0.072
Hilltops		-0.40 ± 1.028	-1.38 ± 0.959		0.00 ± 0.065	-0.16 ± 1.011		-0.01 ± 0.065	-0.14 ± 0.137
Riverland	**-1.11 ± 0.359****	**-1.23 ± 0.441***	**-1.59 ± 0.260*****	**-1.49 ± 0.413****	-0.61 ± 0.505	**-0.90 ± 0.309***	-0.04 ± 0.041	**0.16 ± 0.041***	**0.16 ± 0.036*****
Mudgee		-1.33 ± 0.973			-0.80 ± 0.711			0.03 ± 0.037	
Swan Hill	-0.47 ± 0.412	**-2.03 ± 0.788***	-1.46 ± 0.880	-0.97 ± 0.470	**-1.16 ± 0.465***	-0.80 ± 0.739	-0.08 ± 0.091	-0.06 ± 0.059	0.07 ± 0.113
Cowra	-1.76 ± 0.877	**-3.14 ± 1.055***		**-2.35 ± 0.622****	**-2.19 ± 0.861***		-0.01± 0.056	0.03 ±0.046	
Murray Darling	**-1.38 ± 0.400****	**-2.08 ± 0.338****	**-1.16 ± 0.283****	**-1.78 ± 0.388*****	**-1.93 ± 0.310*****	**-1.34 ± 0.269*****	-0.07 ± 0.046	0.03 ± 0.046	-0.06 ± 0.076

* P < 0.05, ** P < 0.01,*** <0.001

In the period 1993-2006, temperature trends were dominantly positive with a distinct seasonal pattern (Figure 2). March, June and November stand out as the months with few or no negative rates and a comparatively large proportion of statistically significant positive rates. However, the rate of change in temperature for a particular month was correlated with the rate of change in temperature in other months (Table 3). The correlation in the rate of temperature in successive months, say August with September, is not surprising but it is worth noting strong remote correlations, such as that between June and spring months (Table 3).

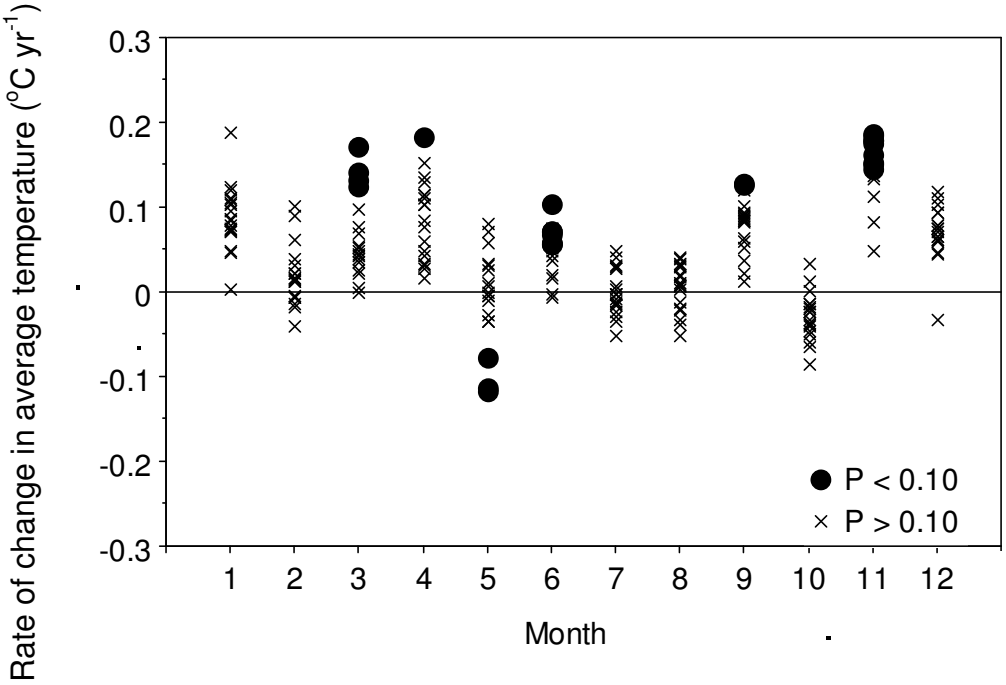


Figure 2. Rate of change in average temperature for 18 wine regions in the period 1993-2006. Rates were calculated as the slope of the linear regression between temperature and vintage year.

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Table 3. Correlation matrix of the rate of change in average temperature between 1993 and 2006

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Jan	1.00	0.68	0.51	0.55	0.30	0.52	0.44	0.63	0.53	0.64	0.64	0.82
Feb	0.68	1.00	0.71	0.39	-0.26	0.19	0.36	0.35	0.25	0.64	0.24	0.56
Mar	0.51	0.71	1.00	0.65	-0.05	0.27	0.71	0.53	0.17	0.52	0.39	0.21
Apr	0.55	0.39	0.65	1.00	0.50	0.39	0.47	0.73	0.51	0.36	0.60	0.29
May	0.30	-0.26	-0.05	0.50	1.00	0.61	0.15	0.59	0.70	0.22	0.50	0.18
Jun	0.52	0.19	0.27	0.39	0.61	1.00	0.46	0.80	0.82	0.78	0.62	0.54
Jul	0.44	0.36	0.71	0.47	0.15	0.46	1.00	0.69	0.35	0.56	0.68	0.33
Aug	0.63	0.35	0.53	0.73	0.59	0.80	0.69	1.00	0.81	0.73	0.87	0.62
Sep	0.53	0.25	0.17	0.51	0.70	0.82	0.35	0.81	1.00	0.75	0.62	0.61
Oct	0.64	0.64	0.52	0.36	0.22	0.78	0.56	0.73	0.75	1.00	0.57	0.71
Nov	0.64	0.24	0.39	0.60	0.50	0.62	0.68	0.87	0.62	0.57	1.00	0.65
Dec	0.82	0.56	0.21	0.29	0.18	0.54	0.33	0.62	0.61	0.71	0.65	1.00

The slope of the regression between the rate of change in the date of designated maturity and the rate of change in temperature represents the rate of change in the date of designated maturity per unit change in temperature (Sadras and Monzon 2006), as illustrated in the inset of Figure 3. The change in the date of designated maturity per unit change in temperature showed a strong seasonal pattern (Figure 3) that partially reflected the pattern of temperature change in Figure 2. Change in the date of designated maturity was particularly associated with temperature in March, June, and October-November (Figure 3). The pattern was very strong for Chardonnay and Cabernet Sauvignon, and it was only insinuated for Shiraz. The association between the rate of change in the date of designated maturity and the rate of change in temperature was particularly strong in winter, i.e. in June it was significant at $P < 0.0001$ for Chardonnay and $P = 0.004$ for Cabernet Sauvignon.

To compare the putative effect of temperature on the rate of change in the date of designated maturity with space (Fig. 1) or time (Fig. 3) we calculated a pooled rate of change for November. The rate associated with time, i.e. 9.3 ± 2.67 d $^{o}C^{-1}$ was higher but statistically undistinguishably from the rate calculated with space as source of variation in temperature, i.e. 6.6 ± 0.92 d $^{o}C^{-1}$.

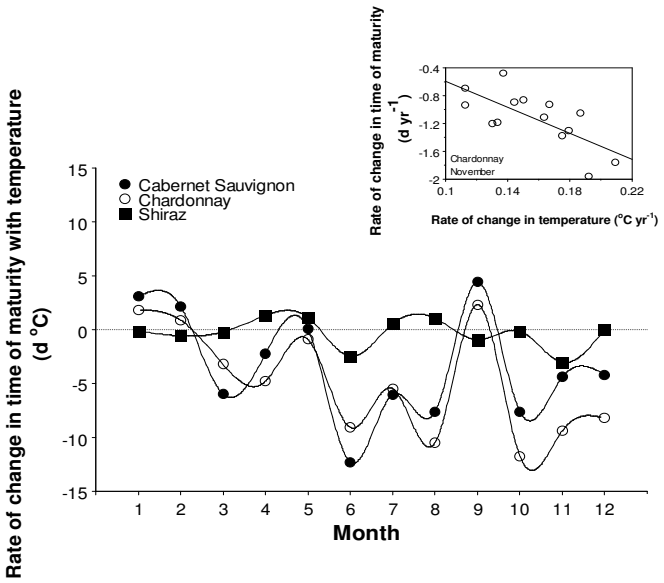


Figure 3. Rate of change in date of designated maturity (21.8 °Brix) with temperature for three grapevine varieties. Rates were calculated as the slope of the regression between the rate of change in date of designated maturity with time, and the rate of change of temperature with time, as illustrated for Chardonnay/November in the inset.

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Time trends in yield and relationships with date of designated maturity

Faster maturity could be associated with lower yield (Pearce and Coombe 2004), hence the need to explore the time trends in crop yield and the possible links with trends in maturity. Between 1993 and 2006, yield in the sampled crops increased noticeably, up to 1.8 t/ha per year, in the warmer regions, e.g. Murray Darling, Riverland and Swan Hill (Table 4). Yield declined at a more moderate rate, between –0.3 and –0.7 t/ha per year in cooler regions, e.g. Yarra Valley, Coonawarra and Padthaway (Table 4).

Table 4
Time-trends in crop yield between 1993 and 2006. Rates and standard errors are the slopes of the linear regression between yield and vintage year; P indicates significance of the regression. Regions are in order of increasing temperature (cf. Table 1)

Region	Chardonnay			Cabernet Sauvignon			Shiraz		
	rate	se	P	rate	se	P	rate	se	P
Adelaide Hills	0.19	0.149	0.226	0.04	0.149	0.785	-0.17	0.235	0.482
Grampians	0.05	0.129	0.733	0.03	0.105	0.765	0.16	0.070	0.039
Yarra Valley	-0.22	0.221	0.343	-0.69	0.285	0.037			
Coonawarra	-0.22	0.161	0.192	-0.20	0.132	0.156	-0.34	0.143	0.036
Padthaway	-0.06	0.182	0.735	-0.14	0.163	0.412	-0.31	0.209	0.167
Langhorne Ck	0.58	0.286	0.064	0.17	0.144	0.262	-0.44	0.144	0.010
Goulb. Valley							0.42	0.089	0.001
Barossa	0.20	0.095	0.062	0.01	0.070	0.853	-0.02	0.077	0.808
Alpine Valleys				0.85	0.181	0.001			
McLaren Vale	-0.05	0.187	0.789	-0.18	0.116	0.143	-0.35	0.148	0.034
Clare Valley	-0.07	0.121	0.561	-0.15	0.104	0.182	-0.20	0.109	0.088
Adelaide Plains	-0.28	0.265	0.318	-0.16	0.177	0.380	0.37	0.132	0.015
Hilltops							0.63	0.226	0.027
Riverland	1.10	0.130	<0.0001	0.91	0.126	<0.0001	0.71	0.099	<0.0001
Mudgee				0.40	0.172	0.055			
Swan Hill	0.93	0.206	0.001				0.94	0.204	0.002
Cowra	-0.28	0.469	0.572	0.29	0.459	0.552			
Murray Darling	0.75	0.203	0.003	1.83	0.238	<0.0001	1.15	0.221	0.001

Pooled across regions, higher yielding crops matured faster (Figure 4a-c). This was explained by the dominance of high-yielding crops in the warmer, mostly irrigated growing regions (Figure 4d-f). Once the effect of temperature was removed, date of designated maturity and yield were found to be largely unrelated (Figure 4g-i). Likewise, there was no association between the rate of change in yield and the rate of change in date of designated maturity (Fig. 4j-l).

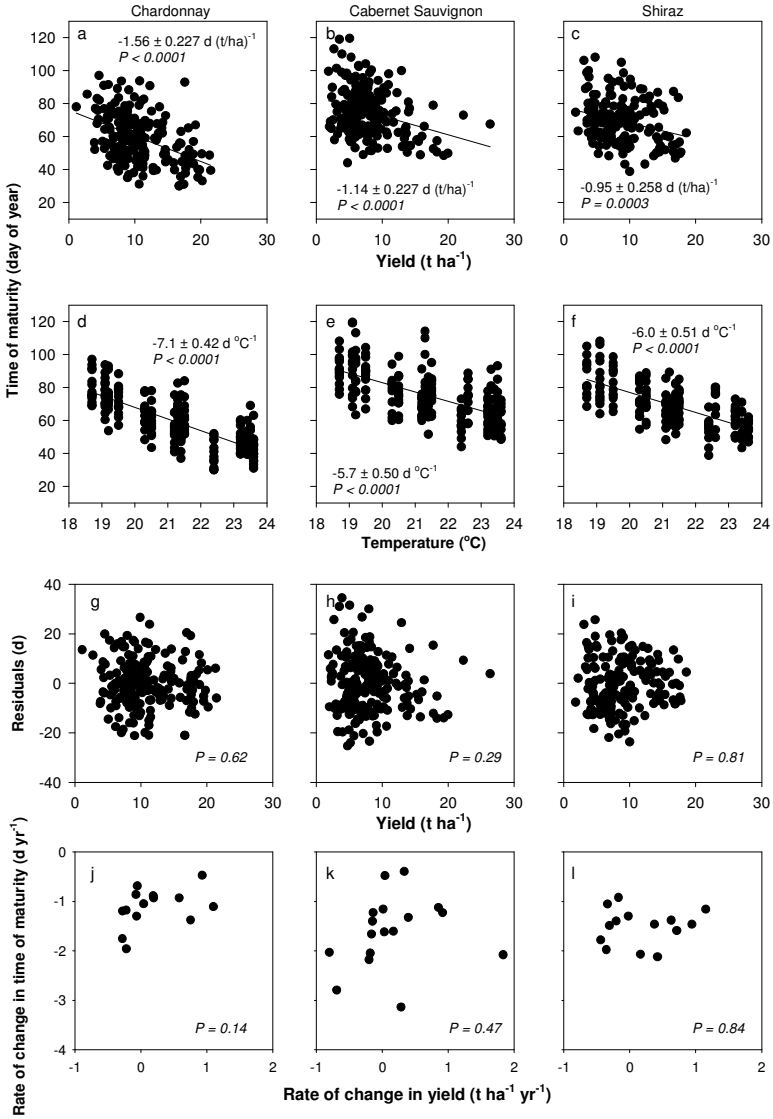


Figure 4. Relationships between (a-c) date of designated maturity (21.8 °Brix) and crop yield, (d-f) date of designated maturity and regional reference temperature, (g-i) residuals of the regression between date of designated maturity and temperature and crop yield, (k-l) rate of change in date of designated maturity and rate of change in yield. Reference temperature is the mean temperature of the warmest month, from Gladstones (1992).

Relationships between change in date of designated maturity, date of harvest and berry sugar concentration at harvest

Between 1993 and 2006, harvest advanced at a rate ranging from -0.4 to -2.4 d yr^{-1} (Table 2). For Chardonnay, the rate of advancement in harvest was commensurate

with the rate of change in maturity; hence berry sugar concentration at harvest remained stable (Figure 5). In contrast for Shiraz and Cabernet Sauvignon, the advancement of harvest only partially offset the faster maturity, with the result of systematic increase in the concentration of berry sugar at harvest (Figure 5, Table 2).

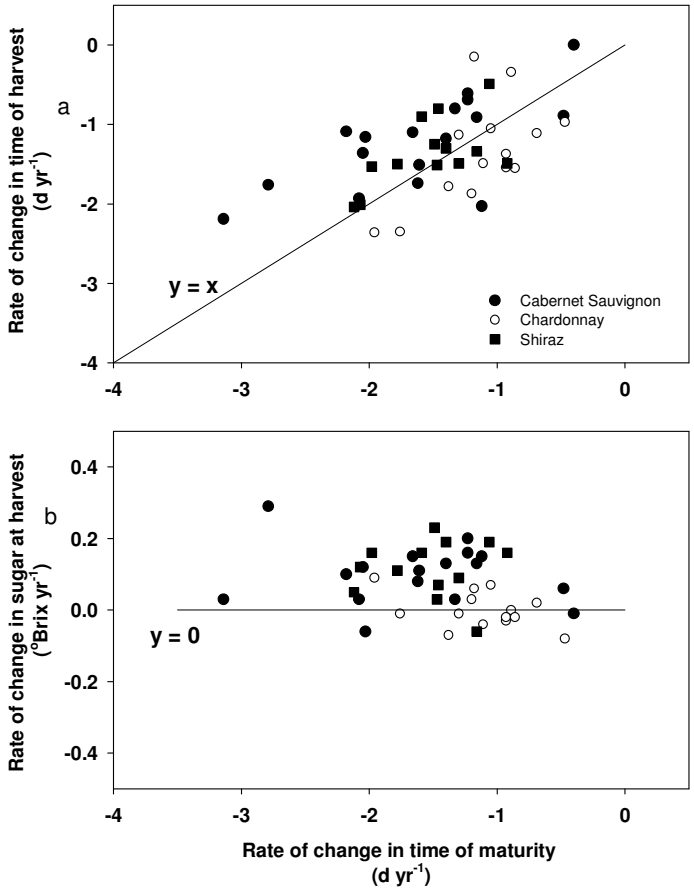


Figure 5. Relationship between (a) rate of change in time of harvest, and (b) rate of change in berry sugar concentration at harvest, and the rate of change in the time of designated maturity.

Discussion

Time trends in the date of designated maturity: relative magnitudes

Owing to the short time series in this analysis, our results need to be interpreted with extreme caution, and extrapolation beyond the time interval investigated should be avoided. For short time series, there is a higher likelihood of few extreme data points exerting a large influence in the sign and magnitude of the slopes of linear regressions. With these constraints considered, short time series may yield relevant information, as illustrated in studies of solar radiation spaning the 1992-2002 period

(Wild et al. 2005). The time trends in grapevine phenology in this paper are therefore best seen as a snapshot of the 1993 and 2006 period in Australia.

The rate of change in date of designated maturity was consistently negative, and ranged from –0.5 to –3.1 days per year (Table 2). There were apparent environment by cultivar interactions, which indicate differential sensitivity of cultivars to temperature. For instance at Langhorne Creek the time trend was minor, non-significant for Chardonnay (-0.7 d yr^{-1}) compared to a rate ≈ -2 d yr^{-1} for Shiraz and Cabernet Sauvignon. The time trend was much stronger for Shiraz than for Cabernet Sauvignon at the Grampians, and the opposite was true at Swan Hill. This crossing over of varieties and environments could be a study artefact (Hunter and Schmidt 1990) or an indication of factors other than temperature affecting the time trend of maturity; the resolution of our data is insufficient to address this question.

On a time basis, the rates of change in date of designated maturity in our study were much larger than the rates of change in phenological responses of grapevine reported for North America and France (Table 5). This could be related to differences in sensitivity of different phenophases, cultivar-dependent responses, and more likely, differences in the rates of change in temperature partially associated with longer time series in the northern hemisphere studies. Comparison of the rates calculated on a temperature basis showed a much closer agreement with the rates for grapevine in our Australian environments (Table 5). Implicit in this comparison is the assumption that temperature is a major driver of time trends in phenological development, as discussed in the next section.

Table 5. Time trends in grapevine variables related to crop phenology

Variety	Region	Period	Variable	Rate (unit)	Source
Chardonnay	Australia	1993-2006	designated maturity	-0.47 to –1.96 (d yr^{-1})	This study
Cabernet Sauvignon				-0.48 to –3.14 (d yr^{-1})	
Shiraz				-0.92 to –2. 12 (d yr^{-1})	
Pooled varieties				-9.3 ± 2.67 (d $°C^{-1}$)[a]	
Chardonnay			Harvest	-0.34 to –2.36 (d yr^{-1})	
Cabernet Sauvignon				-0.31 to –2.19 (d yr^{-1})	
Shiraz				-0.49 to –2.04 (d yr^{-1})	
Chardonnay			sugar at harvest	-0.08 to 0.09 ($°$Brix yr^{-1})	
Cabernet Sauvignon				-0.06 to 0.29 ($°$Brix yr^{-1})	
Shiraz				-0.06 to 0.23 ($°$Brix yr^{-1})	
Chardonnay			potential alcohol	0.05 (% yr^{-1})	
Cabernet Sauvignon				0.17 (% yr^{-1})	
Shiraz				0.14 (% yr^{-1})	
Concord	Northern USA	1965-2001	flowering	-0.15 d yr^{-1}	(Wolfe et al. 2005)
				-6.6 to -.2 (d $°C^{-1}$)[c]	
Cabernet Sauvignon and Merlot	Bordeaux, France	1952-1997	flowering-to-veraison	-0.09 (d yr^{-1})	(Jones and Davis 2000)
			veraison-to-harvest	-0. 12 (d yr^{-1})	
			flowering-to-harvest	-0. 12 (d yr^{-1})	
			flowering-to-veraison	-2.6 (d $°C^{-1}$)[d]	
			veraison-to-harvest	-3.4 (d $°C^{-1}$)	
			flowering-to-harvest	-6.0 (d $°C^{-1}$)	
Riesling	Alsace, France	1972-2003	potential alcohol	0.08 (% yr^{-1})	(Duchene and Schneider 2005)

[a] November average temperature
[b] Assuming an alcohol-to-brix ratio = 0.59 (Jones and Ough 1985)
[c] Calculated from time trends of regional average temperature for April and March
[d] Calculated from the time trends in temperature for Bordeaux from Jones et al. (2005)

Advanced date of designated maturity: putative causes

For the period 1993-2006, we found (a) a general advancement in the date of designated maturity of Chardonnay, Shiraz and Cabernet Sauvignon in most wine growing regions of Australia (Table 2), (b) region-dependent temperature trends ranging from negligible up to 0.19 ^{o}C yr^{-1}, with a clear seasonal pattern (Figure 2), (c) correlations between temperature trends at different times of the year, including correlations between winter and spring trends (Table 3), (d) correlations between rate of change in date of designated maturity and rate of change in temperature (Figure 3), and (e) no apparent general link between date of designated maturity and crop yield after accounting for temperature (Figure 4). This is consistent with, but does not prove, the proposal that temperature is a major driver of the time trend in maturity. The stronger correlations between phenological development and temperature were observed for March, June and October-November. This reflects both the more pronounced changes in temperature in these months and the correlations between rate of change in temperature in different months. Thus, the strong correlation between rate of change in temperature in June and time to maturity could partially reflect a true effect of winter temperature in development (Baldwin 1966, Petrie and Clingeleffer 2005), but also a correlative effect derived from the strong association between rate of change in temperature in June and spring months. To solve this issue, more detailed data on phenology are required to allow for the putative effect of long-term changes in temperature on budburst and on subsequent developmental stages. Quantifying the time trends in timing of budburst is particularly important, as the relative changes in onset of the growing season and maturity may lead to net changes in the total duration of the growth cycle (Linderholm 2006), and early budburst may increase the risk of frost damage in early reproductive stages (Hänninen 2006).

The timing of grapevine maturity depends on temperature and source : sink ratio (Bodin and Morlat 2006, Godwin et al., Naor et al. 2002, Ollat and Gaudillere 1998, Pearce and Coombe 2004, Petrie et al. 2003, Sadras et al. 2007). From first principles, therefore, we could expect faster development towards maturity under conditions that favour photosynthesis, including higher radiation and higher proportion of diffuse radiation (Gu et al. 2003, Petrie 2002, Rodriguez and Sadras 2007), and higher rainfall and lower evaporative demand. However, the expected effect of rainfall is complex because (i) rainfall may influence the rate of ripening indirectly through its effect on yield, and directly during the accumulation of sugars in the ripening phase, and (ii) actual availability of water is also related to variable irrigation regimes and changes in reference evapotranspiration, which has declined in the last decades (Chattopadhyay and Hulme 1997, Cohen et al. 2002, Roderick and Farquhar 2002, Roderick and Farquhar 2004). Rainfall can indeed affect phenological patterns of natural vegetation (Penuelas et al. 2004). For grapevine in Australia, however, it is unlikely that the measured changes in time to maturity were related to total solar radiation, which declined in the last half of the past century in parallel to increasing temperature (Cohen et al. 2002, Roderick and Farquhar 2002, Roderick and Farquhar 2004, Stanhill and Cohen 2001) or rainfall, which showed no substantial time trend except for the drying of a small region in the far south-west of Western Australia (Dore 2005). It is unclear whether the increase in the fraction of diffuse radiation or decline in evaporative demand may have contributed to faster maturity.

The relationship between yield and time to maturity is highly relevant. Targeted experiments clearly show that source : sink reductions established, for instance through defoliation, delays or even precludes the achievement of harvest maturity (Ollat and Gaudillere 1998). Longer time to maturity with increasing yield of Shiraz has been reported for a single season in the Riverland (South Australia) (Pearce and Coombe 2004). Implicit in this relationship is that high yield was associated with reduced source : sink, whereas we could speculate that variation in yield achieved through the maintenance of source:sink ratio should have no effect on time to maturity. Pooling the data across regions and seasons, and accounting for the effect of temperature, we found no evident link between yield and maturity (Figure 4a-i). At the scale of individual regions, the rate of change in date of maturity was largely independent of the rate of change in yield (Figure 4 j-l). The relationship between trends in maturity and trends in yield deserves studies with more detailed account of both phenological development (i.e. segregating relevant phenophases) and source : sink relationships (i.e. dynamics of yield components, canopy photosynthetic activity and carbohydrate reserves) against a framework of increasing temperature.

There are many studies showing significant advancement of phenological development in wild and domesticated plants and animals during the last decades (Chambers 2005, Chen et al. 2005, Hays et al. 2005, Hu et al. 2005, Sparks et al. 2005, Wolfe et al. 2005). Menzel et al. (2006) addressed the possibility of bias in the literature, i.e. the increasing difficulty in reporting “no change” or “change opposite to the direction expected” in peer-reviewed journals. In their comprehensive study, they analysed a phenological data set of over 125 000 time series of 542 plant and 19 animal species in 21 European countries. For the period 1971-2000, they found that 78% of all leafing, flowering and fruiting events advanced. Statistically significant differences included 30% of cases of advanced phenological development and 3% of cases of delayed events. Menzel et al. (2006) also showed correlations between rates of change in phenological development and rate of change in temperature that reinforces the apparent link between these two variables.

It is important to note that, owing to the cumulative effect of temperature on crop phenology, significant changes in the rate of development could be detected even when change in temperature is statistically undetectable (Sadras and Monzon 2006). Indeed, Sadras and Monzon (2006) modelling of the reproductive development of wheat in Australia and Menzel et al. (2006) using phenological records of fruiting phases in Europe, both showed that a rate of increase in temperature ~ 0.02 ^{o}C yr^{-1} is sufficient to trigger substantial phenological responses. Because of the noise in temperature records, rates of temperature change about 0.02 ^{o}C yr^{-1} are often undetectable statistically, as illustrated in the short time-series in this study (Figure 2), and for longer time-series in Sadras and Monzon (2006).

Our own analysis, the scientific literature on phenological time-trends in recent decades, and physiological principles, all support the conclusion that the observed trends of earlier maturity of grapevine in Australia since 1993 likely resulted from increasing temperature. The evidence to support this proposal is very strong, but it is nonetheless primarily correlative and therefore inconclusive. Yet unnoticed or less investigated factors, including diffuse radiation, might have also contributed to the observed trends in maturity of grapevine in Australia.

Advanced date of designated maturity: viticultural implications

In phenological studies, farmers' activities such as tilling, drilling, and harvesting are known as "false phenostages", because they are coupled to climate more loosely than biological processes (Menzel et al. 2006). Nonetheless, this type of activities showed consistent time trends in diverse farming systems of Europe, including the earlier harvest of Riesling in Alsace since 1970 (Duchene and Schneider 2005, Menzel et al. 2006, Sparks et al. 2005). Here we found that harvest of Chardonnay advanced at a rate comparable to the rate of advancement in maturity, with the consequent maintenance of sugar concentration at harvest, and hence the maintenance of potential alcohol. Advanced harvest in Shiraz and Cabernet Sauvignon only partially compensated for faster maturity; hence the trend for greater sugar concentration in harvested fruit, and the corresponding increase in potential alcohol (Figure 4). Our results are qualitatively consistent with an independent report of time trends for Australian wines between 1984 and 2004, i.e. alcohol increased in Cabernet Sauvignon and Shiraz, and remained stable for Chardonnay (Godden and Gishen 2005); lack of reported rates precludes a quantitative comparison. On both a chronological scale (Table 3) and a temperature scale (not shown), the rate of change in potential alcohol reported for Riesling in France was between the rates calculated for Chardonnay and Shiraz-Cabernet Sauvignon in Australia.

Variety-dependent responses are highly relevant for viticultural management and winemaking decisions. The seasonal trend and the magnitude of the association between rate of change in maturity and the rate of change in temperature were very similar for Chardonnay and Cabernet Sauvignon (Figure 3). For these varieties, there was a marked association in early autumn, winter and late spring that was only insinuated for Shiraz. We cannot explain this difference, but there are distinct traits that might contribute to the differential response of Shiraz. First, Shiraz tends to maintain higher stomatal conductance than other varieties in response to soil water deficit (Schultz 2003). This may partially decouple Shiraz canopy temperature from ambient temperature. Temperature of ripening berries, and temperature of other non-transpiring structures such as axillary buds, however, are much less buffered from the environment (Landsberg et al. 1974, Smart and Sinclair 1976). Second, Dunn (2005) discussed the correlation between weight per bunch and bunches per vine in Chardonnay and Cabernet Sauvignon, and the lack of correlation in Shiraz in terms of Shiraz differential developmental response to temperature. In particular, Dunn (2005) emphasised the lack of response in Shiraz bunch primordia size in a range from 20 to 35 ^{o}C. Ebadi et al. (1995) also reported no response of Shiraz fruit set in a range of temperature that caused a 2-fold variation of fruit set in Chardonnay. Third, water loss during late ripening plays a distinct role in development of Shiraz berries (McCarthy 1999). Recent studies showed this is a highly plastic trait whereby loss of water is paralleled by small loss of berry solute, or small gain of solute during the shrinking stage depending upon yet poorly understood environmental drivers (Sadras and McCarthy 2007). (Tyerman et al. 2004) showed that hydraulic conductance of Shiraz berries was 2- to 5-fold higher than that for Chardonnay, and that Shiraz maintained a higher hydraulic conductance past 90 days after flowering than Chardonnay. Physiological differences between Shiraz, Cabernet Sauvignon and Chardonnay could be related to taxonomic differences (Bourquin et al. 1993) that in turn maybe indicative of variation in selective pressures.

Conclusion

This is the first report of recent time trends in phenological development of grapevine in Australia. Our analysis indirectly supported the role of increasing temperature as the main reason behind faster maturity, but the evidence is inconclusive partially due to the short time series used in this study. More detailed data, and possibly ad-hoc experiments are required to disentangle the peculiar behaviour of Shiraz, which unlike Chardonnay and Cabernet Sauvignon showed only weak relationships between change in maturity and change in temperature. The region- and cultivar-specific rates of change in date of designated maturity provide a benchmark for the Australian wine industry. Advancement in date of designated maturity between half and three days per year has substantial implications for crop management and winemaking. On a temperature basis, these rates are comparable to those reported for the northern hemisphere.

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Chapter 5

Quantification of time trends in vintage scores and their variability for major wine regions of Australia

VO Sadras, CJ Soar, PR Petrie

Summary

This paper quantified time-trends of vintage scores and their variability in 24 wine regions of Australia. Our working hypotheses are that, owing to improved crop husbandry and winemaking techniques, (1) vintage scores had increased with time, and (2) variability in vintage scores had decreased with time, whereas (3) interactions between improved technologies and climate should be reflected in temperature-related time trends of vintage score and its variability. Published data were used to calculate rates of change in vintage score and its variability for the period 1980-2005. Rates were calculated as the slopes of regressions between two dependent variables, i.e. 3-year running average of vintage score (10-point scale) and 3-year running coefficient of variation of vintage score (%), and year of vintage as independent variable. The statistical agreement ($r = 0.86$, $P < 0.05$) between rates of change in vintage score derived from two independent sources indicated the vintage scores used in this analysis were fairly robust. Our analysis primarily supported the hypotheses of improvement in vintage score and reduction in its variability, and provided a measure of the magnitude of these trends: the rate of change in vintage scores averaged 0.09 year^{-1}, ranged from –0.07 to 0.20 year^{-1}, was dominantly positive (35 out of 48 cases), and significant ($P < 0.05$) in 29 cases, whereas the rate of change in variability of vintage scores averaged –0.52% year^{-1}, ranged from –2.1 to 0.8 % year^{-1}, was dominantly negative (37 out of 48 cases), and significant ($P < 0.05$) in 19 cases. Consistent with hypothesis 3, the rate of change in vintage score for red wine and the rate of change in variability of vintage score for white wine were inversely related to temperature (long-term daily mean during the month prior to harvest in each of the regions). The rate of change in vintage score for white wine and the rate of change in variability of vintage score for red wine were unrelated to daily mean regional temperature. Owing to the intricate correlations between climate variables, however, the associations between change in vintage scores and temperature cannot be interpreted in terms of cause and effect.

Introduction

Season-to-season variation in temperature, radiation and water availability during critical periods of fruit growth and development contribute to variability in fruit, and potentially wine attributes such as content of phenolics, anthocyanins, acids and flavour compounds (Bergqvist et al. 2001, Coombe and Iland 2004, Gladstones 2004, Jones et al. 2005, Tate 2001).

Overlapping the seasonal variability of key climatic drivers, there are medium and long-term trends in wine quality that may stem from three sources: technological improvement, systematic changes in climatic drivers, chiefly temperature, and the interaction between technology and climate (Duchene and Schneider 2005, Jones et al. 2005). In a comprehensive worldwide analysis of long-term time trends for major wine-producing regions, Jones et al. (2005) showed a sustained increase in vintage quality resulting from complex combinations of improved winemaking and crop management technologies, and warming trends of variable effect and magnitude. Whereas their analysis assumed a quadratic effect of temperature on wine quality, with an implicit expectation of quality improvement with warming in cooler regions, and quality deterioration in hotter environments, trends were positive in 25 out of 30 regions, with only one case of a negative, but statistically insignificant trend in vintage quality (Jones et al. 2005).

The primary aim of this paper is to quantify the time-trends of vintage scores and their variability in the major premium wine producing regions of Australia. Our working hypotheses are that, owing to improved crop husbandry and winemaking techniques, (1) vintage scores had increased with time, and (2) variability in vintage scores had decreased with time, whereas (3) interactions between improved technologies and climate should be reflected in temperature-related time trends of vintage score and its variability. To test these hypotheses, we used Halliday's (1991, 1998, 2003, 2006a) vintage scores for red and white wine from 24 Australian wine regions. The data set spanned the period 1980-2005 and therefore is particularly suitable for the analysis of long-term trends. A secondary aim of this study was to assess the robustness of time-trends derived from Halliday's data by comparison with time-trends derived from the wine scores reported by Stevenson (2005).

Method

Quantifying vintage quality

Wine quality is an elusive concept, and attempts to quantify vintage quality are therefore bound to remain controversial. This stems from the complexity of wine attributes compounded by the complexity and variability of human smell and taste sensitivity (Atanasova et al. 2005, Parr et al. 2004, Pretorious et al. 2004, Verdu Jover et al. 2004). Temporal and regional variation in wine quality has been assessed with price and/or vintage ratings (Ashenfelter et al. 1995, Jones et al. 2005). The drawbacks of each of these approaches are many, including marketing factors influencing price beyond specific quality parameters (Ling and Lockshin 2003), and vintage scores derived from expert, albeit subjective evaluations. From an industry perspective, Halliday (2006b) explained the merits and limitations of a point system to judge wine. Our assumption is that, however imperfect, vintage scores can be used as a first approach to deal with our hypotheses on long-term trends. Here we used Halliday's (1991, 1998, 2003, 2006a) vintage scores for red and white wine from 24 Australian wine regions to calculate rates of change in vintage score and its variability. These vintage scores (10-point scale) are a composite of industry self-assessment, i.e. selected wine makers were asked to rate red and white wines from their specific regions, and Halliday's own notes (1991, 1998, 2003, 2006a).

Cross referencing the vintage scores of Halliday and Stevenson

We used regression analysis to compare the rates of change in vintage scores derived from the data of Halliday (1991, 1998, 2003, 2006a) with the rates derived from the vintage scores of Stevenson (2005). Both authors reported scores for red and white wines from the Hunter Valley, Margaret River and Barossa Valley during the period between 1980 and 2003. Thus, considerable overlap between these independent data sources allowed for the statistical test of Halliday's data. Stevenson (2005) used a 100-point scale to rate vintages for a combination of regions and wines, including the categories from excellent to superb (> 90 points), good to very good (80-89), average to good (70-79), disappointing (60-69), very bad (40-59), and disastrous (0-39). Using both data sources, rates of change in vintage scores were calculated with the approach described in the next section.

Tests of hypotheses

To test hypothesis 1 and 2, rates of change in vintage score and its variability were calculated using linear regression. Three-year moving average of vintage scores (10-point scale) and 3-year moving coefficients of variation (%) (Kuehl et al. 1995, Reichert and Sharma 2001) were used as dependent variables, and vintage year as independent variable.

To test hypothesis 3, linear and non-linear models were used to explore the association between temperature and rates of change in vintage score and its variability. Two temperatures were investigated, daily mean temperature and average monthly highest maximum temperature as defined and calculated with long-term climate records by Gladstones (2004). Both temperatures are calculated for the month prior to harvest, when critical fruit properties are highly responsive to environmental conditions.

Results

Cross referencing the vintage scores of Halliday and Stevenson

Despite the diversity of wine rating systems, generally strong correlations between the various sources indicate that this subjective measure of quality is a reasonable representation of a vintage (Jones et al. 2005). Given our reliance on Halliday's ratings for our analysis, the cross-reference with an independent set of vintage scores was particularly important. The rates of change in vintage score derived from Halliday's data for red and white wine from the Hunter Valley, Margaret River and Barossa Valley, were statistically consistent with the rates of change derived from Stevenson's data (Fig. 1). This lends further support to the robustness of Halliday's vintage ratings previously demonstrated by Schamel and Anderson (2003) (further discussed below).

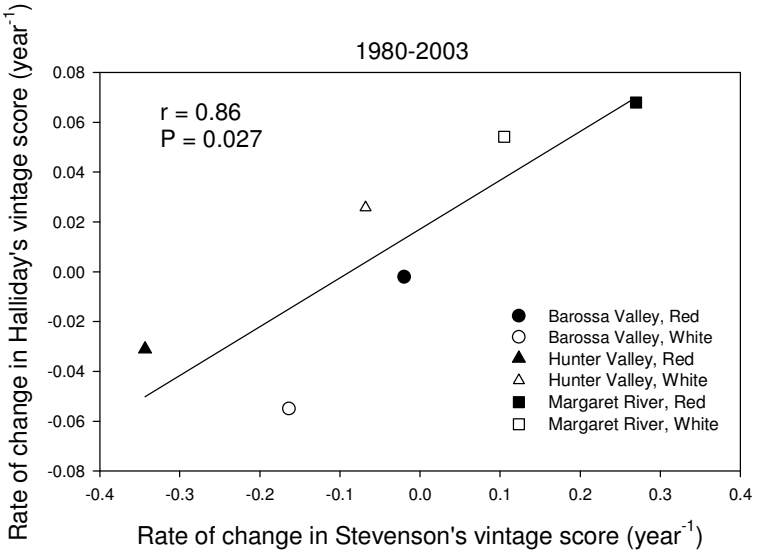


Figure 1. Comparison of rates of change in vintage scores from two independent data sources. Note that Stevenson used a 100-point scale, and Halliday used a 10-point scale, hence the difference in the magnitudes of the rates.

Time trends in vintage scores for 24 Australian wine regions

Figure 2 shows two contrasting cases illustrating the lack of statistical trend for red wine in the Barossa Valley, and a strongly positive time-trend for white wine at the Clare Valley. Table 1 summarises the statistics of time trends for all regions: the rate of change in vintage scores averaged 0.09 year^{-1}, ranged from –0.07 to 0.20 year^{-1}, was dominantly positive (35 out of 48 cases), and significant ($P < 0.05$) in 29 out of 48 cases. There were four cases of statistically significant negative rates: at Mudgee (red and white wine), McLaren Vale (white) and Swan Valley (white). The rate of change in vintage score was an inverse function of the long-term mean daily temperature in the month prior to harvest for red wine and was unrelated to the mean daily temperature prior to harvest for white wine (Figure 3ab, Table 2). Weighting temperature for variety acreage did not improve the relationships (not shown). Similar results were obtained for both daily mean temperature and average monthly highest maximum temperature over the month prior to harvest, which were strongly correlated ($r = 0.77$, $P < 0.0001$).

Time trends in variability of vintage scores for 24 Australian wine regions

The rate of change in variability of vintage scores averaged –0.52% year^{-1}, ranged from –2.1 to 0.8 % year^{-1}, was dominantly negative (37 out of 48 cases), and significant ($P < 0.05$) in 19 cases (Table 1). Of the 19 cases where trends were significant, variability declined in 17 and increased in Coonawarra (white) and Canberra (red). The rate of change in variability of vintage score was an inverse function of the daily mean temperature in the month prior to harvest for white wine, and was unrelated to the daily mean temperature in the month prior to harvest for red wine (Table 2, Fig. 3cd). The rate of change in variability of vintage score and

the rate of change in vintage score were unrelated ($P > 0.57$ for red and $P > 0.39$ for white wine).

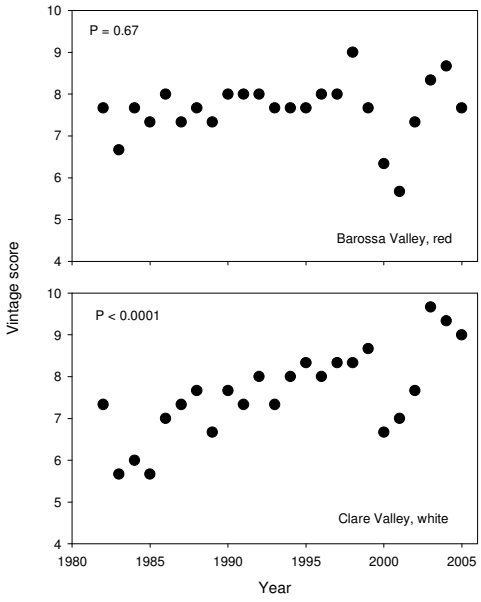


Figure 2. Examples of contrasting time-trends in vintage scores. Values are 3-year running averages.

Table 1. Time trends (1980-2005) of vintage score and variability in vintage score in 24 grape growing regions of Australia. Slope, standard error and P value derived from linear regression of 3-year moving average score vs vintage year, and 3-year moving coefficient of variation vs vintage year. Locations are ranked for temperature, Ta (long-term daily mean during the month before harvest). Rates in bold indicate P < 0.05.

Region	Ta (°C)	Wine	Score			Variability		
			Slope ($year^{-1}$)	S.E.	P	Slope (% yr^{-1})	S.E.	P
Southern Tasmania	14.7	Red	**0.11**	0.027	0.0004	**-0.86**	0.265	0.0061
42º45'S - 147º00'E		White	**0.06**	0.020	0.0041	0.72	0.379	0.0772
Northern Tasmania	15.9	Red	**0.05**	0.019	0.0130	-0.83	0.653	0.2226
41º07'S - 147º05'E		White	**0.05**	0.016	0.0047	-0.37	0.385	0.3574
Adelaide Hills	16.2	Red	**0.07**	0.019	0.0013	0.11	0.871	0.8986
35º07'S – 138º36'E		White	**0.06**	0.016	0.0019	0.85	0.483	0.0989
Geelong	16.6	Red	**0.09**	0.020	0.0001	-0.08	0.507	0.8726
38º07'S - 144º22'E		White	**0.05**	0.025	0.0445	-0.62	0.320	0.0718
Macedon	16.9	Red	**0.11**	0.022	0.0001	0.28	0.424	0.5221
37º25'S - 144º55'E		White	**0.06**	0.014	0.0004	**-0.54**	0.226	0.0309
Yarra Valley	16.9	Red	**0.05**	0.019	0.0111	-1.09	0.564	0.0747
37º45'S - 145º22'E		White	-0.03	0.020	0.1094	-0.40	0.408	0.3383
Grampians	17.0	Red	**0.08**	0.024	0.0025	-**1.38**	0.376	0.0025
37º09'S - 142º50'E		White	0.03	0.012	0.0295	-0.44	0.385	0.2757
Coonawarra	17.1	Red	**0.03**	0.016	0.0408	0.41	0.676	0.5522
37º18'S - 140º49'E		White	**0.07**	0.015	0.0001	**1.09**	0.369	0.0105
Mc Laren Vale	18.3	Red	-0.01	0.016	0.4490	**-2.14**	0.547	0.0015
35º14'S - 138º33'E		White	**-0.07**	0.023	0.0053	**-1.14**	0.520	0.0464
Great Southern	18.5	Red	-0.03	0.020	0.1254	-**0.81**	0.352	0.0381
35º'14S - 138º33'E		White	-0.01	0.013	0.3155	-0.19	0.282	0.5223
Barossa	18.9	Red	0.01	0.021	0.6707	0.77	0.743	0.3174
34º29'S – 139º00'E		White	-0.04	0.025	0.0985	0.08	0.518	0.8867
Pyrenees	19.1	Red	0.03	0.017	0.0588	**-0.72**	0.259	0.0143
37º05'S - 143º29'E		White	**0.04**	0.012	0.0042	**-1.22**	0.491	0.0258
Padthaway	19.3	Red	0.02	0.023	0.3944	**-1.05**	0.239	0.0006
36º37'S - 140º28'E		White	**0.12**	0.019	0.0001	-0.27	0.245	0.2856
Margaret River	19.7	Red	**0.06**	0.014	0.0001	**-0.62**	0.212	0.0109
33º57'S - 115º03'E		White	**0.05**	0.020	0.0175	**-0.79**	0.298	0.0188
Canberra	20.3	Red	**0.05**	0.019	0.0230	**0.72**	0.240	0.0095
35º0'S - 149º20'E		White	0.02	0.015	0.1936	-0.11	0.149	0.4828
Granite Belt	20.8	Red	0.03	0.023	0.1349	**-0.41**	0.183	0.0342
28º40'S - 151º56'E		White	0.05	0.026	0.0891	-0.15	0.298	0.6283
Bendigo	21.0	Red	**0.09**	0.024	0.0014	-0.64	0.474	0.1989
36º45'S - 144º17E		White	0.02	0.026	0.3964	**-0.70**	0.339	0.0582
Clare Valley	21.4	Red	**0.07**	0.023	0.0085	-0.37	0.458	0.4371
33º50'S - 138º38'E		White	0.11	0.022	0.0001	-0.39	0.410	0.3629
Rutherglen	22.0	Red	-0.01	0.031	0.6884	0.07	0.345	0.8339
36º01'S - 140º19'S		White	-0.05	0.026	0.0935	-0.04	0.387	0.9261
Mudgee	22.1	Red	**-0.07**	0.025	0.0148	-0.79	0.604	0.2127
32º36'S - 149º36'E		White	**-0.07**	0.017	0.0008	-0.06	0.333	0.8577
Lower Hunter	23.1	Red	0.01	0.035	0.7847	**-1.06**	0.434	0.0282
32º50'S - 151º21'E		White	0.03	0.029	0.2528	**-1.43**	0.661	0.0483
Upper Hunter	23.9	Red	-0.01	0.027	0.6953	0.23	0.518	0.6684
32º15'S - 150º53'E		White	**0.05**	0.021	0.0210	-1.43	0.702	0.0604
Riverina	24.2	Red	0.00	0.019	0.9815	**-0.99**	0.377	0.0200
34ºS - 146ºE		White	-0.01	0.018	0.5656	-0.38	0.328	0.2671
Swan Valley	24.2	Red	**0.05**	0.022	0.0334	**-1.10**	0.400	0.0158
31º50'S - 116ºE		White	**-0.06**	0.017	0.0028	**-1.34**	0.371	0.0028

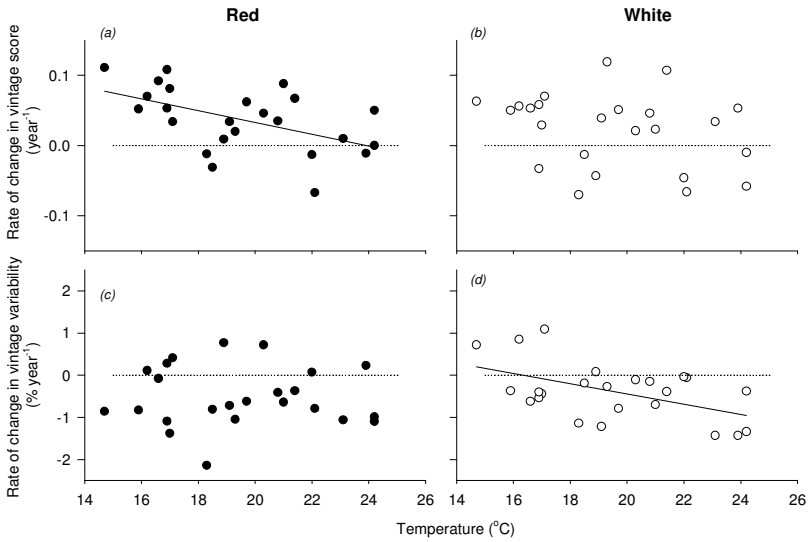


Figure 3. Rate of change in (a, b) vintage score and (c, d) vintage score variability between 1980 and 2005 as a function of long-term daily mean temperature during the month prior to harvest in 24 Australian wine regions. Table 2 summarises the statistics of these relationships.

Table 2. Correlation coefficient (r) between rate of change in vintage score and rate of change in variability of vintage score (1980-2005) and long-term daily mean temperature (T_a) and average monthly highest maximum temperature (T_m) during the month prior to harvest (Gladstones 2004).

Dependent variable	Independent variable	Wine	R	P
Rate of change in vintage score	Ta	Red	-0.51	0.004
		White		0.179
	Tm	Red	-0.49	0.013
		White		0.214
Rate of change in variability of vintage score	Ta	Red		0.901
		White	-0.51	0.010
	Tm	Red		0.784
		White	-0.47	0.021

Discussion

Limitations and strengths of the analysis

Views on vintage scores range from "…controversial, potentially misleading and essentially impossible to get consistently correct…" (Fuller and Walsh 1999) to the proposal of ratings that "…express the likelihood of what might reasonably be expected from a wine of a given year…" (Stevenson 2005).

Our analysis is based on vintage scores which have many limitations, including the clumping of varieties in two coarse categories (red and white), the lack of account of intra-regional variability, variation in the criteria to rank wines over a long time series, and other sources of bias such as the allocation of poor quality fruit to lower quality products without a specific regional designation in extreme seasons (Hooke 2006). The length and time interval of the time series also needs consideration. For instance, trends calculated by Jones *et al*. (2005) using Stevenson's scores (2005) for the Hunter Valley, Margaret River and Barossa Valley were stronger than those in our study because they analysed longer time series, including very low scores in the early-mid 1970s that strongly influenced their rates. Jones et al. (2005), in turn, reported a moderate to strong statistical consistency between the early vintage ratings of Stevenson (2001) and an independent source of vintage ratings for 30 categories of wine during the 1963-2000 period.

Despite these limitations, vintage scores have been used for temporal and regional analysis of variation in wine quality (Fuller and Walsh 1999, Grifoni et al. 2006, Jones et al. 2005, Schamel and Anderson 2003). From an industry perspective, Halliday (2006b) highlighted that the Australian wine show system and their international counterparts had fostered this type of evaluations. Furthermore, the notion that "the number of points determines the fate of the wine rather than the descriptive word" (Halliday 2006b), is statistically justified by the analysis of Schamel and Anderson (2003). These authors estimated price functions for premium wine from Australia between 1990 and 2000 (6866 observations, 27 regions) and New Zealand between 1993 and 2000 (1531 observations, 6 regions), and found a significant correlation between price premium and Halliday's score (Schamel and Anderson 2003).

In conclusion, the vintage scores used in this analysis have a range of limitations but can be considered suitable for a first, coarse assessment of time trends. This conclusion is based on (a) the consistency of the relationships between the rates of change in vintage score using two independent data sources (Fig. 1), (b) the significant correlations between vintage ratings from different sources reported by Jones et al. (2005), (c) the robustness of the relationships between price premia and vintage ratings demonstrated by Schamel and Anderson (2003), and (d) more broadly, previous research showing that vintage ratings can yield biophysically meaningful quantitative models (Grifoni et al. 2006, Storchmann 2005).

Temperature-related time trends in vintage scores and their variability

Our analyses primarily supported all three working hypotheses; for the period 1980-2005 vintage scores tended to increase with time, variability in vintage scores tended to decrease with time, and interactions between improved technology and climate were reflected in temperature-related time trends of vintage scores and their variability. The improvement in vintage scores and the decline in their variability are both the expected consequences of a wine industry with a strong focus on quality, and its commitment to develop and adopt new technologies. The notion that technology has improved quality and consistency of Australian wines is apparent. Little information exists, however, on the realised magnitude of this benefit, the actual time trends, regional differences, and interactions with climate – all of which were the target of our analysis.

The benefit-to-cost ratio of research and extension for the South Australian wine industry between 1983 and 2002 was about 60:1, with more than half of the benefit derived from improvement in quality (Black and Dyson 2006). Here we showed positive trends, i.e. improvement in scores and decrease in variability in more than 70% of the cases considered, with 39-66% of cases reaching statistical significance. An important finding of this study is the lack of association between the rates of change in vintage score and the rate of change in variability, which is contrary to the notion that quality and consistency are generally associated (Stevenson 2005). The possibility that techniques aiming at improving quality might not necessarily improve consistency at the coarse scale of this analysis warrants more detailed investigation.

There was an interesting contrast in the apparent response of red and white wine to temperature during the month before harvest. The relationship between daily mean regional temperature and improvement in quality was significant for red but not for white wine whereas the apparent influence of temperature on vintage variability was strong for white but irrelevant for red wine. Premium red wines are traditionally from warmer regions than premium white wines (Gladstones 2004). The greater rate of improvement in wine quality from red grapes grown in cool regions as opposed to warm regions is therefore not surprising. The greater improvement in consistency, i.e. decrease in variability in scores between vintages, of white wine quality in warmer regions was not expected, especially as there was no apparent influence of mean regional temperature on changing wine quality. It could be speculated that other factors, e.g. harvest rainfall and diseases, could have contributed to this interaction, as white wine varieties are generally more susceptible to late-season diseases, and autumn rainfall in Australia has declined during the time period of our analysis (Emmett et al. 1994, Suppiah et al. 2006). Here it is important to highlight that, however sound in the light of our understanding on the influence of temperature on fruit and wine properties, the relationships between temperature and trends in wine quality in this paper are only correlations, and do not necessarily indicate cause and effect. Owing to the intricate correlations between climatic variables (Rodriguez and Sadras 2007), the correlations with temperature in this study must be taken as a general indication of climatic, rather than temperature, influences. Recent studies with cereals highlight the risk of misinterpreting correlations between climatic variables and biophysical processes (Peng et al. 2004, Sheehy et al. 2006a, Sheehy et al. 2006b). The early conclusion that a “close linkage between rice grain yield and mean minimum temperature” was “direct evidence of decreased rice yields from increased night-time temperature associated with global warming” (Peng et al. 2004) was latter re-interpreted in the light of correlations between temperature and solar radiation, with a revised conclusion that correlation between crop response variables and selected weather elements can be misleading because of correlations among the weather elements (Sheehy et al. 2006a, Sheehy et al. 2006b). Disentangling the actual contribution of technology and climate to the observed trends, and elucidation of the differential response of red and white wines requires finer data, including time series for individual varieties in more geographically restricted environments, and alternative analytical approaches (e.g.Caprio and Quamme 2002).

In summary, despite all the recognised limitations of rating vintages with a point-system, we have (a) shown that the vintage scores of Halliday (1980-2005) are robust and suitable for time-trend analysis, (b) quantified the time-trends of vintage scores and demonstrated a dominant, but region-dependent, improvement in wine quality and decreased vintage variability, and (c) highlighted strong interactions between time trends in vintage scores and climate.

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Chapter 6

Climate-drivers of red wine quality in four contrasting Australian wine regions

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Summary

The understanding of the links between weather and wine quality is fragmented, and often qualitative. This study quantified and integrated key weather variables during ripening and their influence in red wine quality in the Hunter Valley, Margaret River, Coonawarra and Barossa Valley. Long-term records of published vintage scores were used as an indicator of wine quality. A χ^2 analysis was used to compare good (top 25%) versus poor (bottom 25%) vintages in relation to the frequency of defined weather conditions. Using maximum temperature as an example, better quality was associated with: temperatures above 34ºC throughout most of ripening in the Hunter, below 28ºC in early January in Margaret River, 28-33.9ºC towards harvest in Coonawarra, and below 21.9ºC in late January and early February and 28-30.9ºC towards harvest in the Barossa. Our quantitative assessment allows for the timing and magnitude of weather influences on wine quality on a regional basis. The improved specificity of the links between weather and wine quality will help in the development of a risk analysis framework for wine quality across Australia.

Introduction

Maintaining Australia's reputation for high quality wines across a range of price points is important for the continued growth of the Australian wine industry in both domestic and global markets (Winemaker's Federation of Australia and The Australian Wine and Brandy Corporation 2007). Wine quality is as influenced by the attributes of the fruit as it is by the complex biochemistry in the wine making and aging processes. Key berry properties, including relative proportions of skin, seed and flesh, and chemical composition of each component are the result of the interaction between genotype, environment and management (Gil and Yuste 2004, Roby and Matthews 2004, Sadras et al. 2007b, Walker et al. 2005).

Season-to-season variation in weather is recognised as the main source of variation in berry properties and thus variation in wine quality with vintage (Gladstones 1992). Not surprisingly, therefore, the links between climate and wine quality, as mediated by berry properties, have attracted considerable attention (Bodin and Morlat 2006, Duchene and Schneider 2005, Gladstones 2004, Jones et al. 2005). Through a combination of history, trial-and-error, and scientific research, our understanding of these links has improved substantially, but it remains fragmented and often qualitative in its formulation. Gladstones (2004) argued that temperature variability among seasons is a well-recognised factor in viticulture. In cool environments, temperature is "responsible for much of the variation among vintages, with more or less complete failure of grape ripening in the coolest

seasons and incomplete ripening in many others…" (Gladstones 2004). In hot environments, vintages range from relative failure in hot years to "…the best vintages in cool years" (Gladstones 2004). This account of temperature influences on vintage quality illustrates the qualitative nature of much of our current understanding on the links between climate and wine quality. It also illustrates the trend to consider single factors, stemming in turn from the difficulties in accounting for high-order interactions (Chapin et al. 1987, Mooney et al. 1991, Sadras 2005).

This study thus focused on (a) quantifying and (b) integrating the influences of major elements of the weather on wine quality. We used a χ^2 approach (Caprio and Quamme 1999, 2002) to investigate climatic influences on long-term records of vintage scores from four climatically contrasting wine growing regions of Australia (Gladstones 2004), viz. Margaret River (Western Australia), Barossa Valley (South Australia), Coonawarra (South Australia) and Hunter Valley (New South Wales).

Methods

Data sources: wine quality and weather, varietal composition and harvest date
Regional vintage scores were used as a surrogate for wine quality. Sadras et al. (2007a) discussed the strength and limitations of this assumption. Vintage scores for red wines for the Barossa (1973 - 2003), Hunter Valley (1969 - 2003) and Margaret River (1974 - 2003) were extracted from the Sotheby's wine encyclopaedia (Stevenson, 2005). To enable the comparison of these regions with a cooler region, an additional dataset for the Coonawarra (1954 - 2004) was sourced (Mattinson, 2004). The wine scores for Coonawarra were derived from a single test where 48 vintages of Wynn's Coonawarra Cabernet Sauvignon were tasted in succession as opposed to the determination of regional score in the year following the vintage.

We previously showed (Sadras et al. 2007a) that the vintage scores of Stevenson (2005) are statistically consistent with the largely independent vintage scores of Halliday (1991, 1998). In addition, in this paper we found a consistent link with maximum temperature for the vintage scores from Stevenson (2005) and Mattinson (2004), against the vintage scores of Halliday (1991,1998). This cross-reference test reinforced the reliability of the Stevenson and Mattinson data, which were retained in the analysis of this paper due to the longer time series, i.e. >30 years for Stevenson's vs 18 years for Halliday's.

To estimate an average harvest date for each region, a list of the dominant varieties was constructed based on regional makeup described by Halliday (1991, 1998). The percentage of the total vineyard area for each region planted to the major varieties falling within each of eight maturity groups was calculated according to Gladstone (1992). To simplify the analysis, the maturity group or groups containing at least 80% of the total plantings were then used to generate a harvest date range (Table 1). The latest possible harvest date within this window was then used as the final harvest date from which a 14-week window prior to harvest was set for the analysis of association between weather variables and quality.

Table 1. Varietal makeup (% of total vineyard area planted) of dominant varieties derived from Halliday (1991, 1998) and estimates of veraison and harvest date using

vineLOGIC (VL) or Gladstones (1992) estimates (JG). Dates from vineLOGIC are averages ± standard deviation (days) of 36 years of weather simulations for the Barossa Valley (1960-1995), 20 years for Coonawarra (1976-1995), 27 years for Margaret River (1970-1996) and 13 years for the Hunter Valley (1968-1980).

	Ratio of Varieties (%)	Shiraz			Cabernet Sauvignon			Grenache		
	Sh : CS : Gr : Other	Veraison VL	Harvest VL	Harvest JG	Veraison VL	Harvest VL	Harvest JG	Veraison VL	Harvest VL	Harvest JG
Barossa Valley	52 : 25 : 23 : 0	7 Feb ± 9	19 Mar ± 15	23-Mar	9-Feb ± 9	30-Mar ± 18	30-Mar	9-Feb ± 9	4-Apr ± 18	7-Apr
Coonawarra	0 : 100 : 0 : 0				24-Feb ± 10	30-Apr ± 20	22-Apr			
Margaret River	20 : 62 : 0 : 18	01-Feb ± 5	11-Mar ± 7	21-Mar	4-Feb ± 5	21-Mar ± 7	26-Mar			
Hunter Valley	64 : 23 : 0 : 13	1-Jan ± 6	1-Feb ± 7	22-Feb	4-Jan ± 6	9-Feb ± 7	28-Feb			

It is acknowledged that berry quality can be affected by factors that exert influence earlier than the selected window such as at the time of flowering and early berry growth or even bud initiation in the previous season. This current analysis only aims to look at the effects on berry quality associated with weather events during the berry ripening period from the cessation of berry cell division, through veraison to harvest. The same approach can be used to look over longer time periods but has been restricted in this case to keep the scale of the analysis and comparisons between regions manageable.

The mix of varieties within each region has changed slightly with time, however it was determined that the estimated average harvest date based on the predominant varieties did not change and hence a single harvest date was used for the whole time series (data not shown). Climate change induced increases in mean temperatures have resulted in increased rates of maturation (Petrie and Sadras, 2008) which may also have lead in some cases to progressively earlier harvest dates. However advanced maturity does not necessarily directly translate into earlier harvests as there has also been a progressive shift towards higher alcohol content in red wines and thus higher sugar at harvest (Petrie and Sadras, 2008). Vintages with earlier harvest dates than the average used in this study will not change the conclusions of the analysis to be presented but are likely to reduce the precision with which significant associations between weather parameters and quality can be linked to specific phenostages.

For this study it was considered desirable to reference results against the timing of veraison and harvest. Veraison is an elusive yet highly relevant stage in the annual cycle of the grapevine. Typical phenological characterisations include budburst, flowering and harvest but often lack veraison data (see for example Gladstones 1992; Pearce and Coombe 2004). Dates of veraison are infrequently recorded by growers and researchers alike and where they have been recorded the determination method has not been standardised. In this paper, we used VineLOGIC (Godwin et al. 2002) to estimate veraison dates (Table 1). VineLogic is a simulation model of grapevine growth and development that is based on real information from major Australian grape-growing regions. The model uses historical weather records, vineyard soil type, water salinity and depths, planting material and management inputs to model vine phenology and yield. For the purposes of this study a separate simulation was run for each variety, region and year of weather data available for that region within VineLOGIC to calculate a series of harvest dates and veraison dates from which average and standard deviations were derived. Table 1 also presents estimated harvest dates for the dominant varieties in each region from Gladstones (1992).

There is some discrepancy between the harvest dates calculated using VineLOGIC and those reported by Gladstones (1992) particularly for Shiraz in Margaret River and all varieties in the Hunter Valley. This is partially due to model error, and partially to the mismatch between the seasons used in simulations and the seasons used by Gladstones (1992) This discrepancy reduces confidence in the estimates of veraison and harvest for these particular scenarios. The use of these estimates in the discussion is intended only to provide some phenological reference rather than a definitive date to link weather influences on quality to an exact developmental stage. For this reason references to veraison will be used cautiously.

Daily weather data for each region were extracted from the SILO patched point database, including maximum temperature, minimum temperature, relative humidity at maximum temperature, rainfall, solar radiation, evaporation (calculated according to FAO56; Allen et al. 1998) and average vapour pressure deficit at maximum temperature.

Analysis of associations between weather elements and wine quality

The χ^2 test was adapted from Caprio and Quamme (1999, 2002), who applied this approach to test the relationship between crop yield (apple and grape) and temperature. The χ^2 analysis was a two-step process. First it identified significant relationships between each weather component and wine quality in any of the 14 weeks prior to harvest for a given region. Second, where a significant relationship was determined, a subsequent χ^2 test was used to determine the specific range of each element, eg maximum temperature, at which an abundance of days was associated with better or poorer quality wine.

The wine scores for each region were divided into quartiles with the upper quartile representing the better quality wines, the lower quartile the poorer quality wines and the inter-quartile range considered to be years with wines of average quality. Using the upper and lower quartiles of wine score, years that yielded better quality and poorer quality wines respectively were determined. We thus investigated the putative differences in weather components between years with poor, and good wine quality.

In the Coonawarra dataset there was a significant improvement in wine score with time (not shown). To remove this trend from our analysis, we used the residuals from the regression of wine score over time rather than the absolute score. This process assumes that this progressive improvement in quality is primarily due to improved technology and viticultural practice in the region rather than a climate-change driven phenomenon. The residual deviations from the trend tended to be of greater magnitude than the gradient itself which is typical of agricultural systems where large year to year variability is believed to be the result of fluctuations in the weather whereas smaller consistent trends are usually considered to be technology driven and are usually removed from models by de-trending (Jones et al., 2005; Kucharik 2006, Peiris et al. 2008, Sadras et al. 2007a). Despite this it is recognised that some unknown component of the time-trend in quality in the Coonawarra is likely to be temperature driven with warming trends in cool climates such as the

Coonawarra likely to gradually improve quality. A significant time trend was not observed in any of the Stevenson (2005) datasets, thus actual wine scores were used in these cases.

Starting from January 1st, all years were broken into 3 week sliding windows moving forward 1 week at a time; i.e. week 1 to 3, week 2 to 4, and so on to give 52 windows per year. Counting back from the first three-week window that included the estimated harvest date for the region, 12 three-week windows were extracted (14 weeks in total). Using the method described in the previous section, the latest harvest dates were estimated as 7 April for Grenache in the Barossa, and for Cabernet Sauvignon we used harvests dates of 28 February in the Hunter Valley, 26 March in the Margaret River, and 22 April in Coonawarra (Table 1). This 14-week period was chosen to ensure that the entire veraison to harvest period was captured for each region.

For maximum temperature, windows of 3ºC increments starting from 13ºC were created up to a maximum that was greater than any temperature recorded across all years in the analysis for each region. For example in the Barossa Valley the temperature ranges were 13.0-15.9ºC, 16.0-18.9ºC, … 46.0-48.9 ºC. Frequency tables were then constructed with the count of days falling in each temperature window for each three-week period in each year.

The total number of days within each temperature window for all of the "Good", "Average" and "Poor" years respectively were then summed independently for each 3 week period. This generated a frequency table for the "Good", "Average" and "Poor" years, each of size 3 x k where k was the number of temperature windows required to ensure that all days across all years were included in the analysis. Categories with no counts, as was normally the case for temperatures greater than 45ºC, were not included in the frequency table.

A χ^2 statistic was then calculated for each 3-week window to test for a relationship between maximum temperature and wine quality. This χ^2 was compared to the critical statistic on 2 x (k-1) ($P<0.01$) degrees of freedom where k was the number of temperature categories within each window. χ^2 analysis assumes that observed frequencies are greater than 1 and that the average observed frequency is greater than 5. To meet these criteria it was necessary to merge some of the temperature categories in the tails of the frequency distribution. For example it was often necessary to combine temperatures in the 43.0-45.9 ºC range with the counts in the 40.0-42.9ºC range. In this case the category was simply renamed to >39.9ºC. A χ^2 greater than the critical statistic was taken as evidence that there was a relationship between temperature and wine quality in a given 3 week window.

Where a significant association was determined using the χ^2 for a particular 3 week window, a separate χ^2 statistic was calculated for that window for the specific comparison between good and poor years for each of the temperature ranges. Because these "post-tests" each compared the frequency of days in good versus poor years for a single temperature range, the critical χ^2 statistic was determined on 1 df ($P<0.05$).

A reasonably stringent significance level ($P<0.01$) was chosen for the first stage of the analysis because of the large number of tests being performed and thus the greater potential for type 1 statistical error. This was relaxed to $P<0.05$ for the second stage due to the lower number of tests thus keeping the experiment-wise error rate of the two stages similar.

A similar χ^2 analysis was performed for minimum temperature, relative humidity and total radiation. Window widths were 3ºC for minimum temperature, 3 MJ/m^2 for radiation and 10% for relative humidity. Unfortunately this analysis was not appropriate for rainfall data. Irrespective of the rainfall windows chosen, across years there was a large number of zero frequencies for each rainfall range in many of the 3-week sliding windows. A χ^2 statistic cannot be calculated where the observed frequencies are zero.

Results

Association between weather variables

Correlation between weather variables, e.g. temperature and humidity, are well established as a result of geographical and intra-seasonal patterns. The variation in the strength of these associations across regions and seasons, however, needs consideration. Making explicit the intricate associations between climatic variables is critical for the interpretation of climatic influences on vintage quality.

Statistical comparison of the strength of the correlations between weather variables for the pooled seasons, and the seasons with better and poorer vintage quality indicated no seasonal bias (not shown). Comparisons among regions were therefore based on the pooled seasons, and are summarised in Figure 1. Maximum temperature was directly associated with VPD, reference evapotranspiration, radiation and minimum temperature, and negatively associated with rainfall. The association with VPD was strongest and comparable across regions whereas the strength of association between maximum temperature and other variables varied between regions. For instance, maximum and minimum temperatures were more closely coupled in the Barossa than in the Hunter Valley. The coupling of maximum temperature and radiation was stronger at Coonawarra and the Hunter Valley and weakest in the Margaret River. The associations between minimum temperature and the other weather variables were much weaker than for maximum temperature. For instance, the strong direct association between maximum temperature and radiation compares with an insignificant (Barossa Valley, Coonawarra) or weakly negative (Hunter Valley, Margaret River) correlation with minimum temperature. There was a moderate but consistent, negative correlation between rainfall and evaporation and its components, i.e. radiation and VPD. Radiation was an equally important component of evaporation in all four regions, whereas evaporation and VPD were more closely coupled at the Barossa Valley than at the Margaret River. The coupling between radiation and VPD was strongest at the Hunter Valley and weaker at the Barossa Valley and Margaret River

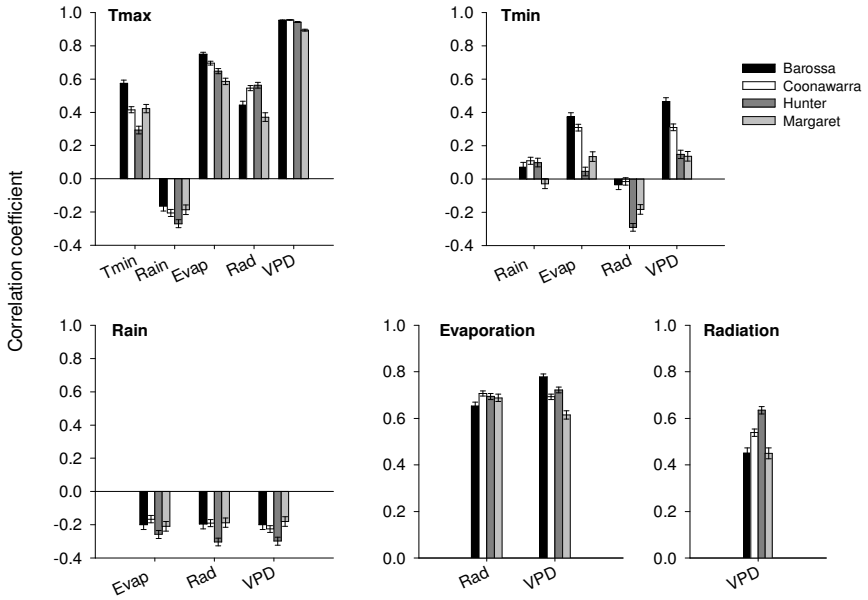


Figure 1. Correlation coefficients between climatic variables in four wine regions of Australia. Variables correspond to the period spanning 12 weeks prior to the average estimated harvest data for each region. Error bars are 95% confidence intervals.

χ^2 – *association between weather components and wine quality*

General patterns

There were strong regional influences on the timing when temperature anomalies were significantly associated with wine quality. In the Barossa Valley, there was an apparent association between maximum temperature and quality from mid January to mid February and again for three weeks from mid March towards the estimated harvest date (Table 2). In the Coonawarra there was a significant association between T_{max} and quality in the six weeks prior to harvest (Table 3), but no association was found between temperature and quality at earlier stages. Margaret River had only a single 3-week window from January 8 when T_{max} and wine quality were significantly associated (Table 4). In contrast to the other regions, the Hunter Valley had a strong association between maximum temperature and wine quality throughout most of the ripening period (Table 5).

Table 2. Frequency distributions (number of days) whose maximum temperature, minimum temperature, and radiation fall within each range for all 3-week windows where a significant association was found between each weather component and quality for the Barossa Valley, South Australia. Shaded cells indicate that differences between good and poor years were deemed significant (P<0.05) by chi-square test. Dark Shading means that an excess of days was associated with poor years and lighter shading the excess days were associated with better years.

		Tmax (ºC)									
		<16	16-18.9	19-21.9	22-24.9	25-27.9	28-30.9	31-33.9	34-36.9	37-39.9	>39.9
Week 3	Good		0.7	2.6	3.3	4.6	3.1	3.1	2.4	0.9	0.3
(15/1 - 4/2)	Poor		0.2	0.7	2.8	4.2	5.0	2.8	2.3	1.8	1.2
Week 4	Good		1.1	3.3	3.9	3.7	2.3	3.9	1.9	0.9	0.1
(22/1 - 11/2)	Poor		0.2	1.8	3.5	4.0	4.7	3.2	1.5	0.8	1.3
Week 5	Good		0.7	3.6	4.0	3.4	2.9	4.1	1.6	0.6	0.1
(29/1 - 18/2)	Poor		0.2	2.0	4.0	3.5	4.2	3.5	2.0	0.7	1.0
Week 12	Good	0.3	2.6	5.0	4.4	3.6	2.6	2.1	0.4		
(18/3 - 7/4)	Poor	1.0	5.3	5.0	4.7	3.2	1.0	0.8	0.0		

		Tmin (ºC)						
		4-6.9	7-9.9	10-12.9	13-15.9	16-18.9	19-21.9	22.24.9
Week 2	Good	0.0	3.1	6.1	6.1	3.6	1.7	0.3
(8/1 - 28/1)	Poor	1.0	1.7	4.3	4.2	4.2	4.2	1.5
Week 3	Good	0.4	3.1	7.3	6.1	2.7	1.0	0.2
(15/1 - 4/2)	Poor	0.7	1.7	3.5	4.8	4.8	4.2	1.3
Week 5	Good	0.9	2.6	9.4	4.1	2.1	1.6	0.2
(29/1 - 18/2)	Poor	0.2	1.8	6.2	5.7	3.3	3.0	0.8

		Total Daily Radiation (MJ/m2)					
		7-9.9	10-12.9	13-15.9	16-18.9	19-21.9	22-24.9
Week 11	Good	0.7	1.1	2.9	4.1	8.6	3.6
(11/3 - 31/3)	Poor	2.2	1.8	3.3	4.5	5.2	4.0
Week 12	Good	0.9	1.0	4.4	4.4	8.9	1.4
(18/3 - 7/4)	Poor	3.0	1.8	5.0	5.3	5.2	0.7

Table 3. Frequency distributions (number of days) whose maximum temperature, minimum temperature and radiation falls within each 3 unit range for all 3-week windows where a significant association was found between each weather component and quality for the Coonawarra, South Australia. Shaded cells indicate that differences between good and poor years were deemed significant (P<0.05) by chi-square test. Dark Shading means that an excess of days was associated with poor years and lighter shading the excess days were associated with better years.

		Tmax (ºC)							
		13-15.9	16-18.9	19-21.9	22-24.9	25-27.9	28-30.9	31-33.9	34-36.9
Week 11	Good	0.1	1.8	5.4	5.3	3.3	1.7	2.6	0.8
(11/3 - 31/3)	Poor	0.0	2.1	6.4	4.6	3.3	2.3	1.4	0.8
Week 12	Good	0.2	2.7	6.1	4.6	2.8	2.3	1.9	0.6
(18/3 - 7/4)	Poor	0.2	4.0	6.8	4.4	2.7	1.5	0.9	0.6
Week 13	Good	0.3	2.9	6.6	3.7	3.7	2.5	1.2	0.3
(25/3 - 14/4)	Poor	0.5	4.7	6.3	4.0	3.1	1.2	0.8	0.4
Week 14	Good	0.3	4.6	6.8	3.2	3.4	2.1	0.7	0.0
(1/4 - 21/4)	Poor	1.3	6.1	5.6	3.9	2.1	1.0	0.8	0.3

		Tmin (ºC)						
		<1	1-3.9	4-6.9	7-9.9	10-12.9	13-15.9	16-18.9
Week 14	Good	0.1	2.1	4.2	6.9	4.6	2.7	0.5
(1/4 - 21/4)	Poor	0.1	0.8	4.5	5.9	5.3	3.2	1.2

		Radiation (MJ/m^2)					
		7-9.9	10-12.9	13-15.9	16-18.9	19-21.9	>22
Week 11	Good	1.4	2.6	4.2	4.8	6.3	1.7
(11/3 - 31/3)	Poor	1.8	3.2	5.6	5.9	3.4	1.2

Table 4. Frequency distributions (number of days) whose maximum temperature, minimum temperature and relative humidity falls within each range for all 3-week windows where a significant association was found between each weather component and quality for Margaret River, Western Australia. Shaded cells indicate that differences between good and poor years were deemed significant (P<0.05) by chi-square test. Dark Shading means that an excess of days was associated with poor years and lighter shading the excess days were associated with better years.

		Tmax (ºC)						
		<22	**22-24.9**	**25-27.9**	**28-30.9**	**31-33.9**	**34-36.9**	
Week 2	**Good**	2.1	10.5	6.1	1.6	0.6	0.0	
(8/1 - 28/1)	**Poor**	1.4	7.8	5.1	3.3	2.1	1.4	
		Tmin (ºC)						
		7-9.9	**10-12.9**	**13-15.9**	**16-18.9**	**19-21.9**	**22-24.9**	
Week 8	**Good**	0.1	3.3	8.4	6.0	2.9	0.4	
(19/2 - 10/3)	**Poor**	0.1	2.5	6.4	6.9	4.9	0.3	
		Relative Humidity at Tmax						
		21-30.9	**31-40.9**	**41-50.9**	**51-60.9**	**61-70.9**	**71-80.9**	**81-90.9**
Week 1	**Good**	0.5	2.0	7.8	7.8	2.4	0.6	
(1/1 - 21/1)	**Poor**	2.0	5.1	6.6	4.9	1.5	0.9	
Week 2	**Good**	0.1	1.9	8.1	7.9	2.1	0.9	
(8/1 - 28/1)	**Poor**	2.3	5.0	7.8	4.3	1.1	0.6	
Week 3	**Good**	0.3	2.5	7.7	7.1	2.8	0.6	0.3
(15/1 - 4/2)	**Poor**	1.6	4.8	8.9	4.3	1.1	0.3	0.1

Table 5. Frequency distributions (number of days) whose maximum temperature, minimum temperature, relative humidity and radiation fall within each range for all 3-week windows where a significant association was found between each weather component and quality for the Hunter Valley, New South Wales. PH week 52 refers to the last 3-week window in the year prior to harvest.Shaded cells indicate that differences between good and poor years were deemed significant (P<0.05) by chi-square test. Dark Shading means that an excess of days was associated with poor years and lighter shading the excess days were associated with better years.

		Tmax (ºC)							
		<22	22-24.9	25-27.9	28-30.9	31-33.9	34-36.9	37-39.9	>39.9
PH Week 52	Good	0.1	1.6	2.9	4.2	5.5	3.4	2.6	0.7
(23/12 -	Poor	1.0	2.0	4.8	6.0	2.8	3.5	0.8	0.0
Week 1	Good	0.1	1.5	2.1	4.7	5.1	3.2	2.9	1.4
(1/1 - 21/1)	Poor	0.8	2.0	5.2	6.5	3.8	1.7	0.8	0.2
Week 2	Good	0.1	1.4	2.2	4.9	4.5	3.5	2.8	1.6
(8/1 - 28/1)	Poor	1.5	2.3	4.5	5.8	3.7	1.5	1.3	0.3
Week 3	Good	0.1	1.1	1.9	5.1	4.4	3.8	3.0	1.6
(15/1 - 4/2)	Poor	1.2	2.5	6.0	5.2	3.5	1.5	0.8	0.3
Week 4	Good	0.0	1.5	2.2	4.7	4.7	3.8	2.9	1.2
(22/1 - 11/2)	Poor	1.5	2.0	7.2	4.8	3.0	1.8	0.5	0.2
Week 5	Good	0.1	1.6	2.3	4.8	4.6	3.5	2.8	1.2
(29/1 - 18/2)	Poor	0.8	2.3	7.5	5.5	2.8	2.0	0.0	0.0
Week 6	Good	0.4	2.3	3.4	4.6	5.0	2.7	1.8	0.8
(5/2 - 25/2)	Poor	1.2	1.7	6.7	6.0	2.7	2.5	0.3	0.0
Week 7	Good	0.5	2.0	3.7	5.3	4.6	2.5	1.8	0.6
(12/2 - 3/3)	Poor	0.8	2.2	6.8	6.7	2.8	1.3	0.3	0.0

		Tmin (ºC)				
		<13	13-15.9	16-18.9	19-21.9	>21.9
Week 1	Good	2.0	4.1	7.7	6.3	0.9
(1/1 - 21/1)	Poor	3.2	4.8	9.3	3.5	0.2
Week 3	Good	1.8	3.8	5.7	8.3	1.4
(15/1 - 4/2)	Poor	0.5	4.8	9.3	6.0	0.3
Week 5	Good	2.2	3.7	6.8	6.5	1.7
(29/1 - 18/2)	Poor	0.5	4.2	9.8	6.2	0.3

		Relative Humidity at Tmax							
		<21	21-30.9	31-40.9	41-50.9	51-60.9	61-70.9	71-80.9	81-90.9
Week 1	Good	0.7	4.5	6.8	5.1	1.8	1.4	0.5	0.3
(1/1 - 21/1)	Poor	0.0	2.8	4.7	7.2	3.2	1.7	1.0	0.5
Week 2	Good	0.6	4.4	6.1	6.2	2.2	1.0	0.3	0.3
(8/1 - 28/1)	Poor	0.0	1.8	3.8	6.7	4.3	2.2	1.8	0.3
Week 3	Good	0.0	3.8	7.2	5.8	2.8	0.8	0.3	0.3
(15/1 - 4/2)	Poor	0.0	1.0	2.8	7.2	5.0	2.8	1.5	0.7
Week 4	Good	0.0	3.2	7.0	6.5	3.0	0.8	0.4	0.1
(22/1 - 11/2)	Poor	0.0	0.5	3.2	6.2	5.7	2.7	1.7	1.2
Week 5	Good	0.5	2.5	7.5	6.5	3.2	0.5	0.2	0.2
(29/1 - 18/2)	Poor	0.0	0.2	2.7	6.8	6.2	2.7	1.3	1.2
Week 6	Good	0.0	2.6	6.4	6.5	3.7	1.2	0.5	0.2
(5/2 - 25/2)	Poor	0.0	0.7	2.8	6.2	6.7	2.7	1.3	0.7
Week 7	Good	0.6	2.7	5.5	6.5	3.5	1.5	0.3	0.3
(12/2 - 3/3)	Poor	0.0	0.5	1.5	7.5	8.0	2.5	0.8	0.2

		Total Daily Radiation (MJ/m2)							
		<13	13-15.9	16-18.9	19-21.9	22-24.9	25-27.9	28-30.9	>30.9
PH Week 49	Good	1.0	0.7	1.1	2.6	3.3	3.3	6.7	2.3
(2/12 -	Poor	3.3	1.5	2.0	1.3	3.0	3.7	4.3	1.8
Week 3	Good	1.3	1.1	1.8	2.3	3.2	5.2	6.2	
(15/1 - 4/2)	Poor	4.7	2.5	1.5	2.7	2.3	4.5	2.8	
Week 4	Good	1.0	1.6	2.4	2.8	3.9	4.7	4.5	
(22/1 - 11/2)	Poor	5.0	2.5	1.8	2.3	2.3	4.3	2.7	

Barossa Valley

In the Barossa, cooler maximum temperatures (16.0 – 21.9ºC) and fewer days with very high maxima particularly over 39.9ºC from mid January to mid February were associated with better quality vintages (Figure 2A and Table 2). The association of more days with lower maxima (below 21.9ºC) with better quality was consistent over the same period albeit only significant in week 3 (19.0-21.9ºC) and week 4 (16.0-18.9ºC) (Table 2). In the 3 weeks prior to the estimated harvest (week 12 window) better quality vintages were associated with more warm days (28.0–33.9ºC) and less very cool days (16.0-18.9ºC) (Figure 2B and Table 2).

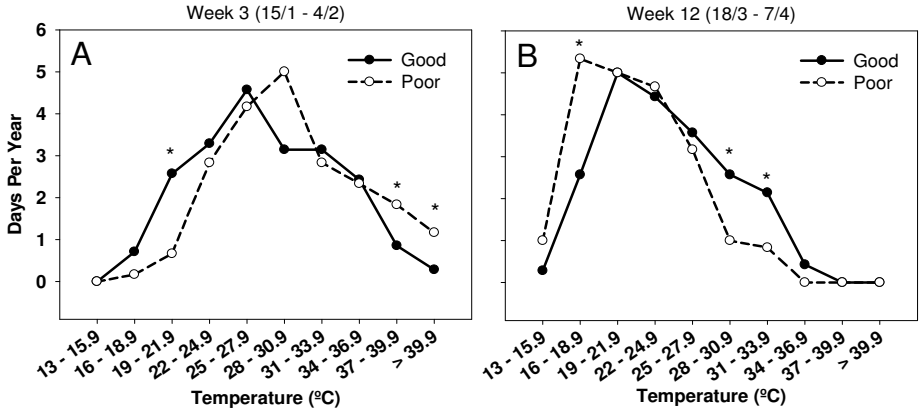


Figure 2. Frequency distribution (number of days) for maximum temperatures (A) near the average time of veraison and (B) pre-harvest in good and poor years for quality in the Barossa Valley, South Australia. Asterisks indicate statistically significant differences indicated by χ^2 analysis ($P<0.05$).

In the Barossa Valley there was also an association between minimum temperature and wine quality in the windows spanning January 8 to February 18. An excess of high minimum temperatures (> 19ºC in week 2 and > 16ºC in week 3) and a corresponding deficit in cool minima between 7.0-12.9ºC were associated with poor vintage scores in this period (Figure 3 and Table 2), albeit the differences in cool nights were only significant in weeks 3 and 5 with significant deficits in the 10.0-12.9ºC range. The difference between poor and good years in terms of minimum temperature were more consistent and distinct than that observed for maximum temperature (for example see Figure 3 versus Figure 2A) with a clear shift towards higher minimum temperatures in poor years across all windows near veraison. Close to harvest, an excess of sunny days (19.0-21.9 MJ/m^2) were associated with better vintages (Table 2).

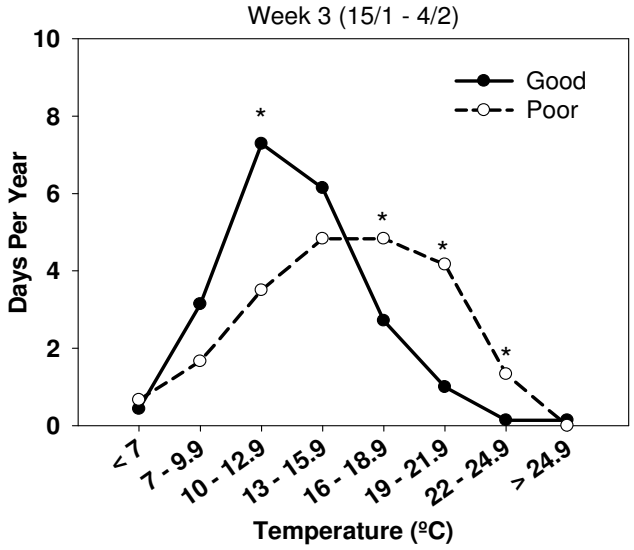


Figure 3. Frequency distribution (number of days) for minimum temperatures near veraison in good and poor years for quality in the Barossa Valley, South Australia. Asterisks indicate statistically significant differences indicated by χ^2 analysis ($P<0.05$).

Coonawarra

Similar to the Barossa Valley, warm but not hot temperatures immediately prior to the estimated harvest date favoured wine quality in the Coonawarra (Table 3). In weeks 11 and 12 an excess of days with maxima between 31.0 and 33.9ºC were better for quality. Later in the season, in weeks 13 and 14, the temperature ranges beneficial for quality decreased (28.0-30.9ºC in week 13 and 25.0-30.9ºC in week 14). In contrast to the Barossa however, minimum temperature was less influential in the Coonawarra with the only significant association with quality occurring in the last 3-week window prior to harvest in which a small excess of days between 1.0 and 3.9ºC was associated with better vintage score. Similarly for radiation, only one window from mid to late March showed a significant association between radiation and quality where sunny days, again in the 19.0-21.9 MJ/m^2 range, were found to be beneficial for quality.

Margaret River

Margaret River had a narrower range of maximum temperatures than any of the other regions in this study with a high concentration of days in the 22.0-30.9ºC range (Table 4). Similar to the Barossa, an excess of high maximum temperatures early in the ripening period, in this case between January 8 and January 28, was significantly associated with poorer quality vintages (Table 4) albeit that the specific range of temperatures detrimental to quality was broader than the Barossa (28.0-36.9ºC). In the Margaret River more days with relative humidity below 41% in January were associated with poorer vintages (Table 4) and an excess of days with relative humidity in the range of 51.0-60.9% (week 1 and 2) and 51.0-70.9 % (week 3) associated with better quality.

Hunter Valley

The Hunter Valley contrasted sharply with the other three regions in this study. The proportion of the season in which the various weather components had a significant association with vintage score was much greater in the Hunter Valley than any other region (Table 5). The associations for maximum temperature and relative humidity were particularly notable (Table 5). Hot, dry and sunny conditions were clearly associated with good wine quality throughout the ripening period (Figure 4 and Table 5). While the specific temperature windows in which a statistically significant association was found between maximum temperature and quality varied with week of the season, there were generally more days in every window above 31ºC in better years than in poorer years. Likewise the number of days in temperature windows below 31ºC was always greater in poorer years. In contrast to other regions, very hot (>37ºC) maximum temperatures and low humidity (21.0-40.9%) throughout the season were associated with better quality. Similarly high minimum temperatures (19.0-21.9ºC week 1, >21.9ºC week 3 and 5) and radiation in the 28.0-30.9 MJ/m^2 range in early December and again from mid January to mid February were more common in better vintages for quality.

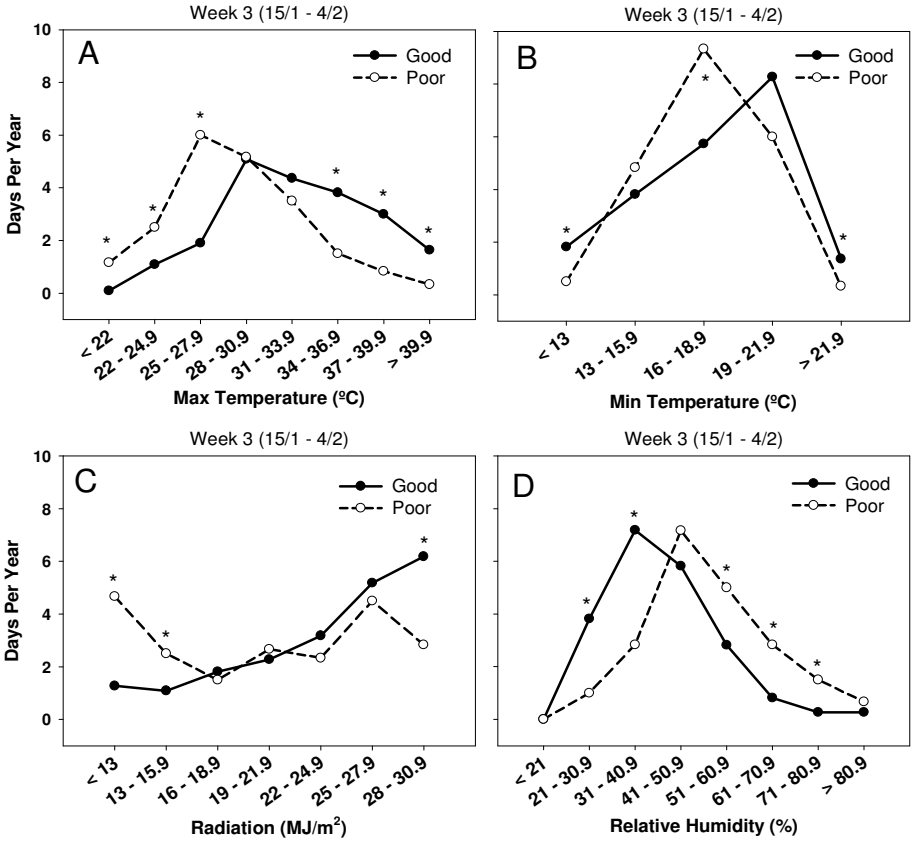


Figure 4. Frequency distribution (number of days) for maximum temperature (A), minimum temperature (B), Radiation (C) and Relative Humidity (D) post veraison in good and poor years for quality in the Hunter Valley, New South Wales. Asterisks indicate statistically significant differences indicated by χ^2 analysis (P<0.05).

Discussion

Limitations of the study: vintage scores and correlations between weather variables

In recent years, there has been dramatic progress in the methods to quantify quality-related components of wine (Iland et al. 2000; Gishen et al. 2005; Herderich and Smith, 2005; DeBolt et al. 2007; Ferreira, 2007; Pollnitz et al. 2007). However, the chemical profiles of wines are fragmented, long-term data are scarce, and the integration of individual wine attributes into overall wine quality remains challenging (Francis et al. 1999; Rivas et al. 2006; Ferreira 2007). In contrast to the repeatability of these scientifically based assessments, an expert's wine or vintage score is a subjective entity relying on the individual senses and preferences of the tasters.

Acknowledging the deficiencies in using wine scores but recognising the paucity of better means to perform the type of analysis presented in this study, we must instead test for the robustness of vintage scores and be cautious about the conclusions drawn. The robustness of vintage scores has been demonstrated in studies showing (a) biophysically meaningful associations between vintage scores and weather drivers, and (b) cross-references whereby vintage scores from independent sources yield consistent information (Ashenfelter et al. 1995, Jones and Davis 2000, Rodo and Comin 2000, Grifoni et al. 2006). Sadras et al. (2007a) recently summarised the limitations and strengths of vintage scores to capture long-term trends in wine quality.

The various components of weather are closely correlated with each other (Figure 1). Therefore a significant association between wine quality score and a given weather variable cannot be taken as evidence of causal relationship. For example the association of high humidity and poor quality in the Hunter Valley could be either a true effect of humidity, increased rainfall, decreased sunshine or other potentially correlated factors such as disease and splitting. Hence in this analysis we have considered a range of interrelated weather components to give a fuller impression of the integrated effect of weather on wine quality. In the following discussion, therefore, we should consider both the imperfect nature of the response variable (Hunter and Schmidt 1990) and the correlations between weather variables.

Weather and wine quality: from qualitative to quantitative accounts of regional influences

The four regions in this analysis have contrasting climates. For example Margaret River and the Barossa Valley have similar average maximum temperatures but Margaret River features a more maritime climate with typically higher minimum temperatures, lower diurnal thermal fluctuation and less day-to-day variation in temperature than the Barossa Valley (Gladstones 1992). Margaret River tends towards higher humidity during ripening and can be adversely affected by stronger winds typical of a maritime environment (Gladstones 1992). Gladstones (1992) summarises the influences of climate on wine quality in a description of "an ideal vineyard climate" which has consistently warm, but not hot days and cool nights throughout ripening but particularly around the time of veraison to favour maximal

carbohydrate accumulation particularly for colour formation. However, these qualitative descriptions lack specificity. In broad terms the results of our analysis are in agreement with Gladstones' descriptions of the influence of climate on wine quality for each of the regions investigated, however the qualitative descriptors have been replaced with quantitative specificity.
The climate of each region will dictate the importance of each weather variable to wine quality. For example, detrimentally high minimum temperatures close to veraison in a cooler region like the Coonawarra have a lower frequency and thus less risk of occurring than in a region such as the Barossa. Thus it might be expected that the importance of minimum temperature at veraison in determining wine quality will be less in the Coonawarra relative to the Barossa. Likewise there is also the possibility of vineyard adaptation to match the environment which could also modify the response of the variety, and hence wine quality, to the weather. This adaptation could be through varietal selection, acclimation of a given variety or via management inputs such as canopy and fruit load management, irrigation and so forth.

Barossa Valley, Margaret River and Coonawarra

The Barossa Valley, Margaret River and Coonawarra were broadly similar in terms of the association between individual weather components and quality. Across these regions, if the same weather component was found to be associated with quality the influence of that component was generally consistent. For example in Margaret River and the Barossa Valley very hot temperatures early in the ripening period (close to the estimate of veraison in Table 1) were associated with poorer quality wines, albeit that the absolute ranges of maximum temperature associated with poorer quality were higher in the Barossa Valley than Margaret River.

Maximum and minimum temperatures in the Barossa tend to be more variable, and extremes more likely compared to either Margaret River or Coonawarra (Gladstones 1992; Dry et al. 2004). In this region an excess of very hot (>37ºC) maximum and warm minimum temperatures (16.0-24.9ºC) in the period immediately prior to the estimated date of veraison (from Table 1) were sensibly associated with poorer quality. This is in keeping with the expected influences of temperature on quality, specifically colour formation. The corollary to this observation is that in the Barossa, years with better quality were generally cooler, which will tend to result in slower ripening. Years in which maturity is delayed or ripening is slow may need more sunshine hours late in the season and the often associated warm days to help reach the sugar concentration required for fuller bodied wines. Thus in these better quality years both high radiation (19.0-21.9MJ/m^2) and warm maximum temperature (28.0-33.9ºC) close to maturity were also associated with high quality.

In Margaret River an association between weather and quality was only found just prior to veraison (from Table 1), and not near harvest like in the Barossa. This suggests that in Margaret River near veraison is either the most sensitive stage of berry development to temperature and/or that the risk of adverse temperatures is much higher earlier in the ripening period than close to harvest.

Margaret River was the only region besides the Hunter Valley to have a significant association between humidity and vintage quality albeit that the apparent relationship between humidity and quality was different between the two regions. In Margaret River humidity below 40% was more common in poorer quality years and humidity in the range 51.0-60.9% was a more common feature of years of comparatively better quality.

Low humidity can contribute to moisture stress. It is thus possible that the association between moderate humidity (51.0-60.9%) in Margaret River and better quality may be related to indirect modulation of water stress as opposed to direct effects on fruit composition. The importance of humidity in Margaret River compared with the Barossa Valley and Coonawarra probably relates to the contrasting maritime climate of the region. In the Margaret River exposure to temperature extremes are less likely and thus perhaps less relevant for quality compared to non-maritime climates. Alternatively relative humidity between 50 and 60% in the Barossa and Coonawarra during the growing season have a lower frequency of occurrence than in Margaret River and thus favourable humidity may not occur frequently enough to be significantly associated with quality.

Because of the cooler nature of the Coonawarra, cooler minimum temperatures and milder maximum temperatures are more a consistent feature of this region. This may explain why high temperature is not closely associated with poor quality early in the ripening period in this region. However of more frequent concern in the Coonawarra is the late ripening of the crop and potential difficulties in reaching full maturity or the sugar concentration required for fuller bodied wines (Gladstones 1992). The χ^2 analysis supported this notion and indicated that seasons that finish with more days towards the warm tail of the frequency distribution and greater radiation (19.0-21.9 MJ/m^2) produce better quality wines, most likely because conditions are conducive to grapes reaching full maturity. Another quality related risk in regions where harvest is generally late is increased likelihood of rain and hail damage, and associated risk of disease.

Hunter Valley

The Hunter Valley is generally warmer than the other regions studied. This results in generally faster ripening, however a tendency towards high humidity and rainfall during the latter stages of ripening and hazy conditions that reduce effective radiation tend to influence wine quality in this region (Gladstones 2002; Dry et al. 2004).

The association between weather components and quality discussed for Margaret River, Barossa Valley and Coonawarra were generally reversed in the Hunter Valley. In the other regions the main periods of influence of weather on quality were estimated to be prior to and near veraison and immediately pre-harvest. The Hunter Valley clearly had the largest window in which weather and vintage scores of red wines were linked. This analysis suggests that in the Hunter Valley, maximum temperatures above 37ºC and relative humidity between 21.0 and 40.9% throughout the ripening period favour quality. This is in contrast to the fact that milder day temperatures and cool night temperatures favour good colour formation (Mori et al. 2004, 2005a, 2005b, 2007, Yamane 2006) and warm, but not

excessively hot temperatures are believed to be good for wine quality overall (Gladstones 1992).

The Hunter Valley has much higher growing season rainfall than the other regions in this study and has a tendency for thunderstorms and heavy rain late in the season. Higher temperatures and low humidity (high VPD) and high radiation tend to be negatively correlated with rain (Figure 1). Therefore, given that the better years for quality have been associated with high temperature, low humidity and high radiation throughout ripening it is not surprising that better years also tend to have 70% lower growing season rainfall than poor years (data not shown).

The moist warm conditions often experienced in the Hunter Valley favour powdery mildew throughout ripening (Dry et al. 2004). Likewise thunderstorms and heavy rains late in the season frequently result in berry splitting (Considine and Kriedemann 1972) which increases the risk of Botrytis bunch rot close to harvest (Gladstones 2004; Dry et al. 2004). The strong association of hot, dry conditions with better quality vintages in the Hunter Valley suggests that the negative impacts of rainfall and high humidity are more critical for quality in this region than the benefits derived from milder conditions and high humidity effects that improve colour and flavour.

Conclusion

This analysis has provided insights into windows during ripening that are most sensitive to weather in terms of wine quality for four major wine regions in Australia. It has also provided greater specificity as to the ranges of temperature, humidity and radiation that are most likely to impact on wine quality. However the analysis does not precisely tell us about the summation of weather conditions either between variables or across time. For example, in the Hunter Valley we have produced evidence that hot conditions favour quality and have suggested that this is due to the negative correlation between temperature, rainfall and humidity. The question remains however whether a single window of adverse conditions for quality is sufficient to ruin the vintage, that is will heavy rain and high humidity three weeks prior to harvest drastically affect quality even if the previous six weeks have been favourable; the answer in this case is likely to be yes. However for some of the more subtle influences such as night temperatures in the Barossa, a single week of warmer than optimum night temperatures at veraison may be offset by several weeks of favourable temperatures. This type of question requires experimental resolution.

The fact that the χ^2 analysis of the association between weather components and wine quality are consistent with expectations based on the regional climate characteristics and most significant concerns facing each region add confidence to our interpretation of the results. The improved specificity of the links between timing and severity of defined weather events and wine quality will help in the development of a risk analysis framework for wine quality across Australia. This information can also be used to guide field experiments designed to examine the effects of weather components on wine quality.

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Chapter 7

Phenotypic plasticity of grapevine phenology and yield

VO Sadras, PR Petrie, R Robinson

Summary

Phenotypic plasticity is "the amount by which the expressions of individual characteristics of a genotype are changed by different environments". Here we (a) quantified phenotypic plasticity of the timing of three phenostages, viz. budburst, flowering, and veraison, (b) tested the hypothesis of hierarchies in plasticity, viz. plasticity for budburst and plasticity for veraison are inversely related, and (c) explored the links between the phenological plasticities of phenology and yield.

Seven varieties, viz. Cabernet Franc, Cabernet Sauvignon, Chardonnay, Merlot, Riesling, Semillon and Shiraz were compared in 14-19 environments of South Australia resulting from the combination of sites and seasons. Averaged across varieties, these sources of variation generated a range of 39 days for budburst, 27 days for flowering and 53 days for veraison. Yield ranged from 1 to 19 t ha^{-1}. Coefficients of plasticity were calculated as the slope of the regression between the actual variable for a given variety and environment (e.g date of budburst) and the environmental mean.

For our combination of cultivars and environments, Cabernet Franc stood out as the variety with above-average plasticity for all three phenostages and veraison as the stage with greater capacity for statistical discrimination of varieties. Hierarchies of plasticities for phenological development were not evident. Plasticity of fruit yield was correlated with plasticity of budburst and flowering, indicating that the capacity to accommodate pre-flowering development to environmental conditions improves the cultivar's ability to capture the benefits of high-yielding environments.

Introduction

Phenological development is critical to the adaptation of wild and cultivated plants and many animals (Bastlova and Kvet 2002, Reisch and Poschlod 2003, Sadras and Trápani 1999, Steinbauer et al. 2004). In grapevine, budburst (E-L stage 4), flowering (E-L stage 19), veraison (E-L stage 35) and maturity (E-L stage 38) are key phenostages (Coombe 1995). The timing of these stages results from environmental drivers, chiefly temperature, and two interplaying biological factors. One is the intrinsic phenological pattern of a variety; for instance Pinot Noir and Traminer are typically early varieties compared to Petit Verdot and Grenache (Gladstones 1992). The second factor is the phenotypic plasticity of phenological development.

Phenotypic plasticity is "the amount by which the expressions of individual characteristics of a genotype are changed by different environments" (Bradshaw 1965). Bradshaw (1965) proposed that plasticity is a trait of its own, with its own

genetic control, and that there is a hierarchy of plasticities, i.e. stable traits are often associated with plastic, related traits. Recently, Reymond et al. (2004) have demonstrated unequivocally that phenotypic plasticity is a trait on its own, with its own genetic control, and Sadras (2007) has provided evolutionary evidence that matches the notion of a hierarchy in the plasticities of related reproductive traits in annual plants. The importance of considering phenological development in terms of phenotypic plasticity is illustrated in the study of Steinbauer et al. (2004), where phenological plasticity is shown to influence voltinism (i.e. number of generations per year) and population dynamics of *Mnesampela privata*, a Lepidopteran pest of Australian forests.

Calò et al. (1998b) comprehensively quantified the phenotypic plasticity of phenological development of 80 grapevine varieties at Conegliano, Italy. In their study, a coefficient of phenotypic plasticity was calculated as the slope (*b*) of the linear regression between a given trait (e.g. date of veraison) of an individual variety in a particular environment, and the mean value of the trait across varieties in that particular environment. A variety with $b = 1$ has average plasticity over all environments, a variety with $b > 1$ has above-average plasticity, and a variety with $b < 1$ has below-average plasticity (Finlay and Wilkinson 1963). The "environment" can involve sites, seasons, specific treatments (e.g. water supply), or a combination of these sources of variation. Calò et al. (1998b) for instance, used records of phenological development at one site during 25 years, and considered each season to represent a distinct environment.

Pearce and Coombe (2004) summarised the phenological patterns of major vine varieties under Australian conditions but not attempt has been made to quantify phenotypic plasticity of phenological development. In this paper, we (a) quantified phenotypic plasticity of three phenostages, viz. budburst, flowering, and veraison for seven grapevine varieties grown under South Australian conditions, (b) tested the hypothesis of hierarchies in plasticity, viz. is high plasticity for budburst related to low plasticity for veraison? and (c) explored the link between phenological plasticity and plasticity of crop yield.

Method

We compiled a data set including seven varieties, viz. Cabernet Franc, Cabernet Sauvignon, Chardonnay, Merlot, Riesling, Semillon and Shiraz grown in 19 environments resulting from the combination of seasons and regions as follows: (a) eight seasons (1997-98 to 2005-06) from commercial crops at Coonawarra (Fosters' Group) (b) seven seasons (2000-01 to 2006-07) from commercial crops at Mt Benson (Norfolk Rise Vineyard) and (c) four vintages from the experimental vineyard of the South Australian Research Institute at Nuriootpa in the Barossa Valley (1982-83 to 1985-86). Crops received limited irrigation (typically below 2 ML/ha per season) and rainfall was the main source of season-to-season variation in yield (Petrie, unpublished). Climate, soils and viticultural practices of these regions have been described elsewhere (Dry and Coombe 2004, Gladstones 1992).

We used the method of Finlay and Wilkinson (1963) to calculate the relative plasticity of timing of critical phenostages including budburst (E-L stage 4;),

flowering (E-L stage 19), and veraison (E-L stage 35) (Coombe 1995). Linear regressions were fitted between the actual date for each combination of phenostage, variety and environment and the average date of the event for each environment, i.e. across varieties. The slope of this regression measures phenotypic plasticity.

In the experimental crops at Nuriootpa, phenological assessments were made in a single block containing all varieties (for details of this data set see Pearce and Coombe 2004). In the commercial crops at Mt Benson and Coonawarra, phenology assessments were made to ensure that vine husbandry practices were carried out at the appropriate time (e.g. the application of fungicides to control *Botrytis cinerea* at flowering). Data were collected from 1 to 31 blocks at Coonawarra, and 1 to 12 blocks at Mt Benson; data from multiple blocks were averaged for the analysis. The intensity of phenology assessments, typically weekly, varied with the stage of the season, with a shorter period between observations during critical stages of development such as flowering.

Using the same approach, we quantified the plasticity of fruit yield for the seven varieties grown in 12 environments, i.e. eight seasons (1997-98 to 2005-06) at Coonawarra and 4 seasons (2003-04 to 2006-07) at Mt Benson. Yield data were unavailable for Mt Benson in 2000-01 and 2002-03, and for Nuriootpa.

Results and Discussion

The method of Finlay & Wilkinson applied to phenological development

Finlay and Wilkinson (1963) developed a method to quantify trait plasticity originally applied to grain yield in annual crops, and Calò et al. (1975) first applied this approach in studies of phenological plasticity of grapevine. Figure 1 illustrates the rationale of this method showing three contrasting responses for veraison under South Australian conditions, i.e. above-average plasticity for Merlot, average plasticity for Shiraz and below-average plasticity for Riesling.

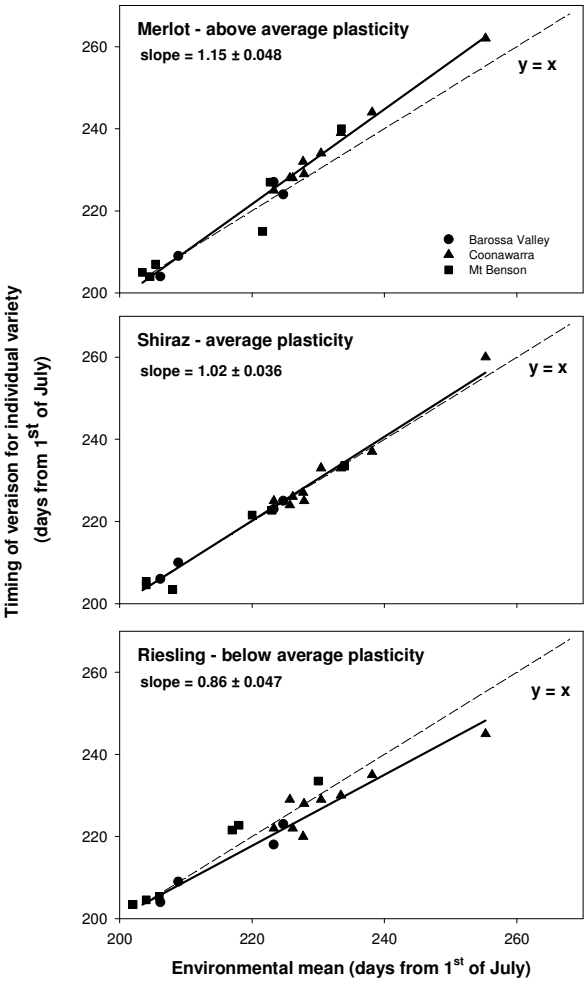


Figure 1. Illustration of method to quantify phenotypic plasticity of grapevine phenological development showing three contrasting responses for veraison under South Australian conditions, i.e. above-average plasticity for Merlot, average plasticity for Shiraz and below-average plasticity for Riesling. Solid lines are fitted regressions.

Despite the existence of quantitative scales of phenological development in grapevine (Coombe 1995) the actual definition of some phenostages, particularly veraison, maintains an element of subjectivity (Pearce and Coombe 2004). This subjective component suggests we need to be cautious in comparing phenological development characterised by different observers. The method of Finlay and Wilkinson, however, largely circumvents this problem by using an environmental mean (independent variable in Figure 1) as a background to compare the timing of a given phenostage for a given variety (dependent variable in Figure 1). Provided there is consistency in the definition of a phenostage for all varieties in a given site and season, the method allows for meaningful comparisons. This is demonstrated in Figure 1, whereby unrelated observers recorded veraison and produced

internally consistent data sets, which in turn showed a strong consistency across sites and seasons, i.e. regressions with $r \geq 0.98$, $P<0.0001$.

Phenotypic plasticity of bud burst, flowering and veraison

The combination of regions and seasons generated a moderate range of variation in timing of budburst, from 32 days in Chardonnay to 46 days in Merlot, a narrower range of variation in timing of flowering, between 21 days in Riesling and 35 days in Cabernet Franc, and a substantial range in timing of veraison, from 43 in Chardonnay and Riesling to 60 in Cabernet Franc (Table 1).

Table 1
Range and coefficients of phenotypic plasticity (dimensionless) for three phenostatges in seven grapevine varieties grown in 19 South Australian environments. Coefficients are the slopes of the regression between the actual date when a phenostage was achieved for a given variety and environment, and the environmental mean date, i.e. across varieties.

Variety	Budburst			Flowering			Veraison		
	Range (days)	Coeff.	SE	Range (days)	Coeff.	SE	Range (days)	Coeff.	SE
Cabernet Franc	40	1.30*	0.099	35	1.18	0.116	60	1.16*	0.088
Cabernet Sauv	43	0.91	0.084	27	0.84	0.090	55	1.03	0.057
Chardonnay	32	1.01	0.106	29	1.09	0.092	43	0.78*	0.052
Merlot	46	0.87	0.090	25	1.06	0.110	58	1.15*	0.048
Riesling	34	0.97	0.123	21	0.84	0.110	43	0.86*	0.047
Semillon	38	1.06	0.129	25	0.95	0.111	55	0.98	0.054
Shiraz	41	0.86*	0.063	30	1.03	0.058	56	1.02	0.036

* Statistically different from 1 at $P < 0.10$

The relative variability of these three phenostages for our combination of varieties and environments agrees qualitatively with the conclusions of Pearce and Coombe (2004) for Australian viticultural regions and Calò et al. (1998a) for a long-term series of vintages in Conegliano. Both studies ranked the variability of these phenostages as veraison > budburst > flowering.

Cabernet Franc stood out as the variety with above-average plasticity for all three phenostages and veraison as the stage with greater capacity to discriminate varieties (Table 1). For timing of veraison, Cabernet Franc and Merlot showed above-average plasticity, Chardonnay and Riesling below-average plasticity, and Cabernet Sauvignon, Shiraz and Semillon average plasticity (Table 1). The genetic basis of the differential phenotypic plasticity of grapevine varieties requires to establish the association between plasticity coefficients (Table 1) and quantitative trait loci, as shown by Reymond et al. (2004) for the plasticity of leaf elongation.

Hierarchies of plasticities

Negative correlations between plasticity coefficients for different phenostages would be indicative of trade-offs, or hierarchies in plasticity (Bradshaw 1965, Sadras 2007), e.g. a high plasticity for bud burst at the expense of plasticity for veraison or flowering. Analysis of correlation showed no evidence of associations between the coefficients in our study. Owing to the limited number of points (n = 7), we expanded the analysis using the data of Calò et al. (1998a) comprising 80 varieties under 25 environments. Both data sets overlapped, and no evidence of hierarchy of plasticities was found for this large combination of varieties and environments (Fig. 2).

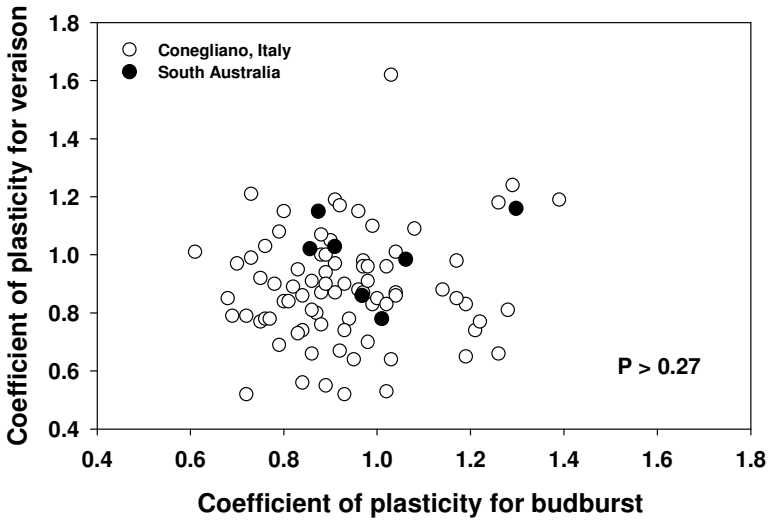


Figure 2. Phenotypic plasticity of veraison under South Australian conditions in relation to genetic similarity in seven grapevine varieties. Coefficients of phenotypic plasticity for veraison (dimensionless) are the slopes of the linear regression between the actual date for each variety and environment and the average date of veraison for each environment, i.e. across varieties. Error bars are standard errors. Electrophoretic similarity degree (dimensionless) reported by Bourquin et al. (1993) was calculated from restriction fragment length polymorphism and is taken as an approximate measure of genetic similarity.

Associations between phenotypic plasticity of yield and phenology

The combination of sites, vintages and varieties generated a 15-fold range in yield (Fig. 3). In low-yielding environments, all varieties performed similarly and averaged 2.6 t ha^{-1} (dashed line in Fig. 3). Under high-yielding conditions, there were substantial differences between varieties that were reflected in contrasting coefficients of phenotypic plasticity for yield (Fig. 3, solid line).

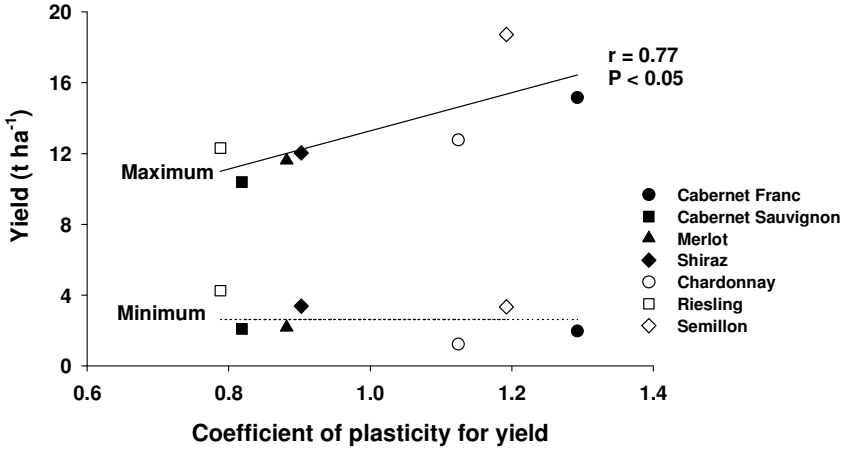


Figure 3. Comparison of coefficients of phenotypic plasticity for budburst and veraison. Our coefficients (closed symbols, 7 varieties in 19 environments) were compared with those from Calò et al. (1998a) (open symbols, 80 varieties in 25 environments).

Plasticity of yield was correlated with phenological plasticity for budburst and flowering, but not for veraison (Fig. 4). We propose therefore that phenotypic plasticity for development until flowering is an important driver of the capacity of a given variety to capture growing conditions favouring high yield. The relatively narrow range of plasticity of flowering time, and the comparatively large errors for this trait did not allow for statistical discrimination among varieties (Table 1). In spite of this lack of statistical resolution, the coefficient of plasticity of flowering time clearly discriminated varieties with extremely high, i.e. Cabernet Franc, and low, i.e. Riesling, yield responsiveness to environmental conditions (Fig. 4b). Conversely, timing of veraison was characterised by plasticity coefficients with statistical resolution to discriminate varieties (Table 1) but this trait was unrelated to yield plasticity (Fig. 4c). The lack of association between plasticity for veraison and plasticity for yield is physiologically meaningful, however, as this phenostage follows the determination of bunch number and berries per bunch, the main yield components. Timing of veraison might have an influence on berry size, but this component plays a minor role in the yield range (around 15-fold, Fig. 3) in this study.

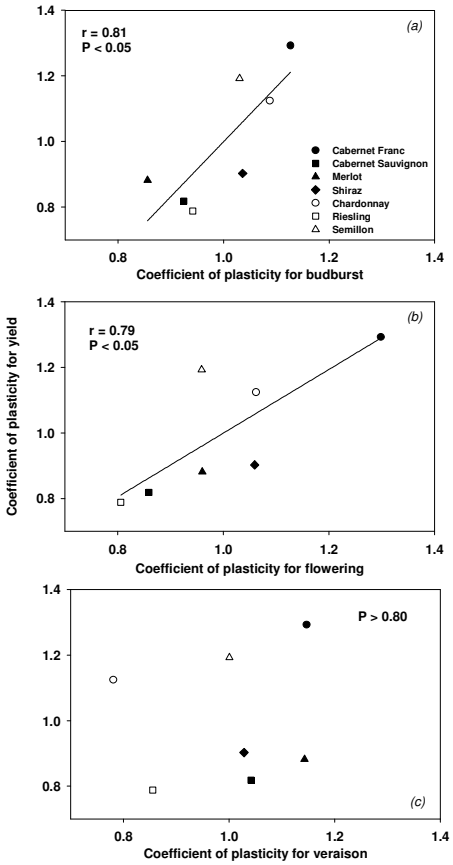


Figure 4. Relationships between minimum and maximum yield in 14 South Australian environments and the coefficient of phenotypic plasticity for yield for seven grapevine varieties.

Table 1
Range and coefficients of phenotypic plasticity (dimensionless) for three phenostatges in seven grapevine varieties grown in 19 South Australian environments. Coefficients are the slopes of the regression between the actual date when a phenostage was achieved for a given variety and environment, and the environmental mean date, i.e. across varieties.

Variety	Budburst			Flowering			Veraison		
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Shiraz	41	0.86*	0.063	30	1.03	0.058	56	1.02	0.036

* Statistically different from 1 at P < 0.10

Conclusions

The method of Finlay and Wilkinson (1963) proved valuable to quantify phenotypic plasticity of grapevine phenology, confirming the pioneering work of Calò et al. (1998b, 1975). For our combination of cultivars and environments, Cabernet Franc stood out as the variety with above-average plasticity for all three phenostages and veraison as the stage with greater capacity for statistical discrimination of varieties. Preliminary evidence supported Bradshaw's (1965) concept of a genetic substrate for plasticity of veraison, but hierarchies of plasticities for phenological development were not evident. Plasticity of fruit yield was correlated with plasticity of budburst and flowering, indicating that the capacity to accommodate pre-flowering development to environmental conditions may improve the cultivar's ability to capture the benefits of high-yielding environments.

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Chapter 8

Quantifying the dynamics of sugar concentration in berries of *Vitis vinifera* cv Shiraz: a novel approach based on allometric analysis

VO Sadras, MG McCarthy

Summary

Concentrations of key compounds (e.g. sugar) in berries are the net result of the relative changes in the amount of compound per berry and berry size. Whereas the complex nature of concentrations is widely recognised, the widespread use of chronological scales for comparisons implies that ontogenetic drift or size-dependent effects are often overlooked. This paper presents an allometric analysis of sugar concentration in berries of cv Shiraz as a way to formally account for ontogenetic drift.

Our starting point is the double-sigmoid growth pattern of the grape berry where we distinguish Phase 1, from flowering to veraison; Phase 2, from veraison to peak berry fresh mass, and Phase 3, after peak fresh mass. Phase 3 explicitly accounts for the late season shrinkage typical of Shiraz berries. We advance an allometric model of sugar per berry with berry fresh mass, rather than time, as descriptor. The condition for an increase in sugar concentration in Phase 2 is that the relative rate of sugar accumulation per berry (R_{SB}) exceeds the relative rate of berry net accumulation of fresh mass (R_{FM}). This is equivalent to an allometric coefficient, calculated as the slope of the regression between amount of sugar per berry and berry mass in a log-log scale, being greater than 1. For Phase 3, the condition for increase of sugar concentration is that a large reduction in berry mass offsets any putative change of sugar per berry ($R_{SB} < R_{FM}$), yielding an allometric coefficient < 1.

Such an allometric model was tested against measured data from sixteen contrasting crops resulting from the combination of eight water regimes and two seasons. Berry mass peaked between 96 and 105 days after anthesis, and these dates were used to separate Phases 2 and 3. In Phase 2, the relative rate of increase in sugar per berry varied from 0.01 to 0.02 d^{-1} in comparison to the relative rate of increase in berry fresh mass that varied from 0.0038 to 0.0066 d^{-1}. Sugar per berry thus increased 2.4-3.3 times faster than berry mass, with allometric coefficients between 1.98 and 2.91 accounting for 78% of the variation in the relative rate of change of sugar concentration. In Phase 3, the relative rate of change in sugar per berry was not different from zero ($P > 0.05$) in most cases, whereas the rate of change in berry size ranged from –0.0013 to –0.0035 d^{-1} and was significant ($P < 0.05$) in 14 out 16 cases. The small changes in sugar per berry and the net loss of berry material yielded allometric coefficients between 0.17 and 1.11, which accounted for 72% of the variation in the relative rate of change in sugar concentration.

We conclude that a model, which pivots around peak berry mass, with allometric coefficients above 1 in Phase 2 and below 1 in Phase 3, is suitable to quantitatively account for ontogenetic drift in the dynamics of sugar concentration in berries of Shiraz. This allometric approach demonstrated that sugar per berry during the stage of berry shrinkage is a plastic trait under significant environmental influence. For the same genotype, environmental conditions could determine either, a putative backflow of water accounting for net loss of berry fresh mass ($R_{FM} < 0$) that could also carry some sugar from berries back to the parent vine ($R_{SB} < 0$) or a small gain of sugar ($R_{SB} > 0$) closely coupled with a net loss of berry fresh mass ($P = 0.003$).

Introduction

The grape berry has a double-sigmoid growth pattern (Fig. 1). The sigmoidal Phase 1, from flowering to veraison, has been termed "berry formation", and the post-veraison Phase 2 has been termed "berry ripening" (Coombe and Iland 2004). To explicitly account for the loss of material in the late ripening stages typical of Shiraz berries (McCarthy 1999), we propose a distinction between Phase 2, from veraison to peak fresh mass, and a Phase 3 of "berry shrinkage" (dashed curve, Fig. 1). The physiological mechanisms involved in the accumulation and loss of materials in ripening grape berries are attracting increasing attention, particularly in relation to the ontogenetic changes in functionality of xylem and phloem (Bondada *et al.* 2005; Keller *et al.* 2006; McCarthy 1999; McCarthy and Coombe 1999; Rogiers *et al.* 2006a; b; Tyerman *et al.* 2004).

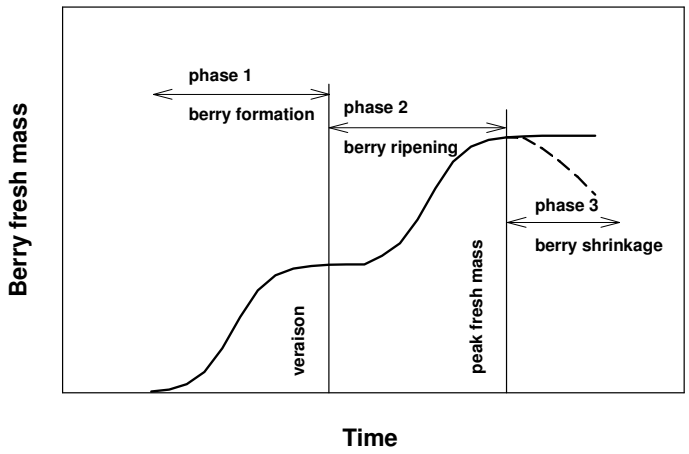


Figure 1. Schematic time-trajectory of grape berry size, adapted from Coombe and Iland (2004). During the late stages of berry ripening, fresh mass may remain stable (solid line) or decline (dashed curve). Our model requires the definition of Phase 3 to explicitly account for the decline of fresh mass typical of Shiraz berries.

Many studies have used time-trajectories to characterise the accumulation of materials (sugars, anthocyanins, minerals), whereas Coombe and McCarthy (2000) have emphasised the interplay between changes in concentrations and berry size. They highlighted, for instance, how the divergence among time-curves of °Brix in berries of cv Muscato Gordo Blanco were consistent with the dynamics of solutes per berry and berry size. However, we know of no attempt to analyse the allometric relationships between berry sugar content and berry size.

This paper uses the original data of McCarthy (1997b) to develop an allometric model of sugar dynamics in Shiraz berries after veraison (Phases 2 and 3 in Fig. 1). Owing to the shrinkage of berries during late ripening, cv Shiraz is a particularly suitable plant model for such allometric analysis.

Ontogenetic drift

As plants grow and develop, their patterns of partitioning among and within organs change in a generally predictable manner (Coleman and McConnaughay 1995). Evans (1972) coined the term “ontogenetic drift” to describe these phenotypic patterns of allocation. One consequence of ontogenetic drift is that plants or plant organs growing at different rates, e.g. as affected by genetic, environmental or management factors, will differ in size at a given time, and can therefore appear to have differences in partitioning (Coleman and McConnaughay 1995; Coleman *et al.* 1994). Owing to ontogenetic drift, analysis of sugar concentration based on a common time scale will be biased if treatments or growing conditions affect berry growth. Figure 2a illustrates the dynamics of sugar concentration in berries of four contrasting crops resulting from a combination of water regime and seasonal conditions. Given the large effect of treatments on berry mass (Fig. 2b), and that sugar concentration is a function of berry mass by definition, comparisons using a common time scale are inappropriate, as demonstrated by Coleman and colleagues (Coleman and McConnaughay 1995; Coleman *et al.* 1994). To account for ontogenetic drift in the analysis of sugar concentration we need an allometric approach (Coleman and McConnaughay 1995; Coleman *et al.* 1994).

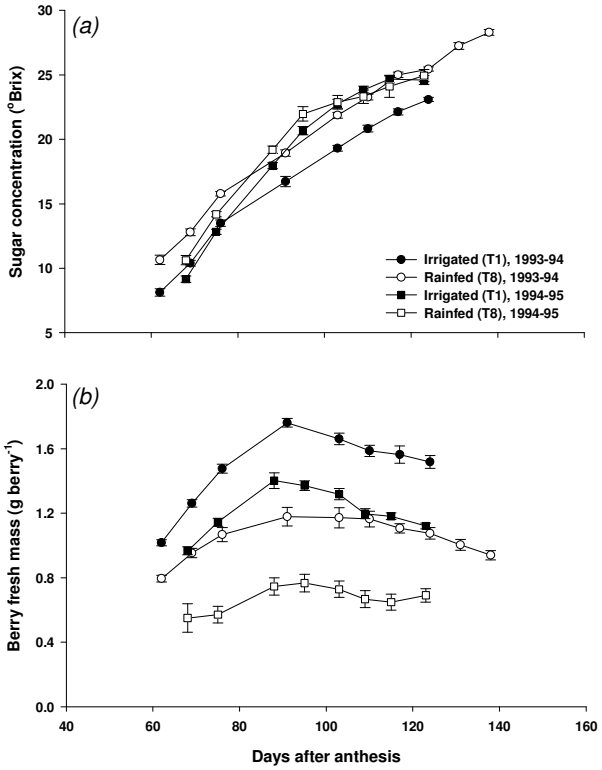


Figure 2. Dynamics of *(a)* sugar concentration and *(b)* berry mass as affected by seasonal conditions and water supply. Adapted from McCarthy (1997b).

Allometric analysis

Allometric or scaling analysis deals with the differential growth rates of the organs of plants and animals (e.g. leaf vs root, liver vs hearth) or process (e.g. body size vs metabolic rate) (McConnaughay and Coleman 1999; Niklas 1994).

Variation in berry sugar concentration is a function of the relative rates of accumulation of sugar and total berry fresh mass. To apply allometric analysis to the problem of sugar accumulation in berries, we propose an allometric model of sugar per berry with berry size, rather than time, as descriptor. The phases comprise the stages before (Phase 2) and after (Phase 3) peak berry mass (Fig. 3).

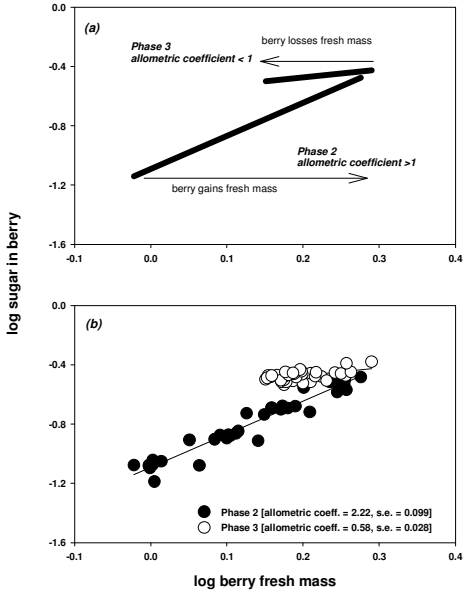


Figure 3. *(a)* Theoretical and *(b)* example of actual allometric relationship between amount of sugar per berry (g) and berry size (g) for *Vitis vinifera* cv Shiraz. The conditions for increasing sugar concentration are: allometric coefficient > 1 for Phase 2, from veraison to peak berry mass, and allometric coefficient < 1 for Phase 3, after peak berry mass. Allometric coefficients are dimensionless. Data in *(b)* are from McCarthy (1997b) fully irrigated treatment in 1993-94.

Figure 3a outlines the allometric relationships required for increasing sugar concentration, and Fig. 3b illustrates these conditions with actual field data. The condition for an increase in sugar concentration in Phase 2, when berries are actively growing, is that the relative rate of sugar accumulation (R_{SB}) exceeds the relative rate of berry growth (R_{FM}). This is equivalent to the condition of an allometric coefficient A (Pearsall 1927) greater than 1:

$$A = (\log S_1 - \log S_2)\,(\log B_1 - \log B_2)^{-1} \qquad \text{eq. (1)}$$

where S is amount of sugar per berry, B is berry fresh mass, and subscripts 1 and 2 indicate time intervals. The allometric coefficient can be calculated as the slope of the regression between amount of sugar per berry and berry mass in a log-log scale, and represents the ratio of the logarithmic rates (Pearsall 1927). For Phase 3, after peak berry mass, the condition for increase of sugar concentration is that any putative loss of berry sugar content is offset by a larger reduction in berry mass, yielding an allometric coefficient < 1. Special cases for Phase 3 include slight increase or no change in sugar per berry ($R_{SB} \approx 0$) in parallel to net loss of berry material ($R_{FM} < 0$).

Test of the concept

The allometric model outlined in Fig. 3 was tested using data from the experiments of McCarthy (1997b). Sixteen contrasting crops resulting from the combination of eight water regimes and two seasons were used in the analysis. Water regimes

include fully irrigated and rainfed treatments, and six treatments in which irrigation was restricted to specific growth periods. Variables derived from this data set include (i) peak berry mass, obtained from fitted quadratic time-trajectories of measured berry mass, (ii) relative rates of change in sugar per berry (R_{SB}), sugar concentration (R_{SC}) and berry fresh mass (R_{FM}), and (iii) the allometric coefficient defined in eq. 1. Allometric coefficients and relative rates of change were calculated as the slopes of linear regressions for Phases 2 and 3 (Fig. 3). Given that both variates in the allometric relationship are measured with error, model 2 techniques have been recommended (Coleman and McConnaughay 1995; Niklas 1994). However, allometric coefficients derived using model 1 regression (ordinary least squares) provided a better description of R_{SC} ($0.72 \leq r^2 \leq 0.78$ using model 1 vs $0.64 \leq r^2 \leq 0.67$ with model 2, reduced major axis). All allometric coefficients and relative rates reported in this paper were therefore calculated with model 1 regression.

Results

Overview of seasonal conditions and treatment effects

Seasonal conditions and treatment effects on yield and its components are fully described elsewhere (McCarthy 1997a; b; 1999). Here, Fig. 4 summarises key environmental conditions and crop responses in the two experimental seasons analysed in this paper. In comparison to their fully irrigated counterparts, the yield of rainfed crops was reduced by 28% in 1993-94, and by 65% in 1994-95, whereas pruning weight was reduced by 23 and 69%, respectively. Water regime did not affect the time of peak berry fresh mass in 1993-94. In contrast, water deficit delayed the peak of berry fresh mass, in relation to fully irrigated controls, up to 9 days in 1994-95 (Table 1). The combined measures of yield, pruning weights and timing of peak berry fresh mass highlight the interaction between water regime and season, with more marked effects of water deficit in 1994-95 than in 1993-94.

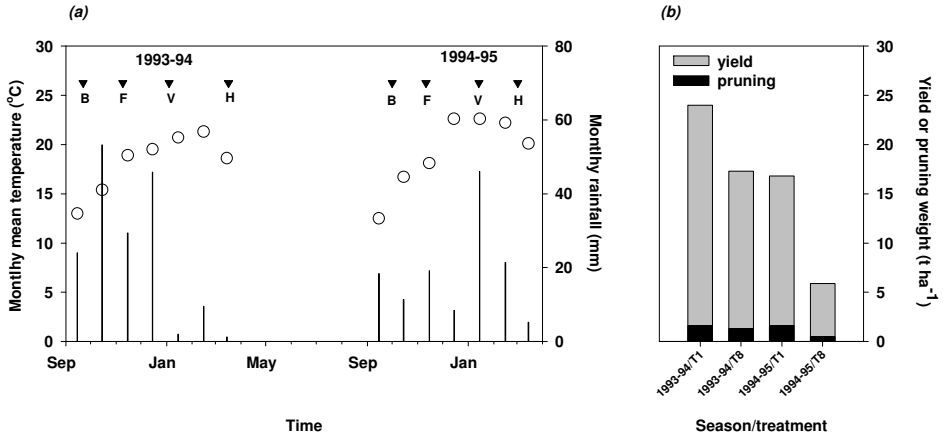


Figure 4. *(a)* Temperature (circles), rainfall (bars) and phenological development (arrowheads) during two growing seasons (September-March) at Waikerie, South Australia. Phenological stages are budburst (B), flowering (F), veraison (V) and harvest (H, approx. 23.5 °Brix). *(b)* Yield and pruning weight of extreme treatments T1 (fully irrigated) and T8 (rainfed).

Table 1. Time of peak berry fresh mass of *Vitis vinifera* cv Shiraz as affected by season and water regime.

Season	Water Regime	Days from anthesis	Degree days from anthesis[A]
1993-94	1: fully irrigated	101 ± 1.5[B]	1038 ± 18.7
	2: post-flowering deficit	102 ± 1.0	1032 ± 7.5
	3: pre-veraison deficit	103 ± 1.0	1045 ± 5.8
	4: post-veraison deficit	103 ± 1.1	1045 ± 8.2
	5: pre-harvest deficit	101 ± 0.7	1028 ± 7.6
	6: flowering-to-veraison deficit	103 ± 0.9	1046 ± 7.5
	7: veraison-to-harvest deficit	101 ± 0.8	1030 ± 6.2
	8: rainfed	103 ± 0.9	1049 ± 9.5
1994-95	1: fully irrigated	96 ± 0.5	1145 ± 3.5
	2: post-flowering deficit	99 ± 0.3	1174 ± 3.4
	3: pre-veraison deficit	99 ± 0.6	1172 ± 7.2
	4: post-veraison deficit	100 ± 1.1	1191 ± 9.7
	5: pre-harvest deficit	96 ± 0.9	1146 ± 10.5
	6: flowering-to-veraison deficit	100 ± 1.3	1190 ± 13.1
	7: veraison-to-harvest deficit	97 ± 0.8	1158 ± 10.1
	8: rainfed	105 ± 3.4	1222 ± 28.3

[A] base temperature 10 °C (Williams *et al.* 1985)
[B] standard error

Allometric analysis of sugar accumulation

The estimated time of peak berry fresh mass for each treatment and season (Table 1) was used to separate Phases 2 and 3 in the analysis of relative rates (Table 2) and allometric relationships (Figures 5 and 6).

Table 2. Relative rate of change (± standard error) in sugar per berry (R_{SB}), berry fresh mass (R_{FM}) and sugar concentration (R_{SC}) as affected by season and water regimes. Asterisks indicate *** P < 0.001, ** P < 0.01, and * P < 0.05.

Season	Water regime[A]	R_{SB} (d^{-1} x 10^3)[B]		R_{FM} (d^{-1} x 10^3)		R_{SC} (d^{-1} x 10^3)	
		Phase 2	Phase 3	Phase 2	Phase 3	Phase 2	Phase 3
93-94	1	15.9 ± 0.99***	1.9 ± 0.66**	6.6 ± 0.51***	-1.6 ±0.69*	9.3 ± 0.65***	3.5 ± 0.27***
	2	15.5 ± 0.99***	0.2 ± 0.35	5.9 ± 0.55***	-3.2 ± 0.39***	9.6 ± 0.64***	3.4 ± 0.18***
	3	13.8 ± 0.72***	1.2 ± 0.39**	5.2 ± 0.41***	-2.6 ± 0.39***	8.6 ± 0.42***	3.8 ± 0.17***
	4	13.3 ± 0.89***	0.7 ± 0.32*	4.8 ± 0.45***	-2.9 ± 0.35***	8.5 ± 0.52***	3.6 ± 0.16***
	5	14.8 ± 0.91***	1.5 ± 0.35***	5.9 ± 0.54***	-2.6 ± 0.39***	8.9 ± 0.51***	4.1 ± 0.16***
	6	13.7 ± 0.85***	0.5 ± 0.38	5.1 ± 0.51***	-2.7 ± 0.45***	8.6 ± 0.51***	3.2 ± 0.27***
	7	16.3 ± 0.89***	0.8 ± 0.39*	6.1 ± 0.43***	-2.9 ± 0.39***	10.2 ± 0.59***	3.7 ± 0.13***
	8	11.5 ± 0.82***	-0.1 ± 0.54	3.8 ± 0.66***	-3.3 ± 0.57***	7.7 ± 0.40***	3.1 ± 0.16***
94-95	1	19.0 ± 1.01***	-0.8 ± 0.67	6.1 ± 0.66***	-3.1 ± 0.63***	12.9 ± 0.56***	2.3 ± 0.41***
	2	20.3 ± 1.18***	-1.8 ± 0.81*	6.1 ± 0.60***	-2.8 ± 0.67***	14.2 ± 0.75***	1.0 ± 0.59
	3	19.7 ± 1.09***	-0.7 ± 0.70	6.6 ± 0.62***	-1.5 ± 0.71*	13.1 ± 0.57***	0.7 ± 0.39
	4	17.2 ± 0.97***	-0.3 ± 0.72	5.2 ± 0.57***	-1.6 ± 0.56**	12.0 ± 0.55***	1.3 ± 0.41**
	5	19.3 ± 1.10***	-0.7 ± 0.80	6.3 ± 0.69***	-3.5 ± 0.70***	13.4 ± 0.59***	2.8 ± 0.44***
	6	16.2 ± 1.10***	-0.4 ± 1.57	5.3 ± 0.72 ***	-1.3 ± 1.37	10.9 ± 0.55***	0.9 ± 0.55
	7	19.3 ± 1.26***	-0.8 ± 0.68	6.2 ± 0.56***	-3.3 ± 0.55***	13.1 ± 0.80***	2.5 ± 0.46***
	8	10.7 ± 2.09***	0.6 ± 2.64	3.9 ± 1.36***	-1.4 ± 2.24	7.8 ± 0.71***	2.1 ± 0.80*

[A] Water regime codes are explained in Table 1 [B] The actual numbers were multiplied by 10^3 to obtain the reported numbers

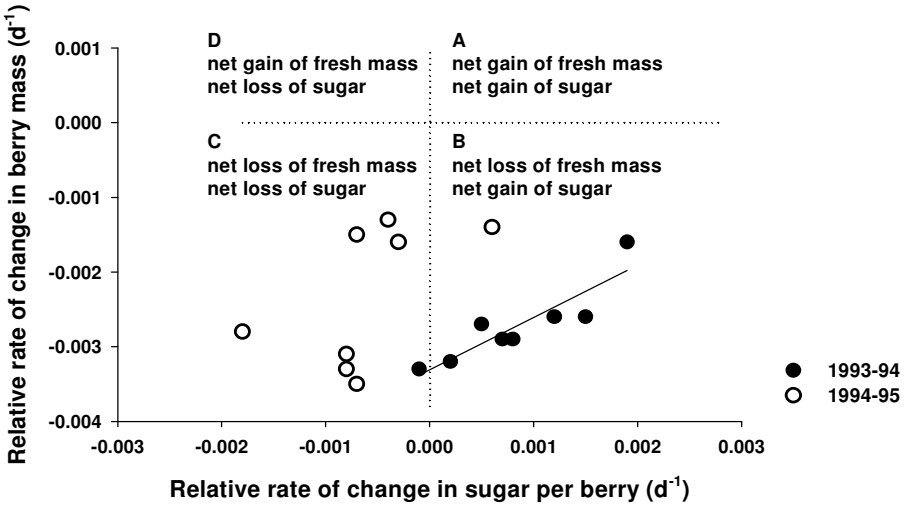


Figure 5. Relationship between the relative rates of change in berry size and sugar per berry in Phase 3 for two growing seasons. Dashed lines delimit four quadrants according to the sign of the rates. The solid line is a fitted linear regression (r^2=0.80, P = 0.003).

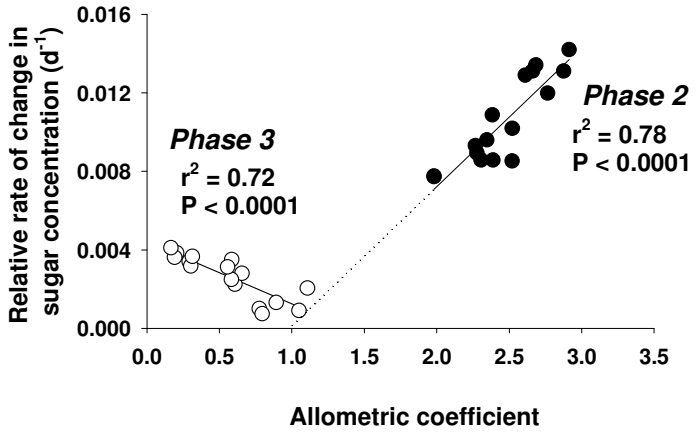


Figure 6. Relationship between relative rate of change in sugar concentration and the sugar-size allometric coefficient (dimensionless) for berries of *Vitis vinifera* cv Shiraz as affected by season and water regime. Solid lines are fitted regressions. The dashed line is a projection of the regression for Phase 2.

In Phase 2, the relative rate of increase in sugar per berry was highly significant in all cases (P < 0.001), and varied from 0.01 to 0.02 d^{-1} (Table 2). In comparison to berries from fully irrigated crops, the rate was considerably reduced in the rainfed treatment, with less evident effects of transient water deficits. In Phase 3, the relative rate of change in sugar per berry was very small compared to the rate in Phase 2, and not different from zero (P > 0.05) in most cases.

In Phase 2, the relative rate of increase in berry fresh mass was highly significant in all cases ($P < 0.001$), and varied from 0.0038 to 0.0066 d^{-1} (Table 2). These rates were 0.3-0.4 of the relative rates of sugar per berry, consistent with the condition for increasing sugar concentration, i.e. $R_{SB} > R_{FM}$ (Fig. 3a). The relative rate of change in berry fresh mass in the rainfed treatment was reduced by 40% in comparison to fully irrigated controls. In Phase 3, the relative rate of change in berry fresh mass was negative reflecting the net loss of berry material, and was on average 50% of the rate in Phase 2. In 1993-94, the relative rate of change in amount of sugar per berry was closely related to the relative rate of change in berry mass ($r^2 = 0.80$, $P = 0.003$), whereas these variables were unrelated in 1994-95 (Fig. 5).

In Phase 2, the relative rate of increase in sugar concentration was highly significant in all cases ($P < 0.001$), and varied from 0.008 to 0.014 d^{-1} (Table 2). In Phase 3, berries maintained a positive rate of change in sugar concentration, but the magnitude of this rate was 40% (1993-94) to 15% (1994-95) of that in Phase 2. The allometric coefficient accounted for 78% of the variation in the relative rate of change in sugar concentration in Phase 2, and 72% in Phase 3 (Fig. 6). For both phases, allometric coefficients close to 1, as shown from the projections of the regression lines, imply no net change in sugar concentration, as expected from the definition in eq. 1.

Discussion

Coleman *et al.* (1994) emphasised the importance of selecting appropriate scales for interpretation of environmental or genetic variation of single phenotypic traits, and more particularly for functionally related traits. A chronological scale, such as that illustrated in Figure 2, is the most widely used in the characterisation of accumulation of berry compounds including sugar, anthocyanins, and minerals (Esteban *et al.* 2001; McCarthy and Coombe 1999; Rogiers *et al.* 2006a; b). This is an appropriated scale for "real-time" management decisions, including the projection of harvest date based on a target sugar concentration. However, from a viewpoint of understanding the physiology of the ripening berry, comparisons on a common time scale can be misleading because substantial ontogenetic drift implies the actual effects investigated (i.e. season and water supply in our case study) are confounded with size-dependent effects. Explicit analysis of allometric relationships is required for the interpretation of both the changes occurring in each trait independently, i.e. sugar per berry and berry size, and the resulting sugar concentration.

To answer specific questions on the functionality of vascular connections and genetic control of sugar accumulation, we need appropriate conceptual models. Models of the type proposed by McCarthy and Coombe (1999) use a chronological scale to account for the dynamics of sugar accumulation in berries, and assumed a fixed time of peak berry mass around 91 days after flowering for cv Shiraz in the warm Riverland environment of South Australia (34° S, 140° W). Here we argue that, owing to ontogenetic drift, a growth-based scale is more appropriate for the interpretation of sugar concentration responses to genetic, environmental and management factors, and that timing of peak berry mass is more variable than previously suggested (Table 1). Indeed, a two-phase allometric model (Fig. 3)

accounted for over 70% of the variability in the rate of change in sugar concentration as driven by water regime and seasonal conditions (Fig. 6). In Phase 2, the relative rate of sugar accumulation in berries was 2.4 to 3.3 larger than the relative rate of change in berry size (Table 2), a necessary condition for the net increase in sugar concentration which was in turn captured in the allometric coefficients significantly greater than 1. In Phase 3, sugar concentration increased, albeit at a much smaller relative rate than in Phase 2, as a primary result of significant loss of materials from shrinking berries.

The actual mechanisms of berry shrinkage are still unresolved and may involve significant intraspecific variation; current hypotheses include water loss through transpiration and/or backflow from the berry to the parent vine via the xylem (McCarthy 1999; Rogiers *et al.* 2006b; Tyerman *et al.* 2004). Our allometric approach allows for further insight into the process of late ripening involving relative changes in berry fresh mass and sugars. The relationship between the relative rate of change in sugar per berry and the relative rate of change in berry fresh mass defines four quadrants (Fig. 5): A, where berries gain both fresh mass ($R_{FM} > 0$) and sugar ($R_{SB} > 0$); B, where berries lose mass ($R_{FM} < 0$) but gain sugar ($R_{SB} > 0$); C, where berries lose both fresh mass ($R_{FM} < 0$) and sugar ($R_{SB} < 0$); and D, where berries gain fresh mass ($R_{FM} > 0$) and lose sugar ($R_{SB} < 0$). From our definition of Phases 2 and 3 centred on peak berry mass, it follows that all data for Phase 3 will be located on quadrants B or C, corresponding to net loss of berry fresh mass. In both seasons, the rate of change in berry fresh mass spanned a similar range (Fig. 5). In contrast, the relative rate of change in sugar per berry showed a strong seasonal influence. In 1993-94, berries gained small amounts of sugars in Phase 3, whereas significant loss of sugars was detected in 1994-95. Another noticeable difference is the close correlation between the relative rates of change in fresh mass and sugar per berry in 1994-95 and the lack of correlation in 1993-94. The actual factors underlying these season-dependent responses are unknown, but we can speculate that differences in the severity of water deficit (Fig. 4b) might have been involved. Irrespective of the actual drivers of the seasonal differences, our analysis demonstrated that sugar accumulation during berry shrinkage is a plastic trait (Bradshaw 1965) under significant environmental influence. For the same genotype, environmental conditions could determine either, a putative backflow of water that could also carry some sugar from berries back to the parent vine (quadrant C response), or a small gain of sugar in parallel to a net loss of berry fresh mass (quadrant B response). Whereas the quadrant C response is consistent with the loss of phloem functionality, the quadrant B response, together with the close coupling of sugar gain and mass loss might indicate some degree of vascular functionality maintained during the shrinking stage of Shiraz berries.

Concluding remarks

Understanding the mechanisms of accumulation of key compounds in berries is a major goal in applied research in viticulture. Here we presented the case for allometric analysis of sugar concentration in berries of cv. Shiraz, and used a data set where seasonal conditions and water regime generated wide ranges of variation in sugar per berry, berry size and sugar concentration. We suggest this approach is a useful framework to investigate the genetic and environmental controls of accumulation of sugars and other compounds in grape berries. A model

that pivots around peak berry mass, with allometric coefficients above 1 in Phase 2 and below 1 in Phase 3, provides a sound approach to account for size-dependent effects on the dynamic of sugar concentration in Shiraz, and possibly other varieties where berries lose material at late stages of ripening. This model could be adapted to varieties with non-shrinking berries, where the existence of phases with distinct allometric coefficients might be driven, for instance, by changes in source : sink activity during ontogeny.

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Chapter 9

Quantifying phenotypic plasticity of berry traits using an allometric-type approach: a case study with anthocyanins and sugars in berries of Cabernet Sauvignon

VO Sadras, RM Stevens, JM Pech, EJ Taylor, PR Nicholas, MG McCarthy

Summary

Biologically, berry phenotypic traits such as content of sugars, acids, phenolics, anthocyanins and flavour compounds are the result of cultivar (G) and environmental influences (E), and often strong G x E interactions. In addition to the trait *per se*, we are interested in the relative stability of the trait, which largely determines the reliability of a cultivar-environment combination. In this paper we advance a novel allometric-type approach to quantify the stability of key berry traits.

To test the concept, we used data from Cabernet Sauvignon grown in a hot environment of South Australia. Sources of variation included water supply, fruit load, seasonal conditions and their interactions. Anthocyanins and soluble solids, a surrogate for sugars, were measured in berry samples taken 7-8 times between veraison and harvest. Rates and durations of accumulation of anthocyanins and sugars per berry were derived from a bi-linear model between amount of compound and thermal time.

We develop a framework based on α, the slope of the regression between rate and duration in a log-log scale, to account for three conditions (a) potentially plastic, rate-driven trait ($\alpha > -1$), (b) potentially plastic, duration-driven trait ($\alpha < -1$), and (c) stable trait, whereby variation in rate and variation in duration cancel each other ($\alpha = -1$).

Under our experimental conditions, amount of anthocyanins (range of variation 148 %) was more plastic than amount of sugars per berry (range of variation 37%). The slope α captured the differential plasticity of these traits: it was significantly greater than –1 for anthocyanins and statistically undistinguishable from –1 for sugars. The rate-dominated accumulation of anthocyanins explained the relatively large variation in this constituent whereas the tightly coupled, inverse relationship between duration and rate ($\alpha \approx -1$) explained the relative stability of sugars per berry. Rates of accumulation of anthocyanins and sugars were physiologically meaningful, i.e. they were inversely associated with sink-related variables, chiefly bunch weight, and relevant for wine properties, i.e. wine colour was correlated with the rate of accumulation of anthocyanins in fruit.

Introduction

The intense, almost black colour of the wine suggests the to the expert that the wine is "…obviously from a thick-skinned grape variety like the Syrah, which has ripened under a very hot sun…" (Stevenson 2005). The smell reinforces his initial

perception, it is definitely Syrah. After tasting, he concludes he is in the presence of a high quality Rhône Syrah, from a top grower in a great year (Stevenson 2005). This is a most graphic example of the connection between implicit berry properties, derived from a particular cultivar in a particular environment, and the final wine product.

Biologically, berry phenotypic traits such sugars, acids, phenolics, anthocyanins and flavour compounds, are the result of cultivar (G) and environmental influences (E), and often strong G x E interactions. To some extent, the reliability of a cultivar-environment combination depends on the stability of key phenotypic berry traits. Thus, in addition to the trait *per se*, we are interested in the relative stability of the trait. Bradshaw (1965) defines *phenotypic plasticity* as "the amount by which the expressions of individual characteristics of a genotype are changed by different environments", and *stability or homeostasis* as "the tendency for the characteristic of a physiological or morphological system to be held constant". This author pointed out that in the evolution of processes maximising fitness, different solutions maybe developed that involve a hierarchy of plasticities. The essential common feature of all such solutions is that some traits are, for various reasons, held constant, whereas others are highly plastic. Furthermore, it is important to recognise that the plasticity of a trait is itself a trait under specific genetic control, rather than the result of the basic pattern of its developmental pathway, and that plasticity also has some degree of specificity in relation to particular environmental influences (Bradshaw 1965; 2006; Pigliucci 2001).

The aim of this paper is to advance an allometric-type approach to quantify the phenotypic plasticity of key berry traits for particular cultivar-environment combinations. In the case study of this paper, we investigated the degree of phenotypic stability of anthocyanins and sugars in berries of Cabernet Sauvignon grown in a relatively hot environment. In this way, our conclusions would be cultivar-environment specific (Bradshaw 1965; 2006; Pigliucci 2001) but we suggest the method could be applied to other combinations of cultivars and environments. Anthocyanins and sugars were considered on the grounds of both, their responsiveness to major environmental and viticultural drivers (seasonal conditions, water supply, fruit load) and their importance for wine properties.

Conceptual framework

If we express a certain maximum amount A, e.g. sugar per berry, in terms of rate and duration of accumulation (Fig. 1a):

$$A = \text{rate} \times \text{duration} \qquad \text{eq. (1a)}$$

it follows that:

$$\log \text{duration} = \log A - \log \text{rate} \qquad \text{eq. (1b)}$$

Implicit in equation 1b is a slope $\alpha = -1$, a condition that has been used to characterise the trade-off between seed size and number (Henery and Westoby 2001; Turnbull *et al.* 1999). Here we propose a quantitative framework based on α to account for three conditions (Figure 1b):

(a) $\alpha > -1$ is necessary for plastic, rate-driven traits,

(b) $\alpha < -1$ is necessary for plastic, duration-driven traits,
(c) $\alpha = -1$ is necessary and sufficient for stable traits, whereby variation in rate and variation in duration cancel each other.

The reasons why $\alpha = -1$ is necessary and sufficient for stability, whereas $\alpha \neq -1$ is a necessary but no sufficient condition for plasticity will be expanded in Discussion. There are cases where $\alpha > 0$, for instance rate and duration of seed filling both increasing in response to increasing source:sink ratios, but the most common condition is of $\alpha \leq 0$ (Sadras and Egli, unpublished).

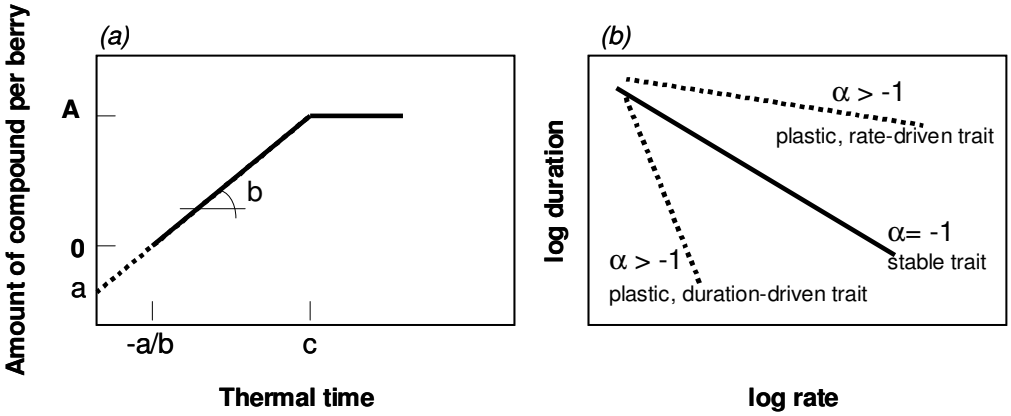


Figure 1. Schematic representation of *(a)* time-trajectory of compound accumulation in berries, and *(b)* allometric-type relationship between duration and rate of accumulation. In *(a)*, parameters derived from the fitted model are *a* (intercept), *b* (slope), and *c* (time to maximum amount of compound). The ratio *–a/b* indicates onset of accumulation, and time between *c* and *–a/b* is the duration of the accumulation period.

Methods

Site and Crop

The trial was established in a vineyard in the Riverland region near Loxton (34 °S, 140 °E) in South Australia. The climate is Mediterranean-like, with mild winter, hot summer and winter-dominant rainfall (Gladstones 2004). The soil is a centeric, rendic, supracalcic calcarsosol (Isbell 1996). Own rooted vines (*V. vinifera* Cabernet Sauvignon) were planted in 1996 in a 2.7 x 1.8m arrangement. The vines were trained on a two-wire vertical trellis with the top wire at 1.6 m, and the replacement canes were mechanically pruned to 10 cm from the cordon.

Sources of variation

Five treatments were established that comprised a combination of water supply during ripening and fruit removal at veraison (Table 1). Our aim was to generate contrasting growing conditions and a wide range of rates and durations of sugar and anthocyanin accumulation, rather than specifically investigate the effects of individual sources of variation, i.e. treatments and seasonal conditions. Treatments were arranged in a randomised block design with six replicates.

Table 1. Summary of treatments established on *Vitis vinifera*, cv Cabernet Sauvignon during three seasons at Loxton, South Australia.

Treatment	Irrigation[a]	Thinning[b]
T1	0.40	30
T2	0.40	0
T3	1.20	30
T4	1.00	0
T5	1.50	0

[a] Fraction of the irrigation used as standard practice during the period between veraison and harvest (T4), which was 1.6 ML ha^{-1} in 2003-04, 2.1 ML ha^{-1} in 2004-05, and 2.2 ML ha^{-1} in 2005-06. Irrigation in the reference treatment (T4) was scheduled using a combination of visual assessment, weather forecasts, monitoring soil water content.
[b] Percentage of fruit bunches randomly removed at veraison

Response variables

In all three seasons, phenological development was characterised from weekly observations using the modified Eichhorn-Lorenz scale (Coombe 1995). Anthocyanins and sugars were measured in 100-berry samples taken 7-8 times between veraison and harvest maturity. We used the method described in Iland et al. (2000) to measure anthocyanins in homogenates (15 s at 10 000 rpm, Gridomix Blender, Retsch, Germany) from fresh berries in 2005 and 2006, and from frozen (-20 ^{o}C) samples in 2004. Juice from crushed samples was analysed for soluble solids with a digital refractometer (Atago RX-5000, Tokyo, Japan) kept at 20 ^{o}C with a circulating water bath. For consistency, both anthocyanins and soluble solids were expressed in units of weight per berry. At maturity, we measured the number of bunches per vine and total yield per vine from which average bunch weight was derived and the number of berries per bunch calculated using average berry weight from 100-berry samples.

In two seasons, 2003-04 and 2004-05, we measured secondary variables related to (i) vegetative growth, including number of buds retained at pruning, number of shoots and calculated percent bud burst, and (ii) wine colour density based on the sum of absorbances at 520 and 420 nm (Iland *et al.* 2000). Wine was made by Provisor® with 50 kg of fruit from each replicate using the technique described by Antcliff and Kerridge (1975). These sets of variables were used to explore the physiological causes and wine-related consequences of variable rates and durations of accumulation of sugars and anthocyanins.

Data analysis

A bi-linear model (Echarte *et al.* 2006; Gambin *et al.* 2007; Rondanini *et al.* 2003; Ruiz and Maddonni 2006) was used to describe the time-trajectory of amount of sugars and anthocyanins per berry (Fig. 1a):

$R = a + b\,TT_{fb}$ if $TT_{fb} \leq c$ eq. 2a
$R = a + b \times c$ if $TT_{fb} > c$ eq. 2b

where R is the response variable (amount of sugars or anthocyanins per berry), TT_{fb} is thermal time from full bloom, *a* is the intercept, *b* is the slope, and *c* is the thermal time to maximum R. The ratio *–a/b* estimates the start of the linear phase and *c + a/b* estimates the duration of the linear phase (Johnson and Tanner 1972). The maximum of the response variables was calculated. Thermal time calculation used a base temperature of 10 °C (Gutierrez *et al.* 1985).

Regression analysis was used to explore the relationships between rates and durations of sugar and anthocyanin accumulation, and putative drivers including yield components, secondary response variables (see above), and variables derived from their combination, e.g. berry number/shoot number.

Results

Seasonal conditions and phenology

On average, temperature and reference evapotranspiration during the period of rapid accumulation of anthocyanins and soluble solids were lowest in 2004-05 and highest in 2005-06 (Figure 2). Whereas on average 2003-04 was intermediate, there was a week-long heat wave shortly after veraison, with a peak maximum temperature of 45.5 °C, and a peak minimum temperature of 26.1 °C (Figure 2).

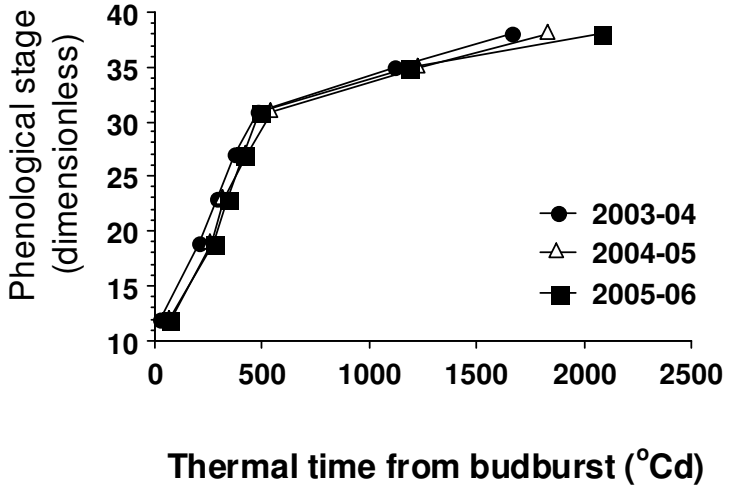


Figure 2. Temperature, solar radiation and reference evapotranspiration (ETo) during the period of active accumulation of sugar and anthocyanin in grapevine berries during three seasons at Loxton, South Australia. Arrowheads indicate veraison. Data from the Australian Bureau of Meteorology.

There was no significant seasonal effect ($P > 0.05$) on the rate of phenological development between E-L stages 12 (10 cm shoot) and 31 (pea size). The rate of development between stages 31 and 38 (harvest) ranked 2003-04 ≥ 2004-05 > 2005-06 (Figure 3).

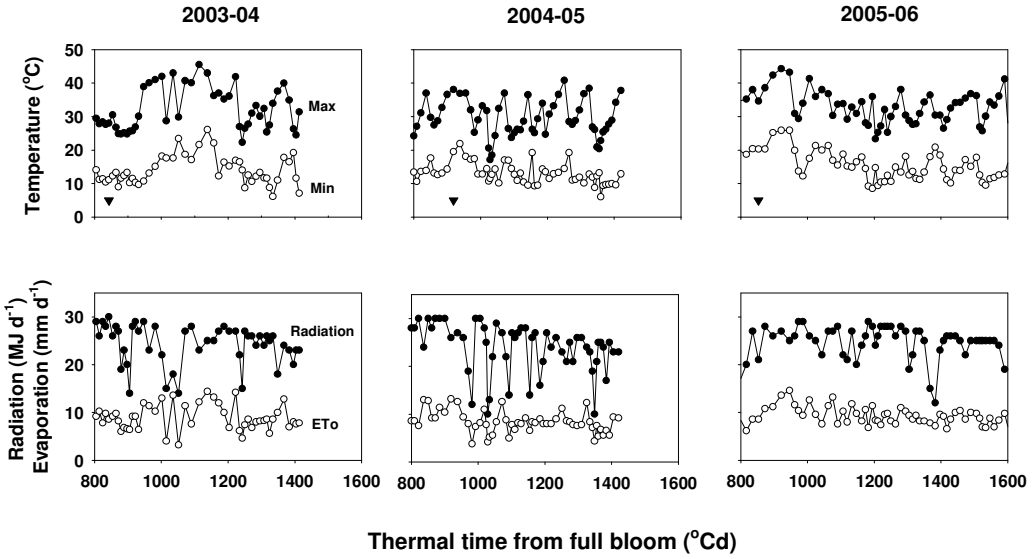


Figure 3. Phenological development of grapevine cv Cabernet Sauvignon during three seasons at Loxton, South Australia. The rate of development between stages 12 (10-cm shoot) and 31 (berry pea size) for the pooled seasons was 0.042 $(^{o}Cd)^{-1}$ (s.e. = 0.0022). The rate between stages 31 and 38 (harvest) was 0.0059 $(^{o}Cd)^{-1}$ (s.e. = 0.00021) in 2003-04, 0.0054 $(^{o}Cd)^{-1}$ (s.e. = 0.00025) in 2004-05 and 0.0044 $(^{o}Cd)^{-1}$ (s.e. = 0.00067) in 2005-06.

Dynamics of accumulation of anthocyanins and soluble solids

Figure 4 and Table 1 summarise the dynamics of accumulation of anthocyanins and soluble solids, which are mostly hexose sugars (Coombe and Iland 2004). In all cases, a bi-linear model provided a statistically sound description of the data ($0.98 \geq R^2 \geq 0.51$). The onset of sugar accumulation varied markedly with both season and treatments; it ranged from 284 to 693 ^{o}Cd from full bloom, or 144%. In contrast, the onset of anthocyanins accumulation was more stable; it ranged from 560 to 781 ^{o}Cd from full bloom, or 38%.

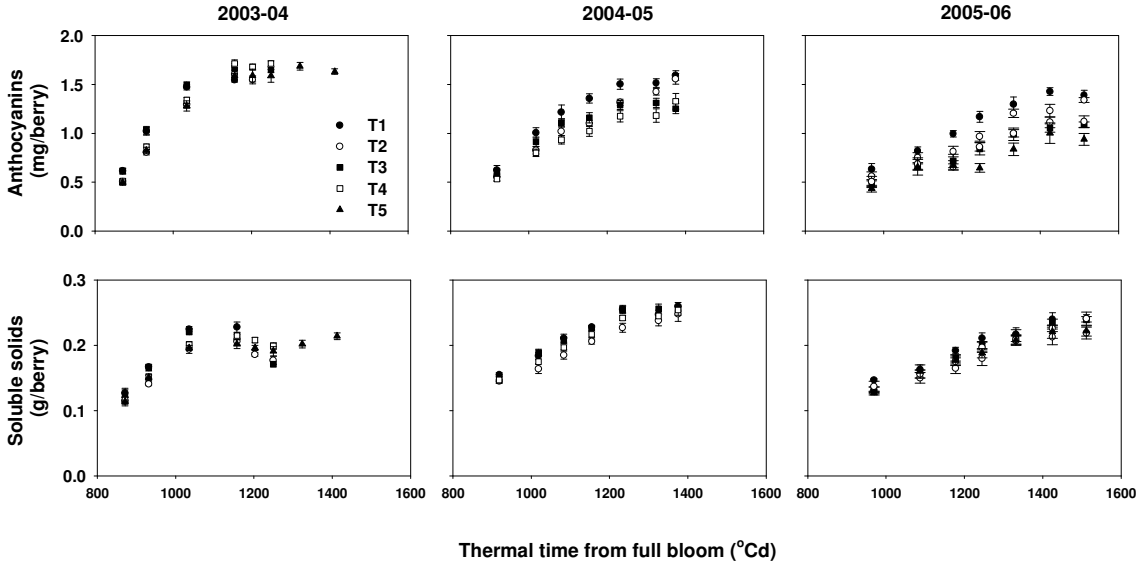


Figure 4. Accumulation of anthocyanins and soluble solids in berries of grapevine cv Cabernet Sauvignon during three seasons at Loxton, South Australia. Symbols are treatments (Table 1), and error bars are two standard errors of the mean.

Plasticity of sugars and anthocyanins in the light of rate-duration relationships

Under our experimental conditions, amount of anthocyanins (range of variation 148 %) was more plastic than amount of sugars per berry (range of variation 37%). The differential plasticity of these traits can be explained in terms of the interplay between rates and durations. Variation in the rate of accumulation of anthocyanins (6.3-fold) was much larger than the variation in duration (3.9-fold) (Figure 5a). In contrast, variation in the rate of accumulation of soluble solids (3.6-fold) was commensurate with the variation in duration (3.9-fold) (Figure 5b). Regressions of log-transformed variables yielded a slope significantly greater than –1 for anthocyanins ($P < 0.05$) and a slope statistically undistinguishable from –1 for soluble solids ($P > 0.05$) (insets in Figure 5).

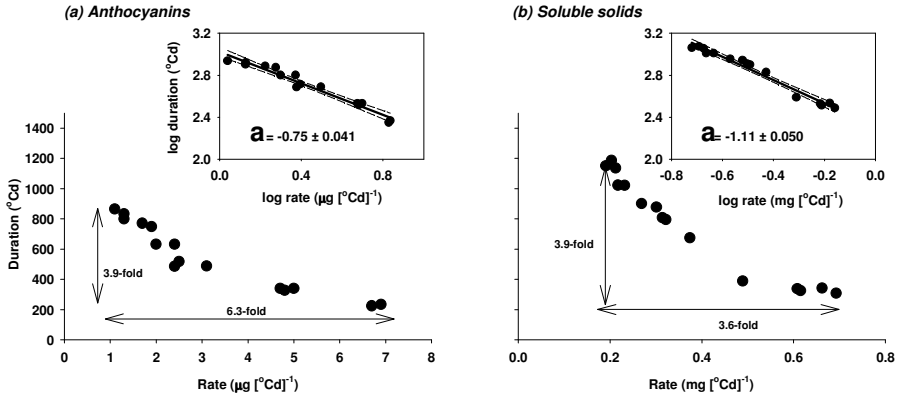


Figure 5. Relationship between duration and rate of accumulation of *(a)* anthocyanins and *(b)* soluble solids in berries of grapevine cv Cabernet Sauvignon. Arrows show ranges. Insets show the relationship between duration and rate using log-transformed variables, with regression lines and their 95% confidence intervals.

Rates were inversely related to yield and its components, particularly bunch weight and berries per bunch (Table 3). Secondary variables such as shoot number did not improve the correlations (not shown).

Table 3. Correlation coefficients of the regressions between rate of anthocyanin and solid sugar accumulation and sink (yield) related variables

Independent variable (range)	Dependent variable	
	Rate of accumulation of anthocyanin	Rate of accumulation of soluble solids
Bunch weight (29-69 g)	-0.90***	-0.79***
Berries per bunch (40-75)	-0.74**	-0.65**
Berry weight (0.7-1.1 g)	-0.70**	-0.62*
Yield (10.8-30.2 t ha^{-1})	-0.64*	-0.52*
Bunches per vine (158-289)	NS	NS

NS, $P > 0.10$; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.00$

Relationships between sugars and anthocyanins

The allometric relationship between anthocyanins and sugars during the lineal phase of accumulation yielded a slope of 1.32 ± 0.094 for the pooled data set (Figure 6a). This is indicative of significantly greater relative rate of anthocyanin accumulation compared to sugars. However, there was an apparent effect of water regime, which was quantitatively captured by the allometric slope, declining from about 1.5 in the crops with more restricted water supply, to approximately 1 in the

crops with ample water supply (Figure 6b). Water deficit therefore substantially increased the relative rate of anthocyanin accumulation in relation to sugars.

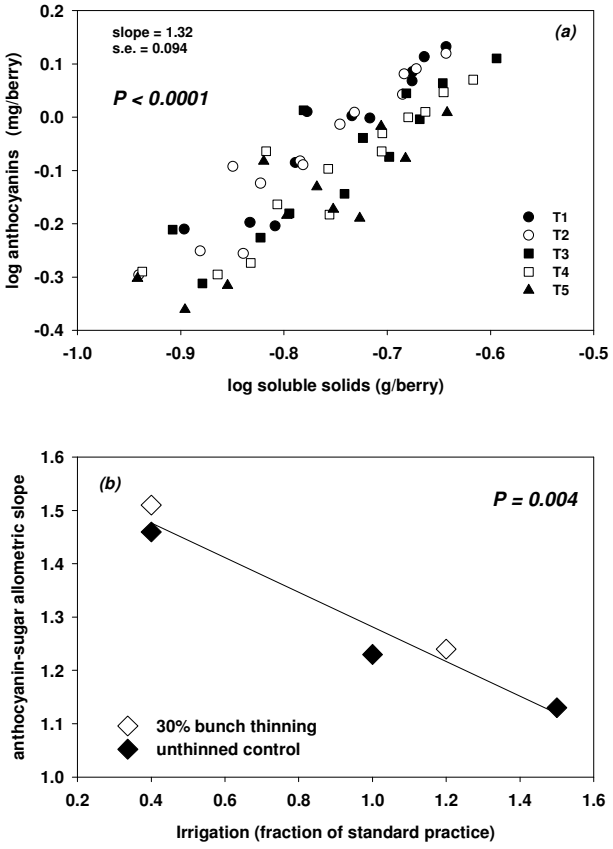


Figure 6. *(a)* Relationship between amount of sugars and amount of anthocyanins during the linear phase of accumulation in berries from crops under five treatments and three growing seasons. *(b)* Relationship between the slope of the regression in *(a)* for the data pooled across seasons, and irrigation regime.

Wine colour density

The rate of anthocyanin accumulation in berries accounted for 63% of the variation in wine colour density at bottling, and the association between rate of anthocyanin accumulation in berries and wine colour persisted 10 months after bottling (Figure 7).

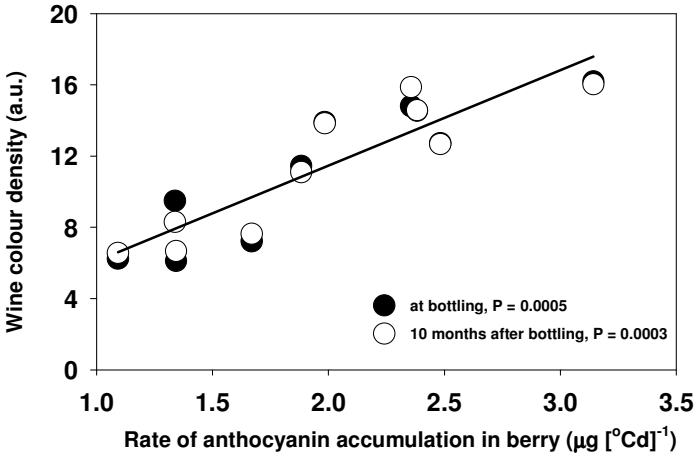


Figure 7. Association between rate of accumulation of anthocyanin in berries and wine colour density at bottling and 10 months after bottling. Regressions for wine colour at bottling and for wine colour 10 months after bottling were statistically indistinguishable ($P < 0.05$). The line is the regression for the pooled data.

Discussion

Trait plasticity and allometry of rate and duration of physiological processes

Negative associations between rate and duration of physiological processes are common (Table 4). However, the actual degree of compensation, i.e. to what extent the increase or decrease in duration compensates for the reduction or increase in rate, needs explicit consideration. Here we propose that the conceptual relationship in eq. 1b, which was previously applied to the trade-off between seed size and number (Henery and Westoby 2001; Turnbull *et al.* 1999), could help to develop a more rigorous definition of the relationship between rate and duration. We cannot discount that the negative association between duration and rate is partially an artefact of calculations, as duration is an inverse function of rate by definition (Methods). Duration calculated with this method, however, can be unrelated or positively related with rate (Borrás and Otegui 2001; Panozzo and Eagles 1999; Rondanini *et al.* 2003; Shrestha *et al.* 2005). More importantly for our analysis, the actual slope of the log-log relationship between duration and rate is not trivial; Table 4 illustrates three types of negative associations between duration and rates, where slopes are indicative of either, processes where rate and duration cancel

each other, or processes where rate or duration dominate the trait. The actual relationship, or lack of it, is expected to depend on the physiological processes involved and on the drivers - their nature, range and interactions.

An important feature of the allometric model in Figure 1b is that $\alpha = -1$ is necessary and sufficient for trait stability: irrespective of the actual magnitudes of rate and duration, these variables cancel each other, and the variation of the trait is small. In contrast, $\alpha \neq -1$ is necessary but not sufficient for plasticity. For example, we used maize data from Echarte et al. (2006) and sunflower data from López Pereira et al. (1999) to derive α for seed size. The $\alpha = -0.16 \pm 0.066$ for sunflower was statistically close to the $\alpha = -0.30 \pm 0.127$ for maize. The variation in seed size range was, however, 183% for sunflower and 28% for maize. This difference was accounted for by the range of variation in rate of grain filling, i.e., 250% in sunflower and 30% in maize. Thus, there is a single condition for stability, namely $\alpha = -1$, and a double condition for plasticity: $\alpha \neq -1$ and variable rate or duration.

Implications for viticulture

Current understanding of grapevine biology in the relatively hot Riverland environment of this study indicates red fruit varieties including Cabernet Sauvignon usually achieve sugar concentrations suitable for quality winemaking, but often fail to colour appropriately (Iland and Gago 2002). The relative stability of sugars in comparison to the plasticity of anthocyanins is partially related to the relative ranges of temperature for optimum activity of sugars (18 to 33 ^{o}C) and pigment producing enzymes (17 to 26 ^{o}C) (Iland and Gago 2002). Our analysis is consistent with this, and allows for deeper understanding: a tightly balanced, negative relationship between rate and duration was behind the accumulation of sugars, whereas accumulation of anthocyanins was rate-driven, with little buffering from changes in duration. Thus, where external drivers including water supply, fruit load and their interactions with seasonal conditions have slowed down sugar accumulation (e.g. season 2005-06 vs 2003-04, or treatment T5 vs T1 in 2005-06), the longer duration of this period led to little variation in maximum amount of sugars in berries (Figure 4, Table 2). In contrast, changes in rate only partially counteracted by changes in duration accounted for the contrasting final amount of berry anthocyanins as affected by season, treatment and their interactions (e.g. T5 vs T1 in 2005-06). Care should be taken in extrapolating the results from these experiments to other varieties and environments. In cooler regions, berries may colour well but sometimes do not reach appropriate amounts of sugars (Iland and Gago 2002). This pattern, which is the opposite of the one we found with Cabernet Sauvignon in the Riverland, might indicate a closer trade-off between rate and duration of anthocyanins accumulation and a rate- or duration-dominated accumulation of sugars. In any case, once the patterns have been established, further insight can be gained by focusing on key aspects of compound accumulation, such as rate-modifiers for anthocyanin accumulation in the Riverland.

Table 4. Examples of negative associations between rate and duration of growth and accumulation processes in plant organs; □ is the slope of the regression between rate and duration in a log-log scale (Figure 1b).

α	Meaning	Variable (Species)	Estimated α	Source of variation	Reference
> -1	Potentially plastic trait subject to rate-dominated variation	Anthocyanin in berries (*Vitis vinifera)*	-0.75	season, water supply, fruit load	This study
		Grain weight (*Zea mays)*	-0.30	genotype, season	Echarte et al. (2006)
		Grain weight (*Triticum aestivum)*	-0.32	CO_2, water, ear position	Li et al. (2000)
		Grain weight (*T. aestivum)*	-0.32	Cultivar, season	Motzo et al. (1996)
		Grain weight (*Sorghum bicolour)*	-0.67	hybrid, panicle position	Gambin and Borrás (2005)
		Grain weight (*Glycine max)*	-0.73	cultivar, radiation	Egli (1999)
		Leaf area (*Helianthus annuus)*	-0.23	nitrogen supply	Steer and Hocking (1983)
≈ -1	Stable trait. Increasing/decreasing rate is perfectly compensated by decreasing/increasing duration	Sugar in berries (*V. vinifera)*	-1.11	season, water supply, fruit load	This study
		Grain weight (*S. bicolour)*	-1.01	sowing date (temperature)	Muchow (1990)
		Spikelet number (*T. aestivum)*	-1.03	temperature, photoperiod, cultivar	Rahman and Wilson (1978)
< -1	Potentially plastic trait subject to duration-dominated variation	Coleoptile length (*T. aestivum*)	-1.33	temperature	Botwright et al. (2001)

Table 2. Parameters ± standard errors of a bi-linear model (eq. 2) of the dynamics of accumulation of anthocyanins and soluble solids in berries of grapevine cv Cabernet Sauvignon at Loxton, South Australia. Duration of the linear phase of accumulation and maximum are derived parameters.

Variable	Season	Treat.	Parameter			Duration	Maximum
			a	*b*	*c*		
Anthocyanins			(mg/berry)	(µg/berry.°Cd)	(°Cd)	(°Cd)	(mg berry^{-1})
	2003-04	1	-5.25 ± 0.656	6.7 ± 0.73	1004 ± 12.0	224	1.51
		2	-3.68 ± 0.220	4.8 ± 0.23	1093 ± 8.9	328	1.58
		3	-5.36 ± 0.944	6.9 ± 1.05	1015 ± 18.3	233	1.60
		4	-3.83 ± 0.241	5.0 ± 0.25	1105 ± 9.4	340	1.70
		5	-3.62 ± 0.390	4.7 ± 0.41	1103 ± 15.6	341	1.62
	2004-05	1	-2.23 ± 0.318	3.1 ± 0.30	1198 ± 19.7	489	1.54
		2	-1.59 ± 0.187	2.4 ± 0.17	1305 ± 22.1	633	1.49
		3	-1.65 ± 0.288	2.5 ± 0.28	1181 ± 21.2	517	1.28
		4	-1.25 ± 0.248	2.0 ± 0.23	1264 ± 31.3	632	1.25
		5	-1.69 ± 0.298	2.4 ± 0.28	1193 ± 23.8	485	1.16
	2005-06	1	-1.20 ± 0.209	1.9 ± 0.18	1388 ± 30.9	748	1.41
		2	-1.08 ± 0.205	1.7 ± 0.18	1417 ± 38.2	770	1.29
		3	-0.82 ± 0.201	1.3 ± 0.17	1410 ± 43.8	800	1.07
		4	-0.82 ± 0.169	1.3 ± 0.14	1441 ± 48.0	833	1.12
		5	-0.61 ± 0.220	1.1 ± 0.18	1425 ± 75.2	865	0.95
Soluble solids			(g/berry)	(mg/berry.°Cd)	(°Cd)	(°Cd)	(g berry^{-1})
	2003-04	1	-0.45 ± 0.129	0.66 ± 0.143	1022 ± 27.6	342	0.23
		2	-0.31 ± 0.121	0.49 ± 0.134	1027 ± 36.1	388	0.19
		3	-0.48 ± 0.140	0.69 ± 0.155	1000 ± 24.1	308	0.21
		4	-0.41 ± 0.097	0.61 ± 0.108	1019 ± 21.9	338	0.21
		5	-0.42 ± 0.127	0.61 ± 0.141	1011 ± 26.3	325	0.20
	2004-05	1	-0.13 ± 0.032	0.31 ± 0.30	1233 ± 22.1	808	0.25
		2	-0.11 ± 0.031	0.27 ± 0.029	1294 ± 31.1	901	0.24
		3	-0.14 ± 0.023	0.32 ± 0.021	1239 ± 16.7	796	0.26
		4	-0.13 ± 0.021	0.30 ± 0.019	1310 ± 38.3	877	0.26
		5	-0.21 ± 0.033	0.37 ± 0.031	1226 ± 19.0	674	0.25
	2005-06	1	-0.06 ± 0.029	0.21 ± 0.025	1419 ± 41.4	1135	0.24
		2	-0.06 ± 0.027	0.19 ± 0.022	1441 ± 56.0	1150	0.22
		3	-0.09 ± 0.021	0.23 ± 0.018	1418 ± 27.3	1022	0.24
		4	-0.06 ± 0.023	0.20 ± 0.019	1489 ± 46.0	1186	0.24
		5	-0.08 ± 0.031	0.22 ± 0.026	1392 ± 39.7	1023	0.22

The onset and finish of accumulation of sugars and anthocyanins deserve more detailed research. For the onset, we found a contrasting variability in response to season and treatments, i.e. high for sugars, smaller for anthocyanins, and no consistent effect of treatments, whereas Petrie and Clingeleffer (2006) showed fruit removal markedly advanced the onset of both sugars and anthocyanins accumulation in grapevine berries. Accumulation of sugars and anthocyanins reached a plateau between 84 and 112 days or 1000 to 1400 °Cd from full bloom, depending on growing conditions. In annual crops, the timing of maximum

accumulation of grain dry matter is tightly linked with the dynamics of grain dehydration (Gambin and Borrás 2005; Schnyder and Baum 1992) whereas preliminary evidence indicates a similarly important link between accumulation of soluble solids and water dynamics in berries of grapevine (McCarthy and Coombe 1999).

The significant correlation between rate of anthocyanin accumulation and wine colour density reinforces the notion that, under the conditions of our experiment, anthocyanin accumulation in fruit was rate-driven, and highlights the relevance of this rate beyond fruit composition into relevant wine properties. Likewise, the inverse associations between rates of sugar and anthocyanin accumulation and yield components support the idea that sink strength (Chamont 1993) played a major role in the dynamics of accumulation of these compounds (Table 3). Negative associations have been found between properties such as pigment or sugar contents in berry, and various measures of plant vigour and crop yield in grapevine (e.g. Cortell *et al.* 2005) and other species such as black chokeberry (*Aronia melanocarpa*) (Jeppsson 2000). These relationships are, however, far from consistent (Coombe and Iland 2004). Disentangling the putative effects of sources and sinks on accumulation of key products requires a stronger focus on physiological processes, and here again rates and durations could be useful. It is interesting to note that the relationships between rate of accumulation of sugars and anthocyanins and yield were weak in comparison to the relationships with berries per bunch and bunch weight. This may be reflecting aspects of plant modularity, i.e. phyllotaxis and source : sink distance affecting allocation of carbohydrates (Hardwick 1986; Kaitaniemi and Honkanen 1996; Lebon *et al.* 2004; Mutsaers 1984; Room *et al.* 1994; Sadras 1995) and degree of synchrony of fruit development and growth (Bangerth 1989; Bassetti and Westgate 1994; Cárcova and Otegui 2001; Cárcova *et al.* 2000).

The differential accumulation of different solutes in the skin and flesh of the ripening berry is well established (Coombe and Iland 2004). The preferential accumulation of certain products, e.g. sugars in the flesh, pigments in the skin, has been related to distinct roles of these berry components, i.e. storage for the flesh and protection for the skin (Coombe and Iland 2004). Allometric considerations, including the influence of berry geometry on the accumulation of compounds in different berry compartments, has attracted less attention. Lets consider (a) a spherical berry where the thickness of the skin is negligible with respect to the radius *r*, (b) that sugar accumulation depends on the volume of flesh, i.e. it is proportional to r^3, whereas (c) accumulation of anthocyanins depends on skin surface area, i.e. it is proportional to r^2. If these assumptions are valid, particularly b and c, then we could expect that the accumulation of anthocyanins and sugars in berries conform to a ⅔ power law. Niklas (1994) discusses in detail the ⅔ power law, and its interpretation in terms of geometry and shape of organs and organisms. Here we found that anthocyanin and sugar accumulation conform to a power law, i.e. the relationship in a log-log scale is linear, but the coefficient for the pooled data is well above ⅔, the value expected from geometry and shape considerations alone (Figure 6a). Interestingly, the allometric slope relating anthocyanins and sugars had a very strong and consistent response to water supply (Figure 6b), highlighting the likely role of a metabolic control of the relationship that overrides any putative effect of geometry and shape.

Concluding remarks

We showed that an allometric-type model relating rates and durations (eq. 1b) could add substantial depth to the quantitative analysis of plasticity of berry traits. The concept was developed and tested for sugars and anthocyanins in Cabernet Sauvignon grown in a warm environment, and we illustrated the insight that can be gained by defining rate-dominated, duration-dominated, or balanced responses of key traits. Under the cultivar-environment combination of this study, sugars were fairly stable in contrast to the rate-driven plasticity of anthocyanins. The principles could be extended and adapted to other compounds, cultivars and environments, and in general to other processes susceptible to be analysed in terms of rate and duration, such as leaf or seed growth.

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Chapter 10

Modelling variety-dependent dynamics of soluble solids and water in berries of *Vitis vinifera*

VO Sadras, MJ Collins and CJ Soar

Summary

We modelled the dynamics of soluble solids, largely sugars, and water in twelve *Vitis vinifera* varieties. Emphasis was placed on maximum concentration of soluble solids (S_{max}) and time of maturity for their viticultural importance.

We measured the concentration of soluble solids and water at weekly intervals during berry ripening. The dynamics of concentration of soluble solids was characterised with a sigmoid model, whereas water concentration was characterised with a concentration-response type curve. Scaling exponents for soluble solids (α_s) and water (α_w) were calculated as the slope of the log-log regression between amount of soluble solids or water per berry and berry fresh mass. S_{max} ranged from 27.1% in Shiraz to 21.2% in Riesling, was associated with both α_w and α_s, and was largely unrelated to source size (leaf area, pruning weight, light interception), source activity (stomatal conductance), sink size (yield components) and source: sink ratios. The time of maturity ranged from 26th January in Verdelho to 27th February in Crimson Seedless, and was an inverse function of the rate of change in concentration of soluble solids, which was in turn a direct function of stomatal conductance.

Traits related to carbon assimilation influenced time of maturity, but their link with maximum concentration of soluble solids in berries was not evident. Quantitative models of accumulation of soluble solids are presented that provide a baseline for comparisons among varieties.

Introduction

Sugar concentration of grapevine berries is a major criterion for crop management and winemaking decisions, including harvesting time. Variety, environmental conditions and their interaction influence the timing of harvest maturity, as determined by concentration of both sugar and quality-related flavour and colour compounds (e.g. Gomez-Miguez et al. 2007, Vian et al. 2006). Recent warming trends have advanced the time of maturity of Shiraz, Cabernet Sauvignon and Chardonnay in Australia, and indirect evidence indicates some decoupling between accumulation of sugars and secondary compounds in ripening berries (Godden and Gishen 2005, Petrie and Sadras 2008). Consistent with these maturity trends, trends for high alcohol content in Australian wines during the last two decades are evident for red but not for white varieties (Godden and Gishen 2005). These trends have multiple drivers, including variety dependent differences in sugar accumulation, which are only partially known.

In grain crops, physiological maturity (i.e. maximum grain dry weight) is closely linked to the dynamics of water (Rondanini et al. 2007 and literature cited therein). In comparison to grain crops, the links between maturity, soluble solids and water dynamics in berries of grapevine have received less attention (e.g. Ristic and Iland 2005). The allometric condition for increasing concentration of soluble solids is that the scaling exponent for soluble solids α_s, i.e. the slope of the regression between amount of soluble solids per berry and berry fresh mass in a log-log scale, is greater than 1 (Sadras and McCarthy 2007). The condition for decreasing water concentration is that the scaling exponent for water α_w, i.e. the slope of the regression between amount of water per berry and berry fresh mass in a log-log scale, is lower than 1. Whereas the allometric conditions for increasing concentration of soluble solids and decreasing water concentration follow from the definitions, i.e. the scaling exponent is the ratio of the relative rate of accumulation of soluble solids or water and the relative rate of berry growth (Niklas 1994, Pearsall 1927), the magnitude of the scaling exponents depends on environmental factors (Sadras and McCarthy 2007, Sadras et al. 2007) and may also differ with variety-dependent traits.

This study presents a quantitative comparison of the dynamics of soluble solids and water in berries of wine and table grape varieties. The primary focus is maximum concentration of soluble solids and the timing of maturity for their implications for vineyard management and winemaking. An allometric approach is used to account for size-dependent changes in soluble solids and water in berries.

Materials and methods

Site and crops

The vines were established on a red brown earth (Northcote 1979) at the South Australian Research and Development Institute, Nuriootpa (34 ^{o}S, 139 ^{o}E) in the Barossa Valley of South Australia. Climate, soils and viticultural practices of the region have been described elsewhere (Dry and Coombe 2004, Gladstones 1992). Varieties were at least 9 years old at the time of the experiment (Table). Unlike management in commercial vineyards that accounts for specific varietal requirements, the experimental blocks under study were managed similarly. Vines are own-rooted and cordon-trained to a single-wire trellis and have been consistently spur pruned since establishment. Each variety comprises a single row with at least 37 vines. The vines are arranged with a row by vine spacing of 3.50 m by 2.25m and have been managed with supplementary irrigation (single 4 l h^{-1} drippers per vine) since establishment.

Berry sampling and analysis

Berries were sampled weekly, between 8:00 and 11:00 a.m., by cutting with scissors through the pedicel as close as possible to their point of attachment. Samples were taken from a minimum of 10 consecutive vines within each varietal row. Three berries were sampled per bunch selecting one each from the bottom, middle and top of each bunch. No more than 5 bunches were sampled per vine. Depending on berry size, each sample comprised 50 (Grenache and table varieties) or 70 (other varieties) berries. Berries were collected into polyethylene

bags, placed immediately into a container cooled with ice in the field, and stored at -20 ºC in the laboratory prior to analysis.

Water concentration was derived from fresh weight and dry weight determined in sub-samples dried at 60 ºC to constant weight. A second sub-sample was thawed in the same plastic bag used for sampling, and crushed between the palm of the hand and a bench top using consistent light pressure. The free-run juice was decanted into a 50 ml centrifuge tube and spun at 2000 x g for ten minutes. Total soluble solids, largely sugars (Coombe and Iland 2004) were measured on the clarified juice sample using a RFM710 digital refractometer (Bellingham and Stanley Ltd, Kent, U.K.).

Modelling the dynamics of soluble solids and water

The dynamics of concentration of soluble solids *(S)* w characterised with a sigmoid model, i.e. a transition function with symmetry about a transition centre in both the x and y dimensions:

$$S = \frac{S_{\max}}{1 + e^{\left[-\frac{x - x_0}{b}\right]}} \qquad \text{eq. 1}$$

where x is time, S_{max} is the transition height, representing maximum concentration, x_0 is the transition centre, i.e. the time when concentration is half the maximum, and b= transition width * 2.197^{-1}(SYSTAT 2002). The transition width is the time (days) it takes for concentration of soluble solids to raise from 0.25 S_{max} to 0.75 S_{max} (SYSTAT 2002). The ratio S_{max} : transition width was taken as a measure of the rate of change in S. From the fitted curves, we derived two measures of timing of maturity. A physiological measure of berry maturity, accounting for both the intra-specific variation in maximum concentration of soluble solids and the shape of the fitted curve, was the time when S reached 0.95 S_{max} (Rawson and Turner 1982). An oenological estimate of maturity was the time when berries reached a concentration of soluble solids of 20% (Pearce and Coombe 2004).

The dynamics of water concentration was characterised with a concentration-response type curve (Saxena et al. 1997):

$$W = W_{\min} + \frac{W_{\max} - W_{\min}}{1 + (x / x_{50})^n} \qquad \text{eq. 2}$$

where W is water concentration, and subscripts indicate maximum and minimum, x_{50} is the time when water concentration is halfway between maximum and minimum, and n is the Hill slope, a scalar that controls the slope of the curve (Saxena et al. 1997).

Allometric analysis

The scaling exponent for soluble solids α_s, was calculated as the slope of the regression between amount of soluble solids per berry and berry fresh mass in a log-log scale, and the scaling exponent for water α_w, as the slope of the regression between amount of water per berry and berry fresh mass in a log-log scale (Sadras and McCarthy 2007, Sadras et al. 2007). Given the tight associations ($r \geq 0.97$), model I and model II regressions yielded similar scaling exponents (Niklas 1994); model I regressions were thus used for consistency with previous studies (Sadras and McCarthy 2007, Sadras et al. 2007).

Sources and sinks

To investigate the physiological drivers of S_{max} and timing of maturity, we measured source size and activity, and sink size in the varieties indicated in Table 1. Three measures of source size were obtained: fractional interception of photosynthetically active radiation (PAR), canopy leaf area and pruning weight. Fractional PAR interception was calculated as the ratio of PAR measured at ground level (in five positions parallel to the row at 0.3 m intervals, and three replicates per variety) and incident PAR (average: 2065 μmol m^{-2} s^{-1}) measured with a ceptometer on February 7th, 2007. Total canopy leaf area was calculated by measuring the leaf area of leaves randomly sampled from the 4th node of shoots and multiplying this by the average number of nodes per shoot and shoots per vine. Ten leaves were sampled on 10 replicate vines, giving 100 leaves in total for each variety. Leaves were scanned (Mirascan, BenQ Taipai, Taiwan) and leaf area was calculated using SigmaScan Pro 4.0 (Systat Software Inc., California, USA). For each variety shoots per vine was counted on 10 vines early in the season prior to flowering (November 2006). Nodes per shoot were counted on the same 10 vines at the end of the season when leaf senescence was occurring (May 2007). Pruning weights of the same 10 vines were measured after spur pruning (June 2007). Yield was estimated from bunch numbers counted in five vines (coefficient of variation = 0.26), and bunch fresh weight from a sample of 10 bunches (coefficient of variation = 0.37).

Table 1. Varieties compared at Nuriootpa (Barossa Valley, South Australia)

Variety	Clone	Type[1]	Vine Age (years)	Measurements[2]
Cabernet Sauvignon	LC84	R	18	S, W, f, LA, Pw, Yc, gs
Chardonnay	I10V1	W	32	S, W, f, LA, Pw, Yc, gs
Crimson Seedless	USDA 1992	T	13	S, W, f, Yc
Dawn Seedless	88-05 Olmo G4-36/VX/UCD	T	16	S, W, f, Yc
Fantasy Seedless	USDA 1992	T	13	S, W, f, Yc
Grenache	139HT 401-1	R	15	S, W, f, LA, Pw, Yc, gs
Merlot	8R	R	9	S, W, f, LA, Pw, Yc, gs
Red Globe	88-07 Olmo 10-23 D	T	17	S, W, f, LA, Pw, Yc, gs
Riesling	I10V14	W	17	S, W, f, LA, Pw, Yc, gs
Semillon	D10V12	W	13	S, W, f, LA, Pw, Yc, gs
Shiraz	BVRC12	R	11	S, W, f, LA, Pw, Yc, gs
Verdelho	SA168	W	11	S, W, f, LA, Pw, Yc, gs

[1] R= red wine, W = white wine, T = table grape variety
[2] S: total soluble solids in berries, W: water concentration in berries, f: fractional PAR interception, LA: leaf area, Pw: pruning weight, Yc: yield components, gs: stomatal conductance

Stomatal conductance was measured as a surrogate of source activity. Mid-morning (9.00-11.00) stomatal conductance was measured with an AP4 porometer (Delta T Devices, Cambridge, U.K.) on six days during the berry ripening stage. All measurements were taken on the western side of the vine on cloudless days. Before commencing measurements each day, the porometer was calibrated using ambient temperature and humidity measured with the porometer. Fifteen leaves over five replicate vines were measured for each variety, and values logged after readings became stable (< 10-15 seconds).

Phenological development to maturity

To investigate variety-dependent time to maturity further, we used published data to account for phenological variation before and after veraison (Pearce and Coombe 2004). Regression was used to analyse the contribution of flowering-to-veraison and veraison-to-20 ^{o}Brix in the variation in time to maturity for a collection of 23

varieties established at Nuriootpa, in the same environment where the current study was established.

Results

Seasonal conditions, yield and source:sink ratio

The experimental season was similar to the typical crop-growing season at Nuriootpa except for higher maximum temperatures (Table 2). A climatic water deficit, i.e. reference evapotranspiration – (rain + irrigation) in the order of 800 mm, was also typical of the viticultural practices in the region.

Table 2. Growing conditions during the 2006-07 season at Nuriootpa (Barossa Valley, South Australia) and long-term (LT) comparison.

Month	Max. Temp (°C)		Min. Temp (°C)		Radiation (MJ m^{-2})		ETo[a] (mm)		Rain + Irrigation (mm)	
	2006-07	LT	2006-07	LT	2006-07	LT	2006-07	LT	2006-07	LT[b]
Sept	20.2	16.9	6.1	6.0	17.4	15.7	88	72	20	61
Oct	23.9	20.3	7.1	8.0	22.7	19.8	135	111	3	47
Nov	27	24.1	10.5	10.1	24.3	23.0	157	141	25	31
Dec	28	26.5	12.3	12.0	25.6	24.7	175	167	39	24
Jan	29.4	28.9	14.6	13.7	25.2	25.5	175	180	63	18
Feb	32.4	28.7	15.6	14.0	24.4	23.4	167	152	12	20
Mar	25.9	25.7	12.9	11.8	17.9	19.3	122	127	33	23
Total							1019	950	195	234

[a] Reference evapotranspiration calculated with FAO56 model described in Allen et al. (1998).

[b] Rainfall only

Yield range was 25-fold, and the source:sink ratio calculated as fractional PAR interception:yield varied by a factor of 29 (Fig. 1). Source:sink ratio based on PAR interception was similar to source:sink ratios based on leaf area : yield (r^2 = 0.88, P = 0.0002) and pruning weight : yield (r^2 = 0.96, P < 0.0001).

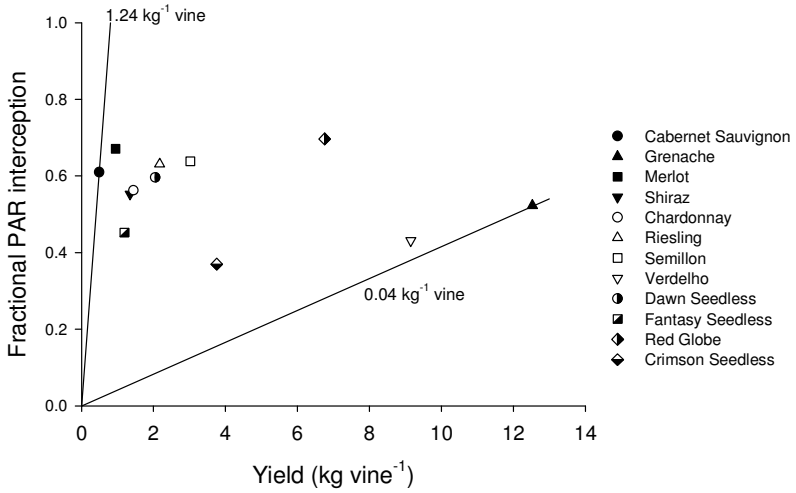


Figure 1. Canopy size, characterised as the fraction of photosynthetically active radiation (PAR) intercepted by the canopy, and fruit yield of 12 grapevine varieties at Nuriootpa, 2006-07. The lines are the boundary source : sink ratios.

Dynamics of soluble solids and water concentration in berries

Figure 2 and Table 3 summarise the dynamics of concentration of soluble solids in berries. A sigmoidal model with three parameters (eq. 1) applied to all varieties (0.85 ≤ adjusted R^2 ≤ 0.98), except for Crimson Seedless, which required a 4-parameter model to account for the pronounced initial tail. Crimson Seedless was thus excluded from analysis of curve-derived parameters.

The maximum concentration of soluble solids ranged from 21.2% in Riesling to 27.1% in Shiraz. The time (day of year) of physiological maturity ranged from 37 (6th February) in Riesling to 69 (10th March) in Merlot, and the time of oenological maturity ranged from 26 (26th January) in Verdelho to 58 (27th February) in Crimson Seedless.

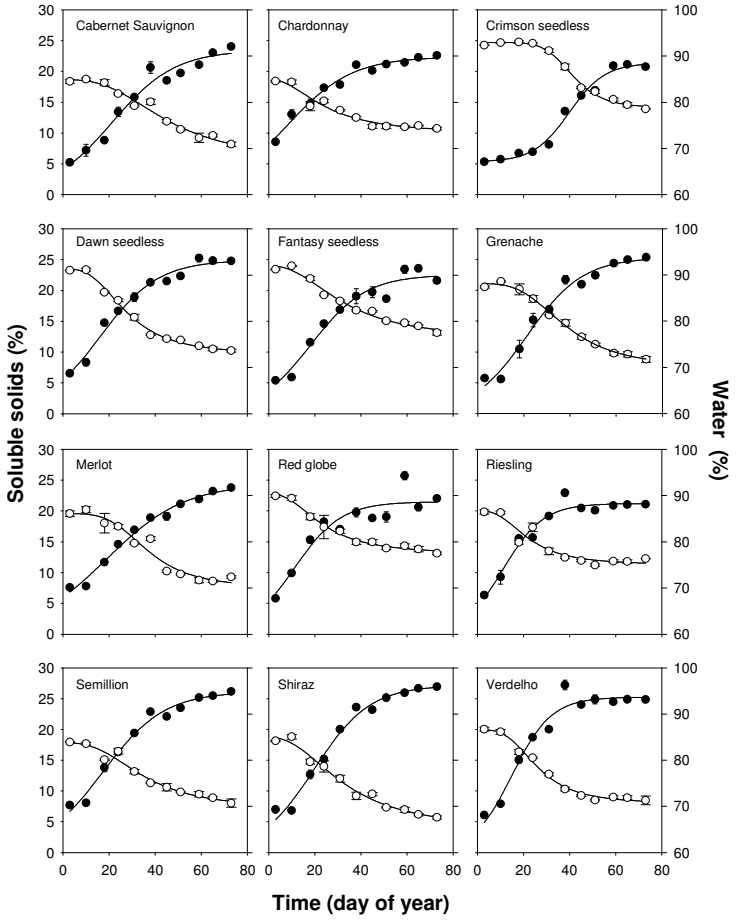


Figure 2. Dynamics of concentrations of soluble solids (closed symbols) and water (open symbols) in berries of *Vitis vinifera* varieties at Nuriootpa, 2006-07. Error bars are two standard errors of the means.

Table 3. Parameters (par.) of a sigmoidal model (eq. 1) accounting for the dynamics of soluble solids in berries. S_{max} is the maximum concentration, x_0 is the time when concentration is half the maximum, and b is related to the transition width, i.e. the time it takes concentration of soluble solids to increase from 0.25 S_{max} to 0.75 S_{max}. From the fitted curves, two measures of timing of maturity were derived: physiological, calculated as the time when berries reached 0.95 S_{max}, and oenological, calculated as the time when berries reached 20% concentration of soluble solids.

Variety	S_{max} (%)		x_o (d)		b (d)		Transition width (d)	Timing of maturity (day of year)	
	par.	s.e.	par.	s.e.	par.	s.e.		Physiological	Oenological
Cabernet Sauvignon	23.5	1.18	21.3	2.31	13.7	2.30	30	62	45
Chardonnay	22.4	0.54	7.9	1.29	14.1	1.82	31	49	38
Crimson Seedless*								60	58
Dawn Seedless	24.9	0.68	16.0	1.29	12.6	1.45	28	53	34
Fantasy Seedless	22.5	0.96	18.5	1.96	11.9	2.04	26	53	43
Grenache	25.3	0.85	21.4	1.51	12.1	1.47	27	57	37
Merlot	24.4	0.81	19.0	1.60	16.9	1.75	37	69	44
Red Globe	21.5	1.11	11.2	2.62	10.1	2.98	22	41	37
Riesling	21.2	0.58	11.3	1.35	8.7	1.44	19	37	36
Semillon	26.1	0.73	17.2	1.31	13.3	1.45	29	56	33
Shiraz	27.1	0.74	19.8	1.25	12.0	1.26	26	55	32
Verdelho	25.2	0.77	15.1	1.41	8.5	1.39	19	40	26

* A different model was used for Crimson Seedless; hence the lack of comparable parameters, except for the timing of maturity derived from fitted curves.

Figure 2 and Table 4 summarise the dynamics of water concentration in berries. A dose-response curve described the dynamics of water concentration in berries of all varieties (**Error! Reference source not found.**; 0.86 ≤ adjusted R^2 ≤ 0.99). The maximum concentration of water in berries was above 90% for table varieties, and below 88% for wine varieties. The minimum water concentration in berries ranged between 79% in Crimson Seedless and 65% in Shiraz, and averaged 76% in table varieties, 72% in white wine varieties and 68% in red wine varieties. The concentration of water in berries at physiological maturity (0.95 S_{max}) ranged from 69.7 to 80.0%, and averaged 78.7% in table varieties, 74.7% in white wine varieties and 71.8% in red wine varieties.

Table 4. Parameters (par.) of a dose-response model (eq. 2) accounting for the time dynamics of water concentration of berries. W is water concentration, and subscripts indicate maximum and minimum, x_{50} is the time when water concentration is halfway between maximum and minimum, and n is the Hill slope, a scalar that controls the slope of the curve. Water concentration at physiological (0.95 S_{max}) and oenological maturity (20% soluble solids) was derived from fitted curves.

Variety	W_{min} (%)		W_{max} (%)		x_{50} (d)		n		Water concentration at maturity (%)	
	par.	s.e.	par.	s.e.	par.	s.e.	par.	s.e.	Physiological	Oenological
Cabernet Sauvignon	67.5	4.14	84.9	0.78	44.9	8.53	2.83	0.943	72.5	76.1
Chardonnay	73.1	1.86	85.0	1.12	24.6	4.59	2.13	0.892	75.3	76.5
Crimson Seedless	78.7	0.56	92.9	0.30	41.3	0.97	6.34	0.873	79.9	80.2
Dawn Seedless	72.7	0.88	91.4	0.58	27.5	1.38	2.93	0.427	75.1	79.4
Fantasy Seedless	76.1	2.09	92.0	0.76	32.6	4.34	2.31	0.597	79.9	81.6
Grenache	69.9	1.12	88.1	0.39	38.1	1.84	3.27	0.423	73.7	79.4
Merlot	70.0	2.46	86.1	1.10	36.9	4.31	3.78	1.470	71.4	75.4
Red Globe	77.3	0.81	90.3	0.61	23.3	1.80	2.41	0.479	80.0	80.5
Riesling	74.9	1.73	86.7	1.62	22.0	4.36	2.71	1.532	77.3	77.5
Semillon	69.4	2.39	83.8	0.87	35.0	5.24	2.75	0.939	72.5	77.2
Shiraz	64.9	2.74	84.9	0.96	32.9	4.57	2.27	0.596	69.7	75.2
Verdelho	70.6	0.78	86.6	0.64	26.0	1.45	3.24	0.581	73.8	78.5

Allometric relationships

As expected for post-veraison berries actively increasing their sugar concentration (Coombe and Iland 2004), the scaling exponent for soluble solids was consistently greater than 1 (range: 1.92 to 2.65), whereas the scaling exponent for water was consistently lower than 1 (range: 0.78 to 0.89). Maximum concentration of soluble solids in berries was related to both scaling exponents, but more strongly with the scaling exponent for water (**Error! Reference source not found.**). Shiraz, the variety with the greatest concentration of soluble solids, had a scaling exponent for water of 0.78 ± 0.051 compared with 0.86 ± 0.015 for Riesling, the variety with the lowest S_{max}. The allometric coefficients for soluble solids and water were unrelated to yield, canopy size or source: sink ratios (not shown).

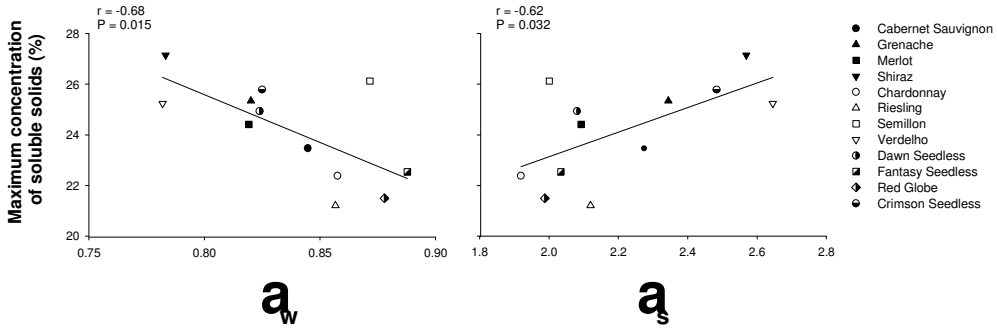


Figure 3. Relationships between maximum concentration of soluble solids in berries and scaling exponents for water ($\square_w$) and soluble solids $\square_s$). The solid lines are linear regressions. Scaling exponents are dimensionless.

Relationships between maximum concentration of soluble solids, sources and sinks

High S_{max}, as in Shiraz (Figure 2, Table 3) could be related to high source:sink ratio. To test this hypothesis, we explored the associations between S_{max} and several measures of source size and activity, sink size and source:sink ratios. Owing to the imperfection of each of these individual variables, we analysed them collectively (Table 5). Except for a marginal positive association with pruning weight, maximum concentration of soluble solids in berries was largely unrelated to source size and activity, sink size and activity, and source:sink ratios (Table 5).

Table 5. Variation in maximum concentration of soluble solids in berries among varieties was unrelated to source size, source activity, sink size, and source:sink ratio. P indicates significance of linear regressions.

Type of variable	Variable		P >
Source size	Leaf area		0.53
	Pruning weight		0.06
	Fractional light interception		0.27
Source activity	Stomatal conductance	25 Jan	0.60
		08 Feb	0.66
		09 Feb	0.93
		14 Feb	0.67
		15 Feb	0.73
Sink size	Yield		0.62
	Bunch number		0.59
	Bunch weight		0.96
Source:sink	Leaf area:yield		0.97
	Pruning weight:yield		0.93
	Fractional PAR Interception:yield		0.64

Relationship between timing of maturity sources and sinks

The timing of maturity was closely associated with the time required for berries to increase concentration of soluble solids from 25 to 75% of maximum ($r^2 = 0.37$, $P < 0.05$ for oenological maturity, and $r^2 = 0.81$, $P = 0.0002$ for physiological maturity). These associations reinforce the conclusion from independent measurements at Nuriootpa that post-veraison development is the main driver of intraspecific variation in time to maturity in this environment, whereas the contribution of variation of pre-veraison development is negligible (Figure 4).

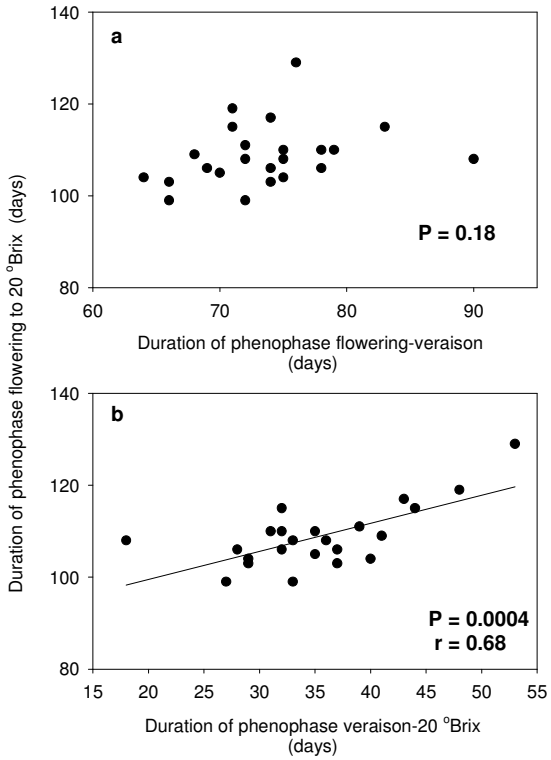


Figure 4. In the Barossa Valley, intraspecific variation in time from flowering to 20 °Brix is (a) unrelated to the duration of pre-veraison phase and (b) closely related to the duration of the post-veraison phase. Data are medians from four seasons and 23 varieties at SARDI experimental station at Nuriootpa (Pearce and Coombe 2004).

The date of maturity was an inverse function of the rate of change in concentration of soluble solids, which was in turn a direct function of stomatal conductance (Figure 5). Associations between rate of accumulation of soluble solids and stomatal conductance were always positive and statistically significant in 5 out of 6 measurement days ($P < 0.02$). Stomatal conductance was an inverse function of source:sink ratio (Figure 6).

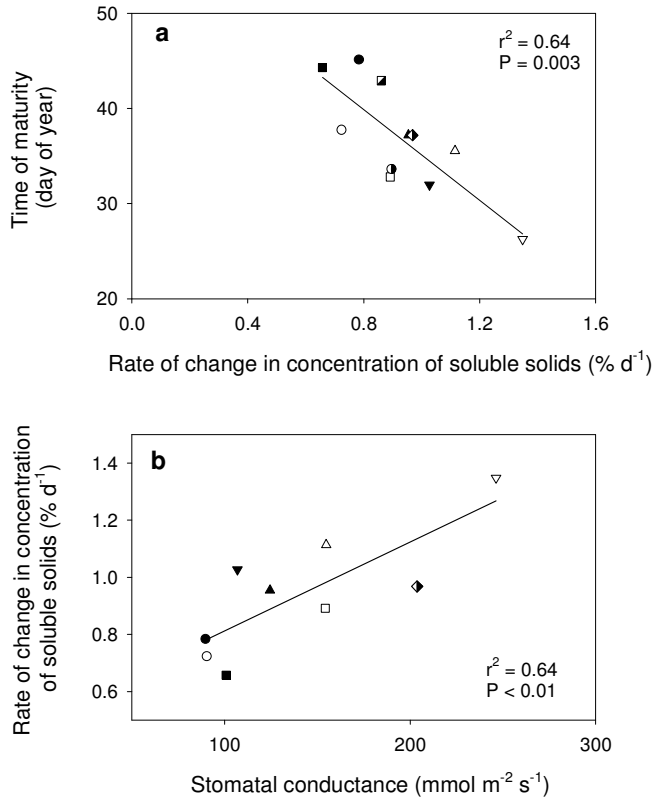


Figure 5. Relationships between (a) time of maturity (20% soluble solids in berries) and rate of change in concentration of soluble solids, and (b) rate of change in concentration of soluble solids and stomatal conductance. Stomatal conductance is the average of six measurement dates between 25 January and 15 February; error bars are two standard errors. Different number of points in the graphs are related to the exclusion of Crimson Seedless, for which rate of accumulation of soluble solids was not calculated due to its unique dynamics (Fig. 2), and the different intensity of measurements as summarised in Table 1.

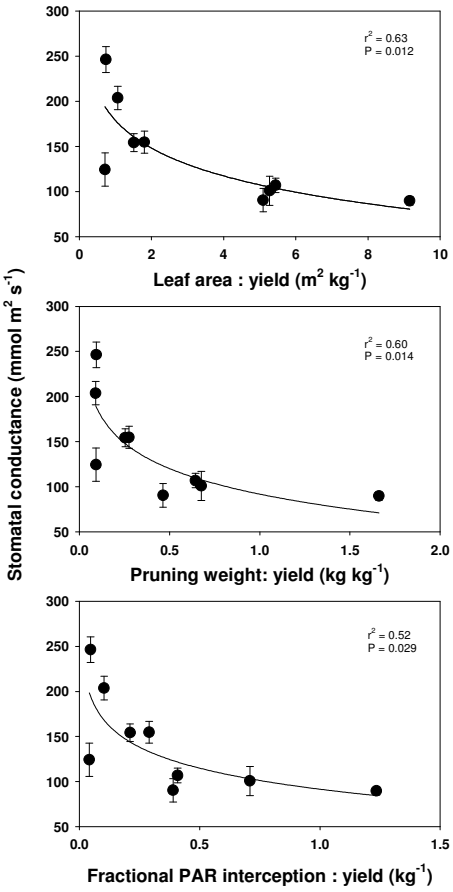


Figure 6. Relationship between stomatal conductance and three measures of source:sink ratio. Stomatal conductance is the average of six measurement dates between 25 January and 15 February. Error bars are two standard errors.

Discussion

We monitored and modelled the dynamics of soluble solids and water in berries of a diverse collection of grapevine varieties under a narrow set of environmental conditions, viz. single season, single location, and uniform crop management. The plasticity (sensu Bradshaw 1965) of the varietal patterns of accumulation of water and soluble solids in berries in relation to management and environmental factors thus requires specific testing. Sadras and McCarthy (2007) found some degree of plasticity in the accumulation of sugar and dehydration of Shiraz berries.

Minimum water concentration

Implicit in the comparison among the varieties in this study was the expectation of distinct patterns of soluble solids and water dynamics in table grape varieties, putatively selected for large berry size and higher water content at maturity, in contrast to wine varieties where turgor maintenance was possibly less relevant. Liu et al. (2006) reported generally lower content of sugar in table varieties compared

to their wine counterparts; implicit in this finding is a greater water content in table varieties. Consistently, here we found the ranking of minimum water concentration in berries, i.e. 76% in table varieties, 72% in white wine varieties and 68% in red wine varieties, supports the notion of distinct patterns of water dynamics, possible related to differential selective pressures between table and wine varieties. This contrasts with the small intraspecific variation for this trait in grain crops (Calderini et al. 2000, Gambin et al. 2007, Rondanini et al. 2006).

Maximum concentration of soluble solids

The maximum concentration of soluble solids in berries is physiologically interesting and relevant for winemaking. We found substantial varietal differences (Figure 2, Table 3) and no association between S_{max} and variables related to the carbon economy of the crop (Table 5). Maximum concentration of soluble solids was related to both allometric coefficients for soluble solids and water, but the relationship was slightly stronger for water (Figure 3). Many studies indicated that water dynamics in berries is (a) cultivar-dependent and (b) linked to sugar accumulation (Greenspan et al. 1996, Keller et al. 2006, Tyerman et al. 2004). For instance Tyerman et al. (2004) showed that single berry hydraulic conductance was 2- to 5-fold higher in Shiraz than in Chardonnay; this trait could therefore play a significant role in the varietal-dependent dynamics of sugars. More work is needed to develop conceptual models linking sugar and water dynamics of berries accounting for both cultivar and environmental conditions (Genard et al. 2007).

The viticultural importance of S_{max} relates to the need to conciliate a target sugar concentration with the concentration of other compounds related to berry colour and flavour. Thus, the trade-offs between sugar and other components resulting from delayed or anticipated harvest would be quite different for a variety such as Shiraz, where concentration of soluble solids could reach high values, up to 27% under our experimental conditions, in comparison with varieties such as Riesling where concentration levels-off at typically lower values, 21% under our conditions. Godden and Gishen (2005) demonstrated substantial, variety-dependent changes in the profiles of Australian wines between 1984 and 2004, including a marked increase in alcohol in Cabernet Sauvignon, Merlot, Grenache and Shiraz. In comparison, alcohol remained stable in Chardonnay, Riesling and Semillon. Differential responses of sugar accumulation to recent warming trends (Petrie and Sadras 2008), and variety-dependent coupling of sugar and other compounds, are some of the potential factors underling the contrasting time-trends in the profile of Australian wine reported by Godden and Gishen (2005). A dynamic view of the processes leading to the final berry composition, rather than a snapshot at the end of the season, will contribute to better understanding and open opportunities for the variety-specific management of crop and winemaking decisions.

Timing of maturity

Variety dependent variation in timing of maturity is a primary function of post-veraison development (Fig. 4). Consistent with this, the timing of maturity was an inverse function of the rate of accumulation of soluble solids in berries after veraison. It could be expected therefore, that source:sink ratios would influence the rate of accumulation of soluble solids and therefore time of maturity (Bindi et al.

2001). Source-to-sink relationships in turn involve both size, e.g. canopy leaf area, and activity per unit size, e.g. photosynthetic rate per unit leaf area. In general, variation in the relative size of sources and sinks is more relevant than variation in activities per unit source or sink (Monteith 1977). Here we found that the rate of accumulation of soluble solids in berries, the key driver of timing of maturity, was a direct function of stomatal conductance (Fig. 5). Leaf photosynthetic rate depends on stomatal and non-stomatal controls (Chen et al. 2006, Grassi and Magnani 2005, Jiang et al. 2006, Massonnet et al. 2007).

The variation in stomatal conductance with source : sink ratio (Fig. 6) can be interpreted in terms of photosynthetic responses to end-product utilisation. In annual crops, low grain set or removal of grain often leads to reduced photosynthetic rate, and reciprocally, stronger sinks could increase photosynthesis (Evans 1993, Fischer 2008). In perennials, or even in annuals where vegetative organs could act as strong sinks, stems and roots could buffer the effects of high source : sink ratio resulting, for instance, from reproductive thinning (Sadras et al. 2000). This could account for the lack of photosynthetic response to source: sink manipulation in some studies with grapevine (Chaumont et al. 1994) in contrast to studies where a 3.5-fold range in source:sink ratio generated through bunch thinning and shoot removal lead to changes in single leaf photosynthesis ranging from negligible to 2-fold (Edson et al. 1993). The variation in response with leaf position in the study of Edson et al. (1993) probably reflects the modularity of the plant (Hardwick 1986, Kaitaniemi and Honkanen 1996). Based on experimental and modelling studies with Cabarnet Sauvignon, Quereix et al. (2001) proposed that the decrease in stomatal conductance associated with feed-back inhibition of photosynthesis could be related to a phloem-based feedback signal. We therefore propose that the negative association between stomatal conductance and source:sink ratio in our experiments is possibly associated with feed-back/feed-forward sink effects on leaf photosynthesis. The influence of source:sink on rate of accumulation of soluble solids in berries, reinforce the importance of management practices, chiefly water and nutrient supply, on time of maturity.

In conclusion, we have modelled distinct patterns of accumulation of soluble solids and water in berries of grapevine varieties, and advanced on the putative links between berry and leaf physiology. We showed that the maximum concentration of soluble solids in berries was unrelated to carbon-related traits, and speculate that water dynamics may play a role. The timing of maturity was clearly associated with the rate of accumulation of soluble solids, which was in turn related to stomatal conductance. Varietal differences in stomatal conductance may involve an important component of phenotypic plasticity in terms of photosynthesis and stomatal responsiveness to source:sink ratio.

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Part 2

Risk Management

The second objective of the project was to develop and deliver a synthesis of information in a risk management framework.

Because risk management is such a generic term we have taken the framework for risk management from the Australia New Zealand Standard AS/NZS 4360 (Fig. 1). This has been adapted by Marsden and Jacobs (2006) for a report to the Australian Department of Climate Change. The framework includes 5 elements, namely establish the context, and identify, analyse, evaluate and treat the risks.



Figure 1. Risk Management Framework from Australian Department of Climate Change

Establish the context and identify the risk

The context for the risk management was developed from the initial meeting held at SARDI in December 2004 where a number of representatives of the wine grape industry met to discuss the impacts of the February 2004 heatwave. The industry reference group was largely made up from members of this original meeting. Although the design and application of heat tents have been the main discussion point we have canvassed the issues of heat stress and questions of better access and communication with the Bureau of Meteorology. Further discussion with industry has occurred in meetings in the Barossa and Coonawarra in July.

We have reviewed the literature on heat stress in viticulture finding that the classic viticulture and climate texts such as Gladstones and Dry and Coombe tend to emphasise parameters such as Mean January Temperature or Growing Season Temperature rather than extremes. Although Gladstones (2005) proposed a Heat Stress Index (HSI) calculated as the difference between the mean monthly temperature over the long term record and the highest average monthly maximum

temperature recorded. White et al (2006) used a count of days over 35 degrees as a measure for quality wine production in the USA.
Chapter 11 reviews the impact of climate change, including heatwaves on the Australian wine industry but includes the wider context is presented in terms of the adaptive capacity of the wine industry at the vine, vineyard, winery and wine marketing levels

Chapter 12 identifies the risk of heatwaves by defining a heatwave in terms of a temperature, duration and timing and describing the meteorology of heatwaves i.e the weather events or synoptic processes that create heatwaves in the wine growing regions of Southern Australia. Identifying the risks is the primary focus of the field experimentation. The field experiment has also been the source of considerable industry discussion on the impact of heat stress at different times.

During workshops in Barossa and Coonawarra, grape growers were asked what aspects of weather they thought influenced quality in their region? They were asked to rate the importance from 1 (insignificant) to 5 (strong influence) for Tmax, T min, Humidity, Radiation and Rainfall. Figure 2 shows that Barossa growers emphasise T max and rainfall as the most important climate drivers.

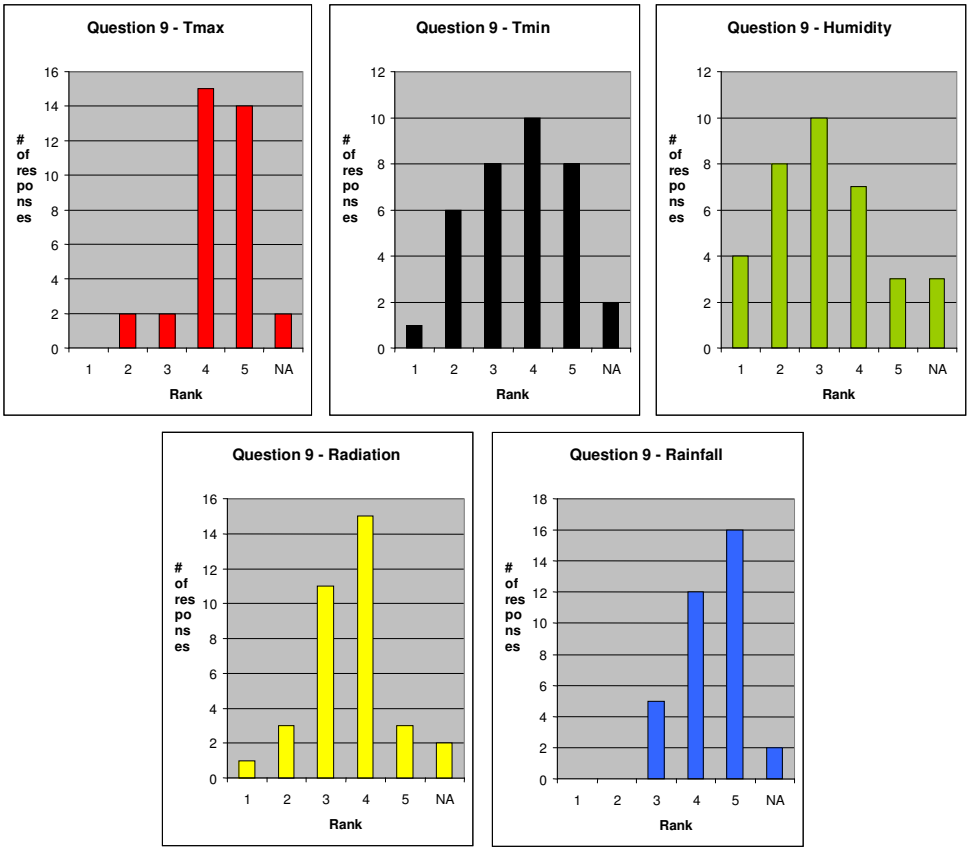


Figure 2. Survey responses from grape growers in Barossa ranking their perceptions of the influence of a range of weather factors on wine grape quality.

Growers were also asked to rate the stages of crop development they thought climate has the greatest influence on berry composition and eventual wine quality. Barossa growers ranked veraison as the most sensitive stage (Fig. 3).

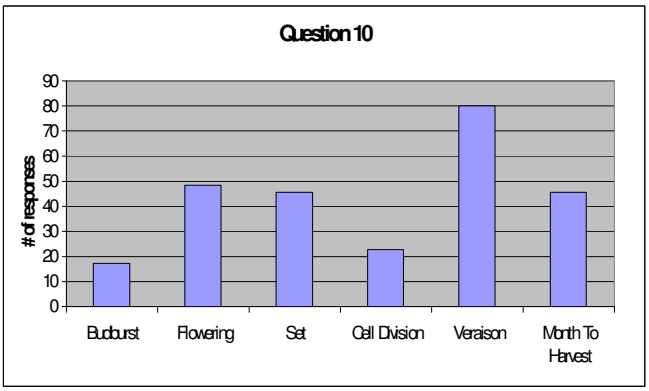


Figure 3. Barossa growers (n=35) response to the question "At what stages of crop development do you think climate has the greatest influence on berry composition and eventual wine quality?"

Analyse and evaluate the risk

We have developed a Microsoft Access database of daily meteorological records for all major wine regions and a number of Excel spreadsheets to analyse trends in extreme temperatures and occurrence of heat waves. Figure 4 shows the time series of days over 35 and 40 degrees during the growing season at Griffith. The spreadsheet developed in conjunction with the GWRDC project on climate change at a regional level also calculates Mean January Temperature, Growing Season Temperature, Growing Degree Days and maximum and minimum temperature thresholds.

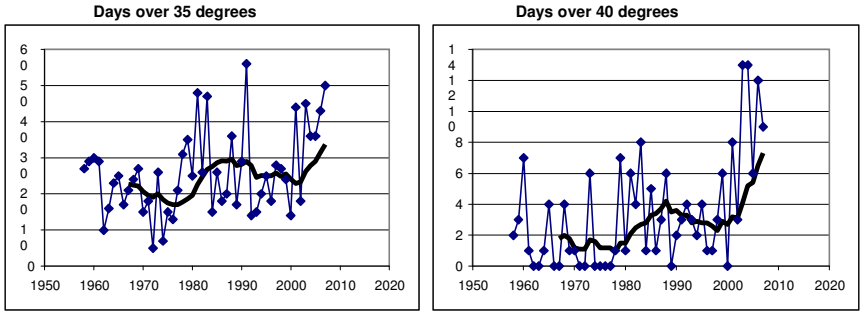


Figure 4. Example of spreadsheet output of days over 35 and 40 °C.

Chapter 13 describes the a mathematical model which characterises the likelihood of any temperature for any run length, this mathematical model is superior to just applying queries to existing data bases as it enables comparisons of regions with differing record length, it also allows for more rigorous risk assessment with analysis of return periods.

Treat the risks

The emphasis of this project is on identification of the risk of heat stress on vines. It is important to correctly diagnose or identify the risk before too much emphasis is made on treating the risk. For example, the appropriate treatment will differ if the problem is warm night temperatures rather than hot day temperatures.

Nevertheless there are a number of ways that grape growers are currently managing the risks and these are summarised in Chapter 14.

Given that there will never be perfect predictions of heatwaves, the cost/loss ratio of different strategies should offer some guidance of appropriate actions for forecasts of different probabilities of being correct. The Bureau of Meteorology has expressed interest in providing information on forecast accuracy for a matrix such as this.

Chapter 11

Addressing the tension between the challenge of climate change and the adaptive capacity of the wine grape industry

PT Hayman, MG McCarthy, CJ Soar, VO Sadras

Summary

The threat of climate change to the Australian wine industry is likely to come from changes in mean temperature, changes in extreme temperature events and the reduction in quality and quantity of water. Large areas of Australian are in localities warmer than many other regions in the world and a number of these are already experiencing water availability issues. Drought, heatwaves, bushfires and floods in recent years have shown that viticulture in Australia is exposed and sensitive to climate. At the same time the grapevine is an extraordinary plastic plant and not only is there an adaptive capacity at the vine level, the Australian viticultural industry has shown considerable adaptive capacity at the vineyard level, the winery level and the wine marketing level. Therefore the question of what is dangerous climate change for Australian viticulture is easier to answer for the Great Barrier Reef or an alpine species than a managed activity such as viticulture.

Identifying dangerous climate change is also made difficult by the year-to-year climatic variability that the industry has managed in the past. This variability is large compared to trends over the last half-century and even projections for the next half-century. Indices such as growing season temperature (October to April in the southern hemisphere) or mean January temperature can be used to classify regions and study shifts under climate change projections. However, the year-to-year variability within regions is often of a similar magnitude of the difference between regions. This variability is likely to be the way that climate change will impose damage. At the same time ability of Australian viticulture to cope with past variability provides some indications of the resilience and adaptive capacity to manage the moderate end of the climate change projections over the coming decades.

Introduction

The impact of climate change on wine makes regular headlines and feature stories. More so than any other agricultural product, premium wine is marketed and appreciated with a strong spatial (region) and temporal (vintage) component. The long-term climate is recognised as a distinguishing feature of a region and the year-by-year climate determines the vintage. It stands to reason that changes in climate will first influence individual vintages and then overall styles of wine and finally threaten the suitability of a region for grape growing. Viticultural regions in Australia are exposed and sensitive to many aspects of a changing climate, but at the forefront are threats posed by a rise in mean temperature, an increase in extreme temperatures and a decrease in the availability and quality of water. A warmer world will also mean that some regions are likely to benefit.

Within the grape and wine industry fewer people are asking the basic science question “What is climate change?” or the more provocative “Is climate change real?” and more are asking about the need to reduce greenhouse gasses, the impact of climate change on the wine industry and appropriate ways to adapt. Within these proceedings the scientific basis of climate change is addressed (Whetton, 2007) as are reductions of greenhouse gases within the wine sector (McNab and Small, 2007; Pearce, 2007) along with impacts on the industry globally (Jones, 2007) and within Australia (Webb *et al.*, 2007; Smart, 2007). In this paper we were asked to provide an overview of impacts and adaptation. We do this by exploring the notion of dangerous climate change for viticulture and argue that this is inherently hard to define partly due to incomplete knowledge but also due to the high level of current year-by-year variability in temperature that the industry has managed in the past.

Dangerous climate change

Viticulture in Australia is sensitive and exposed to climate, but what level of climate change will place it in danger? The term dangerous climate change can be traced back to Article 2 of the 1992 United Nations Framework Convention on Climate Change which called for stabilisation of greenhouse gases at a level that would prevent dangerous anthropogenic interference with the climate system (see Harvey 2007 for full discussion on definitions and politics of dangerous anthropogenic interference and dangerous climate change). The notion was further popularised at an international conference in the UK in 2005 (Schellnhuber, 2006) Although most of the discussion about dangerous climate change relates to the need for greenhouse gas reduction, it is common for the climate science community to ask agriculturalists, ecologists, health workers and engineers “what is dangerous climate change or the critical threshold for a given ecosystem or human activity?” (Steffen, 2006) identified this characterisation of dangerous climate change an important emerging challenge for climate change science in Australia.

We have used the adjective *dangerous* not only because it is a question that is being asked by climate scientists, policy analysts and the wine industry, but also because it makes the point that wine production in Australia is in danger of a warming and drying trend. We agree with (White *et al.*, 2006; Webb *et al.*, 2005; Jones *et al.*, 2005; Smart, 2006) and others who point to the fact that quality wine is produced in a relatively narrow temperature band and as a coupled social/environment system, wine production it is not easy to simply shift to cooler or wetter regions. For more than 15 years the potential danger posed to Australian viticulture from human induced climate change has been highlighted (Smart, 1989; Croser, 1987; Gladstones, 1992; Dry, 1988). Much has changed in more recent years as the arguments from climate science are clearer and have been given unprecedented media and political attention. However, for many in the Australian wine industry, the most convincing change has been the weather. A series of warmer years with events such as SE Australian heatwave in February 2004 combined with drought, bushfire, frosts and floods in 2006/07 have heightened the intensity of the debate on the vulnerability of the wine industry to climate change.

Evidence for climate change at a global and regional level

In the carefully chosen and much scrutinised language of the Fourth International Panel on Climate Change, warming of the climate system is *unequivocal.* (IPCC, 2007). Australia is well served with tools to examine trends in climate and future projections (see Australian Greenhouse Office website for latest links to CSIRO and Bureau of Meteorology analysis).

The most accessible evidence for warming has been the annual analysis of global temperature. The list of warmest years on record is striking - 1998, 2005, 2002,2003,2004, 2006, 2001 with some speculation that 2007 will be even warmer due to a combination of the warming trend and the El Nino event in 2006/07 (1998 and 2002 were both El Nino events). Eleven of the last twelve years (1995-2006) rank amongst the 12 warmest in the instrumental record since 1850 (IPCC, 2007).

To gain an overview of changes in Australia relevant to viticulture we analysed broad grided data from the South East (SE) and South West (SW) areas of Australia (Figure 1)[4]. These cover most, but not all Australian wine regions. The time series of mean annual temperature anomalies for these two regions from 1950 to the present are presented in Figure 2. Each point is the difference between that year and the 1960 to 1990 average. For both regions the linear trend is significant but noisy (0.12 SE and 0.14 SW Australia). The warmest year for SE Australia in the period 1950 to 2006 was 1980. However as can be seen on Figure 2 (a), most of the warm years are in the recent past. Of the 10 warmest years only one was prior to 1980 and 4 were this decade (2000, 2002, 2005 and 2006). The warmest year for SW Australia was 1994 and 8 of the 10 warmest years are after 1980. An interesting standout for SW Australia is 2005/06 as the coolest summer year in the 57-year record. Linear trends are valid, robust and transparent ways to examine trends, however they tend to underestimate the accelerating nature of global warming (Jones and Trewin, 2007). The run of warmer years in the last decade points to the need for more sophisticated time series analysis beyond the scope of this paper that captures break points and accelerating trends.

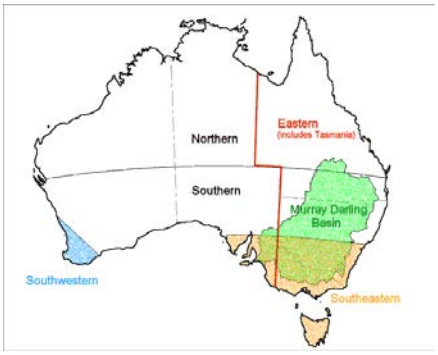


Figure 1. SE and SW Australian regions for grided rainfall and temperature data. Source: BoM.

[4] Bureau of Meteorology www.bom.gov.au For consistency in analysis between regions we used the 1950 to present for temperature and 1900 to present for rainfall.

Figure 2a

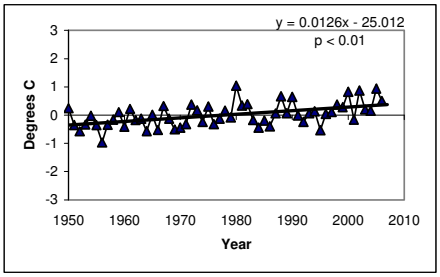


Figure 2b

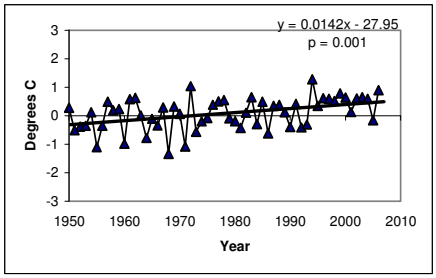


Figure 3 a

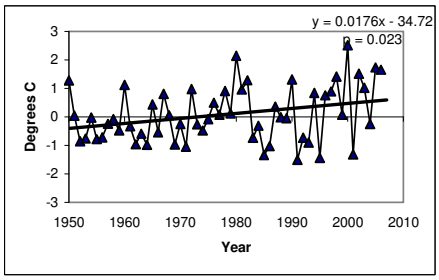


Figure 3 b

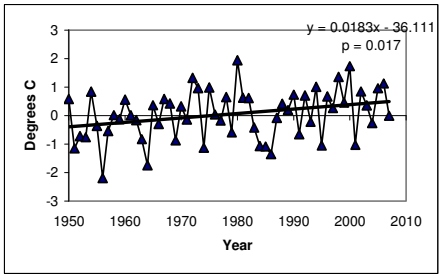


Figure 4 a

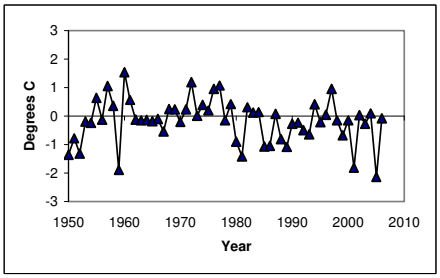


Figure 4 b

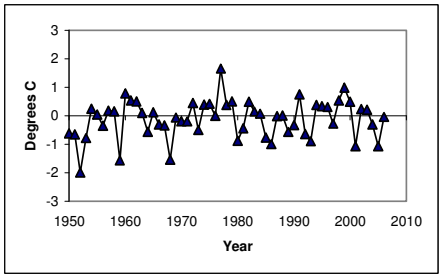


Figure 2. Time series showing anomalies from mean of period 1960 to 1990 of annual mean temperature for (a) South Eastern Australia and (b) South Western Australia

Figure 3. Time series showing anomalies from mean of period 1960 to 1990 of (a) summer maximum temperature and (b) summer minimum temperature for South Eastern Australia.

Figure 4. Time series showing anomalies from mean of period 1960 to 1990 of (a) summer maximum temperature and (b) summer minimum temperature for South Western Australia.

In a study of the impact of global warming on the wine industry (Jones *et al*., 2005) noted the asymmetry warming at a seasonal level (winter more than summer) and diurnal (night more than day). The seasonal asymmetries matter for a perennial with a seasonal growth pattern like the grapevine and warming at day and night are likely to have different physiological impacts. Table 1 shows that for SE Australia, linear trends indicate a greater warming in day than night and that autumn and winter minimum temperatures show no trend. The slower trend in minimum temperatures could be associated with clear night skies across the large inland regions consistent with the more recent drier conditions. SW Australia shows significant linear trends in winter spring and autumn nights and winter and spring

days but no significant trend in summer. The Fourth assessment round (IPCC 2007) noted that although a decrease in diurnal range was previously reported the analysis of more recent data indicate day and night temperatures have risen at about the same rate. They also point out that the trends vary considerably from region to region. The broad analysis shows regional and seasonal variation, but is consistent with an overall warming. The maximum and minimum summer (Dec-Feb) temperatures for SW (Figure 3) and SE Australia (Figure 4) show a summer warming trend for SE but not SW Australia. One of the most striking features of the time series in Figures 2-4 is the year-to-year variability. This is a theme that we shall return to later in the paper.

Table 1. Trends and measures of variability for annual mean temperature and minimum and maximum temperature for summer (DJF), autumn (MAM), winter (JJA) and spring (SON).

SE Australia	Trend			Variability		Range in 2 yr period			Range in 3yr period		
	degree/10yr	R Sq	p value	St Dev	IQR	10th	Med	90th	10th	Med	90th
Annual mean T	0.13	0.25	<0.01	0.4	0.6	0.1	0.4	0.7	0.3	0.6	1.0
Summer max T	0.18	0.09	0.023	1.0	1.6	0.2	0.8	2.1	0.6	1.4	2.4
Autumn max T	0.16	0.17	0.001	0.7	0.8	0.1	0.6	1.3	0.4	1.1	1.6
Winter max T	0.17	0.19	0.001	0.7	1.0	0.1	0.7	1.6	0.6	1.1	1.8
Spring max T	0.18	0.09	0.021	1.0	1.3	0.2	1.2	2.1	0.7	1.6	2.5
Summer min T	0.17	0.10	0.017	0.9	1.2	0.2	0.9	2.0	0.7	1.4	2.4
Autumn min T			ns	0.8	1.0	0.2	0.8	1.9	0.5	1.1	2.3
Winter min T			ns	0.5	0.7	0.1	0.4	1.3	0.2	0.8	1.6
Spring min T	0.13	0.15	0.003	0.5	0.8	0.2	0.6	1.2	0.4	0.8	1.4

SW Australia	Trend			Variability		Range in 2 yr period			Range in 3yr period		
	degree/10yr	R Sq	p value	St Dev	IQR	10th	Med	90th	10th	Med	90th
Annual mean T	0.14	0.18	0.001	0.6	0.9	0.1	0.5	0.9	0.3	0.8	1.2
Summer max T			ns	0.8	0.8	0.0	0.6	1.1	0.4	1.1	1.4
Autumn max T			ns	0.8	0.8	0.0	0.6	1.1	0.4	1.1	1.4
Winter max T	0.14	0.13	0.006	0.6	0.7	0.1	0.7	1.0	0.4	1.0	1.3
Spring max T	0.11	0.05	0.091	0.8	0.8	0.2	0.9	1.4	0.3	1.3	2.0
Summer min T			ns	0.7	0.9	0.0	0.6	1.0	0.4	1.0	1.4
Autumn min T	0.20	0.16	0.002	0.8	0.9	0.1	0.8	1.3	0.6	1.3	1.7
Winter min T	0.13	0.11	0.011	0.6	0.9	0.1	0.6	0.9	0.3	0.9	1.4
Spring min T	0.14	0.13	0.015	0.6	1.1	0.2	0.6	1.0	0.5	0.9	1.2

Although global and regional temperature records make striking headlines, it is the decadal droughts in South Eastern and South Western Australia and the link between climate change and water that has had a dramatic influence on public thinking and has focussed the attention of many in the wine industry. Few enterprises are more vulnerable to shortages in water allocations than high value perennial horticulture designed around a secure supply of irrigation water. In the period from June 2006 to early April 2007 inflows into the River Murray were 60% less than the previous minimum. Given the priority for urban, stock and domestic supplies, the possibility of zero irrigation allocations have been raised leading the Prime Minister to announce in April 2007 that we had reached an unprecedented and ‘dangerous’ situation and drew attention to the devastating impact on irrigators especially perennial horticulture and dairy (Prime Minister of Australia, 2007). The extent of the allocations for the 2007-08 water year depended entirely on the amount of runoff during the winter and spring of 2007. A number of years of above average rainfall is required to return storages to long term average levels.

Time series of rainfall for SE and SW Australia are shown in Figures 5 and 6 respectively. Although the very dry conditions of 2006 and 2002 stand out, there is no strong linear trend in SE Australian rainfall. In SW Australia there is a drying trend of 8mm per decade (Figure 6a) with a strong seasonal bias towards the autumn/winter period (Figure 6c and 6d). The impact of this drying on runoff and water supply in SW Australia has led to its identification along with the Murray Darling Basin and the Great Barrier Reef as one of the key vulnerabilities and focus areas for climate adaptation research (Allen Consulting Group, 2005). While there seems to be a weak but accelerating trend towards hotter and drier conditions, any adaptation strategy that only considered a hotter and drier future without considering variability would have been found wanting in the wet and cool 2006 vintage in WA.

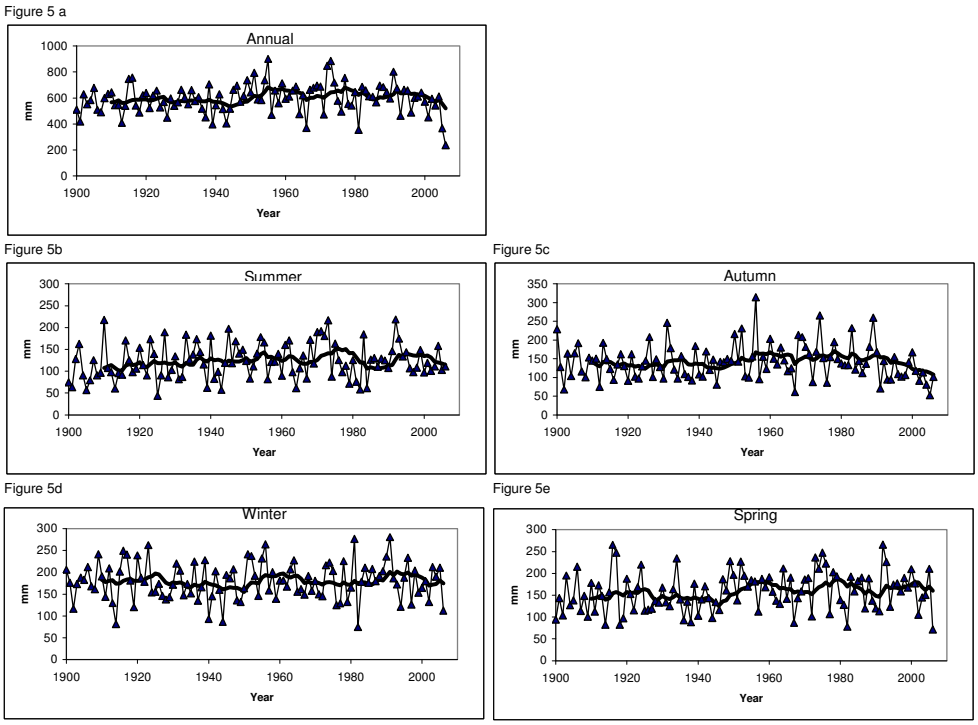


Figure 5. Time series of SE Australian rainfall a) annual b) summer c) autumn d) winter and e) spring. Solid line is moving average of the 11 previous years.

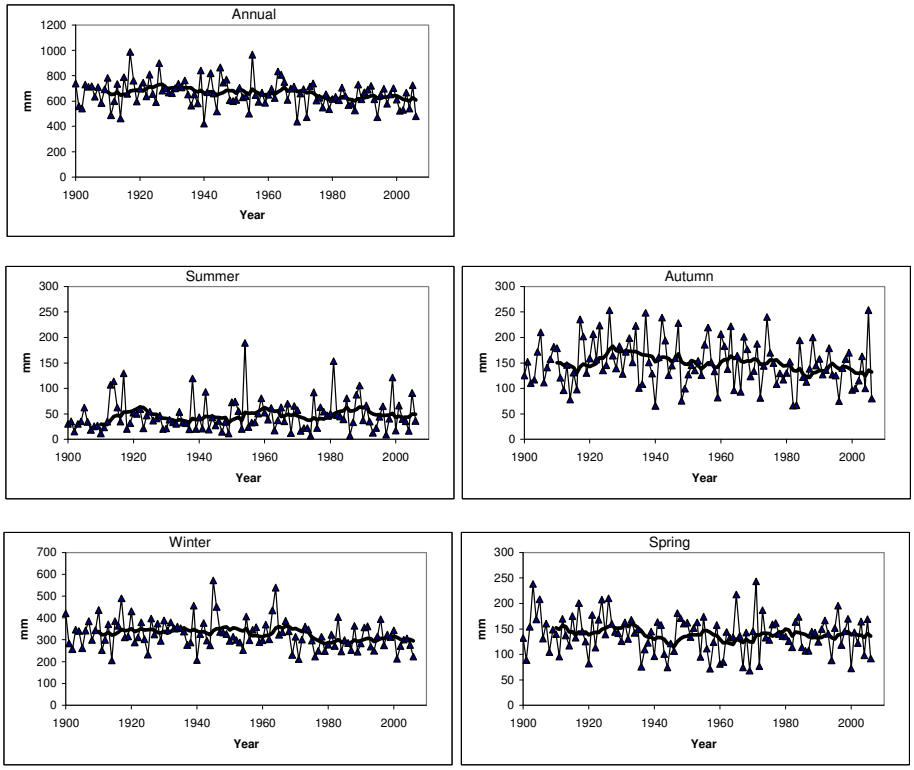


Figure 6. Time series of SW Australian annual summer, autumn, winter and spring rainfall. Solid line is moving average of the 11 previous years.

The exact role of climate change in the recent Australian drought is contested and an active area of research. There is evidence that droughts are hotter for the same rainfall deficiency but it is more difficult to detect a trend against the year-to-year and decade-to-decade variability in Australian rainfall (Meteorology, 2006). The current drought is consistent with a drying trend in most global climate projections for southern Australia (Suppiah *et al.*, 2006). Although using a single episode like the recent drought as proof of climate change is unwise, this drought has highlighted the extreme vulnerability of both dryland and irrigated farming to climate.

Climate and viticulture

Wine production is well understood to be the interaction of variety, soil, climate and culture. These are usually considered as constant or very slow moving variables. The exception is culture, which can be fast moving (especially technology in viticulture and oenology) which and will modify simple relationships between wine production and the environment. Australian viticulture is a case in point especially the production of popular premium wine across the warm inland regions (McKenzie, 1986) for a discussion of some of the innovation). An analysis of the returns to research and extension in the South Australian wine industry showed that about

half the 60:1 benefit-to-cost ratio was due to improvements in quality (Black and Dyson, 2006). Recent studies by (Jones *et al*., 2005) on a global scale and (Sadras *et al*., 2007) in an Australian context show that despite recent warming, wine quality has improved. In some cases this is because warming has been beneficial, but even in regions that are already warm to hot, quality has increased or been maintained.

There are many indices that can be used to link climate to viticulture such as Heat Degree Days HDD, Mean January Temperature MJT, biologically effective day degrees BEDD, Latitude temperature index, Homoclime approaches and Growing Season Temperature GST (Gladstones, 1992). All indices can be used for regional comparison, some can be used to compare vintages. (Davidson, 2004) maintained that biologically effective day degrees (Gladstones, 1992) was the most comprehensive temperature-time measure used in Australian viticulture. However, because BEDD limits summation to between 10 and 19^{o}C it is less suitable for studies of warming.

Textbooks and popular articles on climate and viticulture in Australia have tended to emphasise how climatic variables such as mean January Temperature or Growing Season Temperature vary between *regions* more than the variability between *seasons*. Central to the argument of this paper is that we can learn from both sources of variability. Where there is a reference to variability as part of an index it tends to be diurnal or seasonal (Gladstones, 1992; White *et al*., 2006). This tendency to emphasise the mean of climate variables recorded over years is not exclusive to viticulture. Hutchinson, Nix and McMahon (1992) acknowledged that classification systems such as theirs based on long-term mean monthly data had a "*serious deficiency, since locations with very similar plant growth response patterns based on long-term mean data can have very different probabilities of cropping success."* Commonly used software for bio-climatic analysis Bioclim, Climex and GARP are used with long term average monthly data (Gallagher et al 2006). While it is possible to compare a single year to other years, the variability is not explicitly considered.

Table 2 lists the rules used in some recent climate change studies The authors give thoughtful arguments for their choice of indices including the limitations. Table 2 also lists the growing season temperature optima for a range of varieties. The value of the information in tables such as this is the discussion it promotes. In any discussion of risk, much is gained by quantification. Growers, especially those in regions with a GST greater than 20 degrees, will be quick to point out varieties like Chardonnay in Australia seem to be more climatically elastic than indicated on Table 2.

Table 2. Summary of variables used to identify warm thresholds for viticulture

White *et al*. 2006	Growing season average temperature less than 20°C Growing degree days less than 2499 Days over 35°C; 14 for heat tolerant variety, 7 for heat susceptible											
Jones *et al.* 2005	Optimum for warm region production of quality wine 18°C to 19.9 °C degrees GST											
Smart 2006	Warning that 24°C MJT is hot limit for wine production and 26 °C MJT describes Menindee Table Grape production											
Webb *et al.* 2005	A model based on price and quality from different regions was used to derive an optimum temperature for returns per hectare. For example Cabernet sauvignon a quadratic function with an optimum MJT of 22. A 10% decline for MJT 23°C and 20% decline for MJT 24°C and 50% decline at MJT 25°C.											
Jones 2006	High to premium quality wine production in world's benchmark regions for each variety											
Growing Season Temp	13	14	15	16	17	18	19	20	21	22	23	24
Pinot Gris	X	X	X									
Riesling	X	X	X	X	X							
Pinot Noir		X	X	X								
Chardonnay		X	X	X	X							
Sauvignon Blanc			X	X	X	X						
Semillon			X	X	X	X						
Cabernet Franc			X	X	X	X	X					
Tempranillo				X	X	X	X					
Merlot				X	X	X	X					
Malbec				X	X	X	X					
Voignier				X	X	X	X					
Syrah			X	X	X	X	X					
Table Grapes				X	X	X	X	X	X	X	X	X
Cabernet Sauvignon				X	X	X	X	X				
Grenache				X	X	X	X	X				
Carignane					X	X	X	X				
Zinfandel					X	X	X	X	X			
Nebbiolo					X	X	X	X	X			
Raisins						X	X	X	X	X	X	X

Some observations on year to year variability

To compare climate and climate variability across a limited number of Australian wine regions we have selected individual climate stations in a transect of viticultural regions from cool to warm to hot. The regions selected were Coonawarra in South East South Australia (MJT 19.4, GST 16.7) Nuriootpa in the Barossa valley (MJT 21.4 GST 18.2) Loxton in the South Australian Riverland (MJT 23.3 GST 20.0) and Griffith in NSW Riverina (MJT 24.8, GST 20.9). The range of MJT and GST span the relevant parts of Table 2 with Loxton on the margin and Griffith on the hot side of the margin. The time series of GST for the four sites are shown in Figure 7 and MJT in Figure 8. A noticeable feature of these graphs is the year-to-year variability.

Fig 7

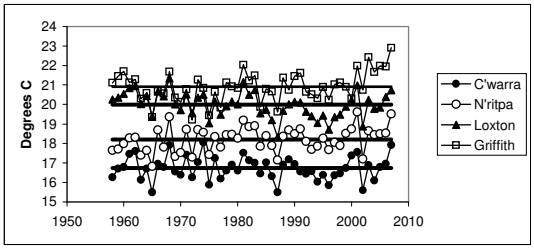


Fig 8 a

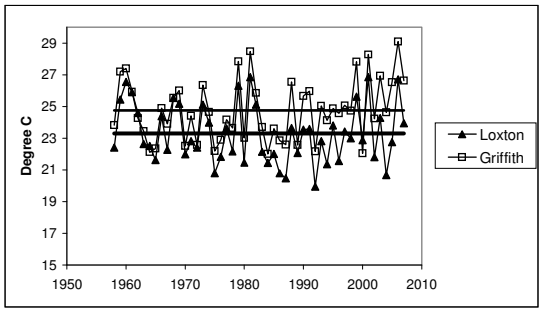


Fig 8b

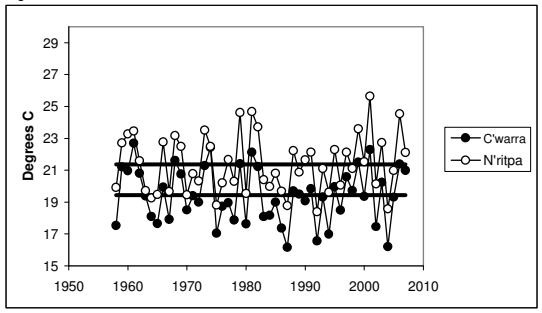


Figure 7. Time series of Growing Season Temperature for Coonawarra, Nuriootpa, Loxton and Griffith.

Figure 8. Time series of Mean January Temperature for a) Coonawarra and Nuriootpa and b) Loxton and Griffith.

1. The variability in the time series of temperature is large relative to the modest linear trends over the last 50 to 100 years

As discussed earlier, linear trends in temperature differ between regions and seasons but are in the order of 0.12 to 0.2 ºC/decade. Table 1 also shows a number of conventional measures of the variability, the standard deviation and inter-quartile range (difference between 25th and 75th percentile). The decadal trend is between a 1/3 and 1/5 of the standard deviation and 1/10 and 1/5 of the inter-quartile range.

Another way to consider the variability is to consider pairs and triplets of years in the historical record. The vine is a perennial crop with yield and quality in any given year influenced by that season and the preceding one or two seasons (May, 1987). Whether the appropriate period is two or three years is likely to differ according to the particular stress. If we ask what is the range of summer maximum temperature that a vine has experienced in any three year period in SE Australia the result is a distribution of ranges with a median of 1.4 degrees with the 10^{th} percentile of the 0.6 degrees and 90^{th} percentile 2.4 degrees (In SW Australia the median is 1.1 degrees 10^{th} and 90^{th} percentile are 0.4 and 1.4 degrees). As might be expected, pairs of years do not show quite as wide year-to- year range as a three year period, but even considering the least variable time series (annual mean temperature), for SE Australia, the median year to year variation is 3.5 times greater than the decadal trend. For this same time series the median range for any three-year period is 5 times the trend. The equivalent ratios for SW Australia are 3.7 and 5.7. This does not discount the linear trend, it just makes it harder to find. It also points to the considerable year-to-year variability that the vine, viticulturalists and wine makers have to cope with.

2. The variability in the time series of temperature is a similar magnitude to the more rapid rise in temperature in the last decade

Variables such as SE Australian maximum temperatures have risen faster in the last decade (Figures 2 and 3). This is consistent with 4 of the 10 warmest years being this decade. This rise in summer temperature (about a degree in the last decade) is worrying and noteworthy. However even this dramatic rise is about one standard deviation of summer maximum temperatures over the 50 year period and 70% of the median range in any 3 year period. Variability is still an important part of the story with 5 warm years but 2 cool years and in SW Australia, 2005 was the coolest year on record. The hot European summer of 2003 was in the order of 3 standard deviations above expectation.

3. The variability in the time series of climate indices is a scale that is significant relative to wine temperature classifications based on MJT, or GST

Figure 9 shows the cumulative density function for Growing Season Temperature and Mean January Temperature for different regions. The variability for Growing Season Temperature spans a range of about 2 degrees for each region, 17.5 to 19.5 for Nuriootpa in the Barossa and 19 to 21 for Loxton in the SA Riverland. These changes are significant against the warm edge of varieties shown in Table 2. All locations span about 5 degrees in MJT. This range is considerable given that Webb et al 2003 found a 50% decline in per hectare returns for Cabernet Sauvignon from different regions with means ranging from 22 to 25 degrees (the decline in quality could be much greater as there is some compensation in yield with increasing temperature).

Figure 9a

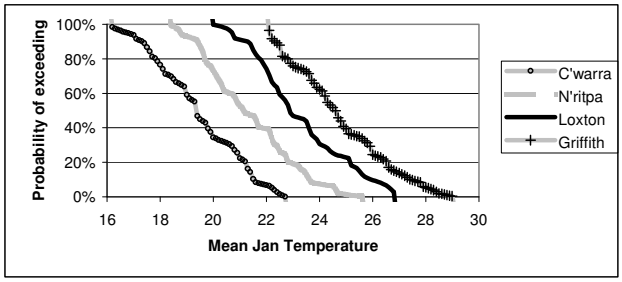


Figure 9b

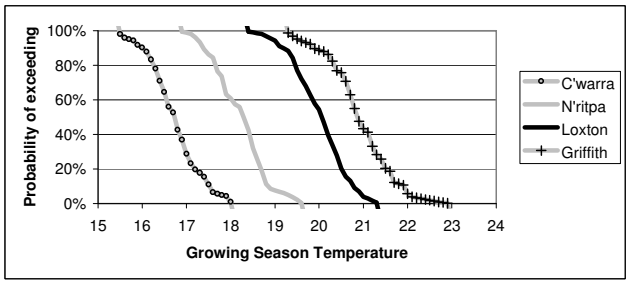


Figure 9. Cumulative density functions of a) Mean January Temperature and b) Growing Season Temperature for Coonawarra, Nuriootpa, Loxton and Griffith.

The interquartile range for GST is about 0.7 to 0.9 degrees and for MJT is almost 3 degrees. In any 3 year period the median range in growing season temperature is about 1 degree and MJT about 3 degrees. Implicit in the use of long term average MJT or GST for a region is that there will be a distribution of yearly values. However, in most climatic analyses (in viticulture and many other fields of bio climatic analysis) this is not explicitly shown.

4. The variability in the time series of climate indices is significant relative to the transect of locations

The regions of Coonowarra, Nuriootpa, Loxton and Griffith span from cool to warm to hot. Yet the time series of MJT show that although there is a difference in the means of these locations, there is considerable overlap (Figure 8). This overlap is more clearly shown in Figure 9 where 20 % of the warmest years in one location exceed the median of the adjacent warmer region. In general the warmest 25% of a region overlaps the cooler 25% of the adjacent warmer region. The time series in Figures 7 and 8 show that this overlap has been a feature of these regions for at least 50 years. Figure 9 shows that the extent of the overlap is greater for MJT than GST.

5. The variability is significant relative to the projections of climate change over the next 30 years

The upper end of the envelope of future projections of global warming is exponential with a strong separation after 2030. In the immediate decades it will be

difficult to separate the trend from variability, this is why most climate change projections are given for periods after 2030. For most wine regions the expected warming is in the order of 0.3 to 1.7 C to 2030 (Webb *et al.*, 2005) in the decades leading up to this time these changes are likely to be noticeable, but difficult to detect from year to year variability. In contrast the expected higher level and rate of change in the latter half of the 21st century will be clearer, especially if warming tracks the upper end of the projections.

6. The variability in GST explains some of the inter-seasonal range in quality

Any regional measure of wine quality is controversial (Sadras *et al.*, 2007). Figure 10 shows a weak but significant correlation between GST and red and white wine scores from Halliday's for the 26 year period from 1980 to 2005 (see Sadras *et al.*, 2007 for a full description of wine score data). There are fewer scores of 9 or 10 at the higher end of the temperature range for any given region, and fewer lower scores at the cooler end. The actual value of the GST is less meaningful than the relative value, so a season with a GST of 20 leads to lower scores in Nuriootpa and higher scores in Loxton. Care must be taken not to over interpret this data, for a more sophisticated analysis see Soar *et al.*, (2007). The simple point for this paper is that within a region, cool to warm years measured crudely with GST seems to show some impact on the crude measure of regional wine quality scores.

Figure 10

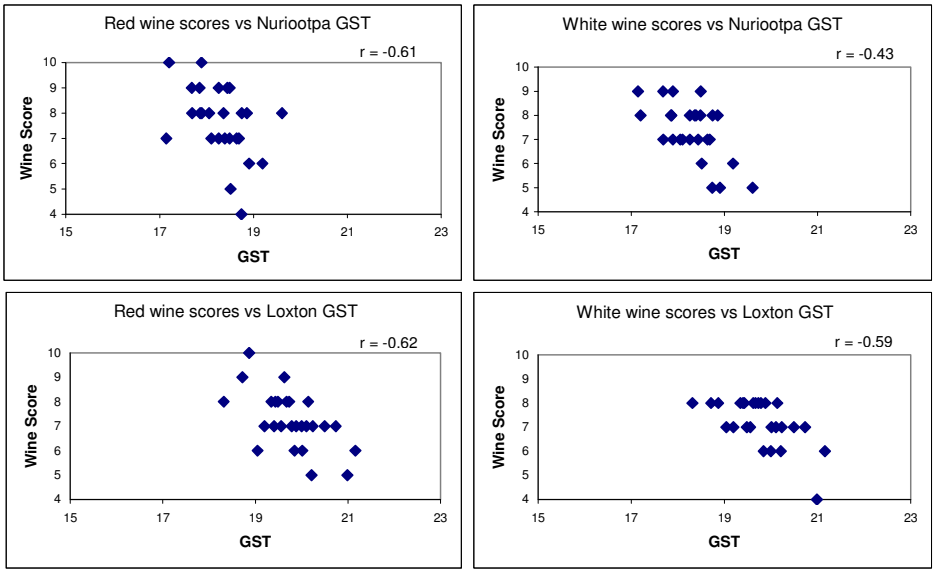


Figure 10. Wine scores for red and white wine from Hallidays and Growing Season Temperature for Griffith and Loxton.

It is interesting to note in passing that in the popular premium price category the industry does not seem to distinguish between fruit from Loxton and Griffith, all the scores were bulked into Riverina. Yet Griffith has a MJT about 1.5 degrees warmer and a GST 1 degree warmer than Loxton.

7. Variability is the likely mechanism for climate change to damage viticulture

Although the variability makes if difficult to define dangerous climate change, it is the variability that is likely to be the main source of danger. In analysing the impact of climate change it has long been recognised that variability is more important than averages (Katz and Brown, 1992). In a climate change study on wheat in the US, (Mearns *et al*., 1997) showed a reduction in simulated yield associated with a rise of 2 degrees with constant variance. Using the same mean warming they found the yield loss increased with higher variance and was ameliorated with decreased variance.

The changes to the frequency of extreme events is an active area of research (Nicholls and Alexander, 2007) and is the main focus of interest from the insurance industry and emergency services for example bushfire risk or storm surges. The resilience of a system is likely to be sensitive to the frequency of stressors. For example two to three hot years in 10 may be manageable now, but 5 in 10 will present a much greater challenge.

Summer is generally more variable than autumn and if the time between phenological stages quickens, this will increase the extent and variability of temperature during ripening, including greatly increasing the chance of damaging heatwaves (Webb et al 2003). Although there is high confidence that the severity and frequency of heat waves will increase, local Bureau of Meteorology data for Adelaide show more heatwaves (35ºC on five consecutive days or 40ºC on three) in the first half of last century than the second half (Szkup and Brooks, 2006). This finding is likely to be sensitive to the exact definition of heat waves and may be a local anomaly. Nevertheless, decadal variability cannot be ignored, especially in the coming decades.

In the previous section we make a number of observations about climate variability in viticultural regions. From the perspective of analysing climate trends, this year-to-year variability is noise and contains limited information. This variability does not challenge the notion of unequivocal warming because it is taken into account in the thousands of climatic analyses that are collated for the IPCC Assessments. However, when seeking to answer the more applied questions of impacts and adaptation, this variability is a rich source of information on vulnerability and resilience to future change.

Adapting to Climate Change

A common way of considering the impact adaptation and vulnerability of climate change is to consider on one hand how sensitive and exposed a system is to climate and use this to determine impact, but also consider adaptive capacity and how this counters the impact. The vulnerability (sometimes referred to as residual vulnerability) is the impact that cannot be managed by current levels of adaptation (IPCC, 2001). This approach to vulnerability is valid but has been critiqued for an over emphasis on biophysical factors and insufficient recognition of social and economic factors that provide multiple exposures to vulnerability (Fussel and Klein,

2006). An interesting case study of multiple exposures for viticulture in the Okanagan valley Canada (Belliveau *et al.*, 2006) pointed to the dynamic nature of vulnerability and how more climatically suited varieties can minimise climate risk but increase market risk. They warned against treating climate as the only or even major source of risk.

The Allen Consulting Group (2005) suggested that the three characteristics of agricultural systems most at risk from climate change would be

1. systems already stressed – economically and or biophysically
2. those at the edge of their climate tolerance; and
3. those where large and long lived investments are made – such as in dedicated irrigation systems, perennial crops and processing facilities.

Much of Australian viticulture is at the warmer boundary and there are reports of wineries making decisions to source fruit and re-plant in cooler sites (Hooke, 2006; Allen, 2007). In their analysis of 27 quality wine regions in the world, (Jones *et al.*, 2005) listed three Australian regions Margaret River, (GST Growing Season Temperature 18.6), The Hunter Valley (GST 19.8) and the Barossa (GST 19.9) as the 21st, 23rd and 24th warmest regions respectively. There is no doubt viticulture in Australia is under stress economically and biophysically with reports of desperate grape growers selling water (ABC, 2006) or working on mines (Ackerman, 2007). The impacts of the 2006/07 season are likely to be felt in a low 2008/09 harvest. Clearly viticulture has a long planning horizon which takes vines planted today well into the period of climate change projections (2030 to 2070). While the industry can rapidly change varieties by topworking there is a risk of stranded assets, if not for varieties, for infrastructure at the farm, regional and industry level.

Before discussing the adaptive capacity of the industry it is important to note that there is a level of climate change that will be almost impossible to adapt to. In a discussion of dangerous climate change (Mastrandrea and Schneider, 2004) suggested five areas of concern from climate change

(I) damage to unique and threatened systems,
(II) damage from extreme climate events
(III) distribution of damage
(IV) aggregate impacts
(V) damage from large scale discontinuities such as melting of ice sheets

Some would argue that we have reached domain I now and as global temperatures rise further areas of concern are added. While all wine regions are unique, there are some that have a particularly high value because of their geographic position. While the industry as a whole could survive by sourcing fruit from other regions, the loss of specific mesoclimates in super premium regions is likely to occur in domain I. In domain II extreme climate events such as heatwaves, droughts and bushfires are likely to be more common. In domain III there are still winners and losers whereby some regions benefit from warming and others have expensive adaptation costs. But as temperatures rise the number of areas benefiting are likely to be fewer. In domain IV much of the wine industry, but also the national and global economy is likely to be adversely affected and it becomes difficult to carry current assumptions about prices, global demand and transport costs and infrastructure forward. If we reach domain V it is no longer sensible to ask what variety of grapes

to grow in the Adelaide hills when Port Adelaide is under water and the global economy is in disarray. Some of the suggested tipping points for domain V (eg 1.5 degrees warming for Greenland Ice Sheet (Schellnhuber, 2006) might be lower than what would cause severe disruption for some of the more robust wine regions.

If climate impact studies are to move beyond projections of likely damage it is necessary to engage decision makers in the process of adaptive management (Fussel and Klein, 2006). As part of a small project with the South Australian Wine Industry Association funded by GWRDC we asked groups of viticulturists in the Riverland, Mildura, Clare and McLaren Vale to rank the impact on their enterprises of a series of changes in mean and extreme temperature and reduced water supply. Not surprisingly, the quality and quantity of water was the main concern. What was surprising was the relatively low rank given to a 1.5 to 2 degree rise in temperature. Of more value than the survey was the discussion that followed. The strongly held opinion seemed to be that a rise in temperature could be managed, providing there was adequate water. In some cases this might involve redesigning irrigation systems to provide more water per day, in other regions such as Clare it may involve a greater emphasis on storing winter rainfall in the soil profile. In Mildura there was also some discussion of vineyard cooling but the availability of quality water and sprinkler was seen as a limiting factor (see review by Swinburn, 2003). There is much to be learnt and researched, however viticulturalists raise ideas of row direction, canopy configuration, vineyard floor management, artificial shading and the use of rootstocks with greater drought tolerance as adaptation options along with new varieties.

There has also been discussion of better using and manipulating meso-climates. (Oke, 2006) studied the within vineyard block temperature on the Mornington Peninsula and found a range of 2.6 ºC in minimum and 1.2 ºC in maximum temperatures in March 2004. (Winter *et al*., 2007) monitored bunch-zone temperature in NE Victoria, and showed that in 2006 (a hotter summer) by having two leaf layers on the northern side of east west rows the bunches didn't reach as hot temperatures as 2005 (a cooler summer). They maintained that loggers could be used to track and avoid heat loads on bunches as a possible adaptation to global warming.

Discussions with viticulturists in the Riverland and Mildura indicated a strong sense of confidence in adapting to climate change – providing there was access to water and reasonable prices. (Gange, 2007) cites Sunraysia winemaker Bob Shields "The quality of production in our region has remained good in a range of hot and cold seasons in the past 10 years – the region has become very good at adapting to hot weather, using techniques such as night harvesting."

The short answer to the question of what is dangerous climate change to viticulture is that we don't know. Research on some of the obvious causes of stress are accumulating and questions of water stress can be built on a large amount of previous research. However the climatic elasticity of different varieties and the direct impact of carbon dioxide are only partly understood, as are the likely impact of pests and disease (Seem *et al*., 2000; Salinari *et al*., 2006). There are also likely to be indirect effects for example (Tate, 2001) noted CO2 induced changes in oak morphology, which has in turn has consequences for barrel texture and wine

quality. Other indirect impacts through more competing demands for water from urban users and environmental flows or international consumers concern about 'green miles'. The South American industry has had a positive benefit from the large amount of corn in the US being used for biofuels opening up a market for grape sugar concentrate.

An interesting perspective on climate change in California was raised by (Lobell *et al*., 2007) in a comparison of a range of horticultural enterprises, including grapes to warmer temperatures. They pointed out that the main asset was the irrigation infrastructure and arable land. They found the main impact of warmer temperatures would be more grapes grown as other horticultural crops suffered. Given the scientific knowledge and practical skill base in Australia to grow grapes with limited water, it is possible that, depending on relative prices for alternative enterprises, water shortages may favour grapes.

Concluding remarks

Predicting when and why systems collapse is inherently difficult, looking at past variability provides only partial insights on future vulnerability. Schneider (2006) estimates that there is about a 10% chance of what he describes as truly catastrophic climate change, 5 degrees warming over the next century or two. It is hard to imagine viticulture in Australia adapting to anything but the mild to moderate projections for the rate and extent of warming and drying. Considering the moderate spectrum of projections especially in coming decades, it is a challenge to identify critical or 'dangerous' thresholds because clever adaptable people have coped with past variability and are likely to do so in the future.

In discussion with viticulturists as preparation for this paper a number remembered back 20 years to May's description at the 6th Australian Wine Technical of the grapevine as a perennial plastic and productive plant. It is good to be reminded that the perennial nature points to vines older than a century which have lived through considerable stress and variability, the plastic nature points to the wide range of environments in which vines can grow and the way that vines seem to cope with extraordinary levels of stress. Ten years ago at this conference Halliday compared the strengths and weaknesses of the Australian industry with other countries and noted that the Australian industry was youthful and dynamic and unrecognisable from 30 years ago (adaptable), but that there were six generation winemaking families (perennial). Climate change will further test this perenniality and adaptability at the vine, vineyard winery and industry level.

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Chapter 12

Understanding heatwaves in South East Australian wine regions

W Grace and PT Hayman

Summary

The 2008 vintage in southern Australia will be long remembered for the extraordinary March heatwave. Some early varieties and regions were harvested prior to the heatwave, but many experienced quality downgrading and loss in yield, and some blocks were not harvested. The logistical challenge for the industry in handling the grapes was enormous.

Figure 1 from the Bureau of Meteorology shows that for the first 17 days of March, the mean maximum temperature was up to 10ºC or more than average for that time of the year. Two unusual features of this heatwave were its length, and its timing in mid-March rather than summer. Figure 2 shows the daily maximum values for the 2008 vintage at Nuriootpa in the Barossa. In the March heatwave, Nuriootpa experienced 13 consecutive days above 35ºC, exceeding its previous record of 10 days. According to the Bureau of Meteorology, Adelaide had 15 consecutive days over 35ºC which broke the previous record by 8 days and 13 consecutive days over 37.8ºC (100º F), breaking the previous record by 7 days.

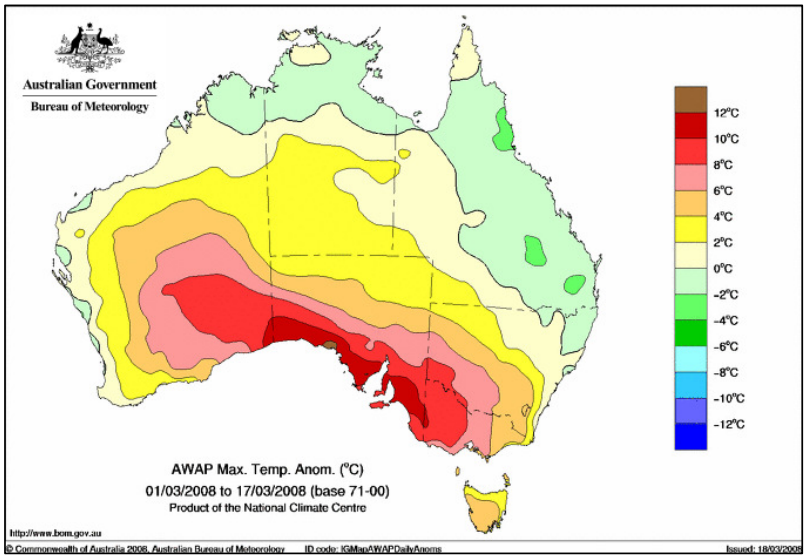


Figure 1. Maximum temperature anomalies for the period 1 to 17 March 2008. Figure courtesy of the Australian Bureau of Meteorology.

For winegrape growing the timing of heatwaves is important. Figure 2 shows that there was a heat event at the end of December and early January but that most of January and February was quite mild.

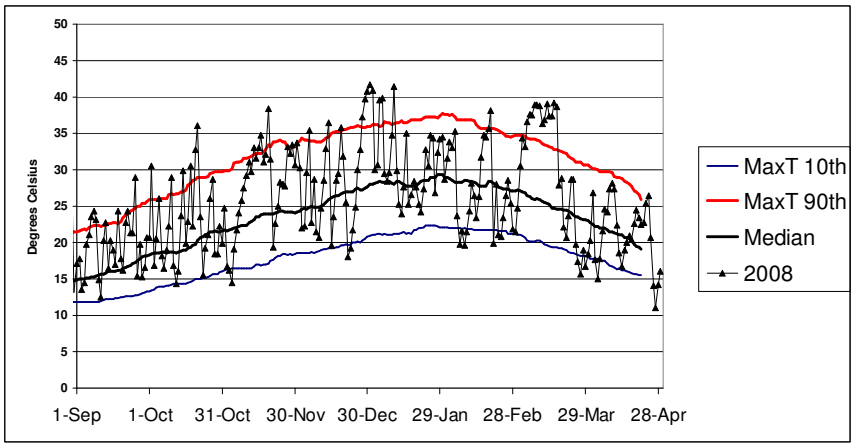


Figure 2. Daily maximum temperatures for Nuriootpa in the Barossa Valley. The red line is the 1 in 10 warmest and the blue line is the 1 in 10 coolest for the 1961 to 1990 period, and the bold line is the median (50th percentile).

In February 2004 there was a significant heatwave which was not as severe as the March 2008 heatwave, but had a major impact on earlier varieties and caused logistical problems for vineyards and wineries. Heatwaves raise issues of occupational and health issues for workers in the vineyard and people dealing with harvesting and handling compressed vintages. Of all natural disasters in Australia, heatwaves are ranked as the most lethal. It is estimated that 438 people died as a result of the January 1939 heatwave in South Australia, Victoria and NSW. Because of the human health aspects of heatwaves and the widespread interest from agriculture, water and energy suppliers there will continue to be a substantial effort to study and understand heatwaves. The Bureau of Meteorology provides valuable information on heatwaves and was very active in the media during the March 2008 heatwave. The purpose of this article is to provide a basic knowledge of the meteorology of heatwaves in wine grape growing regions of South Australia by answering three questions.

1. What is a heatwave?
2. What weather patterns lead to a single hot day in the wine regions of SE Australia?
2. What leads to a run of hot days in wine regions of SE Australia?

What is a heatwave?

There is no general definition of a heatwave beyond the notion of a run of unusually hot days. Just as what is considered a drought is different in England and Australia, a heatwave in London is not the same as a heat wave in Adelaide. The South Australian Regional Office of the Bureau of Meteorology uses a locally accepted definition related to Adelaide, either 5 consecutive days with maximum temperatures above 35°C or 3 consecutive days with maximum temperatures above 40°C.

With this definition the 118 year period of records shows that heat waves occur on average 1 year in 3 and mostly in January or February with a few in December and

March; and 10 years had multiple heat waves (generally 2, but 3 during the summer of 1907/08).

What weather patterns lead to a hot day in the wine regions of SE Australia?

Summer weather across south-eastern Australia is largely determined by the position and strength of large slow moving high pressure systems or anticyclones. Gentilli in his 1972 description of Australian climate observed that the *"regular rise and fall of temperature with the going and coming of anti-cyclones is one of the most characteristic features of Australian summer weather."* These high-pressure systems are about 2,000 to 3,000 km across and usually take 5 to 7 days to cross Australia from west to east. One of the keys to reading a weather map is to follow the anti clockwise movement of air around high-pressure systems and the clockwise movement around low-pressure systems. For most wine regions in SE Australia, the leading edge of a high pressure system will be bringing cool air from the Southern Ocean, the following days warm up as the middle of the high pressure system brings stable still conditions and the trailing edge brings the hot inland air. With typical Australian irony this hot northerly wind is colloquially referred to as the Darwin doctor (in contrast to the Fremantle doctor) or the Alice Springs sea breeze.

These large high-pressure systems move from west to east at about 600 km per day (25km/hr), but the movement is not constant, they change shape and intensity and move more quickly over land and tend to settle in the Great Australian Bight or the Tasman Sea. If you look at a weather map in the middle of summer there is almost always a high-pressure system in one of these two positions. As can be seen from Figure 3 a high-pressure system in the Bight will bring cooler maritime airflow over Southern Australia while a dominant high in the Tasman Sea gives a warmer continental overland airflow to SE Australia. Analyses of Adelaide summer weather by the Bureau of Meteorology have shown that cooler than average summers tends to have a greater portion of high pressure cells in the Bight region and warmer summers have a greater portion in the Tasman.

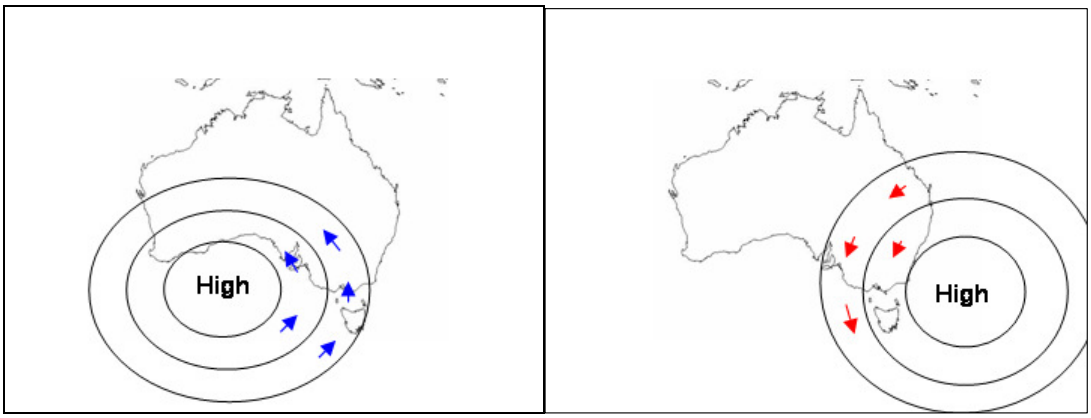


Figure 3. Schematic of airflow patterns affecting Adelaide and vicinity due to either of the dominant high pressure cells according to their commonly favoured positions in the Bight (left) and in the Tasman Sea (right).

But what causes a run of hot days?

The old saying “if you don’t like the weather wait a few days; if you don’t like the climate, move” captures the sense that weather changes on a daily basis. Although the movement of high-pressure systems leads to a run of fine and warm days, they don’t explain a run of exceptionally hot days. For this to happen the high-pressure system needs to stay in the same position. This is what meteorologists refer to as blocking. The process of blocking is responsible for many notable weather events around the world such as heatwaves, prolonged cold spells, floods and prolonged dry periods.

For wine regions in south-eastern Australia, summer heatwaves occur when a high pressure system is blocked in the Tasman Sea. This is where the pattern that is seen in Figure 4 persists and is strengthened. A high-pressure ridge from this Tasman Sea high will usually extend across New South Wales and/or Queensland. The high in the Bight is much weakened, or non-existent, and the trough (low pressure) in Western Australian longitudes is typically broadened and strengthened. This pressure pattern produces a weak but persistent north-easterly stream over eastern South Australia. During this time, frontal systems which move into the trough to the west will weaken and be steered southeast as they move into South Australian longitudes. Eventually the system weakens and a front or surface trough will move across southern South Australia, bringing with it long awaited southerly winds and the associated cool change.

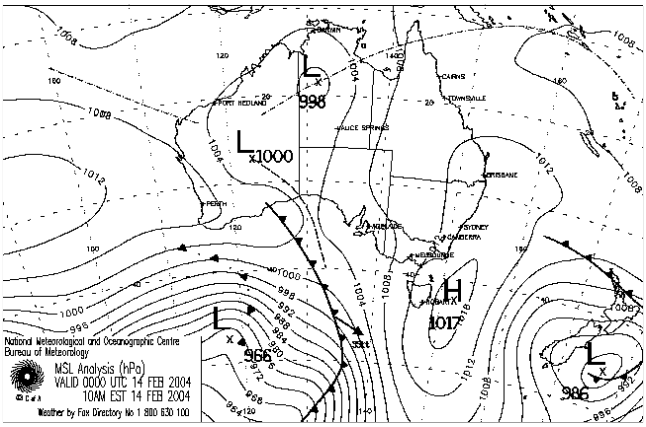


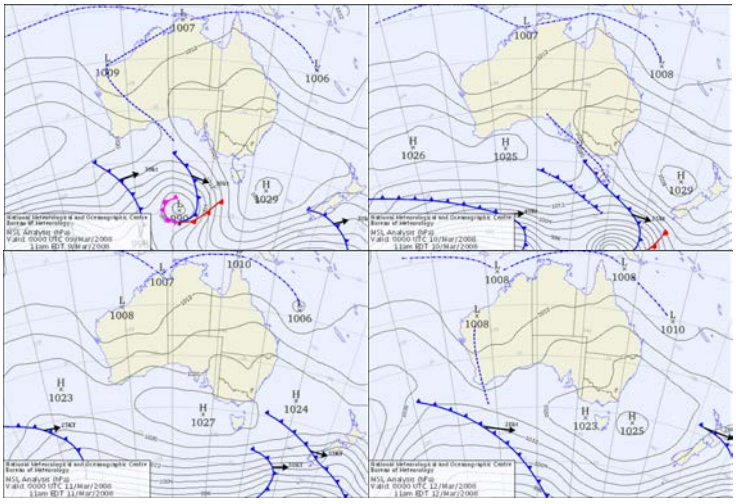
Figure 4. Typical Mean Sea Level (MSL) pressure synoptic pattern associated with a heat wave over south-eastern Australia. This chart shows the Tasman Sea high extending a ridge over south-eastern Australia directing a hot north-easterly stream over inland New South Wales, Victoria and eastern South Australia. A broad low-pressure trough is evident over Western Australia. The Tasman Sea high, reinforced by an upper ridge ‘blocks’ eastward movement of the front causing the front to weaken as it slips to the south east. Figure courtesy of the Australian Bureau of Meteorology.

So far we have identified that the clue to understanding heatwaves is first to be able to recognise that a *hot day* is caused by a high in the Tasman and second that a *run of hot days* is caused when this high pressure system in the Tasman is blocked. This raises the question: what causes blocking?

To understand blocking we need to go beyond the familiar surface weather chart and consider a three dimensional view of the atmosphere, especially the jet stream. Prior to WWII planes flew relatively low and the presence and importance of jet streams was not realised and it was not until US bombers flying at higher altitude discovered strong winds in the upper atmosphere, which are now understood as jet streams. These have been likened to rivers of air circling the earth in meandering paths. In both hemispheres they blow from west to east and this explains why airlines can often save time and money on the flight from Perth to Melbourne.

In the Australian summer this meandering jet stream may have 2 to 7 waves around the hemisphere. The wave themselves usually tend to move slowly eastward. Sometimes the waves temporarily lock onto large features such as the Andes in South America. When this happens the waves tend to become almost stationary. This means that the surface features of highs and lows which are strongly influenced by the jet stream intensity and orientation also become slow moving or stationary, and are said to be blocking.

Figure 5 shows a series of weather maps for the heatwave of March 2008.
In one sense this long heatwave was really two events. The heatwave that affected southern South Australia and western Victoria in March 2008 was abnormal in its duration. Adelaide had 15 consecutive days of 35ºC or more – breaking its previous record of 8 days. The graph of the daily temperatures in Figure 2 shows that on 11th of March there was a minor dip in the heat wave temperatures which was associated with a weakening of the upper ridge which in turn weakened the surface level high and almost allowed a weak cool change on the eastern flank of a Bight high to be vigorous enough to penetrate into SA. If this cool change had done so then this event would have equalled the previous record of 8 consecutive days over 35ºC at Adelaide. Unfortunately for wine grape growers the high in the Bight joined and intensified the High in the Tasman.



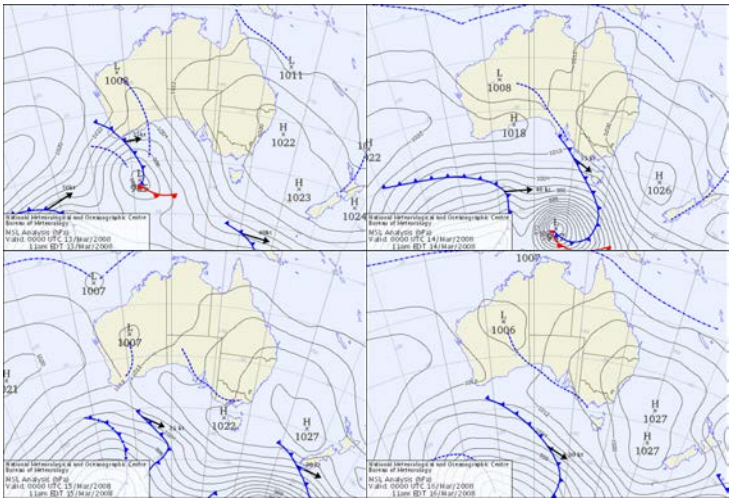


Figure 5. Sequence of weather maps from 9 to 16 March for part of the duration of the March heatwave as discussed in main text. Figure courtesy of the Australian Bureau of Meteorology.

Wine grape growing will benefit from the significant national and international effort in understanding heat waves in our current and changing climate. GWRDC has funded SARDI to conduct chamber experiments in the field to investigate the impact on yield and quality of heat events at different development stages of grapevines. As part of the project SARDI is working on risk management for heat stress. A first step in risk management is to understand the nature of the risk and this article is part of that process.

While heat waves can't be stopped, the nature of the system that sets up a heatwave means that the Bureau of Meteorology is rarely surprised by an event as there are indicators days in advance. Of course, by the same token the smaller scale features such as the weak cool change that did not affect Adelaide on the 11th of March, 9 days into the heatwave, are not easily predicted even one or two days in advance. In terms of understanding forecasts of weather a general rule of thumb is that daily weather comes from looking at current synoptic features, weekly weather comes from the movement of the jet stream in the upper atmosphere and seasonal climate (3 months of summer) comes from ocean features such as El Niño.

It is important to distinguish between weather, climate and climate change. Heatwaves are a dramatic and memorable weather event. Weather is a 'snap shot' of the atmosphere at a particular time and in this article we have discussed persistent weather where the snap shot is held over a week or longer by blocking. Climate is a composite of the weather events and averaged over a 30 year period whereas climate change is a shift in the average climate of a region. Climate change will be delivered to us through weather and part of preparing for future climate change is to better understand extreme and damaging weather events such as heatwaves. It is a mistake to attribute individual heatwaves to climate change, but these events highlight vulnerabilities and provide a window on what to expect more often in a warmer world.

Chapter 13

New insights in the climatology of heat waves in SE Australia

W Grace, VO Sadras, PT Hayman

Summary

Production of quality wine grape is sensitive to heat waves, especially at key phenostages such as flowering and ripening. Climatological models of heat waves with application in viticulture need to account for (a) a range of meteorological variables, (b) intensity, (c) duration and (d) timing of events. The meteorological variable most commonly associated with heat waves is maximum temperature; however, high minimum temperatures associated with heat waves are also relevant for viticulture. Intensity should be expressible as either exceeding a categorical threshold such as 35˚C or a relative threshold such as the 90th percentile. Modelled duration of heat episodes should be sufficiently narrow as to account for the timing of critical phenostages. The model presented here is an attempt to meet these four requirements.

The model is stochastic and incorporates seasonality and daily persistence of temperature through a Markov process and implies that frequency (or the return period) of heat waves decreases (increases) geometrically with each additional day of duration. The final model is expressed as a simple equation involving a single location-specific parameter, *M*, which relates to the maritime influence.

The model was tested over the viticultural regions of south-eastern Australia by comparison with observed data, and by assessing the physical and climatological meaning of parameter *M*. Cross-validated model estimates of annual frequency of heat waves were in good agreement with observations. The parameter *M* proved robust and physically meaningful: it is location-specific, its isopleths have the qualitative impression of seabreeze or maritime influence and it is quantitatively related to the skewness of the summer-time maximum temperature distribution.

Introduction

Crops have species-specific time windows when critical yield components are particularly susceptible to stresses such as shortage of water, frost and heat (Andrade et al., 2005; Dunn, 2005; Sadras, 2007). Management practices often aim at reducing the likelihood of coincidence between crop-dependent critical periods for yield and quality formation, and environment-dependent stress profiles. For example grape varieties are chosen to match the sensitive period of ripening to cooler autumn conditions rather than mid summer conditions.

Gladstones (1992) focussed on the month leading up to grape ripening as the critical stage for quality and suggested a range of maximum temperatures that should not be exceeded for ideal quality wine production. The maximum temperature ranged from 27 ℃ for delicate white sweet wines to 33 ℃ for medium

bodied dry or sweet wines, 36 °C for full-bodied wines and 38 °C for port styles. A temperature of 35 °C has been used as a threshold for white grape varieties in Okanagan, Canada (Belliveau et al 2006) and USA (White et al 2006). Although fixed thresholds such as those above have some indicative value, they are unrealistic when the full complexity of the interactions between grapevine physiology, wine making technology and climate are taken into account (Sadras et al., 2007; Soar et al., 2008). Heat stress may also create logistics problems in the harvest and post-harvest processing of produce, e.g. the extraordinary 2003 heat wave in Europe (Blayteyron and Rousseau, 2005) and the February 2004, March 2008 and January February 2009 heat waves in south-eastern Australia (BoM, 2005, 2008, 2009). The reports from the Australian Bureau of Meteorology describe the meteorological conditions for these events and the historical ranking of the events, but there is limited analysis with regard to frequency or return period as is common for other hazards such as floods and heavy rainfalls. Viticulturists and wineries have requested analysis of the risk of heatwaves to aid with planning of investment decisions such as irrigation infrastructure in the vineyard and handling capacity within the winery.

Within this context, this study (a) describes a new model of heat waves that combines first principles and empirical relationships, (b) tests the model, and (c) briefly illustrates its application in viticultural regions of south-eastern Australia. This initial version of the model is not designed to accommodate non-stationarity in climate, but Section 4.5 discusses potential approaches to do so.

Heat waves and heat stress

Heat waves

Definitions of heat waves generally comprise three components; a meteorological variable (usually maximum temperature), threshold, and duration. Threshold temperatures are either categorical, for example 30 °C, or relative, for example the 90th percentile (Karl and Knight, 1997; Robinson, 2001). Although there are critical temperatures in the literature, heat waves, like drought, are relative to what is considered normal in a region. It is common to use an arbitrary percentile, typically 90%, based on all days of the year for a specified period of record (for example, Tryhorn and Risbey, 2006). Seasonality has been further considered by basing the threshold percentile on three-monthly (Beniston and Stephenson, 2004; Nasrallah et al., 2004; Abaurrea et al., 2007) or shorter windows (for example, 5-days as in Alexander et al., 2007).

The duration of heat waves is typically between 2 and 6 days (Nasrallah et al., 2004; Khaliq et al., 2007; Karl and Knight, 1997; Sanchez et al., 2004; Alexander et al., 2007). The World Meteorological Organization Expert Team on Climate Change Detection, Monitoring and Indices proposed a Warm Spell Duration Indicator, defined as the annual number of days with at least 6 consecutive days above the 90th percentile maximum temperature based on a moving window of 5 days (http://cccma.seos.uvic.ca/ETCCDMI/).

In Australia, Collins et al. (2000) defined Hot Day Events as occurrences of 3, 4 or 5 consecutive days above 35 °C and Relatively Warm Day Events as occurrences

of 3, 4 or 5 consecutive days above a relative threshold. Tryhorn and Risbey (2006) defined a heat wave as a run of days with maximum temperature exceeding T90, the 90th percentile maximum temperature based on all days of the year. They developed four indices based upon this definition; T90 itself, the number of runs of at least 1 day exceeding the threshold, average run length and maximum run length. A fifth index was based on minimum temperature.

All these indices and studies either explicitly or implicitly recognise the dilemma inherent in any quantification of the expectation of extremes: extreme events are by definition rare, and reliable quantification of their frequencies becomes more difficult as the events become more extreme with regard to threshold, duration or both. Most point out that a spread of indices is desirable.

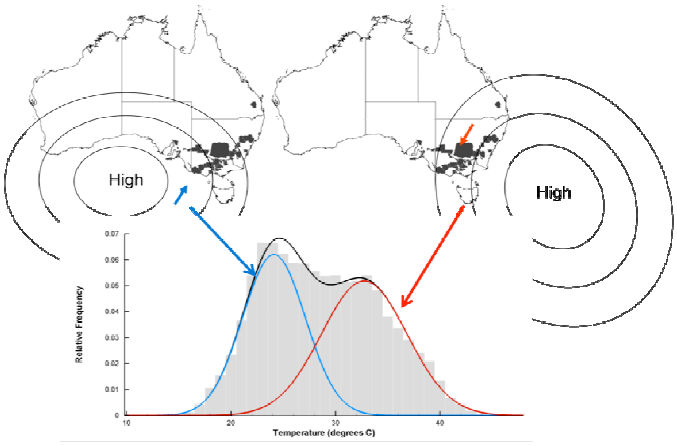
The meteorology of the immediate cause of heat waves in the wine grape growing regions of south-eastern Australia is relatively straightforward. A heat wave is associated with a persistent high, or series of highs, in the Tasman Sea that maintains a continental airstream over the region (Fig. 1). In southern Australia during summer, the subtropical high-pressure cells tend to favour either the Great Australian Bight region or the Tasman Sea. Depending on which cell predominates, the airstream over the region of interest is of either maritime or continental origin. For example, a greater than usual predominance of highs in the Bight results in a cool summer for South Australian and Victorian sites in particular. Grace and Curran (1993) formalised this conceptual model in summer bi-normal probability distribution functions (pdfs) of daily maximum temperature (ϕ) resulting from the combination of maritime and continental normal distributions (Fig. 1):

$$\phi = \frac{w_m}{\sqrt{2\pi}\, s_m} \exp\left[-0.5\left(\frac{T-\mu_m}{s_m}\right)^2\right] + \frac{w_c}{\sqrt{2\pi}\, s_c} \exp\left[-0.5\left(\frac{T-\mu_c}{s_c}\right)^2\right]$$

$$\phi = \frac{w_1}{\sqrt{2\pi}\, s_1} exp\left[-0.5\left(\frac{T-m_1}{s_1}\right)^2\right] + \frac{w_2}{\sqrt{2\pi}\, s_2} exp\left[-0.5\left(\frac{T-m_2}{s_2}\right)^2\right] \qquad (1)$$

where T is daily maximum temperature and w_m, μ_m, s_m, w_c, μ_c and s_c are the weighting, mean and standard deviation of the maritime and continental component distributions respectively. Trewin (2000) showed that the bi-normal distribution accurately modelled the monthly pdfs (including their tails) of maximum and minimum daily temperatures for nearly all stations in Australia.

a



b

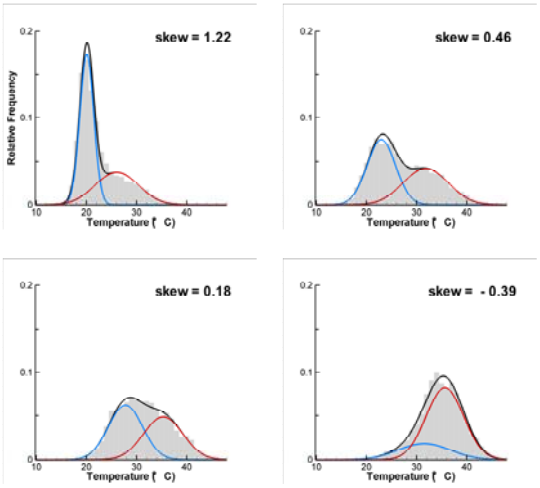


Figure 1. (**a**) Schematic representation of airstream influences over much of the viticultural areas of southeastern Australia (shaded black) due to highs in favoured mid-summer positions in Bight (left) and Tasman Sea (right). Adapted from Grace and Curran (1993). When the Bight high predominates it contributes a normal distribution of summertime daily maximum temperatures with relatively low mean and small standard deviation. When the Tasman Sea high predominates it contributes a normal distribution with higher mean and larger standard deviation; however, along the eastern seaboard the roles of the highs may be reversed. Together the two normal components add to give the observed bi-normal distribution at any location (Equation 1 in main text) as illustrated for Nuriootpa in the Barossa Valley. **(b)** Probability distribution functions (pdf) of daily maximum temperatures for combined mid-summer months of January and February for 4 locations with increasing distance inland (from left to right): Robe , Coonawarra, Loxton, and Walgett. Observed pdf shown by grey histogram; bi-normal model shown by black curve; and the two normal components, maritime and continental, shown by the left and right curves respectively. Typically, closer to the coast the maritime component becomes more dominant thereby increasing the skewness.

A hotter summer is associated with a greater than usual persistence of a high, or series of highs, in the Tasman Sea than in the Bight. The pdf of daily maximum temperatures for the hotter summer is not simply associated with a broad shift of the composite pdf to warmer temperatures. Rather, the bi-normal pattern is changed with an above average continental weighting and below average maritime weighting (Curran and Grace, 1992).

In general such a composite distribution is asymmetric. The moments of any distribution about its mean are related to the respective moments about any arbitrary origin (Spiegel 1980). The first three moments either equate or relate directly to the mean, standard deviation and skewness respectively. By using the fact that the skewness of a normal distribution relative to its mean is zero, it is possible to show that the skewness of the composite bi-normal distribution is an explicit function of the six component parameters. Thus the skewness at a location may be regarded as being determined by the relative influence of each of the airstreams, or more broadly, by the interplay of the geography and the synoptic climate. Figure 1 uses a few example stations to show the skewness of the maximum temperature distribution for the combined peak summer months of January and February changing from strongly positive at the coast to negative far inland. The skewness for all available stations, with at least 15 years of record, is shown in spatial form at Figure 2. In Section 3 we develop the model of heatwave frequency and duration and in Section 4 we test it and show that there is a link between the main parameter of the model and the skewness.

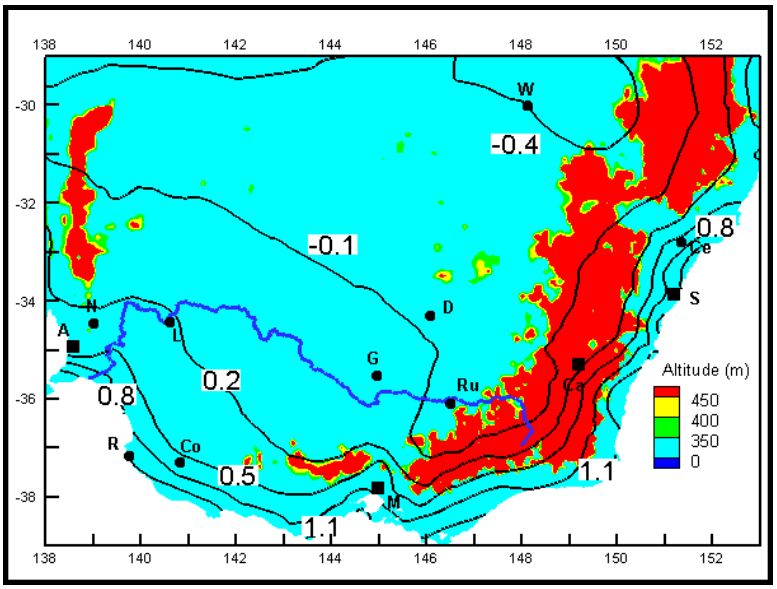


Figure 2. Topography and isopleths of skewness *S* for southeastern mainland Australia. Initial letters indicate the sites analysed in Table 1, namely, Adelaide, Robe, Coonawarra, Nuriootpa, Loxton, Griffith, Deniliquin, Rutherglen, Cessnock and Walgett. Canberra, Melbourne and Sydney are shown as a reference.

Method

Target region and database

Figure 1 shows the wine regions of south-eastern Australia, the target region of this study. Data used in model development and testing were the daily maximum and minimum temperature record to the end of 2007 for all Australian Bureau of Meteorology stations within the states of South Australia, Victoria and New South Wales. The data were then allocated to 'summer years' from July to June. A complete, or near-complete, year of record at a station was regarded as one with no more than two missing observations, and the missing observations were substituted with interpolated values. Only stations with at least 15 complete or near-complete years (but not necessarily consecutive years) were retained and this resulted in a database of 245 stations.

Model Development

The theoretical development of the model applies to maximum and minimum temperatures, but this paper focuses on maximum temperature. A hot day is one with maximum temperature exceeding a threshold *Tp;* otherwise the day is defined as cool. The threshold is the p^{th} percentile maximum temperature over the annual cycle (Tryhorn and Risbey 2006). Hot and cool days are mutually exclusive, and a run is a sequence of hot days bounded by cool days. The days having temperature exceeding *Tp* are expressed as a fraction, $f = 1.0 - 0.01p$

The purpose of the model is to provide a relationship between the expected number of runs with the duration of the runs and the threshold temperature selected. It is assumed that temperature records for a location provide a chronological sequence of length *D* days and that *D* is sufficiently large so that the sequence is a fair representation of the long term climate. The model estimate of the number of runs in the sequence with runs of duration ≥ *j* days is *n*(*j*), and *N*(*j*) is the corresponding estimate of the annual number of runs.

Initially a season-less and memory-free regime is assumed in which *f* is the probability that a given day is hot and that *f* is independent of all previous days. In the example in upper panel of Figure 3, the probability *P* of a run of at least 3 days starting from day d_{+1}, is given by the product (1-*f*) *f f f*. Generalising to a run of at least *j* days, then:

$$\frac{n(j)}{D} = P(j) = (1-f)f^{j} \qquad (2)$$

Next, day-to-day persistence is incorporated with the simplest possible Markov process. The probabilities of a given day's temperature state (either cool or hot) in a two-state first-order Markov process is represented by the transition matrix *B*

$$B = \begin{bmatrix} f_{cc} & f_{ch} \\ f_{hc} & f_{hh} \end{bmatrix} \quad (3)$$

where f_{cc} is the conditional probability that a cool day is followed by a cool day, f_{ch} is the probability that a cool day is followed by a hot day, etc, and where the row values of *B* sum to 1.

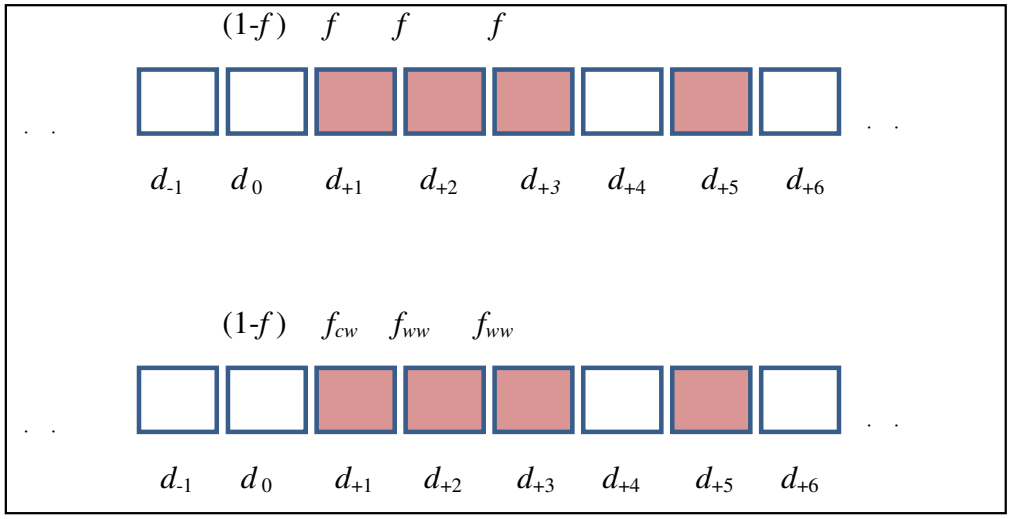


Figure 3. Schematic of sequences of hot (dark) and cool (blank) days (d_{-1}, d_0 …). Top labels show the probabilities associated with individual days in a run of at least 3 hot days with the first hot day being at day denoted d_{+1}. Upper sequence is for a memory-less regime and lower panel is for a persistence-influenced regime.

Accounting for a persistence-influenced regime, with the probabilities indicated in the lower panel in Figure 3, Equation (2) becomes:

$$\frac{n(j)}{D} = (1-f) f_{ch} f_{hh}^{j-1}. \quad (4)$$

In this context, the corresponding steady state probability for a hot day is (Wilks, 2006)

$$f = \frac{f_{ch}}{(1 + f_{ch} - f_{hh})} . \quad (5)$$

Substituting Equation 5 into Equation 4 results in

$$n(j) = D\, f\, (1 - f_{hh})\, f_{hh}^{\,j-1} \,. \qquad (6)$$

If there were no persistence then f_{hh} equals f and Equation 6 reduces to Equation 2. It is next assumed that there exists a 'strong' seasonality such that the sequence of D days consists of D_w winter days and D_s summer days, with no shoulder seasons. In winter it is further assumed that there are no hot days. During the summer, the fraction f_s of the summer days are hot, and the corresponding value for f_{hh} is $f_{hh,s.}$ Since there is no winter contribution to the total number of runs of hot days, then it follows that

$$n(j) = D_S\, f_S\, (1 - f_{hh,s})\, f_{hh,s}^{\,j-1} \,. \qquad (7)$$

But it is apparent that

$$D_S\, f_S = D\, f. \qquad (8)$$

If N denotes the annual number of runs then

$$N(j) = 365\; n(j)/D \qquad (9)$$

and so

$$N(j) = 365\, f\, (1 - f_{hh,s})\, f_{hh,s}^{\,j-1} \; N(j) = 365\, f\, (1 - f_{hh,s})\, f_{hh,s}^{\,j-1} \,. \qquad (10)$$

Equation 10 implies that for a given threshold the expected number of heat waves reduces geometrically by the factor $f_{hh,s}$ for each additional day. In theory, just one observation point, namely $N(1)$, suffices to calculate $f_{hh,s}$; however our calculation procedure has been to take the logarithm of Equation 10 and apply simple linear regression so as to use all the observed N values for the given f.

If $f_{hh,s}$ were a known function of f then Equation 10 would suffice to provide expected likelihoods of occurrence of heat waves for any f, that is, for any Tp value chosen as the threshold. Figure 4 shows the relationship between observed $f_{hh,s}$ and f. It is apparent that $f_{hh,s}$ consistently has the form of Equation 11, at least for $0.02 \le f \le 0.2$, where M is an

$$f_{hh,s} = f^{M} \qquad (11)$$

empirical location-specific parameter. For the 245 stations, the correlation coefficient between $f_{hh,s}$ and f in a log-log scale varied from 0.89 to 0.99 indicating that the empirical relationship of Equation 11 is reliable. For most stations it tends to hold as far as $f \sim 0.5$. When the empirical relationship described by

Equation 11 is applied to Equation 10, the mathematical expression of the model is:

$$N(j) = 365 f (1 - f^M) f^{M(j-1)}. \quad (12)$$

$$N^*(j) = 365 f (1 - f^M)^2 f^{M(j-1)}. \quad (12a)$$

For the special case of a memory-less and season-less environment applicable to Equation 2, then $f_{hh,s} = f$, $f_{hh,s} = f$, and thus $M = 1$, so that Equation 12 reduces to Equation 2.

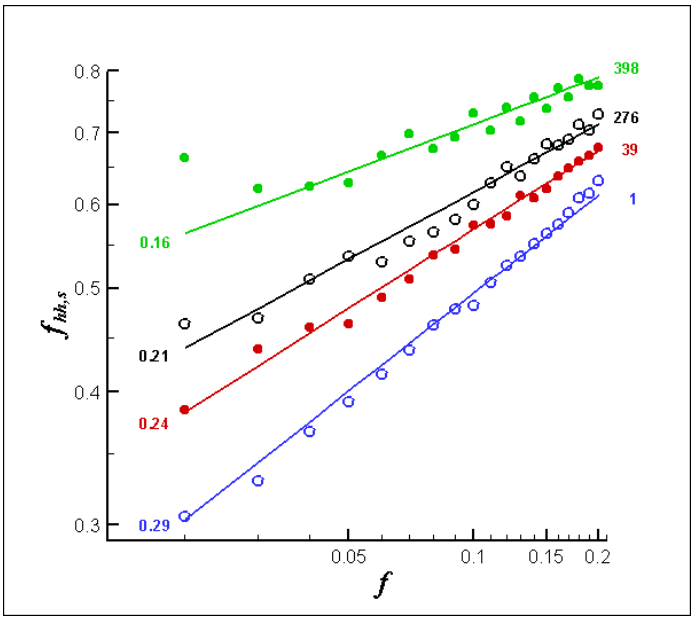


Figure 4. Relationship of f (the probability of a hot day for any day of the year) and $f_{hh,s}$ (the probability of a hot day following a hot day during summer) shown by spot values with corresponding best-fit curves of Equation 11. At left of each plot is the value of M, and at right is distance (km) from coast. From top to bottom, sites are Walgett, Deniliquin, Nuriootpa and Robe. The log-log scale highlights the power relationship of Equation 11.

An alternative approach is to define N^* as the number of runs where duration of the runs are exactly j days, as distinct from at least j days. Using a similar method to the derivation above, N^* may be shown to be given by Equation 12a which is presented for the sake of completeness.

From a station record, estimates of M are obtainable for any chosen f, at least up to ~ 0.5. Ideally estimates of M for different values of f would be identical; in practice it is prudent to estimate M from a best straight-line fit of several estimates of $f_{hh,s}$ as illustrated by Figure 3. The model therefore uses all available information regarding the numbers of runs of all observed durations for all threshold temperatures between T80 to T98 in one percentile increments. Thus model estimates of the frequency of rare events are based upon all numbers of runs at all

thresholds above T80, and so ought to be more reliable than estimates based solely upon the particular events in question.

As developed to this point, the model applies to the number of heat waves during the whole of the summer season. For viticultural applications, however, narrower time windows are needed to account for critical phenostages (Soar et al., 2008). The extension of the model to monthly and fortnightly periods was achieved by assuming that the number of heat waves for a period, such as a month, is proportional to the number of hot days in the period.

Let *f'* be the long-term probability of the daily temperature exceeding a threshold. In the model so far, over the course of the year *f'* is zero during winter and then constant during summer. More realistically *f'* rises from zero to a mid-summer peak before returning to zero. In this extension to the model, the heat wave frequency is assumed proportional to the area *A* under the *f'* curve within the time window of concern. Thus the number of heat waves for a time window is given by

$$N(j) = 365 f A (1 - f^M) f^{M(j-1)}. \qquad (13)$$

If the time window is taken as the whole of summer, then $A = 1$ and Equation 13 reduces to Equation 12.

The value of *f'* is known for sites with long reliable records; for many sites, however, an accurate estimate of *f'* may not be available. Using the relatively long record at Deniliquin, an empirical parameterisation of *f'* was arrived at by trial and error, and subsequently checked at all sites with at least 30 years of record. The only input data required is an estimate of the 12 mean monthly maximum temperatures – it is assumed that these values are available, either readily or by spatial interpolation. Assigning the mean monthly values to mid-month dates, the mean maximum temperature is then linearly interpolated to each calendar day. Equation 14 provides a parameterised estimate of *f'* from a presumed knowledge of mean monthly maximum temperatures as follows:

$$f' = \max\{0, \quad (T - 0.01\, p\, T_{am})^{\alpha}\} \qquad (14)$$

where *T* is mean maximum temperature linearly interpolated to each calendar day, T_{am} is the mean of the twelve monthly means, $\alpha = 1.5 + 0.05(p\text{-}80)$, $\alpha = 1.5 + 0.05(P - 80)$ and $p = 100\,(1 - f)$.

Figure 5 illustrates the agreement between observed long-term frequency *f'* with the estimate from the parameterisation of Equation 14 for Deniliquin (93 years). A similarly good agreement is evident for other thresholds and for all the sites listed in Table 1. For each of these sites and for each of the thresholds (T80, T85, T90 and T95), comparisons of observed mean monthly frequency of days above threshold temperature against that estimated by this method were performed using correlation of observed-estimated pairs excluding those where the observed frequency was zero. All correlation coefficients were above 0.98. For all inland sites with at least 30 years of record (88 sites) the minimum correlation coefficient

was 0.95. The parameterisation was less useful for sites within an estimated 3 km of the coast and these did not form part of the set of 88 above.

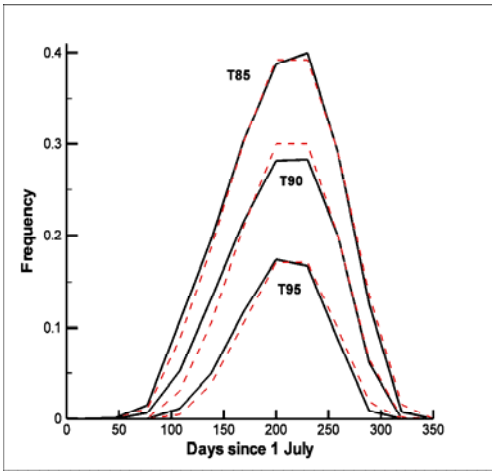


Figure 5. Relationship of observed (solid) frequency(*f*') of days over T85, T90 and T95 (upper, middle and lower pairs respectively) at Deniliquin compared to the parameterization (dashed) from Equation 14.

The model is encapsulated by Equation 13 and as presented to this point estimates the climatological frequencies of heat waves with regard to timing, intensity and duration and chosen meteorological variable.

Model testing approach

Testing a model of rare events is challenging because of the intrinsically high variability of the observed rare events. To test the model, we performed (a) graphical comparisons, (b) cross-validated measures of model performance, and (c) quantitative assessment of the physical and climatological meaning of parameter *M*. The results are presented and discussed in Section 4.

The cross-validation procedure entailed splitting the full data sets for each station into halves by allocating summer years randomly, and without replacement, to either a training set or a test set. Using the training set, *M* was calculated and applied to the test set, and correlation coefficient *r* and root mean square relative error calculated. This was repeated 100 times and the means of the correlation coefficient and relative error obtained. This was done for whole of summer, monthly and fortnightly periods for the 9 stations in Table 1 and for (31) long record stations (all stations with at least 50 years of record such that both training sets and test sets comprised at least 25 years of data). Monthly time windows tested were the calendar months; fortnightly windows were those beginning on the 1st and 15th of each month.

Table 1. Root mean square relative errors (*re*) and correlation coefficients *r* for whole summer, monthly and fortnightly periods aggregating thresholds T85, T90 and T95. Bold figures are errors obtained from dependent data (the training sets). All other values are cross-validated estimates (*XV*). See text for cross-validation procedure. Years refers to years of record in full data sets.

Station	Years	Whole summer			Monthly			Fortnightly		
		re	*re(XV)*	*r(XV)*	***re***	*re(XV)*	*r(XV)*	***re***	*re(XV)*	*r(XV)*
Robe	97	**0.16**	0.18	0.98	**0.15**	0.17	0.98	**0.15**	0.20	0.97
Deniliquin	93	**0.10**	0.11	0.97	**0.18**	0.20	0.96	**0.21**	0.23	0.97
Adelaide	89	**0.11**	0.13	0.97	**0.21**	0.22	0.96	**0.19**	0.23	0.97
Rutherglen	48	**0.19**	0.20	0.98	**0.21**	0.22	0.96	**0.17**	0.20	0.96
Nuriootpa	38	**0.15**	0.16	0.98	**0.13**	0.16	0.96	**0.17**	0.21	0.95
Cessnock	29	**0.22**	0.22	0.98	**0.11**	0.15	0.96	**0.16**	0.21	0.95
Griffith	22	**0.19**	0.21	0.97	**0.18**	0.17	0.94	**0.16**	0.21	0.92
Loxton	19	**0.13**	0.13	0.98	**0.11**	0.14	0.96	**0.14**	0.16	0.93
Coonawarra	16	**0.11**	0.09	0.97	**0.10**	0.13	0.94	**0.13**	0.15	0.92
Long-record stations	? 50									
Mean		**0.16**	0.17	0.98	**0.17**	0.20	0.98	**0.16**	0.20	0.96

The correlation coefficient was calculated between non-zero observed and modelled pairs of frequencies; for the root mean square relative error calculation a further proviso was that there had to be at least 10 observed events within the test data sets. Correlation coefficients and relative error were determined using the thresholds of T85, T90 and T95, in aggregate. Similar results were obtained for the individual thresholds but these are not presented here. The threshold T85 typically corresponds to about the mean of the maximum temperature in January and February and so was judged to be a suitable lower limit for thresholds of practical interest.

Regression analysis was used to explore the associations between parameter *M* and latitude, distance to nearest coast, altitude, and the maritime and continental airstream components (w_m, μ_m, s_m, w_c, μ_c and s_c in Equation 1) and the skewness of the summer-time maximum temperature. A qualitative comparison of the spatial distribution of *M* and skewness is also presented.

Model Performance

For assessing and managing heat stress in vines, an ideal model of heat waves would be:

1. statistically robust in dealing with rare events;
2. comprehensive enough to capture timing, intensity and duration of heat events and flexible as to the choice of parameter (maximum or minimum temperature or a combination) and the choice of threshold type (categorical or relative);
3. meteorologically meaningful;
4. capable of application to locations with climate records of diverse quality and quantity; and
5. capable of identifying trends and of incorporating climate change projections.

Robustness

Modelled number of events per annum for T85, T90 and T95 were in close agreement with observed data (Fig. 6, Table 1). For longer runs and rarer events, actual errors were larger, and model and observations diverged, particularly for Robe (Fig. 6). The cross-validated estimates of correlation for summer for the nine stations in Table 1 were all at least 0.97 and the mean cross-validated correlation coefficient for the long record stations was 0.98. For monthly and fortnightly windows, the cross-validated estimates of correlation for the nine stations were all at least 0.92, and the mean of the long record stations was at least 0.96. For the same sets of stations and for each of the time windows, (summer, monthly and fortnightly) skill score results of root mean square relative error for the training set and for the test set are presented and it is seen that there is a tendency for the cross-validated estimates of error to be slightly greater than those derived from the (dependent) training data sets. We conclude that the model is robust in the sense that the parameter M is not over-tuned to the data sets on which it is based. Table 1 reveals that the cross-validated relative error was found to be about 0.15 for whole of summer and about 0.2 for monthly and fortnightly time windows.

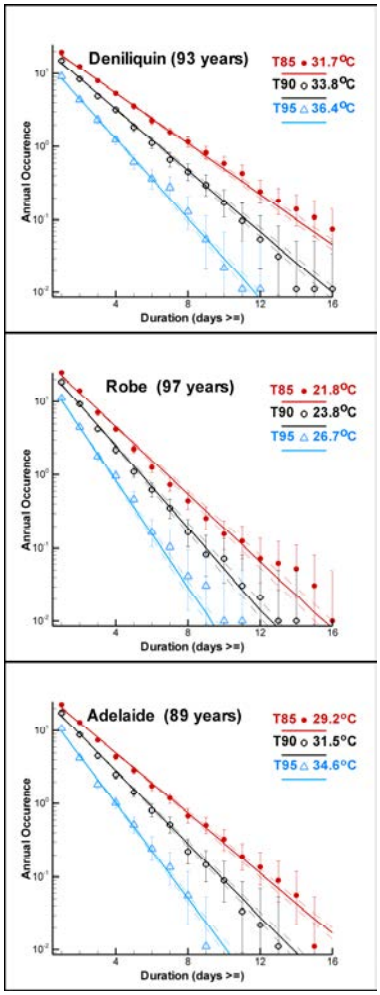


Figure 6. Observed (circles) and modelled (lines) runs for threshold temperatures of T85, T90 and T95 for Deniliquin, Robe and Adelaide. Runs refer to duration ≥ *j* days. For each threshold shown, individual *r* values ≥ 0.99 with $p \leq 0.001$. Error limits are confidence limits (5% and 95%) on observations (bars) and on model (dashed lines) obtained from resampling. The model is plotted as continuous for visual clarity.

Comprehensiveness and flexibility

For monthly and fortnightly periods, correlation coefficients were less than those for the whole summer but greater than 0.92 and relative error was typically ~ 0.2. Figure 7 further illustrates the performance of the model for fortnightly periods in the middle of January, a peak month, and March, a shoulder month.

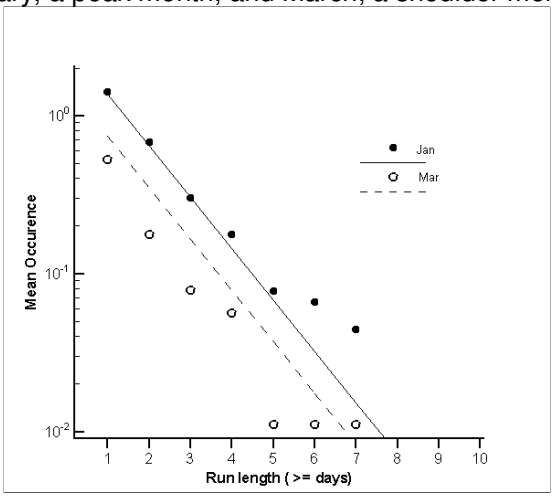


Figure 7. Observed (circles) and modelled (lines) number of runs for "middle" fortnightly period of peak month January and shoulder month March for Adelaide for T95 (34.6°C).

Using data for Nuriootpa in the Barossa Valley, Figure 8 illustrates the flexibility of the model to deal with categorical thresholds for maximum temperature (Fig. 8a), minimum temperature (Fig. 8b) and dual criteria of a day-time maximum temperature above a threshold followed by a night-time minimum temperature above a threshold (Fig. 8c). Similar results (not shown) were obtained for all other sites in Table 1.

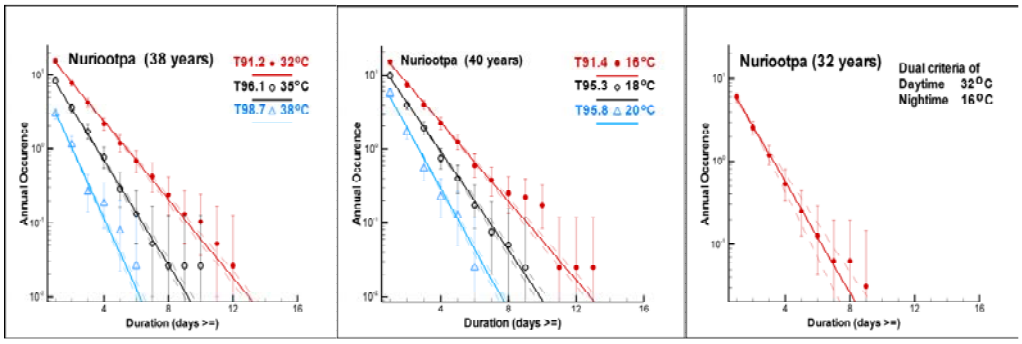


Figure 8. Observed (circles) and modelled (lines) annual number of runs at Nuriootpa in summer for categorical thresholds of (a) maximum temperature, (b) minimum temperature and (c) dual temperature thresholds of minimum and maximum temperature. For each threshold individually, $r \geq 0.99$ with $p \leq 0.001$. Error bars as for Fig. 6.

Relationship of model parameter, M, to geography and synoptic climatology

So far, *M* has been discussed in the context of a single station. The spatial dimension was investigated by estimating *M* for all 245 stations and plotting, with kriging smoothing, onto a topographic map at Figure 9. It is apparent that *M* is spatially coherent and exhibits a latitudinal and maritime-continental nature. Readily evident is that *M* tends to decrease (a) northward and (b) with distance inland, and further, that the rate of decrease inland is increased by mountain barriers. The topographic contours are set at 350, 400 and 450m, about the height of seabreezes, in order to highlight how the pattern of *M* isopleths appears to resemble isochrones of seabreeze penetration. However, there appears to be no comprehensive study to readily support this idea; nevertheless, it is long established that seabreezes, albeit in degenerate form, penetrate 300 km or more inland in southern Australia (Clarke, 1955; Reid, 1957; Abbs and Physick, 1992; Physick and Abbs, 1992).

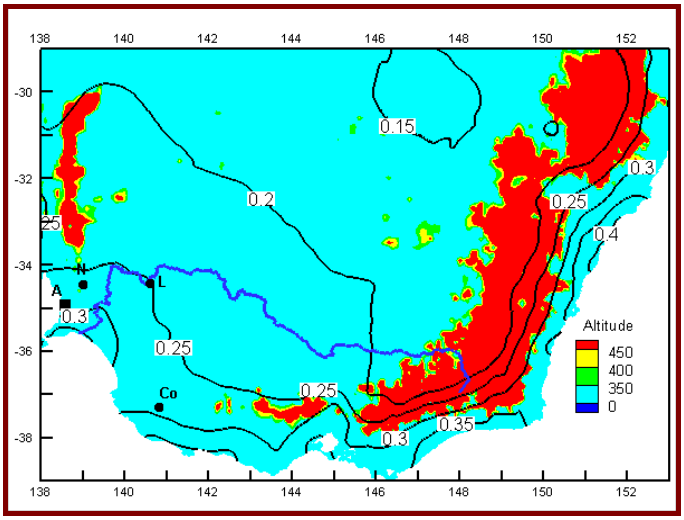


Figure 9. Isopleths of parameter *M*. *M* has the subjective impression of a seabreeze penetration: inhibited by the topography but tending to push in to the major valleys especially the Murray. Note the similarity to the pattern for skewness in Figure 2.

For all 245 stations, the apparent relationship between *M* and the physical geography suggested in Figure 9 was confirmed in quantitative analysis (Fig. 10). As well, but not shown, correlations between *M* and the six airstream component parameters, w_m, μ_m, s_m, w_c, μ_c and s_c were calculated as 0.69, -0.56, -0.80, -0.69, -0.35, 0.69 respectively ($p < 0.001$). Correlation with the mean of the maximum temperature in January and February is - 0.63. A strong positive correlation (r = 0.91) of *M* with the skewness is evident (Fig. 10). In summary, *M* decreases equatorward, and with distance from the sea, and with altitude: *M* increases with the skewness (which is a function of the six component parameters).

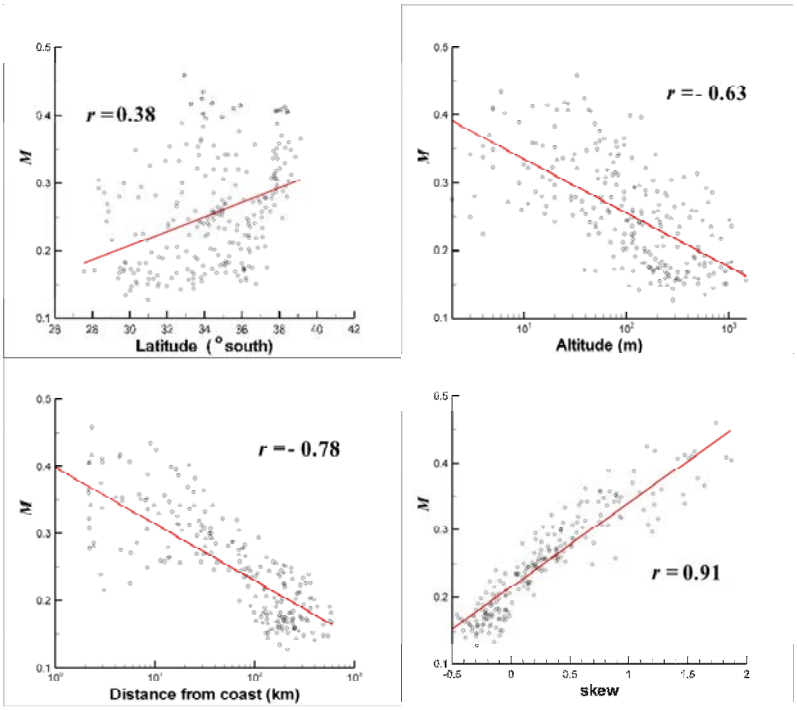


Figure 10. Parameter *M* as a function of (a) latitude, (b) log of distance to nearest coast, (c) log of altitude and (d) skew for the mid-summer months of January and February combined. All *r* were significant at $p < 0.001$.

Inspection of the *M* and skewness patterns (at Figures 9 and 2 respectively) shows a remarkable similarity of their main features, in particular the coastal and topographic modulation. Since the pattern of *M* is similar to the skewness pattern, which is a reflection of the synoptic and meso-synoptic climate of the region, then it is reasonable to suggest that the model, through its parameter *M*, is also a reflection of that climate. This gives greater confidence in the model's assumptions and relevance.

Application to sites with climate records of diverse quality and quantity

For a whole of summer basis, model estimation of the number of heat waves requires knowledge of *f* and *M* (Equation 12). The value of *f* corresponding to a given threshold temperature can be estimated from station records even in those cases with short or incomplete records. Alternatively, maps of T85, T86, T87, and so on, may be compiled in a straightforward manner; from these, *f* for the threshold temperature of interest can be determined. Likewise, *M* can be taken from a map such as Figure 9. This means that the model may be used at sites with little or no record of observations.

In order to estimate the number of heat waves occurring during shorter periods within the summer season, such as a selected month or fortnight, the additional knowledge required is *f'*, the variation over the summer of the frequency of days exceeding the selected threshold. In the absence of a suitable station record, a good estimate of this variation is obtained from the mean monthly temperatures and the empirical relationship in Equation 14. Estimates of mean monthly temperatures are obtainable from incomplete records or from spatial interpolation. Then Equation 13 can be utilised to provide estimates of heat waves for selectable shorter periods.

Trends and other considerations

Although the model presented is limited to a stationary climate, it does provide a basis to investigate trends. Investigations could be carried out on a first half – second half basis: this could be for individual stations with suitable records or more broadly for the region. The model is capable of extension to non-stationary regimes in the manner of Coles (2001) who incorporated linear and non-linear trends of sealevel into the generalised extreme value model originally designed for stationary regimes. For example, the temperature record may be detrended using observed or assumed trends of mean temperatures or threshold temperatures. Another option is to use a sliding window to set the period of record over which the threshold *Tp* value is obtained to one or ten years, for example. An indirect approach would be to investigate any trends in skew and relate any such trend to trends in the synoptic climatology.

The model tended to underestimate the number of runs for durations in excess of 10 days (Fig. 6). This effect was more pronounced for lower thresholds such as T80 and for minimum temperature (Fig. 8b). A possible reason for this bias is that as a run of hot days progresses, soil moisture is depleted and the ground more readily becomes a heat reservoir that attenuates the fall in night-time temperature. However, this hypothesis does not explain why the effect is less pronounced for the higher thresholds. Other possible reasons could involve model assumptions of climate stationarity, the uniform nature of the summer season or the applicability of a Markov process of only the first order.

Conclusions

A new model as encapsulated by Equation 13 incorporating seasonality and persistence of daily temperature through a Markov process was developed. The model implies that frequency of heat waves decreases geometrically with each additional day of duration by a factor $f_{hh,s}$ which is the conditional probability that a hot day follows a hot day during summer. An empirical relationship was found between $f_{hh,s}$ and *f*, the annual fraction or frequency of hot days. This enabled the model to be formulated as a simple equation (Equation 12) involving one unknown - a location-specific parameter, *M*. Using an empirical parameterisation of the mean monthly maximum temperatures, the model was extended to estimate the climatological frequencies of heat waves for monthly and fortnightly windows. The model allows for timing, intensity and duration of heat waves required for applications in viticulture, and flexibly allows for a range of meteorological variables, e.g. maximum and minimum temperatures.

Model estimates of frequencies of heat waves were compared to observed frequencies for selected wine region stations and 31 long record stations (those with at least 50 years of record such that cross-validation could be performed on 25 year training and test sets). Model estimates of occurrence of heat waves on "whole of summer season" basis compared well with observations and were typically accurate to within 15%. On a monthly or fortnightly basis, for the nine selected stations the model estimates of heat wave frequencies were typically accurate to about 20%. The model validity was further supported by the spatial coherence and physical and meteorological consistency of parameter *M*.

In summary, the first four of the five ideal characteristics of a heat wave model for viticultural application as noted above have been attained; it remains to incorporate temporal climate change into the model.

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World Meteorological Organization Expert Team on Climate Change Detection, Monitoring and Indices http://cccma.seos.uvic.ca/ETCCDMI/.

Chapter 14

Estimating the likelihood of heatwaves in grapegrowing regions of SE Australia

W Grace, PT Hayman

Another record-breaking heatwave in wine regions

A dominant feature of the 2008 vintage was the record breaking March heatwave. As of the time of writing (early February 2009), the 2009 vintage will be remembered for a cool December and early January followed by the extraordinary heatwave in late January and early February. Figure 1 shows the pattern of maximum and minimum temperatures for Nuriootpa in the Barossa.

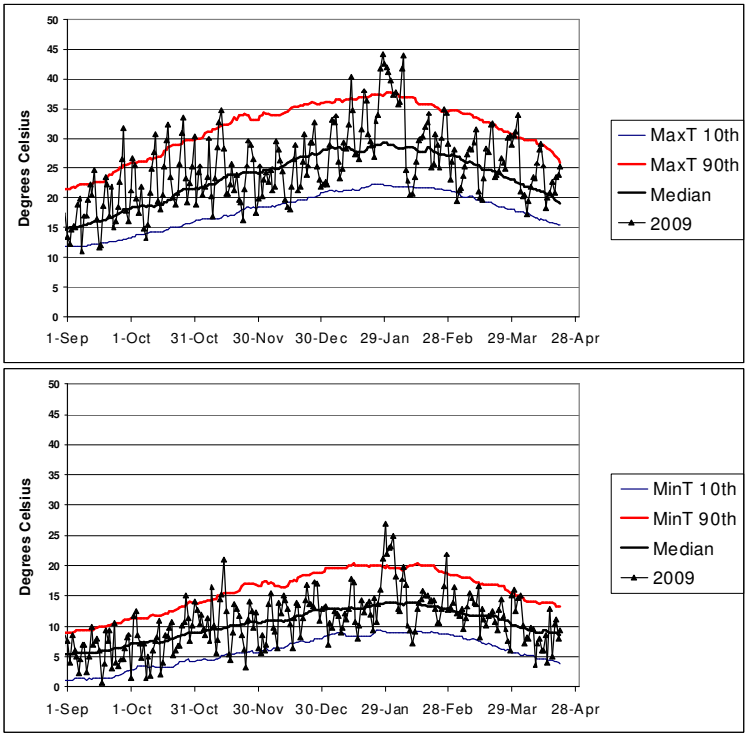


Figure 1. Maximum and minimum daily temperature for Nuriootpa in 2009 showing the cool December and early January followed by the heat wave in late January and early February and the mild conditions following the heatwave. The median, 10th and 90th percentile are based on 1961 to 1990 records.

As outlined in the previous article, the weather patterns that lead to hot summer days in SE wine regions are relatively well understood and are synoptic patterns that bring hot northerly air down to the wine regions. A run of hot days occurs when a slow moving high in the Tasman Sea brings down warm northern air and acts to block prevent any new highs from building into the Bight region, which means that any cool change is blocked.

A feature of the recent heatwave was the very hot nights. On the night of the 28th of January the minimum temperature in Adelaide was 33.4 °C. This means that most hours of that night were hotter than 37.8 (100 °F). The Bureau of Meteorology reported that at RAAF base at Edinburgh a burst of strong northwesterly winds mixed hot air aloft down to the surface so that the temperature rose just after 3am to 41.7 degrees. In a GWRDC funded project where we asked wine grape growers in Clare what their greatest concern for climate change was, many of them pointed to warm nights, which did not allow full recovery after a hot day. The consensus on what constituted a warm night was 20 °C. There are many media reports estimating the losses; in some cases the losses are devastating and obvious, in other cases grape growers are hoping for some recovery in the latter part of the season.

The weather and cricket – a rich source of records

The 2009 heatwave in late January early February after the 2008 March heatwave and the 2004 February heat wave raises the question of what to make of the all these breaking records. The first point is that the weather is a bit like the cricket. A cricket match has numerous combinations (left handed bowler to right handed batter during the second day) and this provides commentators and enthusiasts a record for the books in most matches. In weather, even if we are considering only minimum and maximum temperatures, conditions can be considered remarkably higher or lower than previous years for any given run of days at different times of the year. So it is important to concede that weather enthusiasts can find records. Under a climate that is variable but not changing overall in the long term, we would expect the number of records of cooler conditions to match the number of records of warmer conditions. As some people noticed, the Southern Australian heat wave coincided with a cold snap in England. Dr Blair Trewin from the National Climate Centre from the Bureau of Meteorology observes that for Australia, in recent times, the number of records being broken for higher temperatures is about double the number for lower temperatures.

From weather records to risk assessment

While it is interesting and worthwhile to report these records and the ratio of warm to hot records tells us something about extremes in a variable and changing climate, engineers designing bridges don't refer to single records, they rely on risk assessments and design for 1 in 10, 1in 50 and 1 in 100 year events. These are return periods, although it is noted that sometimes people misinterpret this concept to mean that an event will happen and that it will happen once only during 10, 50 or 100 years. It in fact means that it is expected to happen on average once every 10, 50 or 100 years. Another way of expressing the same data is that in any year there is a 10% (1 in 10), a 2% (1 in 50) or 1% (1 in 100) chance of an event occurring.

One definition of risk is putting numbers on uncertainty. The risk associated with betting on a fair roulette wheel is easily quantified. What about a secretly biased wheel? A study of the wheel's recent history of outcomes may enable you to quantify the risk for this wheel. By the same philosophy, statistical laws and modern data analysis can be applied to heat waves in an attempt to quantify the associated

risks. SARDI has used project funding from GWRDC and the Centre for Natural Resource Management (CNRM) to examine the frequency of heat wave events.

The mathematics of heatwaves

Firstly we define a heat wave as a run of days with the maximum temperature exceeding a designated threshold (35, 37 and 40 °C, in our examples). The duration is the number of days in the run. There are two ways of looking at this. One is that runs of 3 days means all those times the run had exactly 3 days (that is, not 4 or 5 or more. Another way is that runs of 3 days means all those times when the run was at least 3 days long. Most practical people seem to prefer the second meaning so that is what is used here. The two types can be related mathematically if we need, anyway.

Figures 2 and 3 show the annual frequency and duration of heat waves for the Barossa and for Renmark. On the vertical axis is the annual average number of times a heat wave occurred with a duration and along the horizontal axis is the number of days in the run. The ">=" on the horizontal axis just means "at least". Please be aware that at the moment, this work only uses data up to the end of 2007.

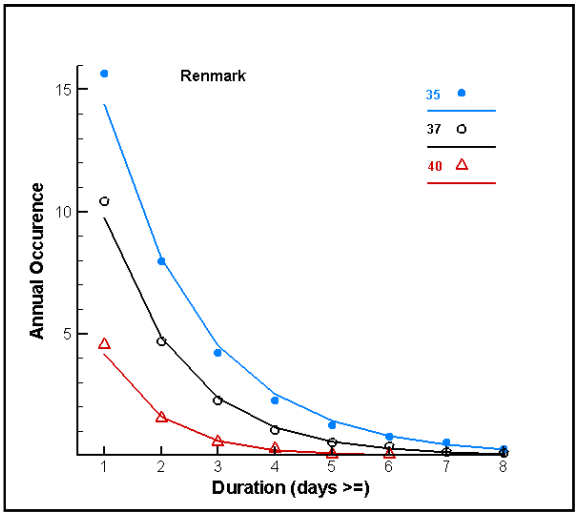


Figure 2. Observed (symbols) and modelled (lines) average annual frequency of occurrence of heat waves at Renmark (SA) in relation to duration, for different threshold temperatures (35, 37 and 40 °C).

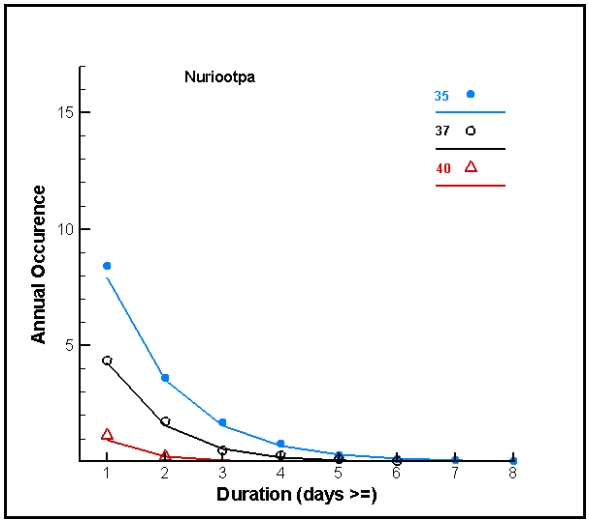


Figure 3. Observed (symbols) and modelled (lines) average annual frequency of occurrence of heat waves at Nuriootpa (SA) in relation to duration, for different threshold temperatures (35, 37 and 40 °C).

These graphs synthesise a huge amount of historical temperature data so that we notice :

1. The curves through the data points show an exponential decline in frequency. For example at Renmark if we are interested in days over 37, we should expect 2 consecutive days about 5 times a year, 4 days in a row about once per year and 5 days in a row about once in every 10 years.
2. For longer runs such as 5 consecutive days over 37 °C we are dealing with very rare events. These are low frequency and high consequence events that are difficult to assess and manage. In many cases these are events we seek insurance for.
3. The different temperatures (35, 37, and 40) have curves that follow the same declining exponential pattern but differ in position and shape.
4. Location matters, the graph for Barossa follows the same pattern, but has important differences to the graph for Renmark

We have found that at any given site, the frequency is related in a predictable way to the temperature threshold and the duration. The exact nature of this relationship is sensitive to location. For the warmer inland site, the frequency reduces more slowly that at coastal sites. This persistence of hot days is of key concern and makes sense. You are more likely to win a bet that tomorrow will be as hot as today in an inland town than on the coast.

Converting to log-linear graphs

Going to the trouble of plotting the same graphs but with a logarithmic vertical scale allows several features to be better appreciated. A challenge of interpreting these log-linear graphs which are at Figures 4 and 5, is that the vertical axis is distorted and the labels reading upwards mean 0.01, 0.1, 1 and 10. However the advantage is that the line of best fit now becomes straight and this emphasizes the

mathematical relationship is indeed one of exponential decline. Another advantage is that the slope of the straight line is easily calculated and we can extrapolate with some confidence when we have limited data. Apart from making each site relatively comparable, we are able to find (and use) a relationship that governs the slope for each of the different thresholds when the thresholds are expressed in percentile terms. The percentile is relatively easy to find, for example the 90th percentile is maximum temperature that, on average is exceeded 10% of the time in a year (about 33 ^{o}C at Nuriootpa and 35 ^{o}C at Renmark). It turns out that at each location if we know the slope of the line for say the 50th percentile, then we can predict the slopes for all the other percentiles - even the more extreme ones for which, even in our longest records, we don't have many readings.

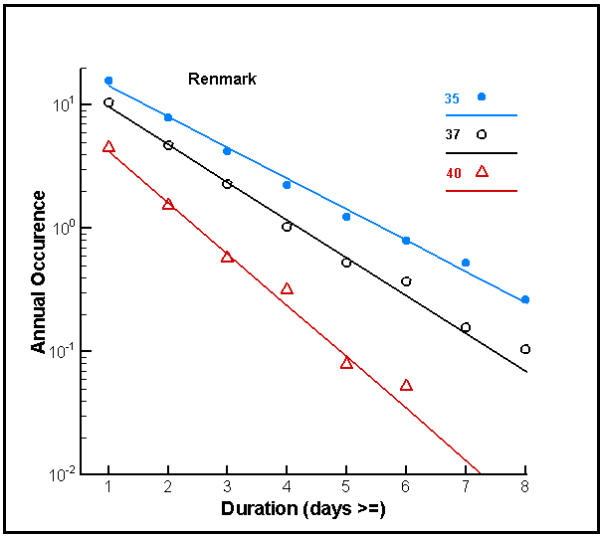


Figure 4. The same graph as before at Figure 2 for Renmark but this time using a log-linear scale. The advantage is that now the curves become straight – effectively proving that the decline is indeed exponential. As well, with limited data, we can draw other straight lines representing other threshold temperatures. For example, The old 100 F (37.8 ^{o}C) would obviously fit about halfway between the black and red lines.

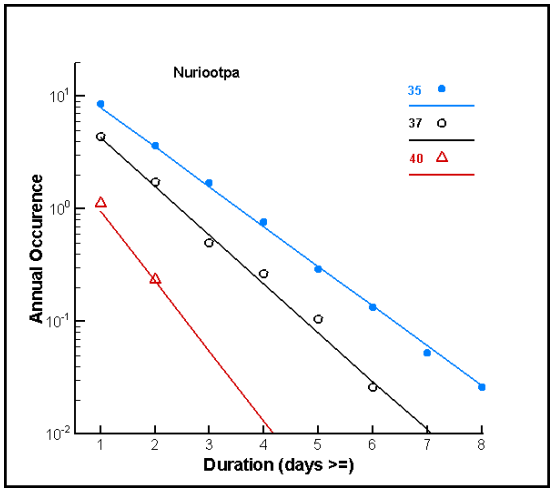


Figure 5. The same graph as before at Figure 3 for Nuriootpa but this time using a log-linear scale. This is based on 38 years of data up until mid 2007. At that point 3 days in a row over 40 °C had never been recorded. But even then from these graphs it seemed that there was about 1 in 15 year chance of 3 days in a row happening.

Making sense of the geographical location term M

As we mentioned earlier, each site is different, but we were surprised to find that the influence of location can be taken into account through just one parameter, which we have named M. Each location has its own M and this M parameter has its own geographic pattern which clearly relates to a maritime effect. In a nutshell, this means that even for places with short records, we can calculate M and in turn use the knowledge of M to estimate the frequency and duration of runs for any threshold we care to nominate.

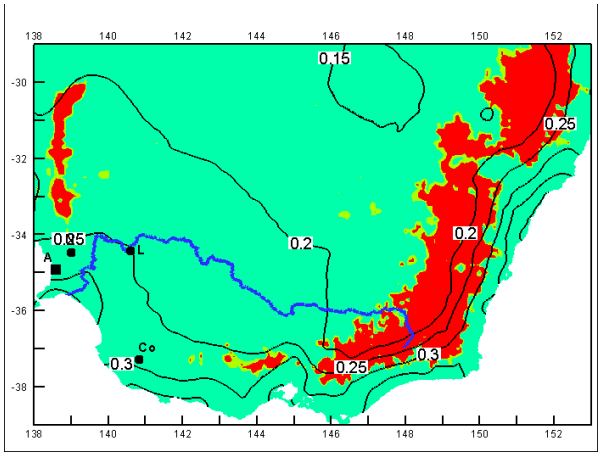


Figure 6. Parameter M plotted as contour lines over southeastern Australia. Note how the lines are held back by the higher ground and seem to surge inland up the larger valleys such as the Murray. Labelled points are Adelaide, Nuriootpa, Loxton and Coonawarra.

Some applications of the model

All the discussion above relates to the number of heat waves per annum, or equivalently per summer period. The wine grape grower will often be more interested to know what about a shorter time window such as a fortnight near harvesting. The scheme that we have built up for a whole-of-summer frequencies can be modified to focus on the frequencies over nominated fortnights. This capability has been built into a spreadsheet whereby, for any location we can assess the risk of a run of days exceeding any temperature for any fortnight of the season. In the next and final issue we will describe the spreadsheet and how this risk assessment can be used to help the industry with risk management.

Returning to the Clare growers with their concerns for warmer nights – everything we have said about day-time maximum temperatures applies to overnight minimum temperatures.

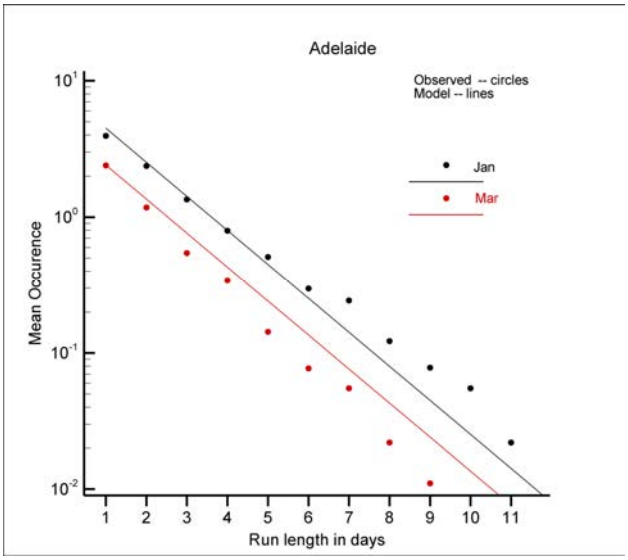


Figure 7. Using the longer record of Adelaide as a check, we compare the heat wave frequencies for the fortnights beginning on the 8th of January and March. With too high a threshold temperature, we don't get enough events to properly check our expectations, which are given by the straight lines, against the data, given by the large dots, so here we have used a temperature of 33 °C.

An obvious and final question relates to climate change. Although single events such as heatwaves are difficult to attribute to climate change, it is likely that with a warmer world that the frequency and severity of heatwaves will increase. This is an active area of research, but this model can be used as a first approximation. Currently the chance of 4 days in a row over 40 °C in Renmark is 2% and the chance of 4 days over 39 °C is 5%. With a degree warming a simple adjustment is that the future chance of 4 days over 40 °C would increase from 2% to 5%. If this logic follows, a run of days exceeding 40 °C would still be rare, but the chance of it happening has more than doubled.

Chapter 15

The application of a risk management framework to information from a weather forecast of a heatwave in the coming week or the climatological odds of a heatwave for a given location over the season

PT Hayman, MG McCarthy, W Grace

Summary

A common definition of a heatwave is a run of unusually hot days. What constitutes a heat wave in Griffith will differ from a heatwave in Coonawarra. This is partly because vines acclimatise to certain conditions but also because viticulturists design the irrigation systems and manage vineyards with a sense of what is normal or expected. In this article we examine the challenge of managing this risk. There is a large amount of literature from psychology that shows that most of us are poor intuitive statisticians and that we struggle when dealing with decisions relating to rare events, especially rare events that have high consequences.

The phrase 'risk management' has become a much used term and means different things to different people. In many cases risk management can be seen as little more than stating that bad things can happen and it is wise to be careful. The Australian New Zealand Standard for risk management AS/NZS 4360 follows the simple logic of first establishing the context and identifying the risks before analysing and evaluating the risk before treating the risk.

In the first issue of this three part series we established the context and identified the risk of heat waves in SE Australian wine growing regions. We noted that a hot day could largely be explained by a high pressure system in the Tasman Sea bringing warm inland air on northerly winds. A run of hot days or a heat wave is when this high pressure system stays in the Tasman and is strengthened through the processes of blocking.

The second issue published last month, addressed the mathematics of heatwaves as a way of analysing the risk. We showed that at any given site in the SE wine growing regions, the likelihood of a heatwave was related in a predictable way to the temperature threshold (for example 37 or 40 ^{o}C) and the duration (for example 3 days or 5 days). We also showed that this relationship between the threshold and duration differed depending on location. Not only are inland regions likely to be hotter, they are also more likely to have a run of hot days. In this issue we address the question of how the knowledge about the weather conditions that lead to heatwaves and the mathematics of heatwaves can be used for risk management.

What are some of the management options for heatwaves?

It is reasonable to ask whether there is anything that wine grape growers can do about heatwaves. In one sense there is nothing that can be done to fully protect against a run of very hot days and nights. The nature of damage from heat events and ways to ameliorate the damage is an active area of research and a subject of much discussion within the industry.

The following table of actions are based on three main sources. First, at a series of meetings in the Barossa and Coonawarra in 2008 SARDI researchers Victor Sadras and Chris Soar asked wine grape growers to list ways that they managed heat waves. Second, Peter Hayman (SARDI) and Peter Leske (then with South Australian Wine Industry Association) discussed challenges of climate change in a series of meetings with the Riverland Viticultural Technical Group and Clare Valley Wine Makers Association from 2007 to early 2009 in a project on managing climate change and finally Mike McCarthy (SARDI Viticulturist) questioned the Barossa Viticultural Technical group and the Riverland Viticultural Technical group on their observations from the late January to early February 2009 heatwave. There are a range of suggestions, some more practical than others and some might be obvious. In fact some are contradictory where one person suggests that a green sward in the inter-row region uses too much water that is needed by vines during a heatwave and another has pointed out that a green sward had a cooling impact. A common comment related to access to water, both in terms of quality and quantity. Certainly any process of using water in vineyard cooling requires good quality water, and access to reasonable quantities. A second general observation was the price of grapes and the cost of production. Many suggestions for dealing with heat stress add cost and this is problematic with low grape prices. This list is not comprehensive and the authors would be keen to hear from any growers with different experience. Blateyon and Rousseau (2005) make some practical suggestions on the challenges of harvesting and winemaking during heatwaves based on their experience of the 2003 summer heatwave in France.

Category	Action
Irrigation	• Irrigate before the heatwave • Try to ensure that the crop has adequate water from previous rainfall and/or irrigation. • Irrigate at night • Don't wait until 3 to 4 days into the heatwave to start the irrigation • Try to reduce the irrigation cycle
Vine health and canopy management	• Balance fruit load and growth • Healthy vines with better nutrition • Canopy cover – the leaves may get burnt but they protect the crop • An observation that a block that was frosted in the spring of 2008 was able to cope with the late January heat wave in 2009. • Greatest impact on small canopies/high crop load

	per vine • Maintaining leaf function. • Early season vine nutrition for building larger canopies • Nutrition for good leaf function at the end of the year
Changing crop development	• Pruning to modify the timing of budburst and subsequent developmental stages • Wire lifting for reducing functional leaf area – slows ripening
Varieties and rootstocks	• Changing varieties to ones that better handle heat stress or ripen at a time that reduces the risk of heat stress • GM vines • Using more vigorous rootstocks • More drought tolerant rootstocks
Vineyard layout	• Avoid western aspect • Use landscape to find cooler mesoclimates • Row orientation – perhaps Nth-East/Sth-West • Windbreaks to limit northerly winds
Inter row management	• Negative impact of green sward under restricted water • Positive impact of green sward in providing cooling • Mulching to minimise reflected heat from inter- row area, especially on sandy soils
Vineyard cooling	• Overhead irrigation for cooling • Under vine irrigation for cooling • Using wind fans for air movement and heat management
Spraying	• Sprays for reducing leaf temp • Reflective surfaces on leaves and bunches • Shading for high value vulnerable vines
Harvesting and winery logistics	• Infrastructure for coping with logistics issues associated with ripening in warmer months and shorter windows. • Careful setting for machine harvesting of grapes in hot conditions • Night-time harvesting • Increased refrigeration capacity
Wine making	• Wine making techniques • GM yeasts

The actions listed above can be categorised in a number of ways. One aspect is the time domain of the action. For example under the general heading of irrigation there are short term operational decisions about irrigation scheduling that rely on weather forecasts and there are tactical decisions made at the beginning of a season such as water purchases, area of irrigation that could be influenced by a seasonal climate forecast of warmer conditions and the likelihood of heatwaves. Finally, there are longer term strategic decisions about redesigning the irrigation system to cope with an increased chance of heatwaves in a warming climate. The categories of short term operational decisions, mid term tactical decisions and longer term strategic decisions fits the distinction between weather (coming week), seasonal climate (coming 3 to 6 months) and climate change (coming decades and longer).

Weather forecasts of a heatwave

The table below shows the four outcomes if a weather forecaster is predicting a heatwave and a wine grape grower is acting on the warning. The two rows show the predictions and the two columns show what happened.

	Heat wave forecast	**No heat wave forecast**
Heat wave occurred	**True Positive** Some damage from heatwave but loss is reduced by extra water applied prior to the event	**False negative** Severe damage from heatwave as action was too late to minimise the damage
No heat wave occurred	**False positive** No damage from heatwave but grower bears cost of extra water applied. Perhaps some negative effects on ripening/quality due to additional water applied	**True negative** No damage and no cost

Obviously we would like to spend most time in the bottom right hand corner where there is no forecast of a heatwave and no losses from a heatwave – this is what we hope for in a comfortable vintage. When heatwaves occur, both forecasters and grape growers want to be in the top left hand corner where warning is given and appropriate action is taken.

The worse outcome is the top right hand corner where a heatwave is a surprise to both the forecaster and the grape grower. The bottom left hand corner is often called false alarms. An important aspect of forecast and decision theory is that for a given level of accuracy of a forecast, there is a trade-off between false negatives and false positives; in other words a tradeoff between not warning of an event and providing false alarms. This is much discussed in terms of bushfire warnings and cyclone warnings.

Heatwaves are rarely a surprise to weather forecasters, as described in the first issue of this series; the synoptic conditions that lead up to a heatwave are well understood, slower moving variables. These conditions make a heat wave quite predictable for experienced forecasters. Exactly how hot it will be and the length of a heatwave is much more difficult to predict.

If we are talking about a heatwave as defined by the South Australian Regional Office of the Bureau of Meteorology as 5 days over 35 or 3 days over 40, we would expect that there would be a high proportion of events in the top right hand corner. If there was a 'miss' it would tend to be that there were 4 rather than 5 days over 35 or a day was in the high 30s rather than 40. The last three heatwaves (February 2004, March 2008 and January 2009) were well predicted and actively communicated by the Bureau of Meteorology. Because the process that ends a heatwave can be relatively difficult to predict, we would expect that there will be more false alarms than failures to warn. A feature of the March 2008 heatwave and the January 2009 heatwave was their length. This is harder to predict and an important area of research.

Forecasts of heatwaves in the coming season or the coming decades

It is something of a paradox that climate scientists would be much more confident to bet on there being more heatwaves in 2030 than being able to say anything about the next 2 years. As the world warms the frequency of heatwaves is likely to increase, but there will still be variability on a year by year basis. One of the advantages of the large amount of resources going into understanding climate change is that there will be improved models of local climate. Because of the human cost of heatwaves, efforts to improve forecasting accuracy and communication will be a high priority. A challenge for the wine grape industry is to access this information and use it in risk management frameworks. In the past it may have been the case that the message about a coming heatwave was not communicated – due to the human health and bushfire risks it is likely that there will be false alarms in the future. This is complicated by the media which never worries too much about false alarms because it sells papers on the day of the alarm and the next day there is a follow up story that scientists got it wrong.

Risk management involves uncertainty

There are some actions to take when a heatwave is coming that have little downside- for example if a grower has access to water and a price for their grapes there is little to be lost by using the water. Even if the heatwave is shorter than predicted, there is little risk of over watering. However, many of the options, especially those for the longer term are costly. If we knew that the next two vintages were going to have another severe heatwave, even with hard to find funds in the current situation, a grower might consider improving their irrigation system with an extra pump. We don't know that this is the case but we can put some numbers on the uncertainty by providing the chance of a defined heat event for any fortnight in the growing season. The role of science funded by GWRDC is to assess

and characterise the risk. As for the question of the exact steps to manage the risk, that is best left to the individual enterprise.

Part 3

Communication activities and directions for future research

Chapter 16

Communication

This project established an active program of communication. Whenever feasible, we first exposed our findings to peer-review in scientific journals. Far from perfect, peer-review is an effective tool for quality control. We communicated our findings and sought feedback from industry in a number of invited workshops or meetings; we also initiated and hosted a series of workshops to achieve this end. Project progress, constraints and activities were discussed in annual meetings with members of GWRDC's sponsored Soil Water Initiative and the Industry Reference Group appointed to guide this project. This chapter lists the communication activities of this project.

Web Site

http://www.scitopics.com/Temperature_vines_and_wines.html

Scientific Publications

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2009 Sadras, V.O., Soar, C.J. Shiraz vines maintain yield in response to 2-4 ^{o}C increase in maximum temperature at key phenostages. European Journal of Agronomy 31: 250-258.

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2008 Soar, C.J., Sadras, V.O., Petrie, P.R. Climate drivers of red wine quality in four contrasting Australian wine regions. Australian J. Grape Wine Res. 14, 78-90.

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

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Industry Publications

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2009 Grace, W.J., Hayman, P.T. The mathematics of heatwaves in South-Eastern Australian winegrowing regions. The Australian and New Zealand Grapegrower and Winemaker 542, 45-49.

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2009 Sadras, V.O., Soar, C.J, Collins M.J. Irrigated Shiraz powers on, despite short heat spells. Australian and New Zealand Grapegrower and Winemaker 547, 24-28.

2009 Sadras, V.O. Petrie, P.R., Robinson, R. Grapevine adaptation to environmental variation: plasticity of phenology and yield Australian and New Zealand Grapegrower and Winemaker, Annual Technical Issue No 37, 24-26.

2009 Soar, C.J., Sadras, V.O., Petrie, P.R. Wine quality and the weather in the Hunter Valley, Margaret River, Coonawarra and Barossa Valley Australian and New Zealand Grapegrower and Winemaker, Annual Technical Issue No 37. 74-77.

2008 Sadras, V.O., Petrie, P.R. Recent warming trends and early maturity of Shiraz, Cabernet Sauvignon and Chardonnay in Australia. Australian and New Zealand Grapegrower and Winemaker June, 28.

2007 Sadras, V.O., Soar, C.J., Petrie, P.R. Long-term time trends in vintage ratings of Australian wines Australian and New Zealand Grapegrower and Winemaker October, 80-81.

Conferences

2009 Hayman, P.T. Questions on extreme events from wine grape growers and wheat farmers in South Australia. Australian workshop for The Atmospheric Circulation Reconstruction for the Earth (ACRE) project. Brisbane. 1-3 April 2009

2009 Hayman, P.T. and Alexander, B.M. 2009. Wheat, wine and pie charts; using recent history to understand the impacts of climate change in South Australian agriculture. Greenhouse 2009. Perth. 23-26 March 2009.

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2007 Hayman, P., McCarthy, M.G., Sadras, V.O., Soar, C.J.. Can we identify dangerous climate change for Australian Viticulture?, 13th Australian Wine Industry Technical Conference, Adelaide

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2007 Sadras, V.O., Soar, C.J., Petrie, P.R.. Long-term time trends in vintage ratings of Australian wines 13th Australian Wine Industry Technical Conference, Adelaide.

2007 Soar, C.J., Collins, M.J., Sadras, V.O. A comparison of experimental systems for increasing grapevine canopy and bunch temperature. 13th Australian Wine Industry Technical Conference, Adelaide.

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2007 Sadras VO. Quantification of time trends in vintage scores and their variability for major wine regions of Australia, Viticulture Seminar Argentina – Australia, Mendoza, 28 May- 1 June 2007.

2007 Sadras VO. Quantifying Phenotypic Plasticity of Berry Traits, Viticulture

Seminar Argentina – Australia, Mendoza, 28 May-1 June 2007.

Industry workshops and presentations

2009 Hayman, P.T. Climate change and heatwave analysis. Wine Grape National Steering Committee. Griffith. 16 April 2009

2009 Hayman, P.T. McCarthy, M. Climatic analysis and discussion of lessons from the January 2009 heatwave in the Barossa. Tanunda. 18 February 2009.

2009 Hayman, P.T. Climatic analysis of the January 2009 heatwave at Clare. Taylor's annual board meeting. Clare. 18 February 2009.

2009 Thomas R, McCarthy M, Biswas T, Sadras VO, Cox J. Next generation irrigation and crop production technology. Riverland Wine Industry Development Council. Berri, 12th June 2009.

2008 Hayman, P.T. The challenge of less water, warmer vintages and increased heatwaves on viticulture. Fosters' winemakers technical conference. Angaston. 7 November 2008.

2008 Hayman, P.T. Impact of climate change on viticulture in McLaren Vale – what can we learn from past heatwaves. McLaren Vale 5 September 2008.

2008 Hayman, P.T. Barossa and climate change; less water, warmer vintages and more heatwaves. CRC for Tourism workshop on the impact of climate change on tourism in the wine industry. Tanunda. 16 September 2008.

2008 Hayman, P.T. Analysing average and extreme temperature in past vintages at Renmark. Renmark to the border action plan annual dinner. Berri. 30 July 2008.

2008 Soar CJ Grapevine response to high and extreme temperatures. Orlando Wines post vintage technical conference, May 2008. McLaren Vale Growers meeting, McLaren Vale Visitor's Centre, July 2008. Langhorne Creek Growers meeting, Langhorne Creek Football Club, October 2008.

2007 Hayman, P.T. Leske P. Climate change challenges in Riverland. Berri. 27 November 2007.

2007 Hayman, P.T., Leske P and McCarthy M. Impacts of climate change – What are the risks for Clare water, average temperatures, hot days or warm nights? Clare Valley Wine Makers Association. Auburn. 2 July

2007.

2007 Hayman, P.T. and Leske P. Identifying the main impacts of climate change – water, average temperature or extreme temperature? Riverland Vit. Technical Group, Loxton. 21 February 2007.

2007 Sadras VO. Quantifying the improvement in Australian wine quality in the last two decades: Can technology counteract warming trends? Viticulture Seminar - Climate Change, Manjimup Horticultural Research Institute, 5 Nov 2007

2007 Sadras VO, Soar CJ Wine quality and climate workshop. Nuriootpa (18 Sep), Coonawarra (20 Sep). These workshops attracted about 70 people, including grape growers, vineyard managers and winemakers.

2007 Soar CJ. Sprinklers to drippers – impacts on grapevine root architecture and implications for water acquisition. ASVO Viticulture Seminar "Water, friend or foe?" Mildura, 2 Nov 2007

Other

This project featured in ABC Landline (March 2008), GWRDC's "R&D at Work" (August 2007 and November 2008), The Advertiser (September 2007), Australian and New Zealand Grapegrower and Winemaker (January 2009) and regional media.

Chapter 17

Recommendations for further research

Indirect and direct methods have been used to investigate the effects of temperature on vines and wines. Indirect methods have compared seasons, regions and analysed long-term data series using a range of statistical tools to infer the putative effects of temperature. Results from this indirect approach are valuable, but are bound to remain inconclusive because temperature is correlated with other factors such as radiation, vapour pressure deficit and rainfall and the confounding effects of technological change. Unequivocal results require direct comparisons where vines are exposed to different temperatures. Manipulation of temperature in controlled environments is straightforward and this has been the favoured method, but potted vines in chambers or glasshouses often bear little relation to vineyard conditions. We thus develop, tested and deployed three novel systems to control temperature in the field (Chapter 1). Application of these methods showed higher than expected tolerance to high temperature in irrigated Shiraz, and some of the physiological mechanisms have been unveiled (Chapters 2-3). Our experiments pointed out the three-way interaction between variety, temperature and water supply as a key area for further research.

The passive, open system we developed to increase daytime temperature can be upgraded to actively increase night temperature and day temperature during cloudy winter days (Chapter 3). An important feature of this system is that it is primarily compatible with free-air carbon dioxide enrichment facilities (FACE)[5]. Our upgraded heating facility will therefore provide a platform for future research on the interaction between temperature and ambient CO_2 concentration in vineyard conditions.

Allometric analysis is necessary to account for size-dependent and size-independent effects of genetic, environmental, and management factors affecting berry properties with relevance for wine making, including sugar and anthocyanins, and possibly also other critical compounds such as tannins (Chapters 8-10). We suggest that these models should be favoured in studies of berry composition.

Matching varieties and climate has been at the core of viticultural decisions in the past, and is likely to be more important in the future with highly dynamic markets and climate shifts. We propose that the framework of plasticity in Chapter 8 will contribute to the understanding and manipulation of the genetic control of vine development and improve the efficiency in selecting specific varities for specific sites.

We assessed long-term records of vine phenology to quantify the advancement in maturity associated with recent warming (Chapter 4), the improvements in wine

[5] Bindi M, Fibbi L, Lanini M, Miglietta F (2001) Free Air CO2 Enrichment (FACE) of grapevine (*Vitis vinifera* L.): I. Development and testing of the system for CO_2 enrichment. *European Journal of Agronomy* **14**, 135-143.

quality driven by technological developments during the last three decades (Chapter 5) and associations between climate drivers and red wine quality (Chapter 6). Further work is required to derive practical models to predict maturity that can be applied to vineyard management and winery scheduling. A critical re-assessment of grapevine cardinal temperatures for development seems necessary (Chapter 3).