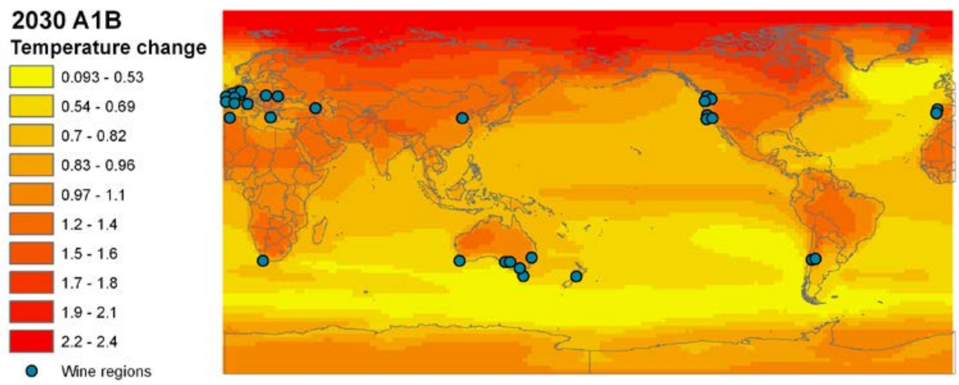
Adaptation of the Australian Wine Industry to Climate Change - Opportunities and Vulnerabilities



FINAL REPORT to

GRAPE AND WINE RESEARCH & DEVELOPMENT CORPORATION

Project Number: **MU 08/01**

Principal Investigator: **Leanne Webb**

Research Organisation: **University of Melbourne and CSIRO**

Date: **30 September 2011**

Table of Contents:

Abstract

Climate projections for various climatic variables have been calculated for Australia and for selected regions globally. A warming climate is projected for all sites and this varies by region and seasonally. Projections for rainfall vary with most regions likely to have a drier future, while a few are likely to get wetter.

Adaptation options directed at phenological shifts and managing grapevines through extreme heat have featured in this project. Visits have been undertaken to many regions around the country discussing vulnerabilities and adaptation strategies with practitioners.

Maintenance of ecosystem function is described from a global perspective as it may improve ongoing vineyard resilience to changes. Finally a review of the genetic potential of winegrape vines as a resource for adaptation to climate change has been undertaken.

Executive summary

Observed climate

Australia and the globe are experiencing rapid climate change. Since the middle of the 20th century, Australian temperatures have, on average, risen by about 1°C with an increase in the frequency of heat-waves and a decrease in the numbers of frosts and cold days. Rainfall patterns have also changed - the northwest has seen an increase in rainfall over the last 50 years while much of eastern Australia and the far southwest have experienced a decline (Australian Bureau of Meteorology 2011).

Observed impacts and surprising adaptation options

Trends to earlier maturity day have been detected in 43 of 44 Australian vineyard blocks studied, and while these trends are partly due to the warming climate, we reveal potential for adaptive action with attribution to reduced water availability, reductions in yield and also introduced management practices, along with observed warming, being made.

Projected climate

Further climate change is expected over the coming decades due to greenhouse gases emitted in the past that remain in the atmosphere, and anticipated emissions in the future (IPCC 2007). For most locations the projected best estimate[1] of mean warming over Australia by 2030 (mid emissions) is 0.7- 0.9ºC in coastal areas and 1-1.2ºC inland. In winter, warming is projected to be a little less than in the other seasons, as low as 0.5ºC in the far south by 2030. Warming is usually less near the coasts than further inland, an exception being in the northwest, where the warming exceeds 1.3ºC in spring (CSIRO and Australian Bureau of Meteorology 2007).

Best estimates of annual precipitation change represent little change in the far north of Australia and decreases of 2% to 5% elsewhere. In summer and autumn decreases are smaller and there are slight increases in the east. Decreases of around 5% occur in winter and spring, particularly in the south-west where they reach 10% (CSIRO and Australian Bureau of Meteorology 2007).

In the global assessment we found that warming is projected for all of the regions studied with greater warming in the Northern Hemisphere continental regions and less for the Southern Hemisphere and coastal regions. Annually, projections for rainfall vary across regions with indications of a likely wetter future some higher latitude regions (e.g. New Zealand; Mosel and North Oregon) and also Chinese vineyards. Other regions in Southern Europe, Australia and South Africa have a drier future climate projected. Winter rainfall is projected to decrease in Chile, Greece, Australia and Spain, with other European regions and the American regions studied here likely to have slight increases in winter rainfall. For summer rainfall China is the only region likely to experience a wetter climate. Comparisons of the relative climate changes are discussed.

[1] Median result (50th percentile) from assessment of 23 climate models (CSIRO and Australian Bureau of Meteorology 2007)

Discussing projections regionally

Workshops based on the SAWIA and SARDI booklet (Hayman *et al.* 2009) and the idea of a stocktake of the resources in terms of current climate, soils, water and varieties were organised. The funding for these was supported by Department of Agriculture Fisheries and Forestry. A cropping calendar was discussed and growers were asked to indicate how they saw their region as vulnerable to current climate variability. Discussion then moved on to projected climate shifts that may impact their region.

Extreme events

Increases in heatwave occurrences in eastern Australia and South Australia since the 1950s have been reported by Deo *et al*. (2007) and projected increase in their frequencies in future reported by Alexander and Arblaster (2009). Furthermore, an increased area is likely to be affected by drought with a reduction in recurrence interval (Hennessy *et al.* 2008). An increased risk of bushfires has also been modelled for south eastern Australia (Lucas *et al.* 2007).

As well as changes to daily precipitation the intensity of precipitation is likely to increase under enhanced greenhouse conditions (CSIRO and Australian Bureau of Meteorology 2007). There is also a projected increase in the number of dry days for Australia. Furthermore, for much of Australia there is an increased chance of extreme rainfall though this varies seasonally (CSIRO and Australian Bureau of Meteorology 2007).

Heatwave survey

While changes to average climate are projected it is perhaps changes to the frequency of extreme events that may cause the greatest impact, at least in the short term. A survey of 92 grape-growers after a severe summer heat wave revealed potential better management practices for coping in extreme heat.

General adaptation

Improving the resilience of the winegrape community to climate change through exploiting the genetic diversity of the winegrape vine was undertaken. This chapter is published in an international publication: Crop adaptation to climate change.

Global issues were also considered with regard to ecosystem services. In improving vineyard sustainability by consciously conserving ecosystems and biodiversity improved resilience to climatic changes are likely.

Conclusions

Much of this project has involved direct engagement with stakeholders. Thirty presentations were given by the principal investigator at national, international and regional workshops and conferences. Twenty-one publications have also been produced relating to this project. In the winegrowing community there is a growing interest in the changing climate and a good deal of intelligent discussion and consideration of the impacts of the changes already observed. Successful engagement should be a continuing strategy in order to ensure the winegrowing community remains as resilient as possible to future climate challenges.

Background:

Of all agricultural crops, wine grapes show greater temperature by variety interaction than any other. This has led to the development of discrete regions, each with their own reputations for excellence of varietal wines. This will be influenced, to a greater or lesser extent, by climate change in the near future.

It is now generally agreed that the globe will warm an average 1°C by 2030 regardless of any global mitigation agreements, and another 1°C by 2050 in the absence of new international agreements aimed at reducing global emissions by greater than 60%. Australia's viticultural areas can expect warming in the order 0.3 to 1.7°C by 2030 and 0.4 to 2.6°C by 2050 (Webb et al. 2008a, 2008b). Recent global emissions data detailing an acceleration of global emissions and reduced capacity of the oceanic and terrestrial sinks to absorb these emissions in the past 6 years indicate that we can expect warming in Australia's viticultural regions to be at the high end of the above projected ranges (Raupach et al. 2007).

The global nature of climate change means that all wine regions in the world will experience varying degrees of warming in the first half of this century. Those of the Southern hemisphere will be less impacted, and parts of Australia, New Zealand and Chile will be among those least affected by projected temperature increase. Undoubtedly, the most resilient national wine industries will be those that adapt the most quickly by identifying opportunities and minimising disruption. This report offers the Australian wine sector such an opportunity through the information it contains.

Recent studies internationally and nationally indicate that in the absence of significant adaptation there may be serious risks to the wine industry in terms of potentially declining quality, infrastructure requirements and the availability of water (Jones et al. 2005, Webb et al. 2008a, 2008b, Nicholas et al. in press). Vine responses to high temperatures and episodes of extreme temperatures (McCarthy and Loveys, GWRDC SAR 05/01) and elevated CO_2 (Tyerman and Barlow, under development) are being assessed but the outcomes of this work will not be available to the industry in the short term.

The AWITC colloquium (2007) on the 'Impacts of Climate Change on the Australian Wine Industry' convened by Dr Richard Smart was voted the most informative and important by attendees. This proposal has sought to address this heightened industry priority by bringing together the viticultural expertise of the University of Melbourne, the climate change impact analysis skills of CSIRO Division of Marine and Atmospheric Research, together with the international viticultural experience of Dr Richard Smart.

The key to our analysis of impacts and adaptation is the quantitative understanding of the temperature/quality relationships for major grape varieties. In our previous work we have used price as a 'surrogate' to develop these important relationships. In this project we refine these relationships using wine show data and the experience of industry professionals to better understand how major varieties are now performing under different climate conditions. Further, we will use homoclime analysis to study very hot regions overseas and local varieties well suited to them. Such germplasm would be the foundation of future breeding programs.

Climate's influence on agribusiness is most evident with viticulture and wine production where it is arguably the most critical aspect in ripening fruit to its optimum to produce a desired wine style. Today's wine production occurs over relatively narrow geographical and climatic ranges, most often in mid-latitude regions that are prone to high climatic variability. Furthermore, individual winegrape varieties have even narrower climate ranges, which limit them to even more select areas suitable for their cultivation. These narrow niches for optimum quality and production put the cultivation of winegrapes at greater risk from both short-term climate variability and long-term climate changes than other crops. And while winegrapes as a crop are not crucial to human survival, the vine's extraordinary sensitivity to climate makes the industry a strong early-warning system for problems that all food crops will likely confront as climates continue to change.

While the exact spatial changes in the magnitude and rate of climate in the future are speculative at this point, what is absolutely clear from historical observations and modelling is that the climates of the future, both over the short term and over the long term, will be different than those today. These changes will likely bring about numerous potential impacts for the wine industry, including – added pressure on increasingly scarce water supplies, additional changes in grapevine phenological timing, further disruption or alteration of balanced composition in grapes and wine, regionally-specific needs to change the types of varieties grown, necessary shifts in regional wine styles, and spatial changes in viable grape growing regions. *In vino veritas*, the Romans said: In wine there is truth. The truth now is that the earth's climate is changing much faster than the wine business, and virtually every other business on earth, is prepared for. While uncertainty exists in the rate and magnitude of climate change in the future, it would be advantageous for the wine industry to be proactive in assessing the impacts, invest in appropriate plant breeding and genetic research, be willing to alter varieties and management practices, or minimise wine quality differences by developing new technologies (Jones & Webb 2010).

Project Objectives

1. To develop realistic spatially specific future climate scenarios for each of Australia's major wine regions based on the most recent regional climate projections for 2030, 2050 and 2070 timeframes.
2. To extend and validate existing studies of major variety by temperature interactions, to allow anticipation of Australian wine regions individual needs to adapt to climate change.
3. To establish adaptation scenarios for major wine regions based on changes to phenology and temperature tolerance of major varieties and future water demand and availability.
4. To explore the availability of land and water for vineyards interpreting 2030-2050 projected climates for major grape varieties using in part homoclime analyses of existing Australian and global wine regions.
5. To develop a regional vulnerability and opportunity methodology by evaluating adaptation options for major wine regions.
6. To conduct a biophysical competitor analysis of major global wine regions for 2030 and 2050 climate scenarios to inform industry planning.

Results/Discussion

Objective 1: To develop realistic spatially specific future climate scenarios for each of Australia's major wine regions based on the most recent regional climate projections for 2030, 2050 and 2070 timeframes.

The climate change projections presented for selected Australian wine regions in this report are consistent with those published in "Climate Change in Australia", the most up-to-date assessment of climate change for the whole of Australia (CSIRO and Australian Bureau of Meteorology 2007). Projections for the following climate variables in 2030 and 2070 are given in this report and in an accompanying Excel file (copy provided in the Appendix).

- Annual and seasonal average temperatures
- Annual average numbers of hot and cold days
- Annual and seasonal diurnal range
- Annual and seasonal average rainfall totals
- Annual and seasonal average potential evapotranspiration
- Annual and seasonal average wind-speeds
- Annual and seasonal average relative humidity
- Annual and seasonal average solar radiation

Projections in the following climate variables are given in this report but not the Excel files.

- Annual average number of rain days
- Heavy rainfall intensity
- Drought frequency (for 2030 only)
- Annual average number of days with extreme forest fire danger (for 2020 and 2050)

The projections provide information on climate conditions averaged over several decades in the future. For example, projections provided for 2030 and 2070 reflect average conditions for periods centred on the years 2030 and 2070.

By 2030, annual average temperatures are likely to increase in these regions by around 0.8°C (with an uncertainty range of 0.7 to 1.0°C). This provides an estimate of the 10-90% range of possibilities. Hence values lower and higher outside this range cannot be excluded. Warming is likely to be greatest in spring and summer. By 2070, the average annual temperature could increase by up to 1.6°C (0.9 to 2.3°C) under a low emission (B1) scenario or by 3.1°C (1.8 to 4.4°C) under a high emission (A1FI) scenario, dependant on the region.

The number of cool days is likely to decrease and the number of hot days is likely to increase. Estimates of the annual average number of extremely hot days were derived by applying projected changes in seasonal-average daily maximum temperatures to observed daily maximum temperatures for the period 1971-2000. In

Mildura, for example, during this period, the temperature reached 30ºC on about 20% of the days of each year, on average. By 2030, 30ºC could be reached on around 25% of days. By 2070, 30ºC could be reached on 25 to 30% of days under a low emission scenario and 30 to 40% of days under a high emission scenario. There were, on average, 32 days per year with temperatures over 35ºC in Mildura during the 1971-2000 period. By 2030, the increase in the annual average number of days with temperatures above 35ºC is around 7 days (4 to 11 days). By 2070, the increase is 13 days (7 to 19 days) under a low emission scenario and 28 days (16 to 44 days) under a high emission scenario. Mildura experienced only 6 days with temperatures over 40ºC in the entire 1971-2000 period. By 2070, an average of 11 or 18 days per year with temperatures over 40ºC could be the norm.

Some climate models indicate future decreases in rainfall for the selected wine regions while others indicate future increases. However, decreases are more likely than increases for all winegrowing regions described in this report except for summer rainfall in the Riverina and Hunter Valley regions (CSIRO and Australian Bureau of Meteorology, 2007). Percentage decreases are likely to be greatest in winter and spring. Changes in annual average rainfall vary by region and are likely to be -6% (-10 to -2%) by 2030 in Margaret River, for example. By 2070, changes in annual average rainfall for this region are likely to be -10% (-18 to -3%) under a low emission scenario or -20% (-35 to -6%) under a high emission scenario.

The intensity of heavy daily rainfall is likely to decrease slightly in some regions, and increase in others. Note that projections of heavy rainfall (defined as the heaviest 1% of 24-hour rainfall) are highly uncertain. By 2030, the range of uncertainty is -9 to +6%. For 2070, the range of uncertainty is -16 to +10% under a low emissions scenario or -30 to +20% under a high emissions scenario (Table 6 in appendix 1).

Drought is projected to increase in frequency and intensity, as are bushfires (see detail of these in the appendix).

With varieties presumably adapted well to the climate of the region in which they are now growing the potential impact of climate change indicates changes to the timing of ripening and this will have consequences for grape quality. Water demand and availability due to GHG-induced rainfall and evaporation change may be altered as well. Impacts from projected climate changes and changes that have already been observed along with proposals of potential adaptation options are outlined in this report and appendices.

(see Appendix 6 for full report and See attached spreadsheet for projections for every wine region in Australia)

Objective 2: To extend and validate existing studies of major variety by temperature interactions, to allow anticipation of Australian wine regions individual needs to adapt to climate change.

Phenological modelling

Previous modelling studies had indicated that winegrape ripening would likely occur earlier in the season given projected warming of the climate (Webb et al. 2007). This model was validated through an extensive assessment of historical trends in winegrape maturity dates from vineyards located in geographically diverse winegrape growing regions in Australia. Records from 44 vineyard blocks were accessed, representing a range of varieties of *Vitis vinifera* L. These comprise 33 short-term datasets (average 17 years in length) and 11 long-term datasets, ranging from 25 to 115 years in length (average 50 years). Time series of the day of the year grapes attain maturity were assessed.

A trend to earlier maturity of winegrapes was observed in 43 of the 44 vineyard blocks. This trend was significant for six out of the 11 long-term blocks for the complete time period for which records were available. For the period 1993-2009, 35 of the 44 vineyard blocks assessed displayed a statistically significant trend to earlier maturity. The average advance in the phenology was dependent on the time period of observation, with a more rapid advance over more recent decades. Over the more recent 1993-2009 period the average advance was 1.7 days per year, whereas for the period 1985-2009 the rate of advance was 0.8 days per year on average in the 10 long-term vineyard blocks assessed for cross regional comparison.

The trend to earlier maturity was associated with warming temperature trends for all of the blocks assessed in the study.

Following on from the detection study, attribution of the observed trend was carried out. While trends in phenological phases associated with climate change are widely reported – attribution studies remain rare. Attribution research in biological systems is critical in assisting stakeholders to develop adaptation strategies, particularly if human factors may be exacerbating impacts (Parmesan *et al.* 2011). This analysis demonstrated that detailed, quantified attribution helps to effectively target adaptation strategies, and countering recent tendencies to over-attribute (Brander *et al.* 2011). Winegrapes have been ripening earlier in Australia in recent years (Webb *et al.* 2011), often with undesirable impacts. Attribution analysis of detected trends in winegrape maturity, using time-series of up to 64 years in duration, indicated that two climate variables, warming and declines in soil water content, are driving a portion of this ripening trend. Crop-yield reductions and introduced management practices also contributed to earlier ripening. Potential adaptation options were identified as some drivers of the trend to earlier maturity can be manipulated through directed management initiatives, such as managing soil moisture and crop-yield.

(see Appendix 7 and 8 for full report)

Quality modelling

Richard Smart and Chris McRae explored the relationship between wine show rankings and regional temperature.

The aim here was to provide an indication of the difference of adaptability to different temperature regimes of the most important wine grape varieties in Australia, and also indicate which regions are most at risk due to loss of reputation for quality.

Australia has an extensive wine show system, with most capital cities having shows as well as national and regional shows. We believe the results of these competitions offer a valuable guide as to the quality of wine produced from different grape varieties grown under different temperature conditions. The wine show system is well regulated and attracts some of the finest wine judges in the land, and there is often continuity of judging at various shows. The wines are tasted blind, and although results are not statistically analysed they do represent normally the consensus of three senior judges and three associate judges.

Based on our assessment of availability of information and similarity of wine classes, we chose four capital city wine shows for analysis. These were Adelaide, Hobart, Melbourne and Sydney. For most of the shows and most of the classes, we had up to 11 years results available, from 2000 to 2010. Data about the medal winning wines, be they gold, silver or bronze, were extracted from the results of these shows, and like classes were sometimes combined in the analyses.

Results were obtained for the major red and white grape varieties, and some minor ones. The varieties which were analysed were Cabernet Sauvignon, Shiraz, Pinot Noir, Merlot, Petit Verdot, Grenache, Durif and Tempranillo for reds, and Chardonnay, Sauvignon Blanc, Semillon, Pinot Gris Viognier, Verdelho and Gewurztraminer for the whites. Also analyse were made for sweet white wines and sparkling wines.

Medal wins were allocated to a total of 65 Australian GI regions which were in existence at the beginning of the project. There were nine from Western Australia, 18 from South Australian, 21 from Victoria, 14 from New South Wales, two for Queensland and one from Tasmania. For the purposes of comparison of show success between regions, the medal scores were accumulated by allocating three points to a gold medal, two to a silver medal and one to bronze. The results were then totalled and averaged for each region for the years available for each show.

The region of origin (GI) was investigated using the maps at Wine Australia website www.wineaustralia.com.au. Wherever possible a central location was determined for each GI which had long-term climate data available, using www.bom.gov.au. We recognise that especially for regions near the sea or those with differences in elevation, a single central point may not be representative of the temperature conditions in all vineyards. We could then match up the results for each variety and each wine show over the period investigated, and correlate with temperature in the region which we describe by the Mean January Temperature MJT°C of the central location.

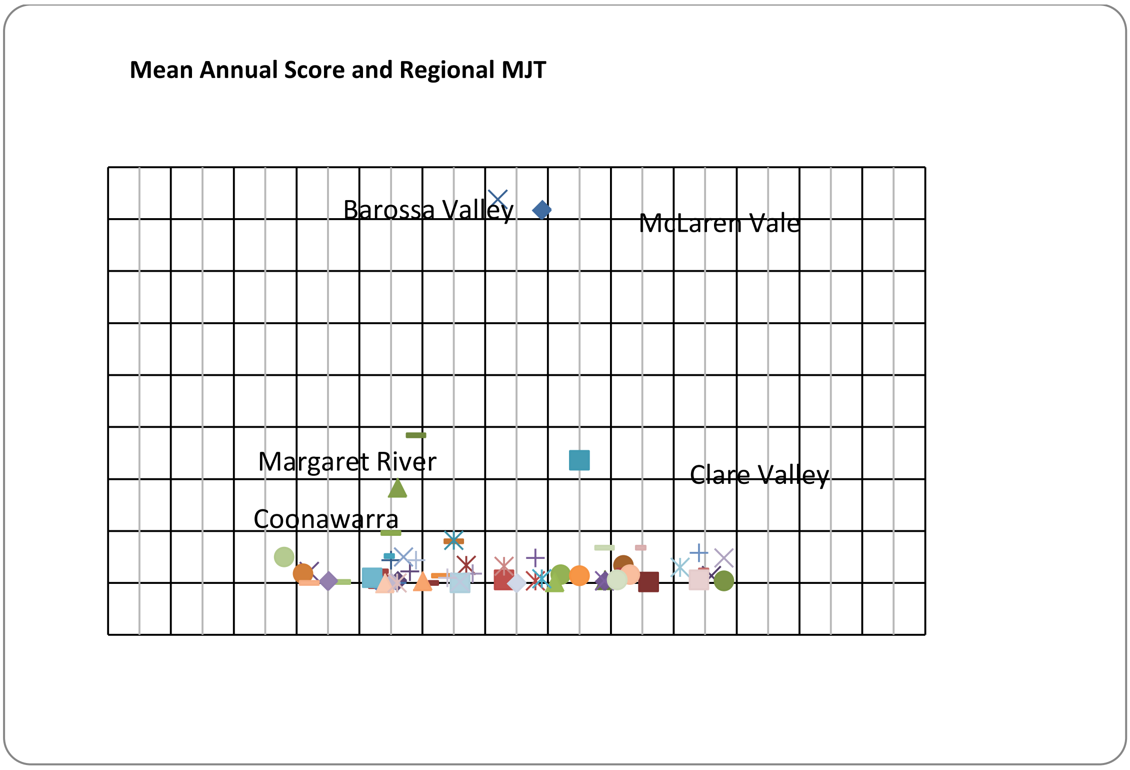


Figure 1 shows such a plot of mean score per year for the Adelaide Wine show for the wine grape variety Shiraz. Note that the GI regions presented span a temperature range from less than 18 to almost 25° C. The two regions with the greatest success in terms of medal wins were the Barossa Valley and McLaren Vale, both between 21 and 22 °C MJT. Note however that Coonawarra, Margaret River and the Clare Valley also experienced reasonable medal tallies. Of the remaining regions, many of which are new and small and produce few wines, the scores are lower. Since we cannot compare the scores obtained to the number of wines entered from a region we cannot speak in absolute terms of the superiority of one region over another for wine quality. However, such a plot does indicate the potential for growing quality Shiraz wines in for example the Barossa Valley and McLaren Vale.

This graph also suggests that Shiraz is quite adaptable to a range of climates, from MJT of 19.5 at Coonawarra to 22.5°C at Clare Valley. This is very different for example for Pinot Noir, which is a noted cool climate variety. For Pinot Noir, the three award winning regions are Yarra Valley, Mornington Peninsula and Tasmania, with an MJT spread from 18.2 to 19.8°C.

Objective 3: To establish adaptation scenarios for major wine regions based on changes to phenology and temperature tolerance of major varieties and future water demand and availability.

Heatwave survey

A survey of 92 vineyards, representing ten winegrowing regions in south-eastern Australia, soon after exposure to a severe heat-wave, revealed variation in the reported heat-related impact. This variation was observed between regions, within regions and within vineyards. Notably the estimates of losses were not always related to the amount of heat above a certain threshold but to the management practices employed in the lead-up and through the event.

Applicable and achievable recommendations for managing severe heat events have resulted from this assessment. We believe this method of capturing information from the diverse knowledge-base of managers is a very effective way to reveal potential adaptive capacity to a changing climate.

(See Appendix 9 for full report)

Genetics and Breeding options evaluated and reviewed

A review of the current literature was undertaken in collaboration with Peter Clingeleffer (CSIRO) and Steve Tyerman (University of Adelaide). In this review, the genetic envelope of winegrape vines was described with a focus on the potential for adaptation to future climate challenges. This analysis has been published in 'Crop adaptation to climate change', a John Wiley & Sons publication. A summary of the review follows here:

Adaptation of the winegrape industry to a warmer and water restrained future is perhaps more urgent and critical than for most of the alternative agricultural land use practices. Winegrape vines (*Vitis vinifera* L.) are traditionally grown in unique '*terroirs*' of which climate is a critical component, the characteristics of wine being directly linked to the climate of the region. A changing climate, therefore, will likely affect the both the style and quality of wine produced at a given site. Furthermore, winegrapes have an expected productive life of more than thirty years so selection of planting material today already requires consideration of the future climate.

Exploiting the genetic diversity of the Vitis species through substitution of better suited *V. vinifera* varieties and clones can be the first step to reducing the impacts of a warmer climate. Planting longer season varieties so that ripening is achieved at a desirable part of the season is fundamental practice to all grape-growing enterprises. Similarly rootstock selection to suit current and future environmental conditions can enhance resilience to a potential water restrained future.

Breeding among the *V. vinifera* varieties, or outcrossing with other Vitis species can be undertaken to produce better adapted progeny, as in some regions and/or further into the future, selection from the existing varietal stock may not be adequate to fully avoid the negative impacts of climate change. This may be the case, for example, in attempting to source well suited vines for regions already considered to be warmer or hot. As well as using conventional breeding, genetic modification and marker assisted breeding can be employed to produce better adapted grapevines, these techniques being no doubt facilitated by the recently completed sequencing of the grapevine genome.

No matter which strategy is used, adaptation of the vine to increased heat stress and drought stress will be the main focus for researchers and winegrape growers interested in avoiding the impacts of the projected warmer and drier climate. It remains to be seen how increasing CO_2 will interact with these other climatic factors on grapevine physiology. More research is required on this topic for this crop.

(Full chapter under copyright)

Objective 4: To explore the availability of land and water for vineyards interpreting 2030-2050 projected climates for major grape varieties using in part homoclime analyses of existing Australian and global wine regions.

Climate modelling

Calculations of estimated projected warming and changes to precipitation for 35 selected wine regions of the world are presented here. In this study 23 CMIP3 global climate models are employed and estimates for the median, 10th percentile and 90th percentile of model results are assessed. Projected climate by 2030 and 2070, resulting from climate model pattern scaling forced using A1B and A1FI emission scenarios are considered. The time-frames and greenhouse gas forcings were selected so as to approximately equate to global average warmings of 1, 2 and 3°C.

The regional inter-comparison made intrinsic to this study informs potential options whereby future climates can be easily compared to current climates across regions. In this way a homoclime analysis is enabled. This study is also described as satisfying objective 6. See that section of the report for further description.

(See Appendix 10 for full report)

Vinecology

Participation in the 2nd International Biodiversity and Vines Workshop (Vinecology) in Davis, California with conservation planners and scientists from the New World Mediterranean winegrowing regions of South Africa, Chile, the United States, Mexico. Participants were invited as these regions share similar climatic and environmental contexts. The Mediterranean biome is characterised by its climate – warm-dry summers and cool-wet winters – and its endemic biodiversity, which has been recognised as a priority for global biodiversity conservation efforts.

Despite the recent plateau in vineyard development in some of the New World winegrowing regions located in the Mediterranean biome, vineyards still contribute substantially to these landscapes. Here we documented the current state of knowledge and program approaches regarding biodiversity and ecosystem services as they relate to vineyard plantings in all of these New World winegrowing regions located in the Mediterranean biome.

As climatic changes interact with the issues of biodiversity and ecosystem services, as native species may be limited in their ability to shift with the climatic conditions suitable to them, it was discussed that new climate regimes might encourage vineyard expansion into biologically sensitive areas, particularly coastal regions and hillsides.

It was noted that vineyard managers have a number of options for changing management to adapt to some degree of climate change (Webb *et al.* 2010). However it is very important to include ecosystem services in the planning process when considering adaptation to climate changes to improve the overall outcome. For example, careful management of winery wastewater may ensure waterways and riparian regions retain their biodiversity and ecological health (Kumar *et al.* 2009). This will become increasingly important as water availability is likely to decrease and demand is likely to increase in latitudes suitable for wine-growing (IPCC 2007). Well-functioning ecosystems that support a healthy flow of ecosystem services are more likely to enhance the overall resilience of a system to projected climate changes.

There is currently a strong and growing trend towards industry certification and a growing awareness of the importance of the issue of environmental sustainability. The Vinecology network aims to support the transfer of scientific information, and generate greater global industry engagement in sustainability programs that are aligned with producer benefits and consumer expectations. Enhanced collaboration between non-governmental organisations, conservation scientists and wine sector leadership will assist with definition of these conservation goals and opportunities.

Ecosystem service protection is a common goal for users of sustainable landscapes. Wine industry practitioners can play a strong leadership role for other land-users by protecting Mediterranean ecosystems, at the same time as sustaining a more resilient industry into the future. Vinecology participants believe better management of biodiversity and underlying ecosystems within vineyard landscapes can be achieved by working together and learning from both shared and varying experiences. This will ensure productive agricultural sectors are sustained while also protecting and conserving the Mediterranean biome - one of the most diverse, yet poorly protected biomes on earth.

(See Appendix 11 for full report)

Objective 5: To develop a regional vulnerability and opportunity methodology by evaluating adaptation options for major wine regions.

Our project collaborated with Dr Peter Hayman as part of a DAFF/GWRDC climate change project.

Regions assessed to date:

- Tasmania: Launceston, Freycinet
- Limestone Coast: Coonawarra, Robe, Mt Benson, Padthaway, Wrattonbully
- McLaren Vale
- Mornington Peninsula
- Barossa.

Due to its high profile, the wine industry is often used as an example of the damage that will be caused by the early stages of climate change and suggested solutions are drastic such as shifting regions and radical changes in varieties. A clear message from the regional workshops was the sense of local identity and long term plans to stay rather than relocate. It may be that locals are overestimating their ability to adapt in the face of climate change, however it is also possible for commentators to underestimate the sense of attachment and sunk capital in any wine region.

Climate change is not the only issue or even the most immediate issue for the wine industry. There are many other stresses on the wine industry in general such as grape over supply, the high Australian dollar and alcohol tax policy. There are other regionally specific issues such as water policy, labour shortage and the challenges (and opportunities) of a working industry in the peri-urban fringes of towns and in some cases cities.

The workshops were based on the SAWIA and SARDI booklet and the idea of a stocktake of the resources in terms of current climate, soils, water and varieties. Obviously any one of these could be the subject of a workshop and we tried to emphasise that the question is not so much what the soils are in a given region, but rather what characteristics of the soils are likely to be important in a warmer and water constrained future.

Climate change projections were provided by this project (Leanne Webb from University of Melbourne and CSIRO) which highlighted the high confidence in warming, the wide range of outcomes for rainfall (with a bias towards drying) and the relatively small changes in solar radiation, relative humidity and wind speed. This information is consistent with the climate change in Australia report from CSIRO and the Bureau of Meteorology that the South Australian Government is promoting through the NRM regions as the authoritative source of information on climate change projections.

The climate information was followed up with a stock-take of soils, water resources and varieties planted in each of the regions.

A crop calendar was then discussed with the intention of identifying vulnerabilities to climate (current conditions) as perceived by the growers and winemakers in a particular region (Figure 1).

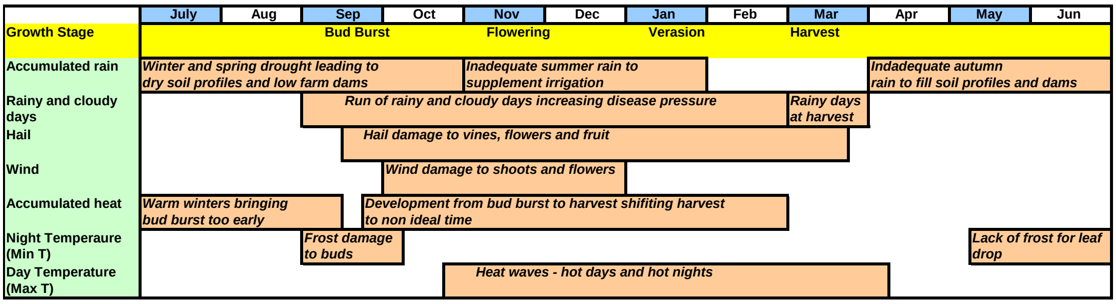


Figure 1 Viticulture calendar used to identify key climate and weather risks for viticulture in a region.

The calendar was used as a means of communication between the vineyard and climate information. The growth stages differ for each variety, different parts of the landscape and different levels of crop load.

The headings on the left hand side were designed to distinguish between seasonal aspects such as rainfall over the winter or accumulated heat over summer and events such as rain at harvest, a frost or heatwave. This is similar to the distinction between weather events (days to a week) and climate events (season). As climate is made up of a series of weather events, climate change will be delivered through warmer summers and extreme heat events.

Events were ranked based on the notion of risk being the product of chance and consequence. The consequence or damage was assessed as the loss to the grape-grower in terms of quality and quantity and the frequency related to how often this damage was expected to occur over a 10 year period. The damage was described first as this enabled the frequency to be assessed. Obviously the level of frost damage that causes 90% damage is rarer than the level of frost damage that causes 30% damage (Table 1).

Table 1 Example of ranking of perceived damage and frequency of weather or climate risk in a region.

Weather or climate risk	Damage	Frequency	Rank
Hot summers shifting development	7%	80%	1
Winter and spring drought	25%	20%	2
Rain at harvest	20%	25%	2
Heat waves	25%	20%	2
Autumn drought	10%	25%	5
Frost damage to buds	50%	5%	5
Hail damage to vines, flrs and fruit	30%	5%	7
Wind damage to shoots and flowers	5%	25%	8
Rainy cloudy summer days (disease)	20%	5%	9
Summer drought	0%	0%	
Warm winters bringing bud burst early	0%	0%	
Lack of frost for leaf drop	0%	0%	

In each region, this table was generated by a consensus, but there was considerable discussion about the final ranking. It is important to note that at 7% damage and 80% frequency hot summers shifting development is ranked first by a small margin. If damage was assessed as 6% rather than 7% or frequency assessed as 70% rather than 80% it would rank 4th.

Adaptation options were then discussed with the workshop participants once the risks were agreed upon.

This project is on-going and being managed by Dr Peter Hayman (DAFF and GWRDC funding).

Objective 6: To conduct a biophysical competitor analysis of major global wine regions for 2030 and 2050 climate scenarios to inform industry planning.

Calculations of estimated projected warming and changes to precipitation for 35 selected wine regions of the world are presented here. In this study 23 CMIP3 global climate models are employed and estimates for the median, 10^{th} percentile and 90^{th} percentile of model results are assessed. Projected climate by 2030 and 2070, resulting from climate model pattern scaling forced using A1B and A1FI emission scenarios are considered. The time-frames and greenhouse gas forcings were selected so as to approximately equate to global average warmings of 1, 2 and 3°C.

Warming is projected for all of the regions studied with greater warming in the Northern Hemisphere continental regions and less for the Southern Hemisphere and coastal regions. Annually, projections for rainfall vary across regions with indications of a likely wetter future some higher latitude regions (e.g. New Zealand; Mosel and North Oregon) and also Chinese vineyards. Other regions in Southern Europe, Australia and South Africa have a drier future climate projected. Winter rainfall is projected to decrease in Chile, Greece, Australia and Spain, with other European regions and the American regions studied here likely to have slight increases in winter rainfall. For summer rainfall China is the only region likely to experience a wetter climate. Comparisons of the relative climate changes are discussed.

Future climate for 2030 and 2070 are compared and contrasted with current climate conditions among the different regions. Under a 2°C global warming for instance, projected summer climate for Mosel in Germany, a region famous for producing Riesling, is likely to be warmer than the current average summer in Bordeaux, France, renowned for production of Cabernet Sauvignon. Implications for viticultural management, particularly suitability of varieties, will be an important issue when planning future vineyard developments. The regional inter-comparison made available here informs potential options whereby future climates can be easily compared to current climates across regions.

(See Appendix 10 for full report)

Outcome/Conclusion

The project achieved the broad objectives set out by the project guidelines.

In summary, we have achieved the following:

1. Developed realistic spatially specific future climate scenarios for each of Australia's wine regions for 2030, 2050, 2070 timeframes.
2. Extended and validated existing studies of major variety by temperature interactions, to allow anticipation of Australian wine regions individual needs to adapt to climate change.
3. Established adaptation scenarios for major wine regions based on changes to phenology and temperature tolerance of major varieties and future water demand and availability.
4. Explored the availability of land and water for vineyards interpreting 2030-2050 projected climates for major grape varieties using in part homoclime analyses of existing Australian and global wine regions.
5. Developed a regional vulnerability and opportunity methodology by evaluating adaptation options for major wine regions.
6. Conducted a biophysical competitor analysis of major global wine regions for 2030 and 2050 climate scenarios to inform industry planning.

In some cases the project took advantage of events that occurred throughout the project. A case in point is the survey undertaken after the 2009 summer heatwave in South-eastern Australia. This activity resulted in considerable acclaim, discussion and many publications that will have ongoing benefit to the wine industry.

The detection and attribution study of trends in winegrape maturity were novel and of international significance, being accepted for publication in significant international journals: Global Change Biology and in Nature Climate Change.

Regional climate vulnerability analysis is ongoing with Peter Hayman (SARDI) managing this with a DAFF/ GWRDC climate change project.

Recommendations:

Broad message

Research and extension agencies can identify adaptation options by:

- Applying existing knowledge in more innovative and effective ways and incorporating greater collaboration with decision makers e.g. heat wave report
- Continuing basic research e.g. detection of maturity trends
- Filling knowledge gaps e.g. global projection analysis.
- Testing validity of key assumptions e.g. Maturity trend attribution study.
- Evaluating the effectiveness of adaptation options e.g. review of the genetic envelope of winegrape vines.
- Broadening the array of research approaches e.g. all of the above.

Further research

Quantification of maladaptive risk exposure needs to be addressed with particular focus on changed exposure to extreme events in a future climate. The industry is now alert to the potential impacts of a changing climate and actively engaged in informing the participants of the potential threats and adaptation strategies. This process can be taken one step further to ensure the proposed adaptation strategies do not place the industry participants in different, unforeseen risk from other climate hazards.

There are situations where responses aimed at dealing with specific aspects of climate change could have unintended negative consequences. For instance, maladaptation by shifting to a region with greater climate variability, and hence increased vulnerability to heatwave damage, could occur. The differences between a continental and a maritime climate provide one such case. Abrupt extreme heat events with a cool lead-up to heat spikes may be more likely in some maritime climates where winds derive from hotter continental regions. In this case the region's vineyards may be exposed to 'non-preconditioned' heat-exposure, therefore more vulnerable to damage.

Looking ahead to the new climate regime to ensure optimisation of proposed adaptation strategies will reduce the possibility of poor or uninformed decision making. Extreme events such as heatwaves, hot nights, frost, extreme rainfall and drought will be considered, taking account of the likely shifts to phenology.

Communication

Publications (peer reviewed shown in bold font)

Viers, J., Williams, J., Nicholas, K. A., Barbosa, O., Kotze, I., Spence, L., Webb, L. B., Merenlender, A., and Reynolds, M., In prep, Vinecology: pairing wine with nature: Conservation Letters

Webb LB, Watterson IG, Bhend J, Whetton PH (in prep) Comparison of temperature and rainfall projections for selected world winegrowing regions. *Australian Journal of Grape and Wine Research,*

Webb L (2011) Projected climate: means and extremes. How will this impact the wine industry? In '7th University House Wine Symposium'. Australian National University, Canberra

Webb LB, Whetton PH, Bhend J, Darbyshire R, Briggs PR, Barlow EWR (2012) Earlier wine-grape ripening driven by climatic warming and drying and management practices. *Nature Climate Change,* 2, 259-264

Webb LB, Barbosa O, Granillo I*, et al.* (2011) Green aims given global perspective. *Australian and New Zealand Grapegrower and Winemaker,* 32-38.

Webb LB, Nicholas K, Barbosa O, Granillo I*, et al.* (under review) Sustainability practices and programs in New World vineyards of the Mediterranean biome. *Practical Winery,*

Darbyshire R, Webb L, Goodwin I, Barlow S (2011) Winter chilling trends for deciduous fruit trees in Australia. *Agricultural and Forest Meteorology,* 151, 1074-1085.

Webb L, Whetton PH, Barlow EWR (2011) Observed trends in winegrape vintages in Australia. *Global Change Biology,* 17, 2707-2719

Webb L, Whiting J, Watt A, Hill T, Wigg F, Dunn G, Needs S. and Barlow E.W.R. (2011) Options for managing heatwaves in vineyards: based on observations from the 2009 heatwave across south-eastern Australia. In 'Fourteenth Australian Wine Industry Technical Conference'. Adelaide. (Ed. K Beames) pp. 203-211. (Winetitles)

Webb L, Clingeleffer P.R. and Tyerman S. (2011) The genetic envelope of winegrape vines: potential for adaptation to future climate challenges. In 'Crop adaptation to climate change'. (Eds SS Yadav, B Redden, JL Hatfield and H Lotze-Campen). (John Wiley & Sons, Inc.: Iowa, USA)

Webb L, Snyder RL (in press) Frost Hazard. In: *Encyclopaedia of Natural Hazards* (Ed. Bobrowsky P). Springer Dordrecht.

Webb L, Whiting J, Watt A, Hill T, Wigg F, Dunn G, Needs S, Barlow E.W.R. (2010) Managing grapevines through severe heat: A survey of growers after the 2009 summer heatwave in south-eastern Australia. *Journal of Wine Research* 21(2): 147 - 165. http://www.informaworld.com/10.1080/09571264.2010.530106

Jones GV, Webb LB (2010) Climate change, viticulture, and wine: Challenges and opportunities. *Journal of Wine Research,* 21, 103 - 106. http://www.informaworld.com/10.1080/09571264.2010.530091

Webb L, Dunn G, Barlow EWR (2010) Winegrapes. In: *Adapting agriculture to climate change: Preparing Australian agriculture, forestry and fisheries for the future.* (eds Stokes CJ, Howden SM). Pp. 101-118. CSIRO Publishing, Melbourne.

Webb L, Whetton PH (2010) Horticulture. In: *Adapting agriculture to climate change: Preparing Australian agriculture, forestry and fisheries for the future.* (eds Stokes CJ, Howden SM). Pp. 119-136. CSIRO Publishing, Melbourne.

Webb L, Whiting J, Watt A, Hill T, Wigg F, Dunn G, Needs S, Barlow EWR. (2010) Managing extreme heat in the vineyard- some lessons from the 2009 summer heatwave. In: *Managing Climate Change. Papers from the Greenhouse 2009 Conference.* Pp 123-135 (eds Jubb I, Holper PN, Cai W). Springer/CSIRO Publishing, Melbourne.

2009

Webb L, Whiting J, Watt A, Hill T, Wigg F, Dunn G, Needs S, Barlow EWR (2009) Reducing impact from heatwaves: some grapevine training systems perform better than others. Australian and New Zealand Grapegrower and Winemaker

Webb L, Watt A, Hill T, Whiting J, Wigg F, Dunn G, Needs S, Barlow EWR (2009) Extreme heat: managing grapevine response based on vineyard observations from the 2009 heatwave across south-eastern Australia. Australian Viticulture 13:39-50

Webb L, Watt A, Hill T, Whiting J, Wigg F, Dunn G, Needs S, Barlow EWR (2009) Extreme heat: Managing grapevine response. Documenting regional and inter–regional variation of viticultural impact and management input relating to the 2009 heatwave in SE Australia., Report to GWRDC

Major Presentations

- Crush 2011 Attribution of trends in winegrape maturity in Australia. September 2011.
- DAFF funded climate adaptation workshops: Fleurieu (Coonawarra, Robe, Padthaway, Mt. Benson), McLaren Vale, Mornington Peninsula. August 2011.
- Trends in Climate and Phenological Changes in California and Australia. K. Nichols, L. Webb, E. Wolkovich. American Society of Enology and Viticulture. Seattle, June 2011 (Presented by K. Nicholas)
- 7th ANU University House Wine Symposium, Projected climate: means and extremes. How will this impact the wine industry? May 20 2011
- Greenhouse 2011 Shifts in winegrape maturity April 4th-8th
- Tasmanian Viticulture workshop. Climate change projections. 24/2/2011
- Extreme Heat, Managing grapevine Response. Presented at Extreme Weather 2011, Australia and New Zealand Meteorological and Oceanographic Society, 9th to 11th February, 2011 Wellington
- Conservation in Vineyard Landscapes: The Australian Perspective. Invited presentation given in Davis California 2nd international Biodiversity and Vines Workshop January 25-28, 2011

- Climate Change presentation to Curtin University, Margaret River, WA September, 2010.
- Attribution of earlier winegrape ripening in the Southern Hemisphere Analysis of vintage records: preliminary results MPVA Vine health workshop 26th Aug 2010
- Yarra Valley – Future Directions, Climate change forecasts Scientific perspective. Tuesday 17th August 2010, Historic Barn, Yering Station
- Options for managing heatwaves in vineyards: based on observations from the 2009 heatwave across south-eastern Australia-Plenary presentation 14th Australian Wine Industry Technical Conference, July, 2010 Adelaide.
- Extreme heat: managing grapevine response**-** 7th International Symposium on Cool Climate Viticulture and Enology June 20-22, 2010 Washington State Convention Center Seattle, Washington USA
- The Inaugural Robyn Van Heeswicjk Lecture, Climate change: Current status and future strategies for the Australian wine industry, Waite Campus Adelaide 15th Feb, 2010.
- Climate Change and the wine industry. Strengthening Resilient Economies. Regional Economic Development Conference. March 5 & 6Griffith Regional Theatre
- Managing extreme heat in the vineyard- some lessons from the 2009 summer heatwave Victorian Wine Industry Association Grassroots workshops (Central Victoria, Southern region and Ballarat) 7th, 8th and 9th Dec, 2009
- Managing extreme heat in the vineyard- some lessons from the 2009 summer heatwave Stressed vines, stressed wines, stressed you Rutherglen Wine Show, 22nd Annual Seminar 24th September, 2009
- Future in the Murray Darling Basin –potential adaptation strategies by agricultural industries in the face of climate change. 3rd Sept, 2009 Presentation to honours students, University of Melbourne, ILFR
- Developing Adaptive Capacity to Extreme Climatic Events: A Bottom-Up Approach. 2009 NCCARF Symposium Brisbane, 22-23 July 2009
- 'Hot, Dry future': 27th April, 2009, University of Melbourne: Panel member http://futurestudents.unimelb.edu.au/research/discover_hotdryfuture.html
- Vic DPI Climate Change Network Climate Extremes Seminar, 24th April, 2009 Mercure Hotel Spring St Melbourne
- Greenhouse 2009: Plenary panel: 'Agriculture and climate change - a growing problem?' Perth, WA March 2009
- Climate Change and Agriculture: impacts, adaptation and vulnerability. University of Melbourne Introduction to Climate Change (800-191) Forum Oct 2008
- Agribusiness Summit: 'The impact of climate change on farming enterprises'. Farming in a changing climate 08, 24/9/2008 Melton Victoria.

Poster Presentations

- Webb LB, Whetton PH, Bhend J, Darbyshire R, Briggs PR, Barlow EWR (2011) The fingerprint of climate change: Attribution analysis of trends in winegrape maturity. CSIRO Climate variablilty and change retreat. Torquay, Vic

- L. Webb, P.H. Whetton and E.W.R. Barlow (2010) Attribution of earlier winegrape ripening in the Southern hemisphere: analysis of vintage records. 2010 Climate Adaptation Futures Conference, 29th June-1st July, Gold Coast, Australia

Workshops

- Adaptation to Climate Change- “What are we going to do?” 14th Australian Wine Industry Technical Conference, July, 2010 Adelaide.

Report Bibliography

Alexander LV, Arblaster JM (2009) Assessing trends in observed and modelled climate extremes over Australia in relation to future projections. *International Journal of Climatology,* **29**, 417-435. http://dx.doi.org/10.1002/joc.1730

Australian Bureau of Meteorology (2011). http://www.bom.gov.au/climate/change/docs/FactSheet3.pdf

Brander K, Bruno J, Hobday A, Schoeman D (2011) The value of attribution. *Nature Climate Change,* **1**, 70-71. http://dx.doi.org/10.1038/nclimate1092

CSIRO and Australian Bureau of Meteorology (2007) *Climate change in Australia, Technical report.* CSIRO and Bureau of Meteorology through the Australian climate change science program, Melbourne, Australia. http://www.climatechangeinaustralia.com.au/resources.php (Accessed 1/5/09)

Deo RC, McAlpine CA, Syktus J, McGowan HA, Phinn S (2007) On Australian heat waves: Time series analysis of extreme temperature events in Australia, 1950 - 2005. In 'MODSIM 2007 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand'. (Eds Oxley L, Kulasiri D) pp. 626-635.

Fennell A (2004) Freezing tolerance and injury in grapevines. In: *Adaptations and Responses of Woody Plants to Environmental Stresses.* (ed Arora R), pp. 201-235. Hawthorn Press, Binghamton, NY.

Hayman PT, Leske P, Nidumolu U (2009) *Climate change and Viticulture. Informing the decision making at a regional level. Version 1.0, October 2009.* South Australian Wine Industry Association and South Australian Research and Development Institute GWRDC Project SAW 06/01. http://www.sardi.sa.gov.au/__data/assets/pdf_file/0005/123476/Climate_Change_Booklet_-_web.pdf

Hennessy K, Fawcett R, Kirono D*, et al.* (2008) *An assessment of the impact of climate change on the nature and frequency of exceptional climatic events.* CSIRO and BOM, Melbourne. http://www.daff.gov.au/__data/assets/pdf_file/0007/721285/csiro-bom-report-future-droughts.pdf

IPCC (2007) *Intergovernmental Panel on Climate Change, Climate Change 2007: The Physical Science Basis, Summary for Policymakers.* WMO, UNEP. http://www.ipcc.ch/SPM2feb07.pdf

Jones GV, Webb LB (2010) Climate Change, Viticulture, and Wine: Challenges and Opportunities. *Journal of Wine Research,* **21**, 103 - 106. http://www.informaworld.com/10.1080/09571264.2010.530091

Jones GV, White MA, Cooper OR, Storchmann KH (2005) Climate change and global wine quality. *Climatic Change,* **73**, 319-343.

Lucas C, Hennessy KJ, Mills GA, Bathols J (2007) *Bushfire weather in Southeast Australia recent trends and projected climate change impacts.* Consultancy report prepared for the Climate Institute of Australia. Melbourne: Bushfire Cooperative Research Centre, Australian Bureau of Meteorology and CSIRO Marine and Atmospheric Research. http://www.cmar.csiro.au/e-print/open/2007/hennesseykj_c.pdf (Accessed 22/7/08)

Nicholas KA, Matthews MA, Field CB, Lobell DB, Willits NH (in press) Effect of vineyard-scale climate variability on Pinot noir phenolic composition. *Agricultural and Forest Meteorology,*

Parmesan C, Duarte C, Poloczanska E, Richardson AJ, Singer MC (2011) Overstretching attribution. *Nature Climate Change,* **1**, 2-4. http://dx.doi.org/10.1038/nclimate1056
Webb L, Whetton P, Barlow EWR (2008a) Climate change and wine grape quality in Australia. *Climate Research,* **36**, 99-111.
Webb L, Whetton P, Barlow EWR (2008b) Modeling the relationship between climate, winegrape price, and winegrape quality in Australia. *Climate Research,* **36**, 89-98.
Webb LB, Whetton PH, Barlow EWR (2011) Observed trends in winegrape maturity in Australia. *Global Change Biology,* **17**, 2707-2719. http://dx.doi.org/10.1111/j.1365-2486.2011.02434.x

Project Staff

Dr Leanne Webb
Prof Snow Barlow
Dr Penny Whetton
A/Prof Greg Dunn
Dr Richard Smart and Chris McRae
Other Melbourne university personnel during the heatwave survey.

Appendix 1: Raw data projections

File provided to GWRDC

Appendix 2: Climate projections for Australian wine regions

Leanne Webb[1,2], Kevin Hennessy[2], James Ricketts[2], Ian Macadam[2], and Snow Barlow[1]

[1]**CSIRO Marine and Atmospheric Research, PMB 1, Aspendale, Victoria 3195, Australia**

[2]**School of Agriculture and Food Systems, University of Melbourne, Parkville, Victoria 3010, Australia**

Feb 2009

A report prepared for GWRDC

Enquiries should be addressed to:

Leanne Webb

University of Melbourne, School of Land and Food Resources, and

CSIRO Marine & Atmospheric Research

PMB 1

Aspendale, Vic, 3195

Ph +61 3 9239 4549

leanne.webb@csiro.au

INTRODUCTION

The climate change projections presented for selected Australian wine regions in this report are consistent with those published in “Climate Change in Australia”, the most up-to-date assessment of climate change for the whole of Australia (CSIRO and Australian Bureau of Meteorology, 2007). Projections for the following climate variables in 2030 and 2070 are given in this report and in an accompanying Excel file (copy provided in the Appendix).

1) Annual and seasonal average temperatures
2) Annual average numbers of hot and cold days
3) Annual and seasonal diurnal range
4) Annual and seasonal average rainfall totals
5) Annual and seasonal average potential evapotranspiration
6) Annual and seasonal average wind-speeds
7) Annual and seasonal average relative humidity
8) Annual and seasonal average solar radiation

Projections in the following climate variables are given in this report but not the Excel files.

1) Annual average number of rain days
2) Heavy rainfall intensity
3) Drought frequency (for 2030 only)
4) Annual average number of days with extreme forest fire danger (for 2020 and 2050)

The projections provide information on climate conditions averaged over several decades in the future. For example, projections provided for 2030 and 2070 reflect average conditions for periods centred on the years 2030 and 2070.

The impact of climate change will often be felt through extreme events. If the coping range of the system is optimised for past climate conditions, then conditions outside the coping range will occur with higher or lower frequency as climate change progresses. Successful adaptation to climate change should alter the coping range in such a way that increases in frequency of conditions outside the coping range are minimised. It is possible that changes in climate variability will also contribute to the vulnerability of systems. However, there is significant uncertainty about potential changes in variability, which is the subject of ongoing research and is not addressed in this report.

Projected changes in climate variables include ranges of uncertainty. A component of the uncertainty is due to different regional responses to global warming in different climate models. As a result, the low (high) scenarios of several climate variables (e.g. temperature and rainfall) *should not be combined* to create best case (worst case) climate change scenarios. This is because since such a combination might not actually be realisable in any individual model. Scenarios that are consistent between climate variables should be derived from the output of *individual* climate models. Model-specific scenarios are critical for detailed risk assessments, for which multiple variables are important. Such scenarios can be sourced from the OzClim climate change scenario generator (CSIRO, 2008). OzClim is designed to provide information about changes in regional monthly-average climate for a range of models and emission scenarios. However, at present, OzClim scenarios include information on only a limited number of climate variables. The utility of the projections presented in this report is in providing an overview of the likely changes in a wide variety of climatic aspects for selected Australian wine regions.

OBSERVED CLIMATE CHANGE

Global Climate Change

In 1988, the United Nations Environment Programme and the World Meteorological Organization established the Intergovernmental Panel on Climate Change (IPCC). This comprises many of the world's experts on climate change, and produces authoritative reviews of our knowledge of climate change. The most recent review includes a summary describing observed climate change and its causes (IPCC, 2007).

Since the Industrial Revolution, around 1750, the atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased by 35%, 148% and 18%, respectively. The increases in concentrations of carbon dioxide are due primarily to fossil fuel use and land-use change, while those of methane and nitrous oxide are primarily due to agriculture.

The Earth's average surface temperature has increased by approximately 0.7˚C since the beginning of the 20th Century. Most of the warming since 1950 is very likely due to increases in atmospheric greenhouse gas concentrations due to human activities. The warming has been associated with more heatwaves, changes in precipitation patterns, reductions in sea ice extent and rising sea levels.

Climate Change in Australia

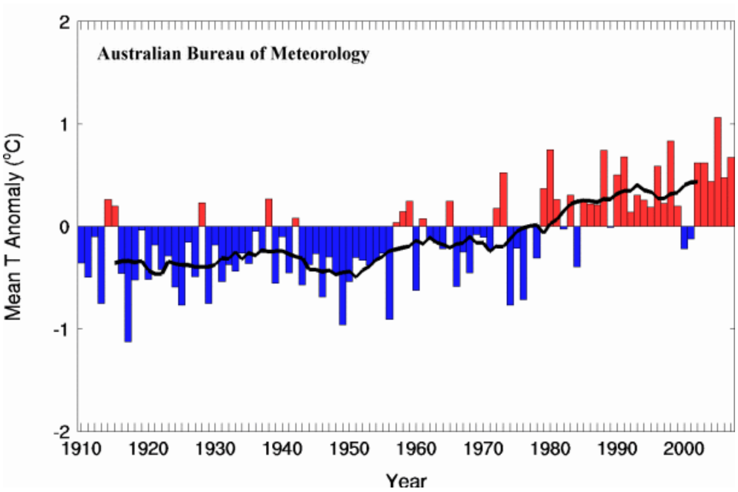


Figure 1 Australian-average annual temperature anomalies relative to the average for the 1961-1990 period. Source: Australian Bureau of Meteorology (2008a).

Australian-average annual temperatures have increased by 0.9ºC since 1910. Most of this warming has occurred since 1950 (Figure 1), with greatest warming in the east and least warming in the north-west (Figure 2). The warmest year on record is 2005, but 2007 was the warmest year for southern Australia (Australian Bureau of Meteorology, 2008c). The number of hot days and nights has increased and the number of cold days and nights has declined (CSIRO and Australian Bureau of Meteorology, 2007).

Since 1950, most of eastern and south-western Australia has become drier (Figure 2). Across New South Wales and Queensland rainfall trends partly reflect a very wet period around the 1950s, though recent years have been unusually dry. In contrast, north-western Australia has become wetter over this period, mostly during summer. Since 1950, very heavy rainfall (over 30 mm/day) and the number of wet days (at least 1 mm/day) have decreased in the south and east but increased in the north (Figure 4) (CSIRO and Australian Bureau of Meteorology, 2007).

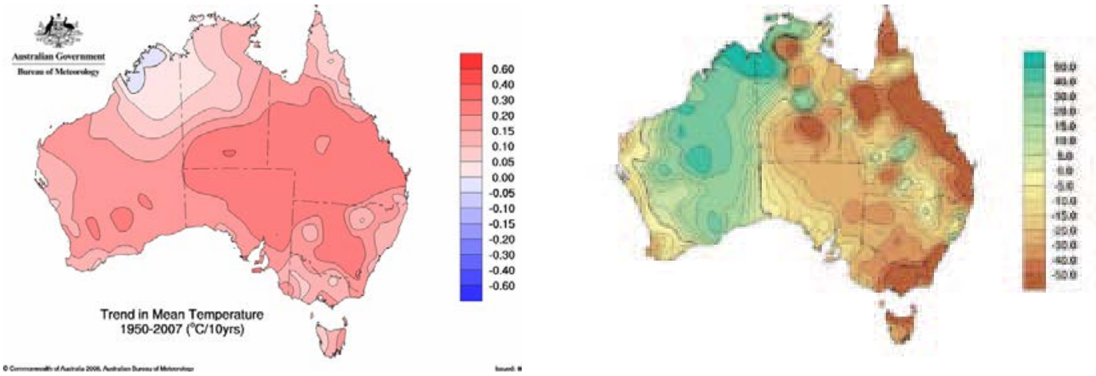


Figure 2 Trends in annual mean temperature and rainfall since 1950. Source: Australian Bureau of Meteorology (2008a).

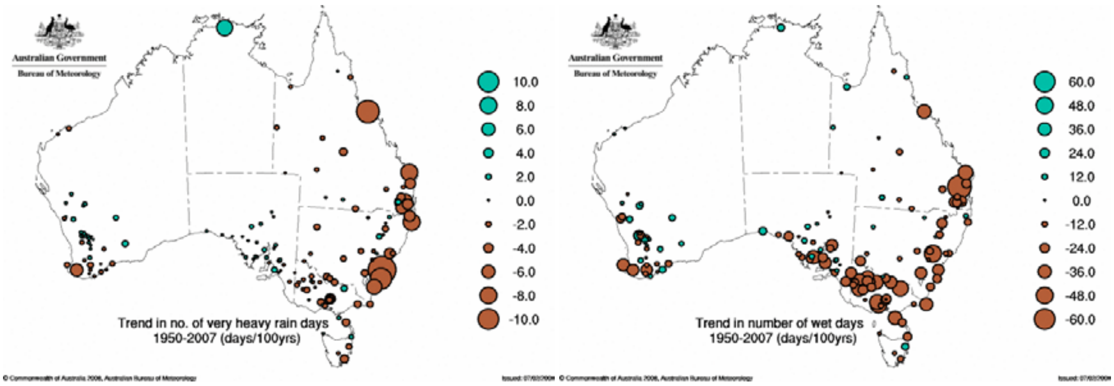


Figure 3 Trends in the frequencies of very heavy rain days (over 30 mm/day) and wet days (at least 1 mm/day) since 1950. Source: Australian Bureau of Meteorology (2008a).

Australian rainfall shows considerable variability from year-to-year, partly in association with the El Niño – Southern Oscillation (ENSO). El Niño events tend to be associated with hot and dry years in Australia, and La Niña events tend to be associated with mild and wet years (Power et al. 2006). There has been a marked increase in the frequency of El Niño events and a decrease in La Niña events since the mid-1970s (Power and Smith 2007).

Climate Change Projections

METHOD

The future climate is strongly influenced by inherently uncertain factors and for this reason it is not possible to make definitive future climate predictions for decades ahead. However, projections of future climate that account for uncertainties can be made. The distinction between predictions and projections is important for correctly interpreting climate change information.

This report presents projections of average temperatures, rainfall, potential evapotranspiration, wind-speed, relative humidity and solar radiation for 2030 and 2070 as changes relative to averages for the 1976-2005 period. The projections are consistent with the most up-to-date assessment of climate change in Australia by CSIRO and the Australian Bureau of Meteorology (2007). They were derived from the output of the most recent generation of climate models, which are mathematical representations of the climate system. These are the best tools for estimating future climate (Watterson (2008). Three main sources of uncertainty are accounted for:

1) uncertainty in the future evolution of greenhouse gas and sulphate aerosol emissions;
2) uncertainty in how much the global average surface temperature will respond to increases in atmospheric greenhouse gas concentrations and changes in sulphate aerosol emissions;
3) uncertainty in the regional climatic response to an increase in global average surface temperature.

The first uncertainty is addressed by considering six different scenarios for the future evolution of greenhouse gas and sulphate aerosol emissions described by the IPCC's Special Report on Emissions Scenarios (SRES) (Nakićenović & Swart, 2000). Each of these SRES scenarios, denoted A1B, A1FI, A1T, A2, B1 and B2, is based on a plausible storyline of future global demographic, economic and technological change in the 21st Century. The second uncertainty is addressed by considering the range of global average warming for different emissions scenarios from 23 climate models (Meehl et al. 2007b). The third uncertainty is addressed through detailed analysis of climate model simulations in the Australian region. The output of 23 models is used to derive projections for average temperatures and rainfall totals, the output of 19 models is used for projections for average wind-speed, the output of 14 models is used for average potential evapotranspiration and relative humidity and 20 models are used for average solar radiation (CSIRO and Australian Bureau of Meteorology, 2007). Each model is given a score based on its ability to simulate average patterns of temperature, rainfall and mean sea level pressure in the Australian regions for the period 1961-1990. Models with higher scores are given greater emphasis in the projections.

The uncertainty in regional projections is represented by a probability distribution. These distributions are used to derive the ranges of uncertainty and central estimates (CSIRO and Australian Bureau of Meteorology, 2007). The lowest and highest 10% of the range of model results (10th and 90th percentiles) define the ranges of uncertainty while the median (50th percentile) provides central estimates.

Changes in the climate of Australia by 2030 do not vary greatly from one emission scenario to another. Therefore, a mid-range emission scenario for 2030, called A1B, is used in this report. However, changes by 2070 are heavily dependent on the emission scenario, because the scenarios are highly divergent beyond 2030. Hence changes for 2070 are presented for a “low” and a “high” emission scenario, called B1 and A1FI respectively. Global carbon dioxide emissions from fossil-fuel burning and industrial processes since 2000 are consistent with the A1FI emission scenario (Raupach et al. 2007). Therefore, the A1FI scenario is considered more likely than the B1 scenario in future.

Regions selected

For this report 5 winegrowing regions are considered (Table 1), though projections for all Australian winegrowing regions have been generated. These will incorporate many of the combinations of impacts that will be applicable to other regions. Most of these regions also align with those selected for quantification of impacts on phenology in a previous assessment (Webb et al. 2007).

Table 1 Wine growing regions selected for focus in this report represent a range of climate categories and regions with various means of access to water sources. Some factors that may have given reason for selection in this analysis are noted.

	Temperature	Water access	Other
Barossa Valley	Medium	Combination	Icon
Coonawarra	Cool	Underground	Icon
Hunter Valley	Hot	Other surface water	Extreme rainfall
Margaret River	Cool	On-farm dam	Maritime
Riverina	Hot	Public irrigation	Production centre
Yarra Valley	Cool	On-farm dam/bore	Frost

Temperature projections

By 2030, annual average temperatures are likely to increase in these regions by around 0.8°C (with an uncertainty range of 0.7 to 1.0°C). This provides an estimate of the 10-90% range of possibilities. Hence values lower and higher outside this range cannot be excluded. Warming is likely to be greatest in spring and summer. By 2070, the average annual temperature could increase by up to 1.6°C (0.9 to 2.3°C) under a low emission (B1) scenario or by 3.1°C (1.8 to 4.4°C) under a high emission (A1FI) scenario, dependant on the region.

Table 2 Annual average temperature (for the 1976-2005 period) and temperature projections for selected wine regions for2030 for the A1B SRES emissions scenario, and for 2070 for the B1 and A1FI SRES emissions scenarios. Numbers inside brackets indicate ranges of uncertainty.

Region	Period	Base 1976 to 2005	Projected temperature change (°C)		
			2030 med	2070 low	2070 high
Barossa Valley	Annual	15.2	0.8 (0.6 to 1.2)	1.4 (0.9 to 2.0)	2.6 (1.8 to 3.8)
	Summer	21	0.9 (0.5 to 1.3)	1.4 (0.9 to 2.1)	2.8 (1.8 to 4.2)
	Autumn	15.7	0.8 (0.5 to 1.2)	1.4 (0.9 to 2.0)	2.6 (1.7 to 3.9)
	Winter	9.7	0.7 (0.5 to 1.1)	1.2 (0.8 to 1.8)	2.3 (1.5 to 3.6)
	Spring	14.5	0.9 (0.6 to 1.3)	1.4 (0.9 to 2.1)	2.8 (1.8 to 4.0)
Coonawarra	Annual	14.2	0.8 (0.5 to 1.1)	1.3 (0.9 to 1.8)	2.5 (1.7 to 3.5)
	Summer	18.9	0.8 (0.5 to 1.3)	1.4 (0.8 to 2.2)	2.7 (1.6 to 4.2)
	Autumn	14.8	0.8 (0.5 to 1.1)	1.3 (0.8 to 1.9)	2.5 (1.5 to 3.7)
	Winter	9.8	0.7 (0.4 to 1.0)	1.1 (0.7 to 1.6)	2.1 (1.4 to 3.1)
	Spring	13.5	0.8 (0.5 to 1.1)	1.3 (0.9 to 1.9)	2.5 (1.7 to 3.7)
Hunter Valley	Annual	16.3	1.0 (0.7 to 1.4)	1.6 (1.1 to 2.3)	3.1 (2.1 to 4.4)
	Summer	22.2	1.0 (0.6 to 1.5)	1.6 (1.0 to 2.5)	3.2 (2.0 to 4.8)
	Autumn	16.7	0.9 (0.6 to 1.4)	1.6 (1.0 to 2.3)	3.0 (1.9 to 4.5)
	Winter	10.1	0.9 (0.6 to 1.2)	1.4 (1.0 to 2.1)	2.8 (1.8 to 4.0)
	Spring	16.2	1.1 (0.7 to 1.6)	1.8 (1.2 to 2.6)	3.5 (2.3 to 5.0)
Margaret River	Annual	16.6	0.7 (0.5 to 1.0)	1.2 (0.8 to 1.7)	2.3 (1.5 to 3.3)
	Summer	20.1	0.7 (0.4 to 1.1)	1.2 (0.7 to 1.8)	2.3 (1.4 to 3.5)
	Autumn	17.8	0.7 (0.4 to 1.0)	1.2 (0.7 to 1.7)	2.2 (1.4 to 3.3)
	Winter	13.3	0.7 (0.4 to 0.9)	1.1 (0.7 to 1.6)	2.1 (1.4 to 3.0)
	Spring	15.2	0.7 (0.5 to 1.1)	1.2 (0.8 to 1.8)	2.3 (1.5 to 3.5)
Riverina	Annual	16.9	1.0 (0.7 to 1.4)	1.6 (1.1 to 2.3)	3.1 (2.1 to 4.4)
	Summer	24.2	1.1 (0.7 to 1.5)	1.8 (1.2 to 2.6)	3.4 (2.3 to 5.0)
	Autumn	17.1	1.0 (0.6 to 1.4)	1.6 (1.0 to 2.4)	3.1 (2.0 to 4.6)
	Winter	9.7	0.8 (0.5 to 1.1)	1.3 (0.8 to 1.9)	2.5 (1.6 to 3.7)
	Spring	16.5	1.0 (0.7 to 1.5)	1.7 (1.1 to 2.5)	3.3 (2.2 to 4.9)
Yarra Valley	Annual	12.9	0.8 (0.6 to 1.1)	1.3 (0.9 to 1.9)	2.6 (1.8 to 3.7)
	Summer	17.8	0.9 (0.6 to 1.4)	1.5 (1.0 to 2.3)	3.0 (1.9 to 4.4)
	Autumn	13.5	0.8 (0.5 to 1.2)	1.3 (0.9 to 1.9)	2.6 (1.7 to 3.8)
	Winter	7.9	0.7 (0.4 to 1.0)	1.1 (0.7 to 1.6)	2.1 (1.4 to 3.1)
	Spring	12.2	0.8 (0.5 to 1.2)	1.4 (0.9 to 2.0)	2.6 (1.8 to 3.8)

The number of cool days is likely to decrease and the number of hot days is likely to increase (Table 3). Estimates of the annual average number of extremely hot days were derived by applying projected changes in seasonal-average daily maximum temperatures to observed daily maximum temperatures for the period 1971-2000. In Mildura during this period, the temperature reached 30ºC on about 20% of the days of each year, on average. By 2030, 30ºC could be reached on around 25% of days. By 2070, 30ºC could be reached on 25 to 30% of days under a low emission scenario and 30 to 40% of days under a high emission scenario. There were, on average, 32 days per year with temperatures over 35ºC in Mildura during the 1971-2000 period. By 2030, the increase in the annual average number of days with temperatures above 35ºC is around 7 days (4 to 11 days). By 2070, the increase is 13 days (7 to 19 days) under a low emission scenario and 28 days (16 to 44 days) under a high emission scenario. Mildura experienced only 6 days with temperatures over 40ºC in the entire 1971-2000 period. By 2070, an average of 11 or 18 days per year with temperatures over 40ºC could be the norm.

Table 3 Annual average numbers of days with temperatures both below 0°C, 2°C and 5°C, and over 30°C, 35°C and 40°C for sites within selected wine regions for the 1971-2000 period, for 2030 for the A1B SRES emissions scenario, and for 2070 for the B1 and A1FI SRES emissions scenarios. Numbers inside brackets indicate ranges of uncertainty.

Site	Thresh-old	Base days	2030 mid	2070 low	2070 high
Adelaide	<0	0.1	0.0 (0.0 to 0.0)	0.0 (0.0 to 0.0)	0.0 (0.0 to 0.0)
	<2	1.2	0.5 (0.4 to 0.6)	0.3 (0.1 to 0.5)	0.1 (0.0 to 0.2)
	<5	19.0	11.8 (9.9 to 13.6)	9.0 (6.0 to 11.6)	3.9 (1.0 to 7.2)
	>30	51.8	58.2 (56.0 to 61.8)	63.3 (58.5 to 70.4)	76.9 (66.2 to 93.6)
	>35	16.7	22.6 (20.6 to 24.6)	25.3 (22.7 to 29.8)	33.2 (27.2 to 43.7)
	>40	2.1	3.2 (2.8 to 4.2)	4.4 (3.3 to 6.2)	8.3 (5.1 to 13.1)
Cape Leeuwin	<0	0.0	0.0 (0.0 to 0.0)	0.0 (0.0 to 0.0)	0.0 (0.0 to 0.0)
	<2	0.0	0.0 (0.0 to 0.0)	0.0 (0.0 to 0.0)	0.0 (0.0 to 0.0)
	<5	0.2	0.1 (0.0 to 0.1)	0.0 (0.0 to 0.1)	0.0 (0.0 to 0.0)
	>30	3.7	4.1 (3.9 to 5.0)	5.0 (4.1 to 5.8)	7.0 (5.3 to 10.8)
	>35	0.5	0.7 (0.6 to 0.9)	0.9 (0.7 to 1.2)	1.5 (1.1 to 2.6)
	>40	0.0	0.0 (0.0 to 0.1)	0.1 (0.0 to 0.1)	0.1 (0.1 to 0.2)
Mildura	<0	5.5	3.1 (2.2 to 3.8)	1.9 (0.9 to 3.0)	0.7 (0.2 to 1.3)
	<2	23.7	14.0 (11.0 to 17.3)	10.2 (6.5 to 14.0)	4.6 (1.6 to 8.2)
	<5	73.6	58.6 (53.3 to 63.6)	51.0 (41.5 to 58.2)	33.6 (18.2 to 46.1)
	>30	80.9	92.1 (87.6 to 98.3)	101.3 (93.6 to 110.9)	123.3 (106.4 to 146.6)
	>35	31.7	38.4 (36.1 to 42.5)	44.7 (39.3 to 50.9)	59.8 (48.3 to 75.6)
	>40	5.9	8.5 (7.5 to 10.2)	11.3 (8.8 to 13.9)	17.8 (12.7 to 28.0)
Nuriootpa	<0	12.3	7.0 (5.7 to 8.9)	4.8 (2.7 to 7.0)	1.6 (0.2 to 3.8)
	<2	32.8	23.0 (19.6 to 26.7)	18.3 (13.6 to 22.6)	10.6 (4.1 to 16.3)
	<5	86.3	68.7 (62.4 to 74.4)	59.5 (50.2 to 68.1)	42.5 (26.7 to 55.5)
	>30	50.5	57.5 (55.0 to 63.0)	64.4 (58.2 to 71.6)	78.9 (67.7 to 94.8)
	>35	16.3	19.7 (18.4 to 23.1)	23.8 (20.4 to 28.8)	32.9 (26.3 to 43.6)
	>40	1.6	2.8 (2.2 to 3.6)	3.8 (3.0 to 6.0)	7.4 (4.7 to 12.3)
Robe	<0	0.0	0.0 (0.0 to 0.0)	0.0 (0.0 to 0.0)	0.0 (0.0 to 0.0)
	<2	0.8	0.3 (0.1 to 0.4)	0.1 (0.0 to 0.3)	0.0 (0.0 to 0.0)
	<5	12.0	7.6 (6.2 to 8.9)	5.6 (3.6 to 7.6)	2.2 (0.7 to 4.9)
	>30	7.4	9.3 (8.4 to 10.7)	10.9 (9.3 to 14.1)	16.1 (12.0 to 23.3)
	>35	0.4	0.7 (0.5 to 1.2)	1.3 (0.6 to 1.8)	2.2 (1.4 to 4.7)
	>40	0.0	0.0 (0.0 to 0.0)	0.0 (0.0 to 0.1)	0.1 (0.0 to 0.2)
Rutherglen	<0	43.9	32.3 (28.6 to 35.3)	26.1 (20.3 to 31.8)	14.4 (8.6 to 22.5)
	<2	80.9	64.1 (57.2 to 67.8)	53.9 (45.9 to 63.1)	37.6 (25.9 to 49.2)
	<5	148.1	126.9 (118.5 to 131.7)	114.5 (101.7 to 125.6)	89.2 (68.7 to 107.7)
	>30	63.2	73.2 (70.4 to 78.9)	81.2 (74.8 to 90.0)	99.9 (86.6 to 118.4)
	>35	17.0	22.2 (20.8 to 25.1)	26.9 (23.0 to 32.4)	40.9 (30.5 to 56.8)
	>40	1.6	2.9 (2.3 to 3.6)	4.1 (3.1 to 5.6)	8.1 (4.9 to 14.3)

Diurnal range

Diurnal range is a measure of the difference in the minimum temperature and the maximum temperature recorded in a 24 hour period. To calculate this seasonal and annual average baseline maximum temperature (1976-2005), and average baseline minimum temperature (1976-2005), were each adjusted with projected change to maximum temperature (average temperature change multiplied by the ratio of change in maximum to mean temperature) and projected change to minimum temperature (average temperature change multiplied by the ratio of change in minimum to mean temperature) (CSIRO and Australian Bureau of Meteorology 2007). The projected diurnal range could then be calculated (Table 4)

Table 4 Annual and seasonal average diurnal range (for the 1976-2005 period) and projections for selected wine regions for 2070 for the A1FI SRES emissions scenario. Numbers inside brackets indicate ranges of uncertainty.

Region	PERIOD	Baseline diurnal range (1976-2005)	Projected diurnal range	difference
Barossa Valley	Annual	12.2	12.6 (12.4 to 12.7)	0.3 (0.2 to 0.5)
	Summer	15.0	15.1 (15.1 to 15.1)	0.0 (0.0 to 0.0)
	Autumn	12.3	12.3 (12.3 to 12.4)	0.1 (0.1 to 0.1)
	Winter	9.1	9.7 (9.5 to 10.0)	0.6 (0.4 to 0.9)
	Spring	12.4	13.2 (12.9 to 13.6)	0.8 (0.5 to 1.2)
Coonawarra	Annual	12.1	12.5 (12.4 to 12.6)	0.3 (0.2 to 0.5)
	Summer	15.3	15.5 (15.4 to 15.6)	0.2 (0.1 to 0.3)
	Autumn	12.3	12.5 (12.4 to 12.6)	0.2 (0.1 to 0.3)
	Winter	9.1	9.4 (9.3 to 9.6)	0.3 (0.2 to 0.5)
	Spring	11.8	12.6 (12.3 to 12.9)	0.8 (0.5 to 1.1)
Hunter Valley	Annual	12.7	12.8 (12.7 to 12.8)	0.1 (0.1 to 0.1)
	Summer	13.1	12.7 (12.9 to 12.5)	-0.4 (-0.3 to -0.7)
	Autumn	12.2	12.0 (12.1 to 11.9)	-0.2 (-0.1 to -0.3)
	Winter	11.8	12.3 (12.1 to 12.5)	0.5 (0.3 to 0.7)
	Spring	13.6	14.0 (13.9 to 14.2)	0.4 (0.3 to 0.7)
Margaret River	Annual	9.0	9.2 (9.1 to 9.3)	0.1 (0.1 to 0.2)
	Summer	10.7	10.7 (10.7 to 10.7)	0.0 (0.0 to 0.0)
	Autumn	9.3	9.3 (9.3 to 9.4)	0.1 (0.0 to 0.1)
	Winter	7.4	7.6 (7.5 to 7.7)	0.2 (0.1 to 0.3)
	Spring	8.9	9.2 (9.1 to 9.3)	0.3 (0.2 to 0.5)
Riverina	Annual	13.6	13.9 (13.8 to 14.0)	0.3 (0.2 to 0.4)
	Summer	15.4	15.1 (15.2 to 15.0)	-0.3 (-0.2 to -0.5)
	Autumn	13.5	13.5 (13.5 to 13.4)	-0.1 (0.0 to -0.1)
	Winter	11.3	12.0 (11.8 to 12.3)	0.7 (0.4 to 1.0)
	Spring	14.1	14.9 (14.6 to 15.3)	0.8 (0.5 to 1.1)
Yarra Valley	Annual	9.6	10.0 (9.9 to 10.2)	0.4 (0.3 to 0.6)
	Summer	12.4	12.6 (12.5 to 12.7)	0.2 (0.1 to 0.3)
	Autumn	9.4	9.7 (9.6 to 9.9)	0.3 (0.2 to 0.4)
	Winter	6.9	7.3 (7.2 to 7.5)	0.4 (0.3 to 0.6)
	Spring	9.7	10.5 (10.3 to 10.9)	0.8 (0.5 to 1.2)

Rainfall

Some climate models indicate future decreases in rainfall for the selected wine regions while others indicate future increases. However, decreases are more likely than increases for all winegrowing regions described in this report except for summer rainfall in the Riverina and Hunter Valley regions (CSIRO and Australian Bureau of Meteorology, 2007). Percentage decreases are likely to be greatest in winter and spring. Changes in annual average rainfall vary by region and are likely to be -6% (-10 to -2%) by 2030 in Margaret River, for example (Table 5). By 2070, changes in annual average rainfall for this region are likely to be -10% (-18 to -3%) under a low emission scenario or -20% (-35 to -6%) under a high emission scenario.

Table 5 Percentage changes in annual and seasonal rainfall totals for 2030 for the A1B SRES emissions scenario and for 2070 for the B1 and A1FI SRES emissions scenarios.

		Base 1976 to 2005	2030 med change (%)	2070 low change (%)	2070 high change (%)
Barossa Valley	Annual	534.4	-4.3 (-9.9 to 1.1)	-7.2 (-16.5 to 1.8)	-14.0 (-32.0 to 3.4)
	Summer	72.3	-2.5 (-12.4 to 8.9)	-4.1 (-20.6 to 14.8)	-7.9 (-39.9 to 28.6)
	Autumn	104	-1.9 (-9.6 to 6.6)	-3.1 (-16.1 to 10.9)	-6.0 (-31.1 to 21.1)
	Winter	212.6	-5.3 (-11.6 to 0.9)	-8.8 (-19.4 to 1.4)	-16.9 (-37.5 to 2.7)
	Spring	155.5	-6.9 (-15.4 to 1.7)	-11.5 (-25.7 to 2.9)	-22.3 (-49.8 to 5.6)
Coonawarra	Annual	612.3	-4.3 (-8.4 to -0.7)	-7.1 (-13.9 to -1.1)	-13.8 (-26.9 to -2.1)
	Summer	83.2	-3.5 (-11.5 to 5.3)	-5.8 (-19.1 to 8.8)	-11.2 (-37.0 to 16.9)
	Autumn	124.3	-2.5 (-8.1 to 3.4)	-4.2 (-13.6 to 5.7)	-8.2 (-26.3 to 11.0)
	Winter	251.5	-4.1 (-8.9 to 0.2)	-6.8 (-14.9 to 0.3)	-13.2 (-28.8 to 0.6)
	Spring	163.7	-6.7 (-13.5 to -0.3)	-11.1 (-22.5 to -0.5)	-21.5 (-43.4 to -0.9)
Hunter Valley	Annual	799.3	-1.9 (-8.1 to 4.4)	-3.2 (-13.6 to 7.4)	-6.1 (-26.2 to 14.3)
	Summer	256.3	1.1 (-7.2 to 10.2)	1.9 (-12.0 to 16.9)	3.6 (-23.1 to 32.7)
	Autumn	209.2	-1.2 (-9.7 to 8.1)	-2.0 (-16.2 to 13.4)	-3.8 (-31.3 to 26.0)
	Winter	143.1	-5.0 (-14.0 to 4.3)	-8.3 (-23.4 to 7.2)	-16.0 (-45.2 to 14.0)
	Spring	188.2	-4.6 (-12.9 to 3.7)	-7.6 (-21.5 to 6.2)	-14.7 (-41.5 to 12.0)
Margaret River	Annual	991.1	-6.1 (-10.8 to -1.8)	-10.1 (-18.0 to -3.0)	-19.6 (-34.8 to -5.8)
	Summer	69.7	-4.7 (-12.6 to 4.0)	-7.8 (-21.0 to 6.6)	-15.1 (-40.6 to 12.7)
	Autumn	208.2	-5.0 (-12.4 to 3.8)	-8.3 (-20.7 to 6.3)	-16.0 (-40.0 to 12.1)
	Winter	526.8	-6.5 (-11.4 to -2.2)	-10.9 (-19.0 to -3.6)	-21.0 (-36.7 to -7.0)
	Spring	210.8	-7.3 (-13.0 to -2.2)	-12.2 (-21.7 to -3.7)	-23.5 (-41.9 to -7.2)
Riverina	Annual	407.2	-2.7 (-9.1 to 3.4)	-4.4 (-15.2 to 5.7)	-8.5 (-29.5 to 11.0)
	Summer	91.5	0.4 (-9.8 to 11.4)	0.6 (-16.3 to 18.9)	1.1 (-31.5 to 36.6)
	Autumn	94.6	-1.1 (-10.1 to 8.8)	-1.9 (-16.8 to 14.6)	-3.7 (-32.5 to 28.3)
	Winter	111.3	-4.9 (-12.7 to 3.4)	-8.1 (-21.2 to 5.7)	-15.6 (-40.9 to 11.1)
	Spring	105.3	-6.3 (-16.5 to 3.7)	-10.5 (-27.4 to 6.2)	-20.3 (-53.0 to 12.0)
Yarra Valley	Annual	1091	-3.5 (-7.4 to -0.1)	-5.9 (-12.3 to -0.2)	-11.3 (-23.8 to -0.3)
	Summer	211.9	-2.6 (-9.9 to 5.5)	-4.3 (-16.5 to 9.2)	-8.2 (-31.9 to 17.8)
	Autumn	234.4	-1.7 (-7.2 to 4.0)	-2.8 (-12.0 to 6.7)	-5.5 (-23.2 to 13.0)
	Winter	334.7	-3.0 (-7.9 to 1.3)	-5.1 (-13.1 to 2.2)	-9.8 (-25.4 to 4.3)
	Spring	315.6	-6.4 (-13.1 to -0.3)	-10.7 (-21.8 to -0.4)	-20.7 (-42.1 to -0.8)

The intensity of heavy daily rainfall is likely to decrease slightly in some regions, and increase in others. Note that projections of heavy rainfall (defined as the heaviest 1% of 24-hour rainfall) are highly uncertain. By 2030, the range of uncertainty is -9 to +6%. For 2070, the range of uncertainty is -16 to +10% under a low emissions scenario or -30 to +20% under a high emissions scenario (Table 6).

Table 6: Percentage changes in the intensity of rainfall on the heaviest 1% of days for selected wine regions region for 2070 for the A1FI SRES emissions scenario.

	% change (2070 high)				
Region	Annual	Summer	Autumn	Winter	Spring

Barossa Valley	-2.4	-1.3	14.5	-1.9	-5.0
Coonawarra	2.5	-7.6	10.1	6.6	-6.3
Hunter Valley	2.2	6.8	-2.9	-4.6	7.8
Margaret River	-11.1	-20.9	-0.3	-13.4	-22.7
Riverina	6.7	-0.1	9.8	0.3	-1.0
Yarra Valley	10.3	11.8	20.3	2.1	0.2

Evapotranspiration, Wind-Speed, Relative Humidity and Solar Radiation

Evapotranspiration is the combination of evaporation of water from the Earth's surface and transpiration from vegetation. It is a key driver of the hydrological cycle and greatly affects the quantity of water on the surface and in the soil. Potential evapotranspiration is that which would occur if the surface was saturated, and thus gives a measure of maximum possible evapotranspiration under those conditions. Annual average potential evapotranspiration is likely to increase in these selected wine regions by between 2% and 3% by 2030, with the largest percentage increases expected in winter. By 2070, annual average potential evapotranspiration could increase by 6% (4 to 8%) under a low emission scenario or by 11% (7 to 16%) under a high emission scenario. Please see appendix for regional projection data.

Annual average wind-speed in the wine regions is likely to increase by 0.7% to 1% (0.1 to 2.9%) by 2030, with seasonal increases and decreases varying regionally (see Appendix). In all cases spring is projected to become slightly windier which may implicate flowering success.

Relative humidity is a measure of the air's ability to hold moisture. It is the ratio of the amount of water in the air to the maximum amount of water that could be absorbed by the air given an unlimited supply of water. A low value of relative humidity indicates that there is little water in the air relative to its capacity to hold moisture while a high value indicates that the air is saturated with water. Projections of relative humidity show a slight reduction likely across all regions and seasons (though the range does include some models showing increased relative humidity).

Solar radiation is essentially sunshine. Projections of solar radiation show slight increases in winter and spring in these regions.

Drought

In Australia, as a result of increasing GHGs, droughts are projected to increase in intensity and duration in the south-eastern part of the continent (Mpelasoka et al. 2007), becoming more frequent and affecting a larger area in the future (Hennessy et al. 2008). In the Murray-Darling Basin (MDB), the frequency and areal extent of exceptionally hot years and exceptionally dry years are likely to increase in the future. Exceptional is defined as the hottest/driest year in 20 years on average from present climate (Hennessy et al. 2008). The mean projections indicate that:

• by 2010-2040, exceptionally hot years are likely to affect about 65% of the region (6% in 1900-2007), and occur every 1.6 years on average (every 22 years in 1900-2007);

• by 2010-2040, little change is likely in the frequency and areal extent of exceptionally low rainfall years;

• by 2030, exceptionally low soil moisture years are likely to affect about 7% (6% 1900-2007) of the region and occur about once every 13 years on average (once every 16 years 1900-2007).

Fire Weather

Fire risk is influenced by a number of factors, including fuel, terrain, land management, fire suppression and weather. The Forest Fire Danger Index (FFDI) is used operationally to provide an indication of fire risk based on four relevant meteorological variables, daily maximum temperature, daily total precipitation, 3 pm relative humidity and 3 pm wind-speed. The FFDI has five intensity categories: low (index value of less than 5), moderate (5-12), high (13-25), very high (25-49) and extreme (at least 50). When the FFDI is extreme, a Total Fire Ban Day is usually declared.

Lucas et al. (2007) generated fire danger projections for 2020 and 2050 for southern and eastern Australia using two climate change simulations of CSIRO's Cubic Conformal Atmospheric Model (CCAM), which has 50km resolution over Australia (McGregor, 2005). One simulation, denoted "CCAM Mark2", was driven by boundary conditions from the CSIRO Mark2 coupled ocean-atmosphere model, while the other simulation, denoted "CCAM Mark3", was driven by boundary conditions from the CSIRO Mark3.0 model. Data from these simulations were then used to generate changes in the relevant meteorological variables per °C of global warming, including changes in daily weather variability. These changes were multiplied by global warming values consistent with the IPCC's Fourth Assessment Report (Meehl et al. 2007b) for 2020 and 2050 and then applied to the daily weather records for the 1974-2007 period for 26 sites in southern and eastern Australia. FFDI values were then calculated for the modified datasets.

An increase in fire risk was indicated at most of the 26 sites in the Lucas (2007) study. By 2020, the frequency of extreme fire danger days generally increases by 5-25% for a low global warming scenario and by 15-65% for a high global warming scenario. By 2050, the increases are generally 10-50% for a low global warming scenario and 100-300% for a high global warming scenario. The fire season is likely to become longer, starting earlier in the year (Table 7), where increases in the frequency of extreme fire danger days are 5-6% in Wagga Wagga, for example, by 2020, and 5-11% by 2050.

Table 7: Annual average numbers of extreme fire danger days for present (1973-2007) conditions and conditions in 2020 and 2050 for low and high global warming scenarios. CCAM Mark2 results are denoted “mk2” and CCAM Mark3 results are denoted “mk3”.

	1974 to 2007	**2020**				**2050**			
		Low mk2	Low mk3	High mk2	High mk3	Low mk2	Low mk3	High mk2	High mk3
Bendigo	1.2	1.5	1.5	1.8	2.0	1.6	1.8	2.8	4.0
Canberra	1.6	1.7	1.7	2.0	2.2	1.8	2.0	3.7	5.1
Hobart	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2
Mildura	7.3	8.0	8.3	9.1	10.0	8.6	9.0	12.8	15.9
Mt Gambier	1.4	1.5	1.6	1.6	1.8	1.6	1.7	2.2	2.9
Wagga Wagga	4.2	4.7	4.8	5.7	5.9	5.2	5.5	9.9	11.1

Recommendations

The projected changes in the climate of selected wine regions described in this report should be interpreted as an overview. They have a number of limitations, which could be mitigated through further work.

In-depth assessments of key impacts of climate change in these regions, on water availability and quality would be facilitated by further studies focussing on the regions individually. Specifically, these should address implications of projected changes in rainfall and potential evapotranspiration on water demand and runoff in the region’s drainage basins.

The climate change projections presented in this report have been designed to sample the uncertainty in the response of regional climate conditions to global warming. The extent to which this has been achieved for an individual climate variable is dependent on the number of climate models used in the analysis. Key parts of the analyses of future changes in hot days, rain days, and heavy rainfall intensity are based on a small number of climate models. This means that the uncertainty has been poorly sampled, so results beyond those presented may be possible. Further work that makes use of the output of a larger set of climate models would facilitate better estimation of uncertainty in these changes. The availability of output from the models on a daily time scale would be critical to such work and each model should be tested for its ability to reproduce relevant aspects of the current climate of Australia at a fine spatial scale.

At present, OzClim scenarios (CSIRO, 2008) include information for only a small number of climate variables from a limited number of climate models. Further work could provide scenarios comprising a consistent set of changes in more of the climate variables of interest. These would be suitable as input for in-depth assessments of the impact of climate change on systems for which multiple climate variables are important. Such a set of projections would rely on a common set of climate models being used to derive changes in all of the climate variables of interest. The set of models would either need to be large or carefully selected to properly sample the uncertainty in the response of regional climate conditions to global warming.

Information about future changes in interannual climate variability is essential for some types of climate risk assessment. Such information is not included in this report and is not available from OzClim. However, CSIRO and the Australian Bureau of Meteorology are proposing the development of a web-based tool for providing time series of regional climate data for a range of climate variables from a selection of climate models. This would provide information on changes in interannual climate variability and it may be prudent to revisit climate change projections for the Australian wine regions in the light of output from such a tool.

Acknowledgments

We acknowledge the modelling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, US Government Department of Energy.

The work of the authors also draws upon research findings of many colleagues within CSIRO Marine and Atmospheric Research and overseas research institutions. CSIRO climate models were developed by members of CSIRO Marine and Atmospheric Research.

References

Abbs, D.J., S. Aryal, E. Campbell, J. McGregor, K. Nguyen, M. Palmer, T. Rafter, I. Watterson and B. Bates, 2006: *Projections of Extreme Rainfall and Cyclones*. A report to the Australian Greenhouse Office, Canberra, Australia, 97 pp.

Australian Bureau of Meteorology, 2008a: *Australian Climate Change and Variability.* Australian Bureau of Meteorology website, http://www.bom.gov.au/cgi-bin/silo/products/cli_chg/.

Australian Bureau of Meteorology, 2008b: *Tropical cyclone trends.* Australian Bureau of Meteorology website, http://www.bom.gov.au/weather/cyclone/tc-trends.shtml.

Australian Bureau of Meteorology, 2008c: *Annual Climate Summary 2007*. http://www.bom.gov.au/climate/annual_sum/2007/

Canadell, J.G., C. Le Que´re´, M.R. Raupach, C.B. Field, E.T. Buitenhuis, P. Ciais, T.J. Conway, N.P. Gillett, R.A. Houghton and G. Marland, 2007: Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the National Academy of Sciences of the USA*, **104**, 18866–18870.

Church, J.A. and N.J. White, 2006: 20th century acceleration in sea-level rise. *Geophysical Research Letters*, **33**, L01602

CSIRO and Australian Bureau of Meteorology (2007) Climate change in Australia, Technical report, CSIRO and Bureau of Meteorology through the Australian climate change science program, Melbourne, Australia http://www.climatechangeinaustralia.com.au/resources.php

CSIRO, 2008: *OzClim.* CSIRO website, http://www.csiro.au/ozclim/home.do.

Hennessy, K.J., Fawcett, R., Kirono, D., Mpelasoka, F., Jones, D., Bathols, J., Whetton, P., Stafford Smith, M., Howden, M., Mitchell, C. and N. Plummer, 2008: *An assessment of the impact of climate change on the nature and frequency of exceptional climatic events*. CSIRO and the Australian Bureau of Meteorology, 31 pp. http://www.bom.gov.au/climate/droughtec/

Horton, R., C. Herweijer, C. Rosenzweig, J.P. Liu, V. Gornitz, and A.C. Ruane, 2008: Sea level rise projections for current generation CGCMs based on the semi-empirical method. *Geophys. Res. Lett.,* **35**, L02715, doi:10.1029/2007GL032486.

IPCC, 2007: *Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jones, R. N., and L. O. Mearns, 2005: *Assessing Future Climate Risks*. *In: Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies and Measures* [Lim, B., E. Spanger-Siegfried, I. Burton, E. Malone and S. Huq (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 119-144.

Leslie, L.M., D.J. Karoly, M. Leplastrier and B.W. Buckley, 2007: Variability of tropical cyclones over the southwest Pacific Ocean using a high resolution climate model*. Continuum Mechanics and Thermodynamics*, **19**, Issue 3-4, 133-175.

Lucas, C., K.J. Hennessy, G. Mills and J.M. Bathols, 2007: *Bushfire Weather in Southeast Australia: Recent Trends and Projected Climate Change Impacts.* A report prepared by the Bushfire CRC, Australian Bureau of Meteorology and CSIRO Marine and Atmospheric Research for The Climate Institute of Australia, 80 pp, http://www.cmar.csiro.au/e-print/open/2007/hennesseykj_c.pdf

McGregor, J. L., 2005: *C-CAM: Geometric Aspects and Dynamical Formulation*. CSIRO Atmospheric Research Technical Paper No. 70, 43 pp,

http://www.cmar.csiro.au/e-print/open/mcgregor_2005a.pdf.

McInnes, K.L., K.J.E. Walsh, G.D. Hubbert and T. Beer, 2003: Impact of sea-level rise and storm surges on a coastal community. *Natural Hazards*, **30**, 187-207.

Meehl, G. A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J.F.B. Mitchell, R.J. Stouffer and K.E. Taylor, 2007a: The WCRP CMIP3 multimodel dataset: A new era in climate change research. *Bulletin of the American Meteorological Society*, **88**, 1383–1394.

Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver and Z.-C. Zhao, 2007b: *Global Climate Projections. In: Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Mpelasoka F, Collier M, Suppiah R, Arancibia J (2007) Application of Palmer Drought Severity Index to observed and enhanced greenhouse conditions using CSIRO Mk3 GCM simulations MODSIM. Christchurch, New Zealand,10-13 Dec

Nakićenović, N., and R. Swart (eds.), 2000: *Special Report on Emissions Scenarios*. A Special Report of Working Group III of the Intergovernmental Panel on Climate

Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 599 pp.

Power, S., M. Haylock, R. Colman and X. Wang, 2006: The predictability of interdecadal changes in ENSO activity and ENSO teleconnections*. J. Climate*, **19**, 4755-4771.

Power, S.B., and I.N. Smith, 2007: Weakening of the Walker Circulation and apparent dominance of El Niño both reach record levels, but has ENSO really changed? *Geophys. Res. Lett*., **34**, L18702, doi:10.1029/2007GL30854.

Rahmstorf, S., A. Cazenave, J.A. Church, J.E. Hansen, R.F. Keeling, D.E. Parker and R.C.J. Somerville, 2007: Recent climate observations compared to projections*. Science*, **316**, 709-710.

Raupach, M.R., G. Marland, P. Ciais, C. Le Que´re´, J.G. Canadell, G. Klepper and C.B. Field, 2007: Global and regional drivers of accelerating CO2 emissions. *Proceedings of the National Academy of Sciences of the USA*, **104**, 10288–10293.

Walsh, K.J.E., K.C. Nguyen, and J.L. McGregor, 2004: Finer-resolution regional climate model simulations of the impact of climate change on tropical cyclones near Australia. *Climate Dynamics*, **22**, 47-56.

Walsh, K.J.E. and B.F. Ryan, 2000. Tropical cyclone intensity increase near Australia as a result of climate change. *Journal of Climate*, **13**, 3029-3036.

Watterson, I. G., 2008: Calculation of probability density functions for temperature and precipitation change under global warming. *Journal of Geophysical Research*, Doi:10.1029/2007JD009254.

Webb L, Whetton P, Barlow EWR (2007) Modelled impact of future climate change on phenology of wine grapes in Australia. Australian Journal of Grape and Wine Research 13:165-175

Appendix

Projected changes in potential evapotranspiration, relative humidity, solar radiation and wind-speed for the Barossa Valley region (top) and Coonawarra region (below). Changes are given for the A1B (mid-range) emission scenario in 2030, relative to the period 1976-2005, and for the B1 (low), A1B and A1FI (high) emission scenarios in 2070. The lowest and highest 10% of the range of model results (10th and 90th percentiles) define the ranges of uncertainty while the median (50th percentile) provides central estimates.

Barossa Valley	PERIOD	2030 mid	2070 low	2070 high
potential evapo-transpiration	Annual	2.1 (0.7 to 4.0)	3.5 (1.1 to 6.7)	6.8 (2.2 to 12.9)
	Summer	1.8 (0.0 to 4.1)	3.0 (0.1 to 6.8)	5.8 (0.1 to 13.2)
	Autumn	3.1 (1.4 to 5.5)	5.2 (2.3 to 9.1)	10.1 (4.4 to 17.7)
	Winter	4.9 (1.7 to 10.6)	8.2 (2.9 to 17.6)	15.8 (5.6 to 34.0)
	Spring	1.2 (-0.8 to 3.3)	2.1 (-1.3 to 5.6)	4.0 (-2.5 to 10.8)
relative humidity	Annual	-0.6 (-1.4 to 0.1)	-1.0 (-2.3 to 0.1)	-1.9 (-4.5 to 0.2)
	Summer	-0.4 (-1.1 to 0.2)	-0.7 (-1.9 to 0.4)	-1.4 (-3.7 to 0.8)
	Autumn	-0.4 (-1.5 to 0.5)	-0.6 (-2.4 to 0.9)	-1.2 (-4.7 to 1.7)
	Winter	-0.5 (-2.0 to 0.4)	-0.9 (-3.4 to 0.7)	-1.7 (-6.5 to 1.4)
	Spring	-0.9 (-1.9 to -0.2)	-1.5 (-3.1 to -0.3)	-3.0 (-6.1 to -0.6)
solar radiation	Annual	0.5 (1.5 to 1.2)	0.8 (2.6 to 2.0)	1.6 (5.0 to 3.9)
	Summer	0.2 (-0.4 to 0.9)	0.3 (-0.7 to 1.4)	0.7 (-1.3 to 2.8)
	Autumn	0.1 (-0.7 to 1.1)	0.2 (-1.2 to 1.8)	0.4 (-2.3 to 3.5)
	Winter	1.5 (-0.5 to 3.9)	2.4 (-0.8 to 6.5)	4.7 (-1.5 to 12.6)
	Spring	0.7 (0.0 to -0.1)	1.1 (-0.1 to -0.1)	2.1 (-0.1 to -0.2)
wind speed	Annual	0.8 (0.6 to 1.2)	1.4 (0.9 to 2.0)	2.6 (1.8 to 3.8)
	Summer	2.1 (-1.2 to 6.0)	3.6 (-2.0 to 9.9)	6.9 (-3.9 to 19.2)
	Autumn	-0.7 (-5.8 to 4.1)	-1.1 (-9.7 to 6.8)	-2.2 (-18.7 to 13.1)
	Winter	-1.5 (-7.1 to 3.5)	-2.5 (-11.9 to 5.9)	-4.9 (-23.0 to 11.3)
	Spring	0.9 (0.6 to 1.3)	1.4 (0.9 to 2.1)	2.8 (1.8 to 4.0)

Coonawarra	PERIOD	2030 mid	2070 low	2070 high
potential evapo-transpiration	Annual	2.6 (0.8 to 4.8)	4.4 (1.4 to 8.0)	8.4 (2.7 to 15.4)
	Summer	2.2 (0.2 to 4.5)	3.6 (0.4 to 7.5)	7.0 (0.7 to 14.6)
	Autumn	3.7 (1.8 to 6.2)	6.2 (3.0 to 10.3)	12.0 (5.7 to 19.9)
	Winter	5.3 (1.2 to 11.2)	8.8 (2.1 to 18.6)	17.0 (4.0 to 36.0)
	Spring	2.2 (-0.2 to 4.9)	3.6 (-0.3 to 8.1)	7.0 (-0.6 to 15.7)
relative humidity	Annual	-0.6 (-1.2 to -0.1)	-0.9 (-1.9 to -0.1)	-1.8 (-3.7 to -0.3)
	Summer	-0.6 (-1.3 to 0.0)	-1.0 (-2.2 to 0.0)	-1.9 (-4.2 to 0.0)
	Autumn	-0.4 (-1.2 to 0.3)	-0.7 (-2.0 to 0.5)	-1.3 (-3.9 to 1.0)
	Winter	-0.3 (-1.4 to 0.2)	-0.5 (-2.3 to 0.4)	-1.1 (-4.4 to 0.7)
	Spring	-0.8 (-1.6 to -0.2)	-1.4 (-2.7 to -0.3)	-2.7 (-5.3 to -0.5)
solar radiation	Annual	0.7 (2.0 to 1.3)	1.2 (3.4 to 2.2)	2.2 (6.6 to 4.2)
	Summer	0.4 (-0.1 to 1.0)	0.7 (-0.2 to 1.7)	1.3 (-0.4 to 3.3)
	Autumn	0.4 (-0.5 to 1.3)	0.7 (-0.8 to 2.2)	1.3 (-1.5 to 4.3)
	Winter	1.2 (-0.3 to 3.2)	2.0 (-0.4 to 5.3)	3.9 (-0.8 to 10.2)
	Spring	1.0 (0.2 to 0.2)	1.7 (0.3 to 0.3)	3.3 (0.7 to 0.7)
wind speed	Annual	0.8 (0.5 to 1.1)	1.3 (0.9 to 1.8)	2.5 (1.7 to 3.5)
	Summer	1.1 (-4.2 to 5.9)	1.9 (-7.0 to 9.9)	3.7 (-13.5 to 19.0)
	Autumn	-1.8 (-8.3 to 3.9)	-3.0 (-13.8 to 6.5)	-5.7 (-26.7 to 12.6)
	Winter	0.4 (-4.3 to 4.9)	0.7 (-7.2 to 8.1)	1.4 (-13.9 to 15.7)
	Spring	0.8 (0.5 to 1.1)	1.3 (0.9 to 1.9)	2.5 (1.7 to 3.7)

Projected changes in, potential evapotranspiration, relative humidity, solar radiation and wind-speed for the Hunter Valley region (top) and Margaret River region (below). Changes are given for the A1B (mid-

range) emission scenario in 2030, relative to the period 1976-2005, and for the B1 (low), A1B and A1FI (high) emission scenarios in 2070. The lowest and highest 10% of the range of model results (10th and 90th percentiles) define the ranges of uncertainty while the median (50th percentile) provides central estimates.

Hunter Valley	PERIOD	2030 mid	2070 low	2070 high
potential evapo-transpiration	Annual	3.1 (1.9 to 4.6)	5.1 (3.1 to 7.7)	9.9 (6.0 to 14.9)
	Summer	3.0 (1.4 to 4.9)	4.9 (2.4 to 8.2)	9.5 (4.6 to 15.9)
	Autumn	3.8 (1.9 to 6.4)	6.3 (3.2 to 10.6)	12.3 (6.2 to 20.5)
	Winter	4.9 (0.9 to 10.0)	8.1 (1.5 to 16.6)	15.7 (2.8 to 32.1)
	Spring	2.2 (0.6 to 4.3)	3.7 (1.1 to 7.2)	7.2 (2.0 to 13.8)
relative humidity	Annual	-0.3 (-1.4 to 0.6)	-0.5 (-2.3 to 1.0)	-1.0 (-4.4 to 1.9)
	Summer	0.0 (-1.0 to 1.1)	0.0 (-1.6 to 1.8)	0.1 (-3.1 to 3.4)
	Autumn	-0.1 (-1.1 to 0.9)	-0.1 (-1.9 to 1.6)	-0.3 (-3.6 to 3.0)
	Winter	-0.4 (-1.9 to 0.8)	-0.7 (-3.1 to 1.3)	-1.4 (-6.0 to 2.5)
	Spring	-0.8 (-2.4 to 0.6)	-1.3 (-4.1 to 1.0)	-2.4 (-7.9 to 1.9)
solar radiation	Annual	0.2 (2.1 to 1.8)	0.4 (3.4 to 3.0)	0.7 (6.7 to 5.9)
	Summer	-0.2 (-2.1 to 1.6)	-0.3 (-3.6 to 2.7)	-0.6 (-6.9 to 5.3)
	Autumn	0.1 (-1.7 to 1.9)	0.1 (-2.8 to 3.2)	0.2 (-5.5 to 6.1)
	Winter	1.2 (-1.0 to 4.0)	2.1 (-1.7 to 6.7)	4.0 (-3.2 to 12.9)
	Spring	0.4 (-1.0 to -1.1)	0.6 (-1.7 to -1.9)	1.2 (-3.2 to -3.7)
wind speed	Annual	1.0 (0.7 to 1.4)	1.6 (1.1 to 2.3)	3.1 (2.1 to 4.4)
	Summer	3.3 (-2.8 to 10.7)	5.4 (-4.7 to 17.8)	10.5 (-9.1 to 34.5)
	Autumn	-0.8 (-7.1 to 5.3)	-1.4 (-11.8 to 8.8)	-2.7 (-22.8 to 17.0)
	Winter	-2.8 (-8.5 to 2.9)	-4.6 (-14.2 to 4.8)	-8.9 (-27.5 to 9.3)
	Spring	1.1 (0.7 to 1.6)	1.8 (1.2 to 2.6)	3.5 (2.3 to 5.0)

Margaret River	PERIOD	2030 mid	2070 low	2070 high
potential evapo-transpiration	Annual	2.4 (0.8 to 4.3)	3.9 (1.3 to 7.2)	7.6 (2.6 to 13.9)
	Summer	1.9 (0.1 to 4.1)	3.2 (0.2 to 6.8)	6.2 (0.3 to 13.2)
	Autumn	3.0 (1.0 to 5.4)	5.0 (1.6 to 9.1)	9.6 (3.1 to 17.5)
	Winter	5.4 (1.7 to 10.6)	9.0 (2.8 to 17.6)	17.5 (5.4 to 34.1)
	Spring	2.0 (0.2 to 4.1)	3.4 (0.4 to 6.8)	6.5 (0.7 to 13.1)
relative humidity	Annual	-0.2 (-0.7 to 0.3)	-0.3 (-1.2 to 0.5)	-0.6 (-2.3 to 1.0)
	Summer	-0.2 (-0.7 to 0.3)	-0.3 (-1.2 to 0.6)	-0.5 (-2.3 to 1.1)
	Autumn	-0.1 (-0.8 to 0.5)	-0.2 (-1.3 to 0.8)	-0.4 (-2.5 to 1.6)
	Winter	-0.2 (-0.8 to 0.4)	-0.3 (-1.3 to 0.6)	-0.5 (-2.5 to 1.2)
	Spring	-0.3 (-0.9 to 0.3)	-0.5 (-1.5 to 0.5)	-0.9 (-2.9 to 1.0)
solar radiation	Annual	0.4 (1.5 to 1.0)	0.7 (2.5 to 1.7)	1.3 (4.8 to 3.3)
	Summer	-0.1 (-0.9 to 0.6)	-0.1 (-1.5 to 1.0)	-0.3 (-2.8 to 1.9)
	Autumn	0.2 (-0.7 to 1.2)	0.4 (-1.1 to 1.9)	0.7 (-2.1 to 3.8)
	Winter	1.5 (0.4 to 2.9)	2.5 (0.7 to 4.8)	4.9 (1.3 to 9.2)
	Spring	0.7 (-0.1 to -0.2)	1.1 (-0.1 to -0.3)	2.1 (-0.2 to -0.6)
wind speed	Annual	0.7 (0.5 to 1.0)	1.2 (0.8 to 1.7)	2.3 (1.5 to 3.3)
	Summer	2.6 (-1.9 to 8.2)	4.3 (-3.2 to 13.7)	8.2 (-6.2 to 26.5)
	Autumn	1.7 (-2.3 to 5.8)	2.8 (-3.8 to 9.7)	5.5 (-7.4 to 18.8)
	Winter	-3.6 (-8.9 to 1.1)	-6.1 (-14.9 to 1.8)	-11.8 (-28.7 to 3.4)
	Spring	0.7 (0.5 to 1.1)	1.2 (0.8 to 1.8)	2.3 (1.5 to 3.5)

Projected changes in, potential evapotranspiration, relative humidity, solar radiation and wind-speed for the Riverina region (top) and Yarra Valley region (below). Changes are given for the A1B (mid-range)

emission scenario in 2030, relative to the period 1976-2005, and for the B1 (low), A1B and A1FI (high) emission scenarios in 2070. The lowest and highest 10% of the range of model results (10th and 90th percentiles) define the ranges of uncertainty while the median (50th percentile) provides central estimates.

Riverina	PERIOD	2030 mid	2070 low	2070 high
potential evapo-transpiration	Annual	2.4 (0.8 to 4.6)	4.1 (1.3 to 7.6)	7.8 (2.4 to 14.7)
	Summer	2.3 (0.3 to 4.8)	3.8 (0.5 to 7.9)	7.4 (1.0 to 15.3)
	Autumn	3.6 (1.4 to 6.4)	5.9 (2.4 to 10.7)	11.5 (4.5 to 20.6)
	Winter	6.0 (0.6 to 14.7)	9.9 (1.0 to 24.5)	19.2 (1.9 to 47.4)
	Spring	1.2 (-1.5 to 4.1)	2.0 (-2.4 to 6.9)	4.0 (-4.7 to 13.2)
relative humidity	Annual	-0.7 (-1.6 to 0.1)	-1.1 (-2.6 to 0.2)	-2.1 (-5.1 to 0.5)
	Summer	-0.3 (-1.3 to 0.7)	-0.5 (-2.2 to 1.1)	-1.0 (-4.2 to 2.2)
	Autumn	-0.4 (-1.7 to 0.7)	-0.7 (-2.9 to 1.2)	-1.4 (-5.6 to 2.4)
	Winter	-0.6 (-2.3 to 0.5)	-1.0 (-3.9 to 0.8)	-2.0 (-7.5 to 1.5)
	Spring	-1.1 (-2.4 to -0.1)	-1.9 (-3.9 to -0.1)	-3.6 (-7.6 to -0.2)
solar radiation	Annual	0.5 (2.0 to 1.8)	0.8 (3.3 to 2.9)	1.5 (6.3 to 5.6)
	Summer	0.0 (-1.2 to 1.2)	0.0 (-2.0 to 2.1)	0.0 (-3.8 to 4.0)
	Autumn	0.1 (-1.2 to 1.7)	0.2 (-2.0 to 2.9)	0.3 (-3.9 to 5.5)
	Winter	2.1 (-0.6 to 5.7)	3.5 (-1.0 to 9.4)	6.7 (-2.0 to 18.3)
	Spring	0.6 (-0.3 to -0.5)	1.1 (-0.6 to -0.8)	2.1 (-1.1 to -1.6)
wind speed	Annual	1.0 (0.7 to 1.4)	1.6 (1.1 to 2.3)	3.1 (2.1 to 4.4)
	Summer	0.0 (-7.5 to 6.5)	0.1 (-12.5 to 10.8)	0.1 (-24.2 to 20.9)
	Autumn	-2.2 (-9.0 to 4.0)	-3.6 (-14.9 to 6.7)	-6.9 (-28.8 to 13.0)
	Winter	-1.0 (-8.1 to 5.3)	-1.7 (-13.5 to 8.9)	-3.3 (-26.2 to 17.1)
	Spring	1.0 (0.7 to 1.5)	1.7 (1.1 to 2.5)	3.3 (2.2 to 4.9)

Yarra Valley	PERIOD	2030 mid	2070 low	2070 high
potential evapo-transpiration	Annual	2.8 (0.6 to 5.4)	4.7 (1.1 to 9.0)	9.0 (2.1 to 17.5)
	Summer	2.4 (0.0 to 5.3)	4.1 (0.1 to 8.8)	7.8 (0.1 to 17.1)
	Autumn	4.0 (1.8 to 6.8)	6.7 (3.0 to 11.3)	12.9 (5.8 to 21.8)
	Winter	8.9 (-3.6 to 25.8)	14.9 (-6.0 to 43.0)	28.7 (-11.5 to 83.1)
	Spring	2.1 (-0.9 to 5.5)	3.5 (-1.4 to 9.1)	6.9 (-2.7 to 17.7)
relative humidity	Annual	-0.6 (-1.2 to -0.1)	-1.0 (-2.0 to -0.2)	-2.0 (-3.9 to -0.3)
	Summer	-0.6 (-1.7 to 0.3)	-1.0 (-2.9 to 0.5)	-2.0 (-5.6 to 0.9)
	Autumn	-0.4 (-1.2 to 0.3)	-0.7 (-2.0 to 0.5)	-1.3 (-3.9 to 1.1)
	Winter	-0.4 (-1.2 to 0.2)	-0.7 (-2.0 to 0.4)	-1.3 (-3.8 to 0.7)
	Spring	-1.0 (-1.9 to -0.2)	-1.6 (-3.2 to -0.3)	-3.1 (-6.1 to -0.5)
solar radiation	Annual	0.9 (2.5 to 1.7)	1.4 (4.2 to 2.9)	2.8 (8.2 to 5.6)
	Summer	0.6 (-0.3 to 1.6)	0.9 (-0.5 to 2.6)	1.8 (-1.0 to 5.0)
	Autumn	0.6 (-0.4 to 1.7)	0.9 (-0.7 to 2.8)	1.8 (-1.3 to 5.4)
	Winter	1.4 (-0.2 to 3.4)	2.4 (-0.3 to 5.6)	4.6 (-0.7 to 10.8)
	Spring	1.3 (0.3 to 0.2)	2.1 (0.4 to 0.3)	4.1 (0.8 to 0.6)
wind speed	Annual	0.8 (0.6 to 1.1)	1.3 (0.9 to 1.9)	2.6 (1.8 to 3.7)
	Summer	-1.0 (-9.2 to 5.5)	-1.7 (-15.3 to 9.2)	-3.2 (-29.5 to 17.9)
	Autumn	-2.3 (-9.3 to 3.6)	-3.8 (-15.5 to 6.0)	-7.4 (-29.9 to 11.7)
	Winter	1.6 (-3.4 to 6.2)	2.6 (-5.7 to 10.3)	5.1 (-11.0 to 19.9)
	Spring	0.8 (0.5 to 1.2)	1.4 (0.9 to 2.0)	2.6 (1.8 to 3.8)

Appendix 3: Observed trends in winegrape vintages in Australia.

(Running title: Observed trends in winegrape maturity in Aust.)

L. B. Webb[1,2], P.H. Whetton[2] and E.W.R. Barlow[1]

1. School of Land and Environment, University of Melbourne, Parkville Victoria, Australia

2. CSIRO Climate Adaptation National Research Flagship, Melbourne, Victoria, Australia.

Corresponding author:

L. B. Webb Tel: +613 92394549, Fax: +613 92394444, e-mail: leanne.webb@csiro.au

Abstract

An extensive assessment of historical trends in winegrape maturity dates from vineyards located in geographically diverse winegrape growing regions in Australia has been undertaken. Records from 44 vineyard blocks, representing a range of varieties of *Vitis vinifera* L., were accessed. These comprise 33 short-term datasets (average 17 years in length) and 11 long-term datasets, ranging from 25 to 115 years in length (average 50 years). Time series of the day of the year grapes attain maturity were assessed.

A trend to earlier maturity of winegrapes was observed in 43 of the 44 vineyard blocks. This trend was significant for six out of the 11 long-term blocks for the complete time period for which records were available. For the period 1993-2009, 35 of the 44 vineyard blocks assessed displayed a statistically significant trend to earlier maturity. The average advance in the phenology was dependent on the time period of observation, with a more rapid advance over more recent decades. Over the more recent 1993-2009 period the average advance was 1.7 days per year, whereas for the period 1985-2009 the rate of advance was 0.8 days per year on average in the 10 long-term vineyard blocks assessed for cross regional comparison.

The trend to earlier maturity was associated with warming temperature trends for all of the blocks assessed in the study.

Keywords

Phenology, climate change, winegrapes, viticulture, harvest.

Introduction

Responses to climate by biophysical systems can be used to complement meteorological observations of climatic changes (Rosenzweig *et al.* 2008). Phenology is the study of the phases of biological systems through the seasons and is affected by the climate (Schwartz 2003). Many phenological time-series trends have been studied in the Northern Hemisphere and most of the trends are consistent with warming temperatures (Menzel *et al.* 2006; Rosenzweig *et al.* 2008). In Australia over past decades the climate has also been warming (Karoly & Braganza

2005). However, to date, there exist sparse long-term systematic phenological data collections from natural and managed biological systems in the Southern Hemisphere (Chambers 2006) with which to make similar comparisons. In fact, limited studies of observed changes in physical systems exist and no studies were listed for agricultural (managed) systems in Australia (at least 20 years of data were required for analysis) in the latest assessment report published by the IPCC (Rosenzweig *et al.* 2007; Koch 2010). In this study we assess time-series of observed phenological responses in a managed biological system, using records from vineyards and wineries in southern Australia, to determine whether trends in these systems are evident. While one assessment of shorter term observed phenological records (from 1993-2006) has been undertaken (Petrie & Sadras 2008) the Australian analysis presented here is the first broadly spatially-based and comparative assessment of observed short-term and long-term winegrape maturity time series from the Southern Hemisphere.

Shifts in the timing of winegrape maturity can have implications for grape-growers. It is well established that temperature at, and leading up to harvest, influences winegrape quality (Jackson & Lombard 1993, Coombe & Iland 2004). Due to normal seasonal temperature fluctuations, earlier ripening translates to warmer ripening temperatures for winegrapes. Warming temperatures in cool climate regions could lead to more consistent vintage quality, as for example with Riesling in the Mosel region in Germany (Ashenfelter and Storchmann 2010) while negative impacts on winegrape quality as a result of ripening in a warmer climate during a warmer part of the year have been modelled for Australia (Webb *et al.* 2008a, 2008b). These results can be explained by the rate of change in fruit composition being strongly influenced by temperature (Coombe 1987; Jackson & Lombard 1993; Coombe & Iland 2004), with higher temperatures increasing the speed of sugar development and hastening acid degradation (Coombe & Iland 2004; Lund & Bohlmann 2006; Conde *et al.* 2007; Zamora 2007). A further consequence of this is the production of higher alcohol wines; it has been noted that in recent warmer vintages a possible de-coupling of sugar development from that of flavour and aroma components may have resulted in increased alcohol levels in wine (Duchene & Schneider 2005; Godden & Gishen 2005; Petrie & Sadras 2008). Higher temperatures may also reduce anthocyanin levels (Haselgrove *et al.* 2000; Bergqvist *et al.* 2001; Spayd *et al.* 2002) and increase volatilisation of aroma compounds (Bureau *et al.* 2000; Marais *et al.* 2001). Detection of trends in observed phenological time series across multiple varieties, and both cooler and warmer winegrape growing regions may alert the industry to shifts which may be having an impact on winegrape quality.

Furthermore, if changes to phenology in response to climatic shifts do not affect all varieties in the same way a compression or expansion of the harvest period may occur. A compression would occur if later ripening varieties are more sensitive to climatic changes than earlier ripening varieties causing the harvest window to reduce, consequently impacting vineyard logistics, intake scheduling and winery infrastructure (Webb *et al.* 2007; Van Vliet 2010). Measurement of the spread of winegrape maturity dates across regions and time series from this analysis is explored to determine whether or not a compression of the harvest period has occurred over the time period of these observations.

While the specific biological mechanisms relating major phenological phases with temperature are poorly understood (Pearce & Coombe 2004), empirical evidence suggests that as climates warm, winegrape phenology progresses more swiftly and grapes ripen earlier (Le Roy Ladrie 1988; Chuine *et al.* 2004; Jones *et al.* 2005; Seguin & de Cortazar 2005). Because temperature is often described as the major driver of phenological shifts of winegrapes (Rosenzweig *et al.* 2007), a preliminary analysis of an association of any biophysical shifts with observed temperature changes is presented here.

Anthropogenic emissions of GHGs are projected to increase in future with resultant climate shifts that will continue to impact on biological systems (IPCC 2007a). Projections for future changes to climate have been modelled for Australia and a warming and drying climate is likely for the wine growing regions of Australia (CSIRO 2007). Modelling of projected warming on phenology of wine grapes in Australia indicates that winegrape maturity will occur earlier in the season in future (Webb *et al.* 2007). These shifts were found to vary by region with Chardonnay harvest date in Coonawarra, a cooler region, to advance by 12-22 days with warming of average growing season temperature of approximately 0.3-0.7°C. In the Clare Valley, a warmer region, Chardonnay harvest day was modelled to advance by 7-14 days by with a warming of about 0.4-1.0°C. In this modelling study, the Margaret River was the one region where, with some future warming scenarios, a later harvest was predicted for the future (Webb, 2006). Comparison of observation and model results may serve to validate this earlier study.

Analysis of winegrape maturity datasets from a range of wine growing regions in Australia is undertaken here in order to determine the presence of any trends in phenological time series. This analysis serves to contribute to the global biophysical response record, addressing the paucity of Southern Hemisphere data. In this article, associations of shifts in phenology with observed shifts in temperature, assuming that temperature is the likely major driver, are introduced. However, it should be noted that other climatic and non-climatic drivers have also been described as affecting the timing of maturity of perennial horticultural crops e.g. reduced rainfall has been correlated with advanced full bloom dates in apple and pear in South Africa (Grab & Craparo 2010); and lower yields were correlated with earlier maturity in the Riverland region of Australia (Botting *et al.* 1996). Due to the large number of datasets being assessed here, and the potential complexity of assessing the multiple drivers of any trends in these broadly spatially based, managed biological systems, the focus of this article will be on detection of a shift in the timing of winegrape maturity. The more comprehensive attribution study of any detected trends, exploring many potential climatic and non-climatic drivers of change, will be presented in a subsequent analysis.

Method

Data from wineries and vineyards in Australia

Records of observations made during winegrape harvests from 44 vineyard blocks in 12 winegrape growing regions in Australia, encompassing the periods 1895-2009, have been assessed (Figure 1). The regions studied represent the full range of temperatures in which most winegrapes are grown in Australia (Smart *et al.* 1980). The regions, varieties and blocks represented are listed as well as the latitude/longitude of the vineyard sites (Table 1). Where more than one block of the same variety was assessed in a given region the variety was given a block code e.g. Shiraz (L) and Shiraz (M) from the Eden Valley. For the short-term datasets the latitude/longitude was estimated to be located centrally in the respective region as confidentiality of these sites was requested by the provider of the data.

Table 1. Details of data sets used including: Average growing season temperature (°C) baseline1976-2005; designated total soluble solids (°Bé); the average block ripening rate (°Bé per week) where measured; the range of years represented (N) (with number of missing years in brackets); and the period represented. Long-term blocks (more than 25 years in range) shaded grey.

Region	**Ave GST (°C)**	**Variety (Block)**	**TSS (°Bé)**	**Ripening rate (°Bé/wk)**	**N range (years)**	**Period**
Mornington Peninsula (144.98E,38.36S)	16.6	Pinot Noir	11.6	0.7	26	1984 to 2009
		Chardonnay	11.6	0.4	25	1985 to 2009
Eden Valley (139.11E,34.61S)	17.2	Shiraz (L)	13.5	N/A	32 (2)	1973 to 2009
		Shiraz (M)	13.5	N/A	33	1977 to 2009
McLaren Vale (138.56E,35.18S)	18.4	Shiraz	12.0	N/A	115 (10)	1895 to 2009
Margaret River (115.03E,33.91S)	18.6	Cabernet Sauvignon	12.0	0.7	34 (1)	1976 to 2009
Rutherglen (146.46E,36.04S)	18.7	Muscat a petit grains	15.0	N/A	65 (11)	1945 to 2009
Central Victoria (145.09E,36.80S)	18.9	Shiraz (Mc)	11.0	0.7	64 (6)	1940 to 2009
		Shiraz (S)	11.0	0.7	50 (1)	1959 to 2009
		Marsanne	10.0	0.9	68 (5)	1939 to 2009
		Riesling	11.0	0.5	30	1978 to 2007
Coonawarra (140.84E,37.29S)	16.8	Shiraz	12.0	0.7	14	1996 to 2009
		Cabernet Sauvignon (1)	12.0	0.5	14	1996 to 2009
		Cabernet Sauvignon (3)	13.0	0.5	13 (1)	1996 to 2009
Adelaide Hills (138.5E,35.00S)	17.1	Chardonnay	11.0	0.9	17	1993 to 2009
Eden Valley (139.11E,34.61S)	17.2	Chardonnay	12.0	0.9	14 (1)	1993 to 2007
		Shiraz	13.0	1	15 (1)	1994 to 2009
		Riesling	10.0	0.6	16	1994 to 2009
Barossa Valley (138.99E,34.47S)	18.5	Chardonnay (2)	11.0	0.9	17	1993 to 2009
		Chardonnay (5)	11.0	1.1	17	1993 to 2009
		Chardonnay (6)	11.0	0.9	17	1993 to 2009
		Chardonnay (8)	11.0	1.2	17	1993 to 2009
		Cabernet Sauvignon	11.0	0.6	17	1993 to 2009
		Semillon	11.0	0.9	17	1993 to 2009

		Riesling (4)	10.0	0.8	17	1993 to 2009
		Riesling (7)	11.0	0.9	17	1993 to 2009
		Riesling (9)	10.0	0.9	17	1993 to 2009
		Grenache	12.0	1.2	17	1993 to 2009
Clare Valley (138.61E,33.83S)	18.5	Cabernet Sauvignon	12.0	0.8	16	1994 to 2009
		Riesling	11.0	0.8	16	1994 to 2009
Langhorne Creek (139.03E,35.29S)	18.6	Shiraz (1)	13.0	1	17	1993 to 2009
		Shiraz (5)	13.0	0.8	17	1993 to 2009
		Grenache	13.0	1	15 (2)	1993 to 2009
		Malbec	12.0	0.7	17	1993 to 2009
		Chardonnay	11.0	0.8	17	1993 to 2009
Riverland (Loxton) (140.57E,34.45S)	20.5	Chardonnay (2)	11.0	0.9	16 (1)	1993 to 2008
		Chardonnay (3)	11.0	0.9	17 (4)	1993 to 2009
		Mataro	12.0	1	17 (3)	1993 to 2009
		Colombard (1)	11.0	0.7	17	1993 to 2009
		Colombard (7)	9.0	0.6	17 (3)	1993 to 2009
Riverland (Waikerie) (139.99E,34.18S)		Shiraz	10.0	0.8	14	1993 to 2006
		Muscat Gordo Blanco (10)	12.0	0.7	17	1993 to 2009
		Muscat Gordo Blanco (9)	12.0	0.7	17 (5)	1993 to 2009
		Grenache	10.0	1	15	1993 to 2007

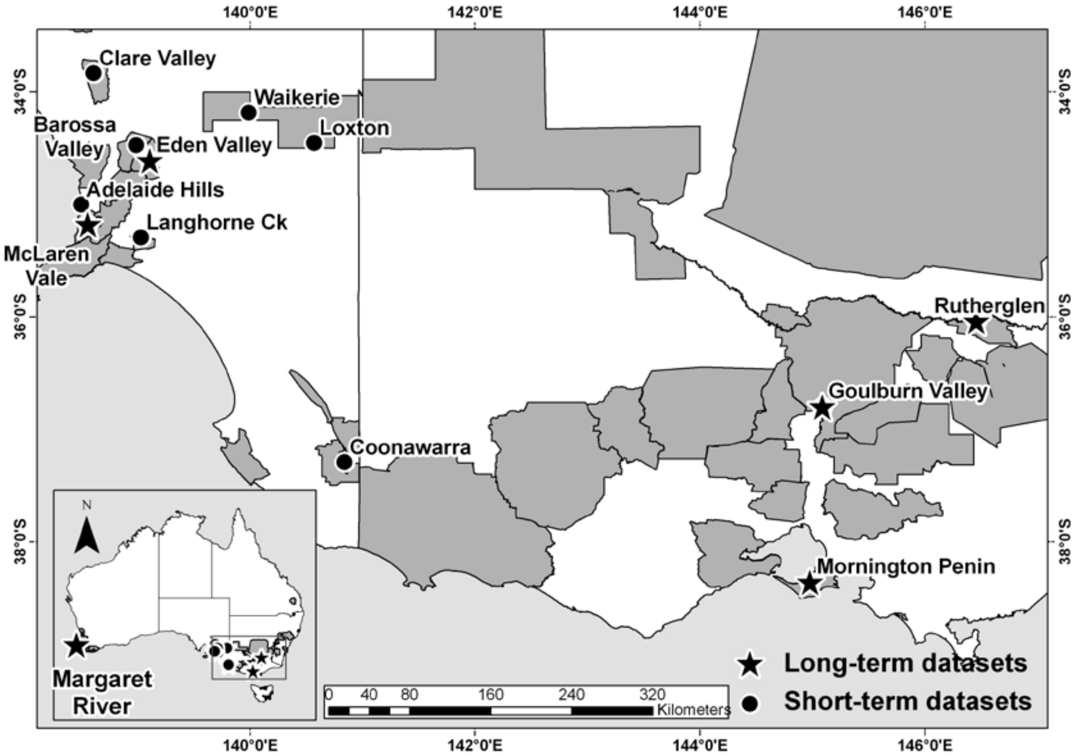


Figure 1. Winegrowing sites in the 11 regions in southern Australia (see inset map) where study blocks are located: long-term (stars) and short-term (circles). Registered winegrape growing regions are depicted (grey). State and territory boundaries are marked with the grey lines in inset map.

Data were classified as long-term (a range of 25 years or longer, shaded grey in Table 1) and short-term where the range of fewer than 25 years of records were available. The number of years in the range of observations was listed with the number of missing years noted in brackets. Data are listed in order of increasing average growing season temperature, Ave GST (°C), of the region, within the overall 'dataset length' groupings (Table 1) (see Climate Data section for a definition of Ave GST (°C)).

In most vineyards, representative samples of grapes are collected from separate blocks at short intervals in the lead-up to harvest and sugar concentration measurements are taken from these samples. These measurements assist the grower in planning when to start harvesting a particular block. These records, or similar, were used in this study. Winegrape ripening profiles were derived from the recordings of changing sugar concentrations found in vintage diaries. From this information the day of year grapes attained 'maturity' was derived for each year in every block. The method whereby maturity day was calculated from this data is described below (see 'Calculation of maturity day' section).

In most cases, the records were kept on site, though for the McLaren Vale site the records have also been included in the archival collection at the Adelaide library. Data were obtained through personal visits to wineries with manuscripts and vintage diaries being made available for perusal. Efforts to gain access to additional records from other regions were attempted but were unsuccessful for a variety of reasons such as insufficient time series length, records not kept or lost, or sugar concentration measurements were not available.

Calculation of maturity day

In many phenological studies the harvest phase is defined as the date that the crop is picked (e.g. Chuine *et al.* 2004; Meier *et al.* 2007). However, with regard to winegrapes, harvest day has been described as a false phenophase because this date can be selected to suit changing style preferences or other constraints that can occur through the harvest period, e.g. impending rain or winery logistics (Jones *et al.* 2005; Petrie & Sadras 2008). For these reasons winegrape harvest day is not a physiologically consistent phenophase. In order to make a comparison of inter-annual 'harvest date' we assess the changing timing of the day of year a designated maturity, or level of ripeness, was attained (hereafter known as DOY_M) (after Petrie and Sadras, 2008).

Sugars, or total soluble solids (TSS) (unit: degrees Baumé or °Bé) (Iland 2000), accumulate in grapes from véraison to harvest as they ripen (Conde *et al.* 2007). TSS (°Bé) are typically measured and recorded periodically in the month leading up to harvest to assist with vintage planning, as growers attempt to pick the grapes at the optimum TSS level for their purpose (Krstic *et al.* 2003). By analysing the records of the TSS concentrations as these accumulate we can produce an 'inter-annually comparable' physiological measure of a phenological stage as close as possible to harvest date. The day of year where the ripening profile reached a 'designated TSS (°Bé)' level was the metric used to represent 'maturity date' the harvest proxy in this study, i.e. DOY_M. The designated TSS (°Bé) was selected for each block according to the wine style produced and the likelihood of it being recorded through the course of the harvest planning. For example, the TSS level selected to represent the Muscat à Petit Grains variety grown in the Rutherglen region was 15°Bé as these grapes were generally picked riper to produce a fortified wine, while the Marsanne grapes grown in Central Victoria are used to make a lighter style table wine, hence 10°Bé was the designated TSS in this case (Table 1).

The DOY_M had to be derived in cases where the designated TSS (°Bé) for the block (Table 1) was either above or below those recorded for the particular year. Two different methods were employed by which to make adjustments, the approach being guided by the availability and type of data recorded in the diaries. In the majority of cases winegrape harvest planning records were available (i.e. for all of the short-term datasets, Mornington Peninsula, Margaret River and Central Victorian blocks). For these datasets DOY_M was extrapolated from annual ripening profiles. An example of the extrapolation procedure is demonstrated for the Marsanne block (Central Victoria), over the observation period 1970-1979 (Figure 2). In this example the accumulation of sugars is noted for each year of the decade as the grapes progressed through the ripening period. Where grapes did not actually achieve the designated maturity level of 10°Bé (the value selected as representative of maturity for this variety at this site), i.e. in 1972 and 1977, the line was extrapolated with the calculated average ripening rate for the block[2] (0.9°Bé per week) (Table 1) (the average rate of accumulation of sugar (°Bé per week) has been calculated from the records for each block and this varies, ranging from 0.4°Bé per week for Chardonnay in the Mornington Peninsula to 1.2°Bé per week for the same variety in the Barossa

[2] This process was also carried out using a decadal ripening rate for each block in case there was some change in the rate through time. Using this method made no difference to the results so the more simple approach of applying the average ripening rate calculated over the entire period of observation is presented here.

Valley). Therefore, the derived maturity date for the years 1972 was ‘adjusted day 79’ and 1977 was ‘adjusted day 83’. This method was used to estimate DOY_M in about one third of the years overall and for half of these, records were less than 1°Be different from the designated TSS(°Be).

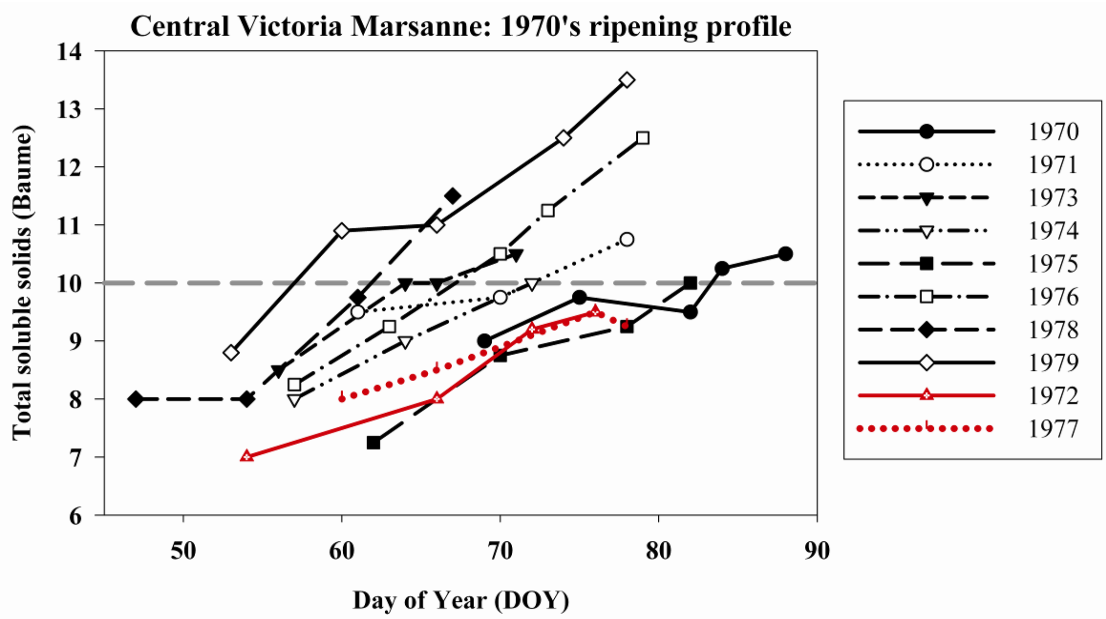


Figure **2.** Harvest planning records (total soluble solids (°Bé), plotted for the years 1970 to 1979 for the Marsanne block (Central Victoria). In the years 1972 and 1977 (red lines) the level of 10°Bé was not attained so the ‘maturity date’ was extrapolated using the average ripening rate for the block. Average rate of sugar accumulation for this block was 0.90°Bé per week (see Table **1**).

In the case of the Eden Valley and Rutherglen, diary records were kept of harvest day, TSS level (°Bé) and tonnes harvested for that day (where the grapes were harvested over successive picks), but harvest planning records were not available. For these datasets the yield weighted average harvest day and TSS level (°Bé) were calculated. The maturity day was adjusted using the average rate of advance calculated for all of the datasets combined (0.8°Bé per week[3]; the average of the ripening rate (°Bé per week) for all blocks listed in Table 1), with the ‘adjusted day’ estimated to be when the ‘designated TSS (°Bé) level’ would be attained for the particular site. For the Eden Valley site only about 20% of the years had adjustments that involved a greater than 1°Bé shift. For the Rutherglen region however, the grapes were harvested across a wider range of Baume levels so greater adjustments were necessary; about half the years with adjustments of greater than 1°Bé.

Due to the extremely long time series of harvest dates available for the McLaren Vale Shiraz block (1895-2009), we elected to present the ‘harvest date’ data alongside the DOY_M data of all of other blocks in this study. The winery owner stated that approximately 12°Bé was the targeted level of ripeness at harvest throughout the history of the site. While the harvest date was recorded for McLaren Vale Shiraz, TSS was only noted through the latter part of the time series (1990-2009). Adjustments were made for the 1990-2009 series where necessary using the

[3] When considering the regions for which we are adjusting the DOY at maturity in this case, they are in the mid-range of climate relative to the other regions in the study. Selection of a mid-range, or average, rate of ripening used to make adjustments therefore seemed sensible.

average rate of 0.8°Bé per week (as above). We emphasise however, 'the maturity date' was likely to vary from the 'harvest date' if grapes were harvested at a different sugar concentration each year.

Trend in maturity day

Trend analysis of DOY_M of all of the time series has been undertaken for:

- the total period of observation for the long-term datasets as these vary;
- for 1985 to 2009 (25 years), the time period common to long-term blocks;
- and 1993 to 2009 (17 years) the time period common to all blocks.

Linear regression against time is a long established statistical tool widely used in phenological research to study trends (Sparks & Tryjanowski 2010) and has been applied in this analysis. Other regression models were also tested to determine the presence of higher order relationships.

Calculation of length of harvest period

If DOY_M is more advanced in later ripening varieties than earlier ripening varieties a compression of the harvest period may occur i.e. the time from the beginning to the completion of harvest is reduced. To determine whether this occurred, the range of days from the first DOY_M and the final DOY_M across varieties was assessed for all the blocks in each region, and over all regions, over comparable parts of the time series. These time periods are 1985-2009 inclusive (10 blocks[4] from six regions) and 1993-2009 inclusive (30 blocks[5] from 9 regions) were included. Blocks with missing data at the beginning and end of the series were omitted to ensure a consistent time-frame was used (see Table 1).

Climate data

Average growing season temperature from October to April (°C) (an average of the mean monthly temperatures (monthly maximum temperature + monthly minimum temperature)/2, from October to April inclusive), hereafter abbreviated to Average GST (°C), was selected as a temperature measure for comparison with trends in DOY_M. This temperature measure has been found to be most closely associated with the timing of phenological phases of véraison and harvest in similar studies (Jones *et al.* 2005). Daily maximum and minimum temperature data from 1911-2009 were obtained from 0.05° x 0.05° gridded data produced for the Australian continent by Jones *et al.* (2009). These daily surfaces were calculated using Australian Bureau of Meteorology's network of high quality temperature stations. Data were extracted from the daily temperature surfaces corresponding to the latitude/longitude location of the site (Table 1). Average GST (°C) was also calculated for the climatological baseline period of 1976-2005 for each region to illustrate the range of climates and relative differences between the regions (Table 1).

A temperature time series of average GST (°C) were calculated for each year corresponding with vineyard observations at each location. Linear trends in the

[4] Central Victoria (Cr2) block was omitted from this grouping as 2008 and 2009 data are missing.

[5] McLaren Vale (Bl6), Eden Valley (L) and Central Victoria (Cr2), Coonawarra (Co2, Co1, Co3), Eden Valley (E1, E2, E3), Clare Valley (Cl1, Cl2), Loxton (R2), Waikerie (R5, R11) are omitted as the vintage year 1993 was not represented in these blocks.

temperature measure were calculated for three time periods: period of vineyard observations; 1985-2009; and 1993-2009, as with DOY_M described previously.

Results

Trend in maturity day

Time series of maturity date for the total period of observation are shown for six blocks from four selected sites (Figure 3), with calculated trends also shown for all sites (Table 2). For two blocks from the Central Victorian region, Marsanne and Shiraz (M) (Figure 3a), a trend to earlier maturity is evident through the time series as indicated by the slope of the fitted linear regression lines (also shown in Table 2). The shift in average DOY_M across this time series of about 24 days is observed for these blocks over this period, about 0.3 days earlier per year. A similar response was observed in the Muscat à Petit Grains block in the Rutherglen region, though this trend is not significant (Figure 3b). Compared to these, the Mornington Peninsula blocks display a significant trend to earlier ripening at a faster rate (Chardonnay and Pinot Noir at 1.5 days per year), though this trend was noted through a shorter and later period of observation (Figure 3c). The Eden Valley sites have lower (non-significant) rates of change to maturity (Table 2). It is interesting to note that in the Margaret River, Cabernet Sauvignon site, the best fit linear regression line indicates grapes were ripening slightly later in the year over the time series, and while this is not statistically significant, this was the only block showing this trend direction (Figure 3d).

Table **2.** Trends in day of year at maturity (days per year): the full period of observation of the long-term series (see **Table 1**); the time period common to long-term blocks (1985-2009); and the time period common to all blocks (1993-2009). Significant trends (**P<0.01, *P<0.05) are shaded grey and 95% confidence interval indicated.

Region	Variety (Block)	Trend DOY_M (days/year)		
		Full period of obs.	1985-2009	1993-2009
Mornington Peninsula	Pinot Noir	-1.5 ± 0.5**	-1.6 ± 0.6**	-2.3 ± 1.0**
	Chardonnay	-1.5 ± 0.7**	-1.5 ± 0.7**	-2.6 ± 1.0**
Eden Valley	Shiraz (L)	-0.1 ± 0.5	-0.4 ± 0.8	-1.5 ± 1.6
	Shiraz (M)	-0.2 ± 0.4	-0.8 ± 0.8	-1.5 ± 1.1**
McLaren Vale	Shiraz	-0.2 ± 0.1**	-0.6 ± 0.8	-1.4 ± 2.1
Margaret River	Cabernet Sauvignon	0.1 ± 0.5	-0.1 ± 0.7	0.1 ± 1.4
Rutherglen	Muscat a petit grains	-0.3 ± 0.3	-0.3 ± 1.4	-2.9 ± 2.4*
Central Victoria	Shiraz (Mc)	-0.3 ± 0.1**	-0.8 ± 0.5**	-1.6 ± 0.9**
	Shiraz (S)	-0.4 ± 0.2**	-1.3 ± 0.6**	-2.3 ± 1.0**
	Marsanne	-0.3 ± 0.1**	-0.8 ± 0.6**	-1.4 ± 1.0*
	Riesling	-0.4 ± 0.7	-1.0 ± 1.1	-1.3 ± 2.2
Coonawarra	Shiraz			-3.5±1.7**
	Cabernet Sauvignon (1)			-3.8±1.3**
	Cabernet Sauvignon (3)			-3.5±1.8**
Adelaide Hills	Chardonnay			-0.9±1.1

Eden Valley	Chardonnay	-2.0±1.3**
	Shiraz	-3.2±1.5**
	Riesling	-2.1±1.8*
Barossa Valley	Chardonnay (2)	-1.3±1.0*
	Chardonnay (5)	-1.9±1.1**
	Chardonnay (6)	-1.1±1.0*
	Chardonnay (8)	-1.4±1.0**
	Cabernet Sauvignon	-1.7±1.3*
	Semillon	-1.3±1.1*
	Riesling (4)	-1.0±1.0*
	Riesling (7)	-0.8±1.1
	Riesling (9)	-1.1±1.0*
	Grenache	-1.4±1.3*
Clare Valley	Cabernet Sauvignon	-1.7±0.9**
	Riesling	-1.8±1.0**
Langhorne Creek	Shiraz (1)	-1.4±1.2*
	Shiraz (5)	-2.7±0.7**
	Grenache	-0.4±1.0
	Malbec	-1.1±0.9*
	Chardonnay	-1.3±0.9**
Riverland (Loxton)	Chardonnay (2)	-1.5±1.2*
	Chardonnay (3)	-1.6±1.2*
	Mataro	-1.4±1.6
	Colombard (1)	-3.2±0.9**
	Colombard (7)	-1.8±1.5*
Riverland (Waikerie)	Shiraz	-1.5±1.0**
	Muscat Gordo Blanco (10)	-2.6±1.1**
	Muscat Gordo Blanco(9)	-1.5±1.3*
	Grenache	-1.1±1.6

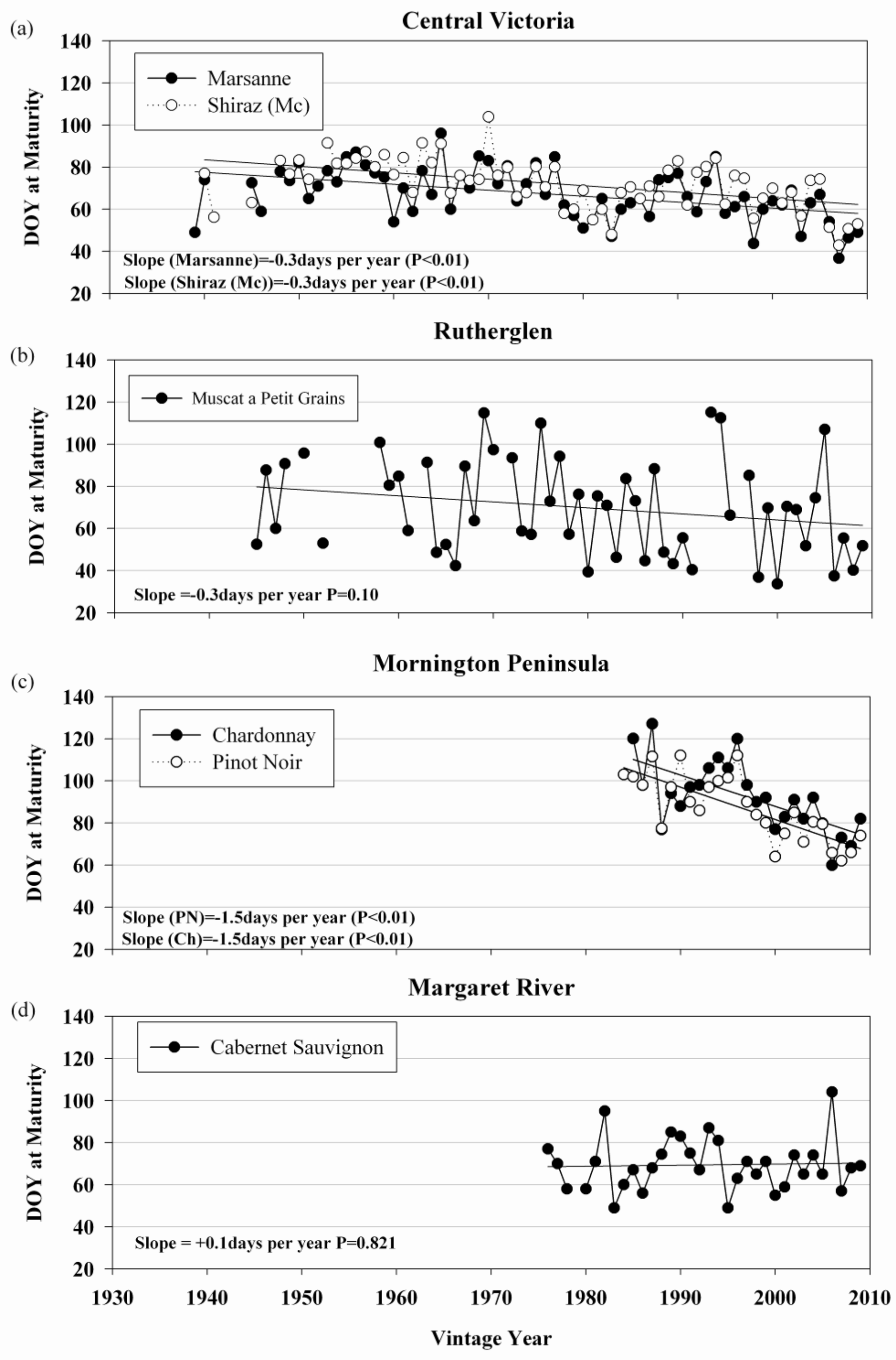


Figure 3. The observed DOY at maturity recorded for six blocks from four regions (a) Central Victoria: Marsanne (1939-2009) (solid circles), Shiraz (Mc) (1940-2009) (open circles) and (b) Rutherglen: Muscat a Petit Grains (1945-2009) (c) Mornington Peninsula: Chardonnay (1985-2009) (solid circles) and Pinot Noir (1984-2009) (open circles) and (d) Margaret River: Cabernet Sauvignon (1973-2009). The best fit linear regression indicates the average trend in the maturity day (see also Table **2).**

For the McLaren Vale site, TSS level was available only from 1990, but harvest date data extended back to 1895. Trends in both harvest date and estimated DOY_M are shown (Figure 4). For both series a trend to earlier maturity is evident, although it is also clear that after 1990 grapes were harvested at a higher sugar level than 12°Bé (i.e. later in the year). The trend in DOY_M, where sugar levels were recorded (1990-2009) was about 1.2 days per year earlier for this block (not shown in Table 2).

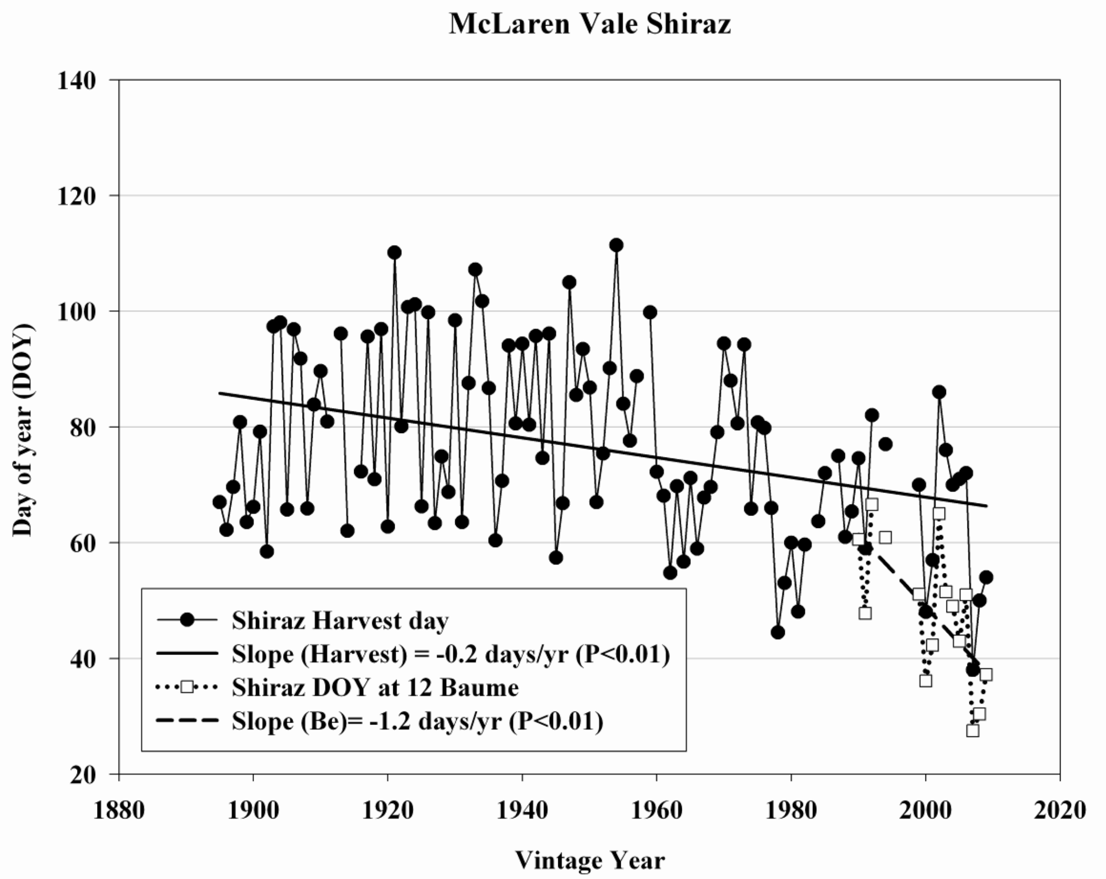


Figure 4. McLaren Vale Shiraz: Observed harvest date (solid circles) and Day of Year at Maturity, DOY_M (hollow squares) recorded for respective time series (see Table 1). Regression lines indicate the trends in the harvest day and DOY_M as these vary.

It is apparent that, with the exception of the Margaret River Cabernet Sauvignon block, a trend to earlier maturity for all of the blocks and through all of the time series has occurred. The trend to earlier maturity is statistically significant for six out of the 11 long-term blocks for the time period for which records were available. For the period 1993-2009, 35 of the 44 vineyard blocks assessed have a statistically significant trend to earlier maturity (Table 2).

A cross regional trend comparison is possible where consistent time frames, 1985-2009 and 1993-2009, are imposed on the data (Table 2). For the 1985-2009 period the trend in the DOY_M ranges from about 1.5 days per year earlier in the Mornington Peninsula, about one day per year earlier in Central Victoria, to 0.1 days earlier in Margaret River. The average shift in DOY_M was 0.8 days per year earlier across the 1985-2009 period. The average shift over all the long-term blocks for the time-period of 1993-2009 for was 1.6 days per year earlier, about twice the rate compared to the period 1985-2009 for the same long-term datasets.

This accelerating rate of change was observed across all the long-term datasets where earlier maturity was detected (Table 2) and is illustrated by the comparison of linear trends, fitted for the three time periods for the Marsanne block (Central Victoria) (Figure 5). In this case, for the observed series (1939-2009) the trend of about 0.3 days per year earlier is found, whereas for the period 1985-2009 the rate increased to 0.8 days per year, and finally over the 1993-2009 period, grapes were ripening about 1.4 days per year earlier for this variety in Central Victoria. Because the pattern of the change in the ripening rate may indicate a non-linear trend, all the long-term datasets were fitted with a quadratic model. However, no improvement to the fit of the data was detected by using the higher order relationship.

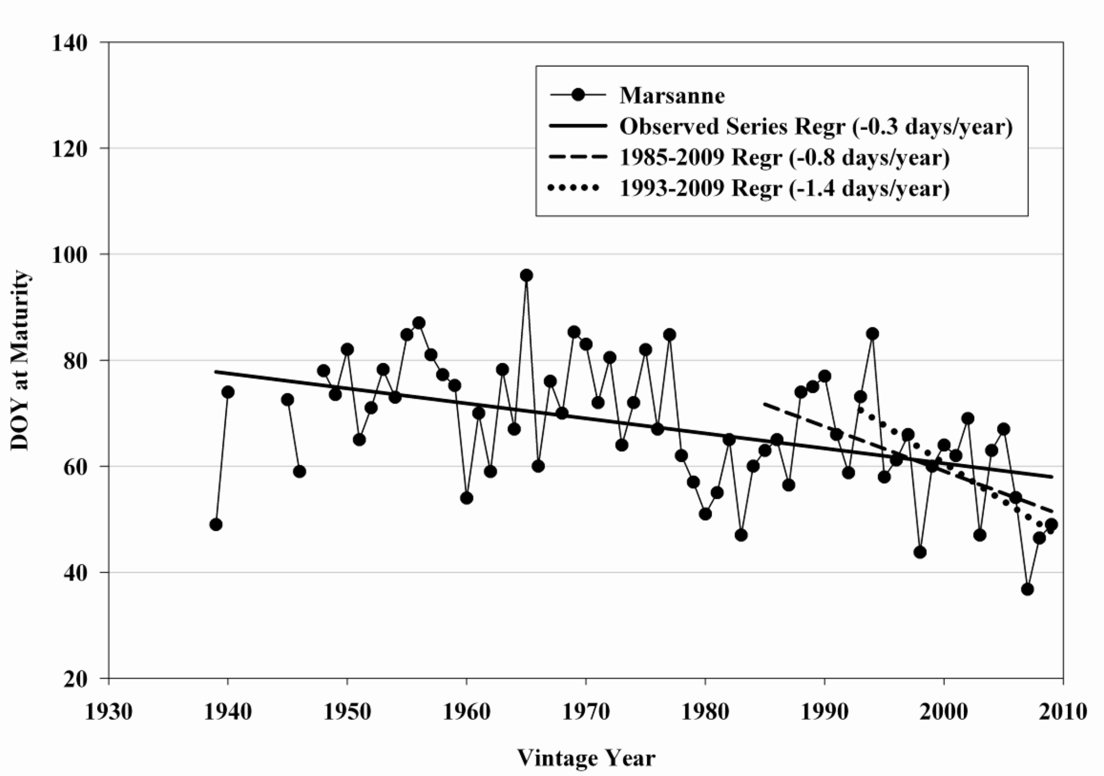


Figure 5. Marsanne (Central Victoria): Trends in rate of change in DOY_M for three time periods calculated: observed series (1939-2009) solid line; 1985-2009 dashed line; and 1993-2009 dotted line (also see Table 2).

Winegrape harvest compression analysis

For the period, 1993-2009, the average range of DOY_M over the 30 blocks was 63 days (from 46 to 79 days) (Figure 6), with individual vineyards DOY_M period ranging from 24 to 120 days depending on the region and year (not shown). Analysis of the trend in the range of DOY_M for the 30 blocks over this period indicated a compression of 1.1 days per year over all of the regions through this period (P=0.02).

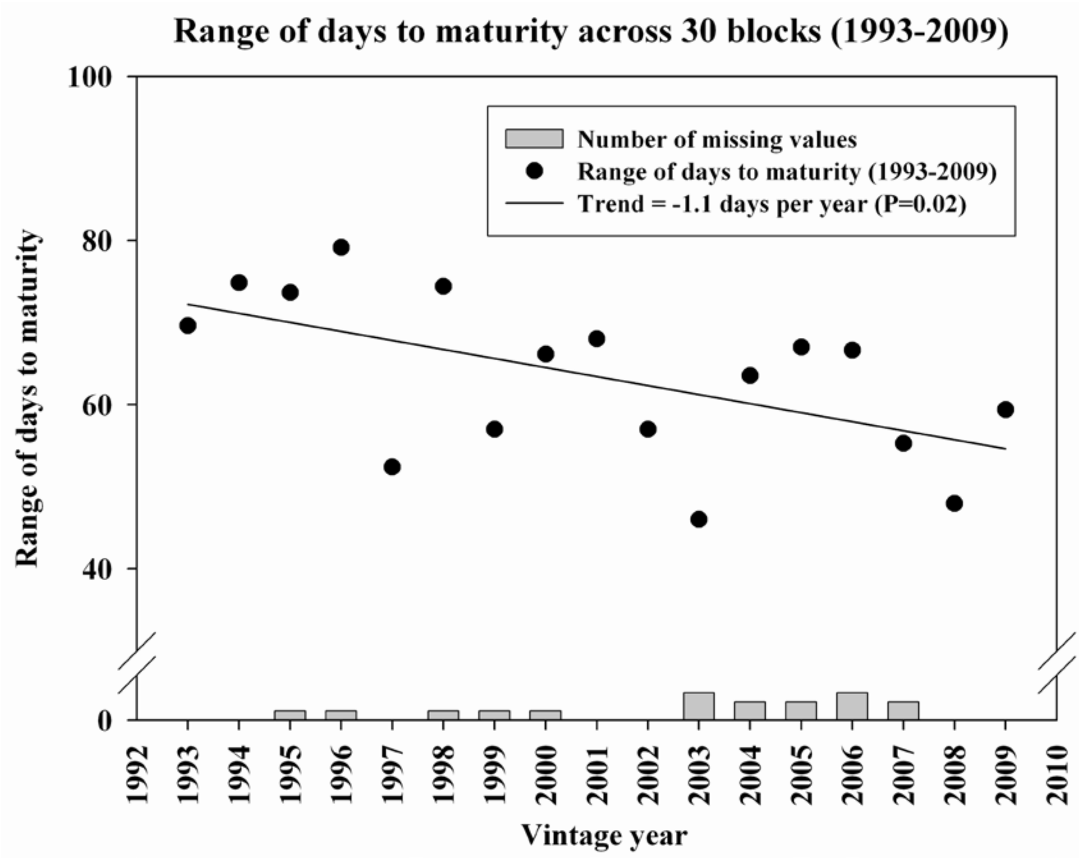


Figure **6.** Range of days of year at maturity for 30 blocks (where data for 1993 and 2009 are recorded) as this varies through the time series (1993-2009). The number of missing data are plotted (grey bars) indicating the lowest representation being 27 blocks in years 2003 and 2006.

For the 10 blocks, representing the period 1985-2009 the average maturity day range was 55 days (34 to 84 days), with individual regional minimum of 38 days, and maximum of 135 days. While it was evident that the range of maturity days, from earliest to latest observed, was decreasing at about 0.4 days per year through the time period 1985-2009, this trend was not significant (P=0.37) (data not shown). From this evidence it appears that, to date, there has been no significant trend in compression of the harvest period from 1985-2009.

This trend in compression was also studied on a regional basis where more than one block had been assessed in the region. A significant trend to a compression in DOY_M was found for the six Riverland blocks (1.3 days per year; P=0.02) and also the three Central Victorian blocks (0.6 days per year; P=0.01). There was a non-significant trend in compression of maturity evident for the ten Barossa Valley blocks (0.4 days per year; P=0.47) and the five Langhorne Creek blocks (0.1 days per year; P=0.9). In the Mornington Peninsula, no compression of maturity was evident. While not exhaustive, this analysis suggests that compression of the harvest period was likely to be site specific and dependent on the varietal mix.

Average growing season temperature trend in relation to the maturity trend

Average growing season temperature for all but one region (Margaret River) has been warming (Table 3), the rate varying by region and by time period, with the more recent period warming faster than over the longer term. When comparing the same period of time 1985-2009 or 1993-2009, it was generally the inland regions that were warming at a faster rate compared to the more coastal sites (Table 3).

Table **3.** Trend in average GST **(°C** per year): the full period of observation of the long-term series (see **Table 1**); the time period common to long-term blocks (1985-2009); and the time period common to all blocks (1993-2009). Significant trends (**P<0.01, *P<0.05) are shaded grey and 95% confidence interval indicated.

Region	**Variety**	**Trend in Ave GST (°C/year)**		
		Full period of obs.	**1985-2009**	**1993-2009**
Mornington Peninsula	Pinot Noir	0.03 ± 0.03	0.02 ± 0.03	0.06 ± 0.06*
	Chardonnay	0.03 ± 0.03		
Eden Valley	Shiraz (L)	0.01 ± 0.02	0.03 ± 0.03*	0.07 ± 0.06*
	Shiraz (M)	0.02 ± 0.02		
McLaren Vale	Shiraz	0.01 ± 0.00**	0.03 ± 0.03	0.07 ± 0.06*
Margaret River	Cabernet Sauvignon	-0.01 ± 0.02	-0.002 ± 0.03	-0.02 ± 0.05
Rutherglen	Muscat a Petit Grains	0.01 ± 0.01*	0.06 ± 0.04*	0.12 ± 0.07**
Central Victoria	Shiraz (Mc)	0.01 ± 0.01**	0.04 ± 0.04*	0.09 ± 0.06**
	Shiraz (S)	0.01 ± 0.01		
	Marsanne	0.01 ± 0.01**		
	Riesling	0.01 ± 0.03		
Coonawarra (1996-2009)				0.06 ± 0.09
Adelaide Hills				0.07 ± 0.06*
Eden Valley (as above)				0.07 ± 0.06*
Barossa Valley				0.08 ± 0.06*
Clare Valley (1994-2009)				0.07 ± 0.07
Langhorne Creek				0.06 ± 0.05*
Riverland (Loxton)				0.08 ± 0.04**
Riverland (Waikerie)				0.06 ± 0.06*

[1]see Table 1

In all regions where a warming trend in the average GST (°C) was observed, maturity was trending earlier. It was interesting to note that, where there has been a cooling trend in average GST (°C) for the period of observation, this has been associated with a trend to later maturity (Margaret River), though the trends were not significant.

Discussion

Ten out of the eleven long-term blocks in this assessment were maturing earlier in the year, compared to earlier decades (six significantly so). Further, in 43 of the 44 winegrape blocks assessed across Australia, though over a shorter period (1993-2009), a trend to earlier maturity has been detected with 35 of these displaying a statistically significant trend. The trend to earlier ripening over the 1993-2009 period of between half and three days per year was of the same order as that reported by Petrie and Sadras (2008).

Assessment of trends in harvest dates may inadvertently include some non-climatic influences or signals (Pearce & Coombe 2004). By assessing the trend in a biophysical measure of maturity i.e. sugar concentration, rather than the 'harvest date' measure (as used by Le Roy Ladrie (1988), Chuine *et al.* (2004), Meier *et al.* (2007), and Rochard (2009), for example), the influence from many non-climate drivers that may affect timing of harvest can be eliminated. For example, with trends to higher alcohol wines being produced in recent decades (Godden & Gishen 2005, Seguin & Gaudillere 2007), measurement of a trend in harvest day rather than 'maturity' may have under-estimated the actual phenological shift. This 'non-climatic' driver effect on phenological time-series can be clearly seen when comparing the trend of the harvest date with that of the maturity date of the McLaren Vale Shiraz block in this study. In order to measure phenological sensitivity to climate, use of a biophysical harvest proxy, rather than actual harvest date, gives potentially more accurate results.

Winegrape intake schedules are often designed around the capacity of the winery. If the phenology of the different varieties is affected to varying extents, then the harvest period can be either compressed or spread out. If DOY_M is advanced more in later ripening varieties than earlier ripening varieties a compression of the harvest period may occur (Webb *et al.* 2007; Van Vliet 2010). This would create problems for winegrape intake scheduling in wineries at harvest time, and make it more difficult to process each batch of fruit at the time when grape quality in the vineyard is deemed 'optimal', having important implications for planning of infrastructure and staffing during this time (Webb *et al.* 2010). Based on this assessment a compression of maturity date of 1.1 days per year was observed for the 1993 to 2009 period (all regions were included in this analysis), and across some regions individually. We suggest that while this phenomenon is likely to be vineyard specific and dependent on the relative sensitivity of varieties to temperature changes, with further warming projected compression of the harvest period may increase further, exacerbating scheduling problems.

For the period of observation and for the sites assessed in this study a warming trend has been observed in average GST (°C) in all but the Margaret River region in Western Australia; the Margaret River being the site of the only block not maturing earlier. Furthermore, the increased rate of warming in the later periods is consistent with the trend to earlier DOY_M also increasing over time.

This study provides evidence that regional warming may be advancing maturation, and given that recent warming trends in Australia have been attributed to anthropogenic influence (Karoly & Braganza 2005), this study may indicate the effect of anthropogenic climate change on winegrape phenology. However, before this conclusion can be drawn, all possible causes of the shift in maturity day should be considered. In a recent study, rainfall, as well as temperature, was found to be important in relation to advance of full bloom dates of apple and pear trees in South Africa (Grab & Craparo 2010). If rainfall shifts are affecting DOY_M in these blocks, then support for an anthropogenic GHG fingerprint on the trend is weakened. This is because to date, in southern Australia, causes of shifts in rainfall have not been linked to anthropogenic climate change; changes are attributed to normal inter-annual variability (Nicholls 2008; CSIRO 2010).

Furthermore, as this was a study of a managed biological system, direct human influence in the biophysical response should be considered. Introduction of some vineyard management practices in Australia over the recent decades may have influenced physiological processes and therefore the ripening rate. Changing irrigation practices through time from flood irrigation to drip irrigation (Iland 2004), and further reduced water availability in recent drier years (Nicholls 2008) may have resulted in reduced yields in some regions (Gunning-Trant 2010). Reduced yields are associated with earlier ripening, all other variables remaining equal (Botting & Dry 1996). Reduced yields have, in fact, been encouraged at some sites by intentionally reducing irrigation rates (Goodwin & Jerie 1992) in an effort to improve the quality of the grapes for winemaking (McCarthy *et al.* 1986).

Finally, changes to atmospheric carbon dioxide (CO_2) concentrations may also impact winegrape maturity either directly through increased accumulation of carbon containing compounds (Drake *et al.* 1997), through altered phenological processes caused by increased atmospheric CO_2 (Springer & Ward 2007; Springer *et al.* 2008), or perhaps through increased plant temperatures produced from reduced evapotranspiration (Leakey *et al.* 2006). Whether increased CO_2 concentrations would advance maturity or delay it is unknown. Past free CO_2 enrichment (FACE) studies in winegrapes (Bindi *et al.* 1996, Bindi *et al.* 2001) report some effects on yield and on grape sugar level through the ripening period, but at time of harvest there was no difference in timing due to CO_2 effects. For this reason it is suspected that CO_2 would not have a large impact on maturity dates, though further work on effects of enhanced concentrations of CO_2 on winegrape phenology and other physiological impacts would be of interest to the industry.

Modelling of anticipated changes to winegrape phenology has been undertaken for Australia (Webb *et al.* 2007). Comparing the sensitivity of DOY_M to temperature shifts of the observed with the modelled results is of interest. The direction of change in the observations is found to be consistent with results from modelling studies, with projected warmer temperatures expected to result in earlier maturity dates at all sites except for the Margaret River (Webb *et al.* 2007). However, the magnitude of the observed shifts are in some cases larger than would be expected. Modelled shifts would be expected in the order of up to 15 days earlier a warming of about 0.7°C occurred (Webb *et al.* 2007), not the 24 days that has been observed in Central Victoria, or the 40 days as was observed in the Mornington Peninsula. At some sites e.g. the Margaret River and Eden Valley sites, the observed result is consistent with modelled result. With regard to regions where shifts in the observations greater than expected, it could be plausible that either, a) drivers other than temperature are having an influence on the vineyard maturity rate or, b) that the previous modelling study may have underestimated possible future shifts in phenology.

Further study of the shift in maturity rate is warranted. A range of potential climate drivers and non-climate drivers that may be affecting the trends in maturity day will be explored in a subsequent attribution analysis of these winegrape maturity trends. By understanding the factors driving phenological timing shifts there may be potential to better manage time to maturity if desired, and therefore potentially enhancing the adaptive capacity of vineyard managers to these shifts to earlier maturity of winegrapes (Webb *et al.* 2007).

Conclusion

A trend to earlier maturity of the winegrape crop in Australia has occurred in all but one region (of 12 assessed) in recent decades. Where the trend in this shift to earlier maturity is observed, it has been accelerating through the time series. The trend to earlier maturity was associated with warming temperature trends for all of the blocks assessed in the study. In the one region where maturity was not earlier, no warming was observed for the period studied. Indications of a possible link between the maturity rate and the average GST (°C) of the respective regions require further exploration. Attribution of the trend to earlier ripening, where temperature and other potential climate and non-climate drivers are assessed, will be investigated in a subsequent analysis.

A shift in maturity date, and therefore harvest date, has implications for the wine industry with quality impacts likely and the possibility of vineyard logistics being affected. With projected climate shifts likely to result in continued advancement of maturity, and perhaps further compression of the vintage period, these impacts will continue to occur with increasing implications. Adaptation planning to reverse some of the potential negative consequences is advised.

Acknowledgements

I wish to thank Roger Jones (Victoria University), Greg Jones (Southern Oregon University), and Rebecca Darbyshire (University of Melbourne) for assistance with vineyard datasets and analysis. Ian Smith and Peter Briggs (CSIRO), and Ailie Gallant (University of Melbourne) for provision of climate data. Pandora Hope (Australian Bureau of Meteorology) for useful discussions regarding the climate trends. Lynda Chambers (Australian Bureau of Meteorology), Jonas Bhend (CSIRO), and three anonymous reveiwers for useful critical comments. Finally, Paul Petrie (Fosters Group Limited), Nat White (Main Ridge Estate), Alister Purbrick and Robyn Sutherland (Chateau Tahbilk), Stephen and Bill Chambers (Chambers Rosewood Wines), Trevor Kent and Vanya Cullen (Cullen Wines, Western Australia), Stephen and Prue Henschke (Henschke Wines) and Colin Kay (Kay Brothers Amery Wines) and their forebears who all recorded vineyard datasets and made them available for this analysis. This work was partly funded by the CSIRO Climate Adaptation National Research Flagship and also by the Australian Grape and Wine Research and Development Corporation.

Bibliography

Ashenfelter OC, Storchmann K (2010) *Measuring the Economic Effect of Global Warming on Viticulture Using Auction, Retail, and Wholesale Prices.* American Association of Wine Economists AAWE WORKING PAPER No. 60.

Bergqvist J, Dokoozlian NK, Ebisuda N (2001) Sunlight exposure and temperature effects on berry growth and composition of Cabernet Sauvignon and Grenache in the Central San Joaquin Valley of California. *American Journal for Enology and Viticulture,* **52**, 1-7.

Bindi M, Fibbi L, Gozzini B, Orlandini S, Miglietta F (1996) Modelling the impact of future climate scenarios on yield and yield variability on grapevine. *Climate Research,* **7**, 213-224.

Bindi M, Fibbi L, Miglietta F (2001) Free Air CO_2 Enrichment (FACE) of grapevine (Vitis vinifera L.) II. Growth and quality of grape and wine in response to elevated CO_2 concentrations. *European Journal of Agronomy,* **14**, 145-155. <Go to ISI>://000167134200005

Botting DG, Dry PR, Iland, P (1996) Canopy architecture-implications for Shiraz grown in a hot, arid climate. *Australian and New Zealand Grapegrower and Winemaker,* **390a**, 53-57.

Bureau SM, Razungles AJ, Baumes RL (2000) The aroma of Muscat of Frontignan grapes: effect of the light environment of vine or bunch on volatiles and glycoconjugates. *Journal of the Science of Food and Agriculture,* **80**, 2012-2020.

Chambers LE (2006) Associations between climate change and natural systems in Australia. *Bulletin of the American Meteorological Society,* **87**, 201-206. http://155.187.2.69/soe/2006/publications/drs/pubs/433/co/co_76_climate_change_and_natural_systems.pdf

Chuine I, Yiou P, Viovy N, Seguin B, Daux V, Ladurie ELR (2004) Historical phenology: Grape ripening as a past climate indicator. *Nature,* **432**, 289. http://dx.doi.org/10.1038/432289a

http://www.nature.com/nature/journal/v432/n7015/suppinfo/432289a_S1.html

Conde C, Silva P, Fontes N*, et al.* (2007) Biochemical changes throughout grape berry development and fruit and wine quality. *Food,* **1**, 1-22.

Coombe BG (1987) Influence of temperature on composition and quality of grapes. *Acta Horticulturae,* **206**, 23-35.

Coombe BG, Iland P (2004) Grape berry development and winegrape quality. In: *Viticulture Volume 1 - Resources. 2nd edition* (eds Dry PR, Coombe BG), pp. 210-248. Winetitles, Adelaide, South Australia.

CSIRO (2010) *Climate variability and change in south-eastern Australia: A synthesis of findings from Phase 1 of the South Eastern Australian Climate Initiative (SEACI).* Commonwealth Scientific and Industrial Research Organisation, Australia. http://www.seaci.org/publications/documents/SEACI-1%20Reports/Phase1_SynthesisReport.pdf

CSIRO and Australian Bureau of Meteorology (2007) *Climate change in Australia, Technical report.* CSIRO and Bureau of Meteorology through the Australian climate change science program, Melbourne, Australia. http://www.climatechangeinaustralia.com.au/resources.php

Drake BG, Gonzalez-Meler MA, Long SP (1997) More efficient plants: A consequence of rising atmospheric CO_2. *Annual Review of Plant Physiology and Molecular Biology,* **48**, 609-639.

Duchene E, Schneider C (2005) Grapevine and climatic changes: a glance at the situation in Alsace. *Agronomy for Sustainable Development,* **24**, 93-99.

Godden P, Gishen M (2005) Trends in the composition of Australian wine. *Australian and New Zealand Wine Industry Journal,* **20**, 21-46.

Goodwin I, Jerie P (1992) Regulated Deficit Irrigation: concept to practice. Advances in vineyard irrigation. *Australian and New Zealand Wine Industry Journal,* **7**, 258-261.

Grab S, Craparo A (2010) Advance of apple and pear tree full bloom dates in response to climate change in the southwestern Cape, South Africa: 1973-2009. *Agricultural and Forest Meteorology,* doi:10.1016/j.agrformet.2010.11.001 http://www.sciencedirect.com/science/article/B6V8W-51M58SW-5/2/630ebc4635769b83165d9975a8d00724

Gunning-Trant C (2010) *Australian wine grape production projections to 2011-12.* Australian Bureau of Agriculture and Resoruce Economics Report 10.4 for the Grape and Wine Research and Development Corporation, Canberra, Australia. http://www.abare.gov.au/publications_html/crops/crops_10/winegrapes.pdf

Haselgrove L, Botting D, Van Heeswijck R, Hoj PB, Dry PR, Ford C, Iland PG (2000) Canopy microclimate and berry composition: the effect of bunch exposure on the phenolic composition of *Vitis vinifera* L cv. Shiraz grape berries. *Australian Journal of Grape and Wine Research,* **6**, 141-149.

Iland P (2000) *Techniques for chemical analysis and quality monitoring during winemaking.* Patrick Iland Wine Promotions, P.O. Box 131, Campbelltown, South Australia, Australia, 5074.

Iland P (2004) Development and status of Australian viticulture. In: *Viticulture Volume 1- Recources* (eds Dry P, Coombe BG). Winetitles, Adelaide, South Australia.

IPCC (2007a) *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, UK.

IPCC (2007b) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge. http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf

Jackson DI, Lombard PB (1993) Environmental and management practices affecting grape composition and wine quality- A review. *American Journal for Enology and Viticulture,* **44**, 409-430.

Jones DA, Wang W, Fawcett R (2009) High-quality spatial climate data-sets for Australia. *Australian Meteorological and Oceanographic Journal,* **58**, 233-248. http://www.bom.gov.au/amm/docs/2009/jones_hres.pdf

Jones GV, Duchene E, Tomasi D*, et al.* (2005) Changes in European winegrape phenology and relationships with climate. In 'Proceedings for the XIVth GESCO Viticulture Congress'. Geisenheim, Germany. (Eds Schulz HR, et al.) pp. 55-61.

Karoly DJ, Braganza K (2005) Attribution of recent temperature changes in the Australian region. *Journal of Climate,* **18**, 457-464. <Go to ISI>://000227305600005

Koch E (2010) Global framework for data collection- Data bases, data availability, future networks, online databases. In: *Phenological research: methods for environmental and climate change analysis* (eds Hudson IL, Keatley MR), pp. 23-61. Springer, Dordrecht.

Krstic M, Moulds G, Panagiotopoulos B, West S (2003) *Growing quality grapes to winery specifications – Quality measurement and management options for growers.* Winetitles, Adelaide.

Le Roy Ladrie E (1988) *Times of feast, times of famine. A history of climate since the year 1000.* Farrar, Stratus and Giroux by arrangement with Doubleday and Company, Inc., USA.

Leakey ADB, Uribelarrea M, Ainsworth EA, Naidu SL, Rogers A, Ort DR, Long SP (2006) Photosynthesis, productivity, and yield of Maize are not affected by open-air elevation of CO_2 concentration in the absence of drought. *Plant Physiology,* **140**, 779-790. http://www.plantphysiol.org/cgi/content/abstract/140/2/779

Lund ST, Bohlmann J (2006) The molecular basis for wine grape quality-A volatile subject. *Science,* **311**, 804-805.

Marais J, Calitz F, Haasbroek PD (2001) Relationship between microclimatic data, aroma component concentrations and wine quality parameters in the prediction of Sauvignon Blanc wine quality. *South African Journal for Enology and Viticulture,* **22**, 22-26.

McCarthy MG, Cirami RM, Furkaliev DG (1986) The effect of crop load and vegetative growth control on wine quality. In 'Proceedings of the sixth Australian wine industry technical conference'. Adelaide (Eds Lee T) pp. 75-77. (Winetitles).

Meier N, Rutishauser T, Pfister C, Wanner H, Luterbacher J (2007) Grape harvest dates as a proxy for Swiss April to August temperature reconstructions back to AD 1480. *Geophysical Research Letters,* **34**, L20705. http://dx.doi.org/10.1029/2007GL031381

Menzel A, Sparks TH, Estrella N*, et al.* (2006) European phenological response to climate change matches the warming pattern. *Global Change Biology,* **12**, 1969-1976. http://dx.doi.org/10.1111/j.1365-2486.2006.01193.x

Nicholls N (2008) Local and remote causes of the southern Australian autumn-winter rainfall decline, 1958–2007. *Climate Dynamics,* **34**, 835-845. http://dx.doi.org/10.1007/s00382-009-0527-6

Pearce I, Coombe BG (2004) Grapevine Phenology. In: *Viticulture Volume 1 - Resources* (eds Dry P, Coombe BG), pp. 150-166. Winetitles, Adelaide, South Australia.

Petrie PR, Sadras VO (2008) Advancement of grapevine maturity in Australia between 1993 and 2006: putative causes, magnitude of trends and viticultural consequences. *Australian Journal of Grape and Wine Research,* **14**, 33-45.

Rochard J (2009) Title Evolution of growing cycle and harvest dates (*Évolution du cycle végétatif et des dates de récolte*). *Progres Agricole et Viticole,* **5**, 111-119.

Rosenzweig C, Casassa G, Karoly DJ*, et al.* (2007) Assessment of observed changes and responses in natural and managed systems. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds M.L. Parry, O.F. Canziani JPP, P.J. van der Linden and C.E. Hanson), pp. 79-131. Cambridge University Press, Cambridge, UK.

Rosenzweig C, Karoly D, Vicarelli M*, et al.* (2008) Attributing physical and biological impacts to anthropogenic climate change. *Nature,* **453**, 353. http://dx.doi.org/10.1038/nature06937

http://www.nature.com/nature/journal/v453/n7193/suppinfo/nature06937_S1.html

Schwartz M (2003) *Phenology: An integrative environmental science.* Kluwer Academic Publishers, Netherlands.

Seguin B, Gaudillere J-P (2007) Climate change and viticulture. In 'Global warming: new oenological challenges. Les XIXes entretiens scientifiques'. Margaux, France (Eds pp. 9-14. (Lallemand).

Seguin B, de Cortazar IG (2005) Climate warming: consequences for viticulture and the notion of *'terroirs'* in Europe. *Acta Horticulturae,* **689**, 61-71.

Smart RE, Alcorso C, Hornsby DA (1980) A comparison of winegrape performance at the present limits of Australian viticultural climates- Alice Springs and Hobart. *The Australian Grapegrower and Winemaker,* **184**, 28 and 30.

Smart RE, Robinson M (1991) *Sunlight into Wine. A handbook for winegrape canopy management.* Winetitles, Adelaide.

Sparks T, Tryjanowski P (2010) Regression and Causality. In: *Phenological Research* (eds Hudson IL, Keatley MR), pp. 123-145. Springer, Dordrecht Heidelberg London New York.

Spayd SE, Tarara JM, Mee DL, Ferguson JC (2002) Separation of sunlight and temperature effects on the composition of *Vitis vinifera* cv. Merlot berries. *American Journal of Enology and Viticulture,* **53**, 171-182.

Springer CJ, Orozco RA, Kelly JK, Ward JK (2008) Elevated CO_2 influences the expression of floral-initiation genes in *Arabidopsis thaliana*. *New Phytologist,* **178**, 63-67. <Go to ISI>://000253711800006

Springer CJ, Ward JK (2007) Flowering time and elevated CO_2. *New Phytologist,* **176**, 243-255. <Go to ISI>://000253711800006

Van Vliet AJH (2010) Societal adaptation options to changes in phenology. In: *Phenological research: methods for environmental and climate change analysis* (eds Hudson IL, Keatley MR), pp. 75-98. Springer, Dordrecht.

Webb L (2006) *The impact of greenhouse gas-induced climate change on the Australian wine industry*. PhD Thesis. School of Agriculture and Food Systems, University of Melbourne, Parkville Victoria, 277 pp.

Webb L, Dunn G, Barlow EWR (2010) Viticulture. In: *Adapting agriculture to climate change: Preparing Australian agriculture, forestry and fisheries for the future.* (eds Stokes CJ, Howden SM). CSIRO Publishing, Melbourne.

Webb L, Whetton P, Barlow EWR (2007) Modelled impact of future climate change on phenology of wine grapes in Australia. *Australian Journal of Grape and Wine Research,* **13**, 165-175.

Webb L, Whetton P, Barlow EWR (2008a) Climate change and wine grape quality in Australia. *Climate Research,* **36**, 99-111.

Webb L, Whetton P, Barlow EWR (2008b) Modeling the relationship between climate, winegrape price, and winegrape quality in Australia. *Climate Research,* **36**, 89-98.

Zamora F (2007) Phenolic maturity as a criteria for choosing the best winemaking strategy. In 'Global warming: new oenological challenges. Les XIXes entretiens scientifiques'. Margaux, France (Eds pp. 27-34. (Lallemand).

Appendix 4: The fingerprint of climate change: Attribution analysis of trends in winegrape maturity.

L. B. Webb[1,2 *], P.H. Whetton[2] , J. Bhend[2], R. Darbyshire[1], P.R. Briggs[2,3] and E.W.R. Barlow[1]

1. School of Land and Environment, University of Melbourne, Parkville Victoria.

2. Centre for Australian Weather and Climate Research, a partnership between CSIRO and the Bureau of Meteorology, Aspendale, Victoria.

3. CSIRO Marine and Atmospheric Research, Canberra, ACT.

* Corresponding author: Tel: +613 92394549, Fax: +613 92394444, e-mail: leanne.webb@csiro.au

Trends in phenological phases associated with climate change are widely reported – yet attribution remains rare. Attribution research in biological systems is critical in assisting stakeholders to develop adaptation strategies, particularly if human factors may be exacerbating impacts[1]. This analysis demonstrates that detailed, quantified attribution helps to effectively target adaptation strategies, and counters recent tendencies to over-attribute[2]. Winegrapes are ripening earlier in Australia in recent years[3], often with undesirable impacts. Attribution analysis of detected trends in winegrape maturity, using time-series of up to 64 years in duration, indicates that two climate variables, warming and declines in soil water content, are driving a portion of this ripening trend. Crop-yield reductions and introduced management practices have also contributed to earlier ripening. Potential adaptation options are identified as some drivers of the trend to earlier maturity can be manipulated through directed management initiatives, such as managing soil moisture and crop-yield.

The winegrape industry is intimately wedded to the concept of *terroir:* matching premium grape-varieties to select combinations of climate and soils producing unique wines of distinctive styles. The winegrape industry around the world is alert to effects of global warming and associated changes to precipitation patterns because these changes alter *terroirs* directly[4]. In fact, grapevines can be regarded as the 'canary' in the climate change 'coal-mine' as the balance of winegrape components is very sensitive to climatic changes. The technical requirements for making quality table-wine, including accurate documentation of winegrape vintages through time, result in this particular agricultural industry being an excellent model from which to analyse fingerprints of climatic changes.

Physical and biological systems on all continents are already being affected by recent climate changes[5]. Over recent decades, winegrape maturation trends have been detected, advancing about eight days decade^{-1} (1985-2009) in southern Australia[3]. In the Northern Hemisphere, similar trends have been reported. For example, an eight days decade^{-1} earlier harvest was observed in Colmar, France (1972-2004) and four days decade^{-1} in Geisenheim, Germany (1955-2004)[6].

In most regions where winegrapes are grown, earlier maturation is undesirable[7]. Because winegrapes mature in autumn, ripening earlier tends to increase ambient temperatures at this time. These increased temperatures are associated with altered balance of flavour and aroma compounds[8], hastening acid degradation[9] and increasing speed of sugar development[6]. Lower anthocyanin concentrations, affecting red wine colour, are also associated with warmer growing conditions[10].

Empirical evidence supports theories that temperature is a major driver of plant phenological response[11], though precise effects of environmental cues on phenological development are not well understood[12]. In this attribution study we examine temperature as a driver of maturation trends, but notably we also consider the effect of other potential drivers on phenology. Correct attribution to temperature and 'non-temperature' climatic drivers such as rainfall[13], together with non-climatic influences like management and technology advances[14], could potentially inform alternative adaptation options.

Our analysis also contributes to the important task of linking biological and anthropogenic-atmospheric changes[15]. One recent study in Australia has linked phenological shifts in the emergence of the butterfly *Heteronympha merope* to anthropogenic climate change[16]. With observations across southern Australia for periods up to 64 years (average 41 years) our assessment supplements the paucity of these types of analyses originating from the Southern Hemisphere[5].

Recently, historical observations of day-of-year winegrapes reach a designated maturity (DOY_M), based on records of grape-sugar accumulation, were analysed for 44 sites in southern Australia with trends to earlier maturation detected[3]. Here attribution of these trends is examined for ten of these 44 sites where time series of at least 25 years were available. DOY_M is considered for sites in southwest and south-eastern Australia (Figure 1) for various observation periods (Table 1) and also a common period of 1985-2009. (For further information on these data-sets see the Materials and Methods section, Supplementary Information and Webb *et al*. [3]). Nine of the ten sites show trends to earlier ripening, with an acceleration of changes in the 1985-2009 period compared to earlier periods. Only the Margaret River vineyard, situated in the west of the Australian continent, ripened later through time when assessed over the full-observed period (non-significant trend) (Table 1).

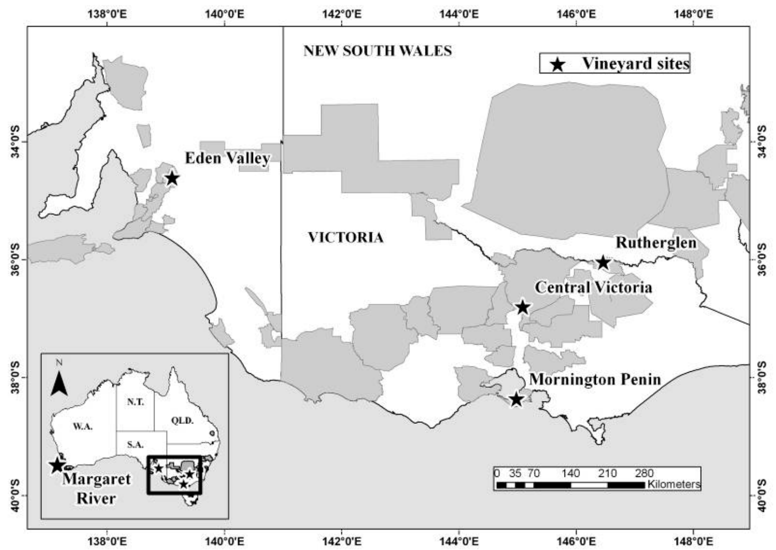


Figure 1 Vineyard sites in five regions in southern Australia (see inset map) from where data was accessed (stars). Registered winegrape growing regions are depicted (grey). State and territory (capital letters) boundaries are marked with the black lines.

Table 1 Region and site description and trends in DOY_M. Where the same variety is grown at different sites in the one region they are identified (A or B). Significant trends: P<0.05 *, P<0.01 ** and are shaded grey.

Region	Baseline climatology (1976-2005)		Variety	Site code name (see Figure 2),	Number of years in range. Misssing years in brackets	Period of observation	Trends in DOY_M (days decade^{-1})	
	Ave GST (°C)	Ave RainGS (mm)					Full period	Common period (1985-2009)
Mornington Peninsula (144.98E,38.36S)	16.6	402	Pinot Noir	MP_PN	25	1985 to 2009	-15.7±5.9**	-15.7±5.9**
			Chardonnay	MP_Ch	24	1986 to 2009	-13.8±7.7**	-13.8±7.7**
Eden Valley (139.11E,34.61S)	17.2	218	Shiraz (A)	EV_ShL	31 (3)	1979 to 2009	-2.4±5.4	-3.9±7.6
			Shiraz (B)	EV_ShM	32	1978 to 2009	-2.3±5.7	-7.9±8.0
Margaret River (115.03E,33.91S)	18.6	246	Cabernet Sauvignon	MR_CSauv	33 (2)	1977 to 2009	0.5±5.1	-0.6±6.9
Rutherglen (146.46E,36.04S)	18.7	302	Muscat a petit grains	Ruth_Musc	64 (17)	1946 to 2009	-4.0±3.7*	-1.6±13.4
Central Victoria (145.09E,36.80S)	18.9	244	Shiraz (A)	CV_ShM	61 (2)	1949 to 2009	-4.0±1.5**	-8.3±5.3**
			Shiraz (B)	CV_ShS	48	1962 to 2009	-4.5±2.5**	-12.5±6.4**
			Marsanne	CV_Mar	61	1949 to 2009	-3.8±1.5**	-8.4±5.5**
			Riesling	CV_Rie	29	1979 to 2007	-3.8±7.1	-7.2±11.0

In absence of a bio-physical model for winegrape maturity, we determine influences of different driving factors on maturity trends using an empirical model. This model is based on year-to-year variability in maturity and 'potential driver' time-series, after Nicholls[17]. We use first order differences (removing trend effects), to examine sensitivity of DOY_M to the potential drivers. Climatic variables assessed include temperature measures, rainfall, and soil wetness indices. Additionally, we assessed crop-yield variation for some sites. Of these, the most influential drivers were identified and used in multivariate modelling of DOY_M. The modelled estimated shift in DOY_M (DOY_{MEst}) is then calculated by multiplying independent sensitivities established through the multivariate modelling by respective observed trends for each driver, and summing these. Finally, DOY_{MEst} is compared to the actual DOY_M for model validation (Materials and Methods has further details of the approach).

The variables identified as most suitable for modelling DOY_M were growing season average temperatures (GST_{ave}), soil moisture (0.2-1.5m) ($Soil_{low}$), and crop-yield. While these variables have some inter-relationship (drier soils are significantly associated with lower crop-yields (2/10 sites) and warmer temperatures (7/10 sites), further details not shown), the multiple regression accounts for the independent effects of these drivers on maturity. Model coefficients, or sensitivities, computed from multiple regression analysis are shown for the period 1985-2009 (Figure 2, upper). It is evident that warmer GST_{ave} (7/10 sites), lower soil moisture (5/10 sites) and lower crop-yields (4/10 sites) significantly drive earlier ripening (Figure 2, upper). The Central Victorian Riesling site's maturity response to temperature variation contrasts all other sites. This vineyard is afflicted with Phylloxera, a root parasite. This case, however, serves to highlight the consistency in response across other sites, in particular to temperature and soil moisture, which is especially noteworthy considering climatic (Table 1) and management-regime diversity under which these winegrapes are grown (Supplementary Table 1). The diseased site will not be considered further here.

Trends in GST_{ave}, $Soil_{low}$ and crop-yield are present through the periods of vineyard observations (Supplementary Table 3). Warming has occurred in most regions, the rate varying by region and time period. However a cooling trend is detected at one site which may be explained by differing regional climate influences[18]. Soil moisture has been decreasing, significantly in most Victorian sites, especially more recently where parts of southeast Australia have been subject to protracted drought[19]. Southwest Western Australia has also experienced an accelerating drying trend. Trends to lower crop-yields (t ha^{-1}) are observed at all sites. This decline may be due partly to management decisions as well as the drought[19].

Our methodology now allows us to calculate the expected contribution from each driver to trends in DOY_M. Shifts of between 4 to 11 days can be attributed to warming (1985-2009) (Figure 2, lower), with later ripening due to slight cooling computed for the Margaret River site. The drying trend and trend in crop-yield make contributions to advanced ripening, each with a similar magnitude to that of temperature (Figure 2, lower). Total shifts in DOY_{MEst}, ranges between five to 33 days earlier.

The shift in DOY_{MEst} may now be compared with the observed shift in DOY_M (Figure 2, lower). The coefficient of multiple determination (R^2) (Figure 2, lower) indicates over 50% of variance is explained in 7/10 cases of model reconstructions of DOY_{MEst} compared to DOY_M (Supplementary Table 5 tabulates R^2 for reconstructions calculated using various driver-combinations). Over 1985-2009, shifts in DOY_M

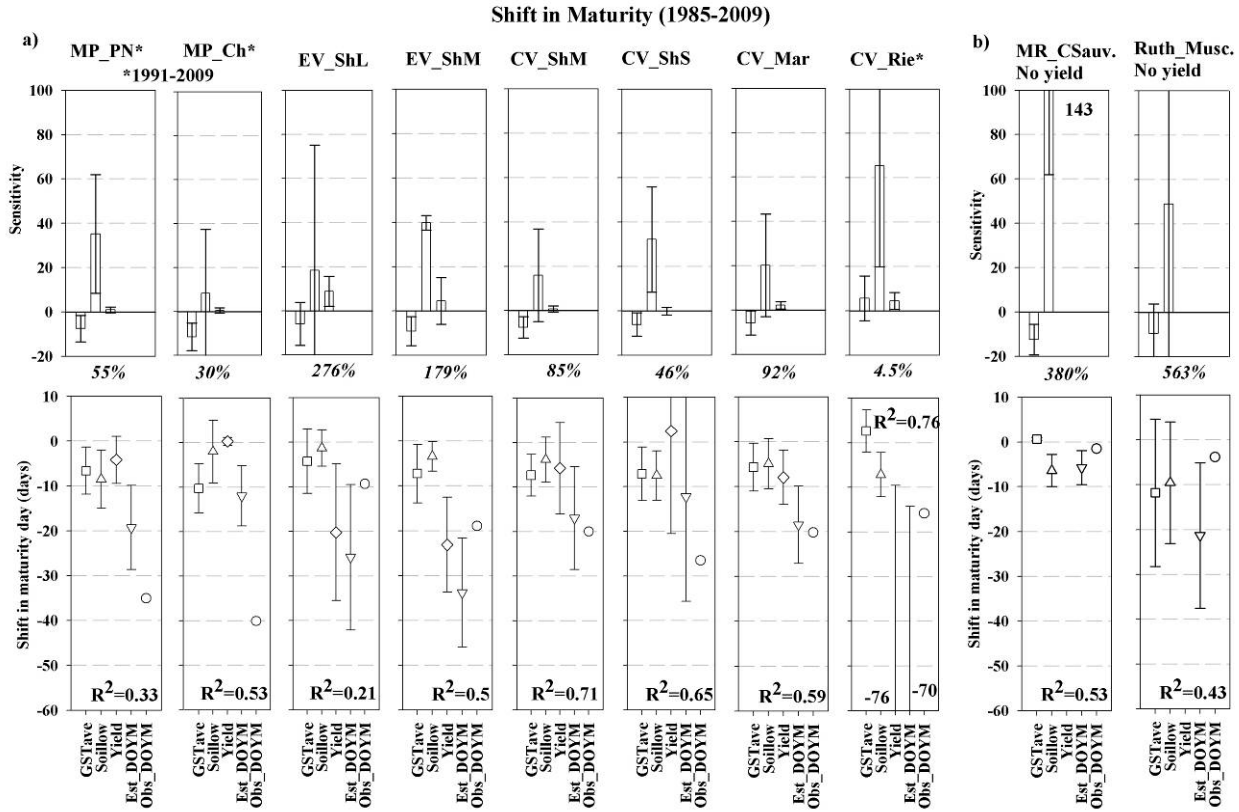


Figure 2 Upper panel: Multiple linear regression estimates of the sensitivity of variability (first order differences) in DOY_M to each of GST_{ave} (days C^{-1}), $Soil_{low}$ (days soil units^{-1}), and crop-yield (days/tHa^{-1}) for each of the sites studied (see Table 1) for the common period of observation (1985-2009) and for where crop-yield data is available (a) and where it is not (b). Lower panel: Modelled shift in maturity in days contributed from trends in GST_{ave} (square), $Soil_{low}$ (upward triangle), and crop-yield (diamond) and the sum of the individual contributions, DOY_{MEst} (downward triangle). The DOY_{MEst} can be compared to the observed shift in DOY_M (circle) for model validation. The percent of the observed shift (DOY_M) explained by the model (DOY_{MEst}) is shown (italics). R^2 values for reconstructed series and 95% confidence intervals are indicated. * Riesling from central Victoria is afflicted with Phylloxera (an incurable root parasite).

varied from one to 40 days earlier. In 4/10 of the sites, observed shift in DOY_M falls within the 95% confidence interval of DOY_{MEst} (Figure 2, lower). Of the remainder, 4/10 slightly over-explain DOY_M, and 2/10 under-explain the shift.

At many sites over the full period of observation the shift in DOY_M was under-explained (7/10, See Supplementary Figure 1 for other sites 'full-observed period' modelling). We selected the Central Victorian Shiraz (A) site to explore this result further (Figure 3). Skill is demonstrated in modelling shifts in both the earlier (1949-1978) (Figure 3a) and later (1979 to 2009) (Figure 3b) periods but not the full-observed period (1949-2009) (Figure 3c). Analysis of vineyard diary records showed fertiliser application was introduced in 1979 in the Central Victorian vineyard, continuing since then. Our analysis employing year-to-year differences would not capture such 'step-changes'. However, by incorporating a step-change into the model to represent this management introduction the shift in DOY_M over the full-observed period is explained with much higher skill (Figure 3d and Figure 4) (Supplementary Figure 2 shows management shift modelled in Central Victorian Marsanne site).

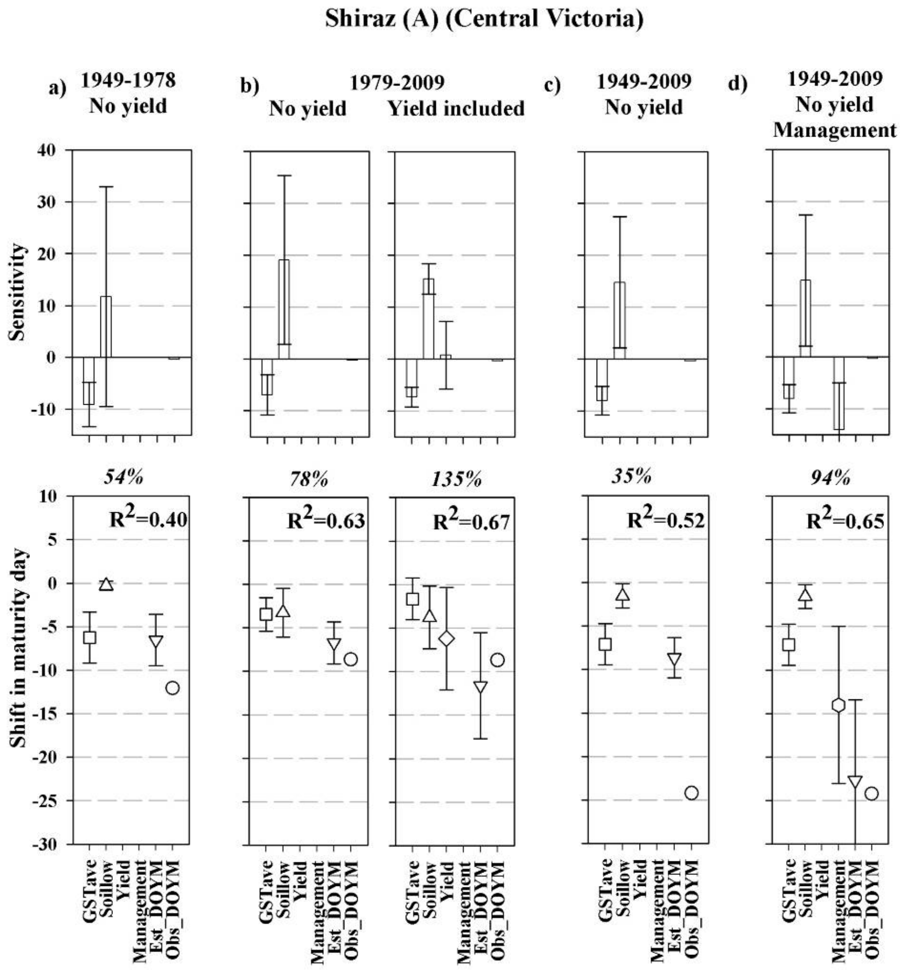


Figure 3 As for Figure 2, but for Shiraz (A) (Central Victoria) for (a) the earlier period (1949-1978) (b) the later period (1979-2009), with and without crop-yield included in the model (c) the entire period (1949-2009) and (d) the entire period (1949-2009) with a management step change factored into the model.

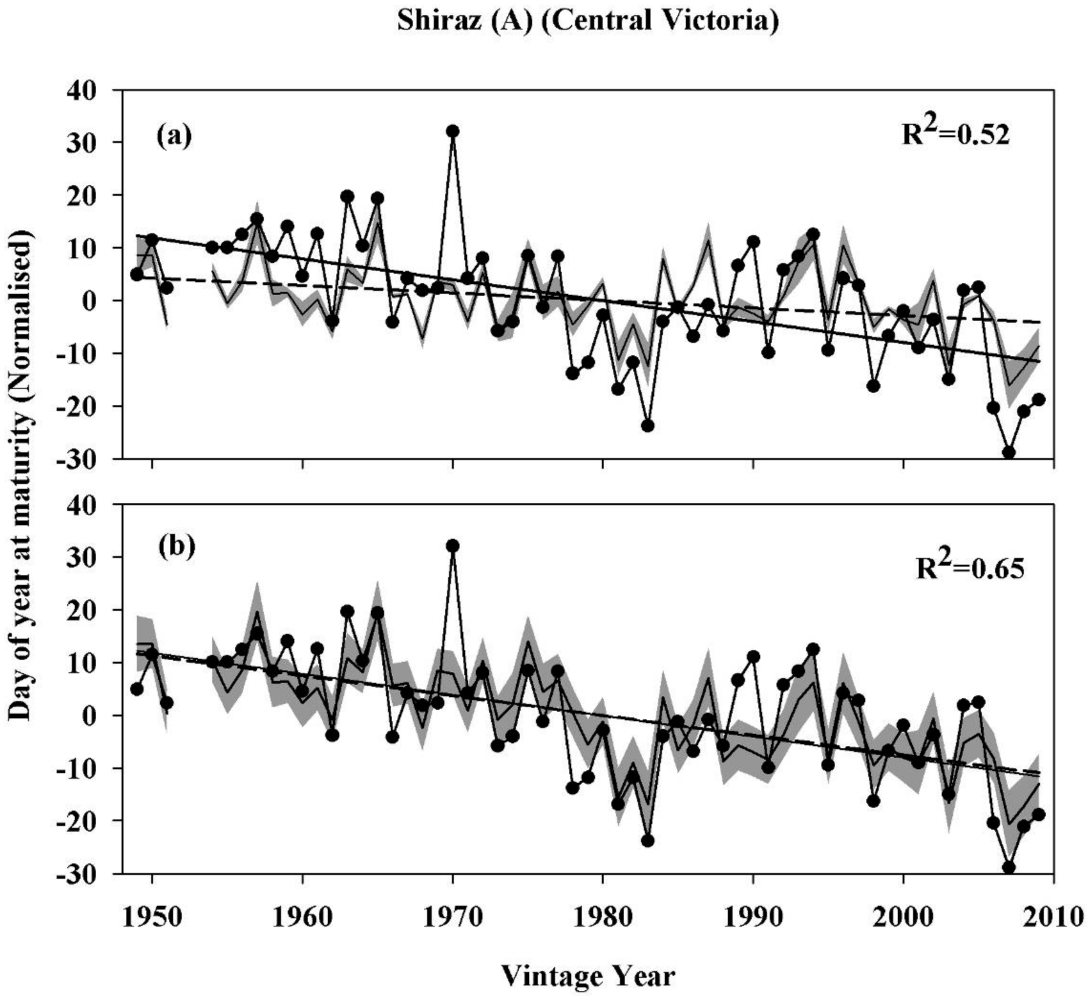


Figure 4 Time-series of DOY_M for Shiraz (A) (Central Victoria) (a) Observed DOY_M (black dots, fitted trend: black line) and DOY_{MEst} modelled using GST_{ave} and $Soil_{low}$ (grey band, 95% confidence interval indicated by band width, fitted trend: dash line) and (b) Observed DOY_M (as above) and DOY_{MEst} modelled using GST_{ave} and $Soil_{low}$ and the 1979 step change (management) (as with (a)).

We thus suggest that longer-term observed trends in winegrape maturity not explained by climate-drivers or crop-load alone, are likely due to technological advances in plant-husbandry. Management practices have evolved in vineyards in Australia, particularly since the 1980's, with changes to trellising, irrigation, pruning, improved nutrition and disease and pest control[20]. Notably, many of these practices would have improved the health and photosynthetic-capacity of the grapevine, perhaps inadvertently leading to earlier maturity.

Given that warming in Australia has been attributed to anthropogenic influence[21], we can thus now report that anthropogenic warming has contributed to advancing winegrape maturation. Furthermore, as recent drying trends in southern Australia have also been attributed to anthropogenic greenhouse-gas emissions[19] and we associate advancing maturity to reduced soil moisture independent of increasing temperature, attribution of advanced maturity to anthropogenic climate change is reinforced. More specifically, on average over the period 1985-2009, equal portions of trends to earlier maturity of winegrapes are attributed to each of two climate-related drivers, GST_{ave}, and $Soil_{low}$, and, one management-related variable, crop-yield.

Irrespective of attribution of trends, our demonstration of the sensitivities of DOY_M to soil moisture and crop-yield is a notable finding. The association seen here between soil moisture in lower parts of the soil profile and winegrape phenology has not been previously reported from field-observation studies. At least two mechanisms may be operating. First, drier soils are associated with production of the plant hormone abscisic acid (ABA) in vine roots[22], and increasing concentrations of ABA are also correlated with earlier maturity of winegrapes[23, 24]. Secondly, drier soils are likely to warm rapidly in the growing season. In glasshouse studies, higher root temperature was related to increased vine growth and higher sugar levels in grapes[25]. Notably at some sites where shifts in DOY_M are over-explained by our model, soil-mulching has been practiced (Supplementary Table 1). We can explain the effect of variation in crop-yields on DOY_M using a source-to-sink model[24]. Sugar accumulation is a function of photosynthetic capacity, and distribution is a function of volume of grapes. Lower crop-yields will therefore mature faster, all other factors equal.

Our demonstration of the sensitivity of phenology to water availability may have implications for studies of future changes to winegrape maturity in response to projected warming[26]. With drying projected, as well as warming, for winegrowing regions in Australia[27], future changes to harvest dates may be greater than those reported based on warming projections alone[26]. This is potentially an important consideration for projected impacts on viticulture in other regions globally.

The implications of our results for adaptation are perhaps more significant. Since earlier maturation is usually undesirable, growers may wish to intervene to limit this phenological shift. Examples of adaptation to warming include providing artificial shading, or mist-spraying, to reduce temperatures, although these would be expensive or possibly impractical. On the basis of our study, adaptations to the effects on maturity of changing soil moisture, or to unintended effects on maturity of crop-yield or other management variations, can now also be considered. For example, growers can manage soil moisture (increasing irrigation, or application of mulch), crop-yield (increasing crop-load), or vine response (selecting rootstocks less sensitive to plant stress hormones[28], or leaf removal[7]). Our study thus provides an example of how attribution analysis assists adaptation research[2]. By identifying factors driving shifts in phenological phases, it is possible to improve the adaptive capacity of these systems. We suggest that through using this approach other sectors or systems may also find factors other than temperature trends affecting biological capacity and responsiveness[1].

Materials and Methods

Vintage records, encompassing the periods 1946-2009, from 10 vineyard sites situated in five winegrape growing regions in Southern Australia are assessed (Figure 1 and Table 1). Winegrape ripening profiles were obtained from the recordings of accumulating sugar concentrations found in vintage diaries. When a desired sugar concentration is reached, grapes are described as having attained maturity[3]. The day of year grapes attained maturity (DOY_M)

was derived from the harvest diaries for each year and site studied. Methods for calculating this metric, including approaches to extrapolate this where necessary, are explained elsewhere[3]. Crop-yield data (t ha^{-1}) was analysed over the 1985-2009 period for eight vineyards where records were kept; of these six sites had recorded crop-yield in the period prior to 1985. Management methods and practices introduced through the time-series of all vineyard sites have been tabulated (Supplementary Table 1).

Climatic measures used represented most influential seasonal phases that had potential to affect the rate of phenological advance. These include temperature measures: Average growing season temperature (Oct-Apr) (GST_{ave}) (°C)[6], Maximum and minimum GST (GST_{max} and GST_{min}), and average maximum temperature (Dec-Feb) (T_{max_djf}). Water availability measures considered were: Growing season rainfall (GSR_{ave}) and soil wetness index ($Soil_{low}$ and $Soil_{upp}$) (See Supplementary Table 2 for more detail of climate variables). The climate indices were based on monthly time-series of maximum and minimum temperature (°C), and rainfall (mm) for the relevant periods, extracted for each site (the nearest 0.05° grid cell) from the Australian Bureau of Meteorology's Australian Water Availability Project (AWAP) Version 3 interpolated meteorology grids[29]. Soil moisture data were model estimates developed for AWAP using the WaterDyn model of Raupach *et al.*[30]. This model is a simple dynamic water balance model which determines the state of soil moisture in two layers and all water fluxes contributing to changes in soil moisture: precipitation, transpiration, soil evaporation, surface runoff, and deep drainage (irrigation and off-takes are not considered). The soil moisture stores are defined with spatially varying depth and water holding capacity, and daily surfaces of AWAP Version 3 meteorology (precipitation, minimum and maximum temperatures, and solar radiation)[29] are used as model forcings. The water balance is computed in discrete cells without lateral water transfer (river routing). Monthly AWAP soil moisture data have been validated against long-term stream-flow measurements. In AWAP WaterDyn the mean monthly state of each soil moisture store is expressed as a proportion of the saturated capacity (0 to 1). Time-series of relative soil moisture in the upper ($Soil_{upp}$) and lower ($Soil_{low}$) layers were extracted for the 0.05° cell corresponding to each site. The upper layer is to 0.2m deep, and lower is 0.2-1.5m deep.

Modelling DOY_M involved the following steps. *Step 1:* We correlated year-to-year variation in the response of DOY_M and potential drivers using first order differences, thus ensuring that underlying trends did not influence these derived sensitivities[17]. Sensitivities were calculated for the full period of observation relevant to each vineyard site (Table 1) and for 1985-2009, the common time frame through which all vineyard sites were measured (Supplementary Table 3). *Step 2:* Using the results of Step 1, we selected variables to be used in multiple regression modelling of DOY_M across all sites (we did not optimise selection on a site by site basis). Of the four temperature measures, we selected GST_{ave}, as the most highly correlated in most cases. $Soil_{low}$ was the best moisture variable in most cases; rainfall and $Soil_{upp}$ were less highly correlated. Though variation in crop-yield was not highly correlated with variation in DOY_M, it was still included because crop-yield variations are likely to affect the ripening rate of the winegrape[24], and thus this variable had the potential to predict some management influence on our maturity response. A multiple linear regression model for DOY_M was then created using GST_{ave}, $Soil_{low}$, and crop-yield as the predictors, with all data first order differenced. *Step 3:* Trends for vineyard and climate variables (without first order differencing) were then calculated using standard least-squares regression analysis for the full period and the common period (1985-2009) for all sites (Supplementary Table 4). *Step 4:* Sensitivities calculated in the multivariate modelling (Step 2) were multiplied by the actual observed trend (Step 3) and the individual contribution of each driver to the empirical model of DOY_M is calculated. In this way the separate attribution, and therefore the individual contribution, of component drivers is highlighted. The components are summed together to give the total DOY_{MEst}. *Step 5:* To validate the model, DOY_{MEst} is compared to the shift in DOY_M for each site.

Acknowledgements

We wish to thank Roger Jones (Victoria University), Ailie Gallant and David Karoly (University of Melbourne), Pandora Hope (Australian Bureau of Meteorology), and Ian Smith (CSIRO) for helpful discussions. Greg Jones (Southern Oregon University) located one of the data sets. Steve Tyerman (University of Adelaide) assisted with understanding of berry physiology. Lynda Chambers, Ian MacAdam and Alistair Hobday reviewed the manuscript. Also, we thank Nat White (Main Ridge Estate), Alister Purbrick and Robyn Sutherland (Chateau Tahbilk), Stephen and Bill Chambers (Chambers Rosewood Wines), Trevor Kent and Vanya Cullen (Cullen Wines, Western Australia), Prue and Steven Henschke (Henschke Wines) who all provided information and records, without which this analysis could not have been done. This work was partly funded by the CSIRO Climate Adaptation National Research Flagship and also by the Australian Grape and Wine Research and Development Corporation.

Bibliography

1. Parmesan, C., Duarte, C., Poloczanska, E., Richardson, A.J. & Singer, M.C. Overstretching attribution. *Nature Climate Change* **1,** 2-4 (2011).
2. Brander, K., Bruno, J., Hobday, A. & Schoeman, D. The value of attribution. *Nature Climate Change* **1,** 70-71 (2011).
3. Webb, L.B., Whetton, P.H. & Barlow, E.W.R. Observed trends in winegrape maturity in Australia. *Global Change Biology* **17,** 2707-2719 (2011).
4. Seguin, B. & de Cortazar, I.G. Climate warming: consequences for viticulture and the notion of *'terroirs'* in Europe. *Acta Horticulturae* **689,** 61-71 (2005).
5. Rosenzweig, C. et al. in Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden & C.E. Hanson) 79-131 (Cambridge University Press, Cambridge, UK, 2007).

6. Jones, G.V. et al. Changes in European winegrape phenology and relationships with climate. *Groupe d'Etude des Systemes de Conduite de la vigne (GESCO)*, 54-61 (2005).

7. Stoll, M., Lafontaine, M. & Schultz, H.R. Possibilities to reduce the velocity of berry maturation through various leaf area to fruit ratio modifications in *Vitis vinifera* L. Riesling. *Progrès Agricole et Viticole* **127,** 68-71 (2010).

8. Marais, J. Effect of Grape Temperature and Yeast strain on Sauvignon Blanc Wine Aroma Composition and Quality. *South African Journal for Enology and Viticulture* **22,** 47-51 (2001).

9. Liu, H.F., Wu, B.H., Fan, P.G., Li, S.H. & Li, L.S. Sugar and acid concentrations in 98 grape cultivars analyzed by principal component analysis. *Journal of the Science of Food and Agriculture* **86,** 1526-1536 (2006).

10. Cozzolino, D., Cynkar, W.U., Dambergs, R.G., Gishen, M. & Smith, P. Grape (*Vitis vinifera*) compositional data spanning ten successive vintages in the context of abiotic growing parameters. *Agriculture, Ecosystems & Environment* **139,** 565 (2010).

11. Schwartz, M. Phenology: An integrative environmental science. (Kluwer Academic Publishers, Netherlands, 2003).

12. Sadras, V.O. & Petrie, P. Climate shifts in south-eastern Australia: early maturity of Chardonnay, Shiraz and Cabernet Sauvignon is associated with early onset rather than faster ripening. *Australian Journal of Grape and Wine Research* (in press).

13. Grab, S. & Craparo, A. Advance of apple and pear tree full bloom dates in response to climate change in the southwestern Cape, South Africa: 1973-2009. *Agricultural and Forest Meteorology* **151,** 406-413 (2010).

14. Lobell, D.B., Schlenker, W. & Costa-Roberts, J. Climate trends and global crop production since 1980. *Science* (2011).

15. Rosenzweig, C. et al. Attributing physical and biological impacts to anthropogenic climate change. *Nature* **453,** 353-357 (2008).

16. Kearney, M.R. et al. Early emergence in a butterfly causally linked to anthropogenic warming. *Biology Letters* **6,** 674-677 (2010).

17. Nicholls, N. Increased Australian wheat yield due to recent climate trends. *Nature* **387,** 484-485 (1997).

18. Hendon, H.H., Thompson, D.W.J. & Wheeler, M.C. Australian rainfall and surface temperature variations associated with the Southern Hemisphere annular mode. *Journal of Climate* **20,** 2452-2467 (2007).

19. Frederiksen, C.S., Frederiksen, J.S., Sisson, J.M. & Osbrough, S.L. Changes and projections in Australian winter rainfall and circulation: Anthropogenic forcing and internal variability. *The International Journal of Climate Change: Impacts and Responses* **2,** 143-162 (2011).

20. Iland, P. in Viticulture Volume 1- Resources (2nd Edition) (eds. Dry, P. & Coombe, B. G.) 1-16 (Winetitles, Adelaide, South Australia, 2004).

21. Karoly, D.J. & Braganza, K. Attribution of recent temperature changes in the Australian region. *Journal of Climate* **18,** 457-464 (2005).

22. Davies, W.J., Bacon, M.A., Stuart Thompson, D., Sobeih, W. & Gonzalez Rodriguez, L. Regulation of leaf and fruit growth in plants growing in drying soil: exploitation of the plants' chemical signalling system and hydraulic architecture to increase the efficiency of water use in agriculture. *Journal of Experimental Botany* **51,** 1617-1626 (2000).

23. Wheeler, S., Loveys, B., Ford, C. & Davies, C. The relationship between the expression of abscisic acid biosynthesis genes, accumulation of abscisic acid and the promotion of Vitis vinifera L. berry ripening by abscisic acid. *Australian Journal of Grape and Wine Research* **15,** 195 (2009).

24. Conde, C. et al. Biochemical changes throughout grape berry development and fruit and wine quality. *Food* **1,** 1-22 (2007).

25. Zelleke, A. & Kliewer, W.M. Influence of root temperature and rootstock on budbreak, shoot growth, and fruit composition of Cabernet Sauvignon grapevines grown under controlled conditions. *Americal Journal of Enology and Viticulture* **30,** 312-317 (1979).

26. Webb, L., Whetton, P. & Barlow, E.W.R. Modelled impact of future climate change on phenology of wine grapes in Australia. *Australian Journal of Grape and Wine Research* **13,** 165-175 (2007).

27. CSIRO and Australian Bureau of Meteorology. *Climate change in Australia, Technical report* (Melbourne, Australia, 2007).

28. Soar, C.J., Dry, P.R. & Loveys, B.R. Scion photosynthesis and leaf gas exchange in Vitis vinifera L. cv. Shiraz: Mediation of rootstock effects via xylem sap ABA. *Australian Journal of Grape and Wine Research* **12,** 82-96 (2006).

29. Jones, D.A., Wang, W. & Fawcett, R. High-quality spatial climate data-sets for Australia. *Australian Meteorological and Oceanographic Journal* **58,** 233-248 (2009).

30. Raupach, M.R. et al. *Australian Water Availability Project (AWAP): CSIRO Marine and Atmospheric Research Component: Final Report for Phase 3* (2009).

Supplementary information to "Attribution analysis of detected trends in winegrape maturity in Australia"

By Leanne B. Webb, Penny H. Whetton, Jonas Bhend, Rebecca Darbyshire, Peter R. Briggs and E.W.R. Barlow

- Vineyard metadata is presented (Supplementary Table 1) describing the location, soil type and varieties and areas planted. Also presented is the period of years for which records were available, and then a description of the management practices commonly employed, or introduced at the vineyard. Vine health status is mentioned if known.
- Climate variable description (Supplementary Table 2) is given detailing the availability of the data and how these data were measured (See also http://reg.bom.gov.au/jsp/awap/ and www.csiro.au/awap).
- Sensitivity of the maturity day to the various drivers (Supplementary Table 3) and time-series trends (Table 4) were computed for all of the variables separately for the period of observations for each of the blocks, and for the period common to all blocks (1985-2009).
- Modelling of the long term shift in DOY_M using the climate variables, GST_{ave} and $Soil_{low}$ for the period of observations is depicted (Supplementary Figure 1). In many cases the observed shift (circle) is much greater than that described by the model (triangle).
- The variance explained (R^2) by the reconstructed series compared to the observed series over the observed period and also the period 1985-2009 (Supplementary Table 5). Comparison of the model created with GST_{ave} alone, GST_{ave} and $Soil_{low}$, and for the 1985-2009 period, GST_{ave}, $Soil_{low}$ and yield.
- An example of the reconstruction of the trend in DOY_M compared to the observed series for the Marsanne Block in Central Victoria (Supplementary Figure 2). The top panel shows the reconstruction of the time series using the climate variables, while the bottom panel shows the same but with the 'step-change' management shift included in the modelling as well.

Table 1 Regions from where observations were recorded; varieties represented; the period for which the data-set extends. Reported management practices and notable events are also listed.

<table>
<tr><th>Region (climate data location)</th><th>Variety (Block)</th><th>Soil type</th><th>Area (ha)</th><th>Range of years</th><th colspan="2">MANAGEMENT METADATA FOR ALL SITES</th></tr>
<tr><td rowspan="2">Mornington Peninsula (144.98E,38.36S)</td><td>Pinot Noir</td><td rowspan="2">Heavy clay soil over broken basalt rock</td><td>0.6</td><td>1985-2009</td><td colspan="2" rowspan="2">Not irrigated. Spur pruned Scott Henry converted from Vertical Shoot Positioned in the early 1990’s. Hand pruning and hand harvest.
Crop thinning applied to maintain yields at 5 t ha^{-1}
Natural subterranean spring drying out from about 2000.</td></tr>
<tr><td>Chardonnay</td><td>2.4</td><td>1986-2009</td></tr>
<tr><td rowspan="2">Eden Valley (139.11E,34.61S)</td><td>Shiraz (A)</td><td>Grey-brown loamy sand rock fragments, overlying mottled yellow-brown, yellow-grey, and red finely structured clay subsoil</td><td>0.2</td><td>1979-2009</td><td colspan="2">Not irrigated.
Very traditional/ consistent management practices throughout the history of the block.</td></tr>
<tr><td>Shiraz (B)</td><td>Deep red silty/fine sandy loam over deep red-brown/ yellow-brown mottled clay loam to clay</td><td>16</td><td>1978-2009</td><td colspan="2">Flood irrigated in the 70's just prior to Christmas. In wet years no irrigation applied (e.g. most of the 80's). Then in 1994-2003 withdrawn due to increasing salinity in water supply.
Biodynamic management (5 years) started mulching in the 1990’s. Some Eutypa. Aim for yield of 6 t ha^{-1}. Slow conversion of half vineyard to Scott-Henry trellis from 1989.</td></tr>
<tr><td>Margaret River (115.03E,33.91S)</td><td>Cabernet Sauvignon</td><td>Granite and gravely sandy loam, overlaying lateritic subsoils</td><td>7.9</td><td>1977-2009</td><td colspan="2">Dry grown (no irrigation). Biodynamic management, mulch applied undervine. Hand pruned and hand harvested with low yields maintained. Scott-Henry trellising is used.</td></tr>
<tr><td>Rutherglen (146.46E,36.04S)</td><td>Muscat a Petit Grains</td><td>Red duplex (loam)</td><td>1.0</td><td>1946-2009</td><td colspan="2">Not irrigated, grass sward sprayed out in summer. Recently started applying straw mulch to conserve water.
Fortified wine producer, 0.4-0.6 tha^{-1} but grapes shrivelled by harvest.</td></tr>
<tr><td rowspan="4">Central Victoria (145.09E,36.80S)</td><td>Shiraz (A)</td><td rowspan="4">Red/sandy loam with high Ferric-oxide content</td><td>4.6</td><td>1949-2009</td><td>Healthy</td><td rowspan="4">From 1984 irrigation was strategically applied flowering/fruit-set and veraison. Post 2001 it was not possible to wet the soil profile more than 60-70% of the rootzone.
Fertiliser was applied from 1979.
Frost leading to massive yield decline (2007).
Heatwaves affected yield (2008/2009).</td></tr>
<tr><td>Shiraz (B)</td><td>1.2</td><td>1962-2009</td><td>Fail to thrive</td></tr>
<tr><td>Marsanne</td><td>6.7</td><td>1949-2009</td><td>Thriving</td></tr>
<tr><td>Riesling</td><td>1.3</td><td>1979-2007</td><td>Afflicted with phylloxera *Daktulosphaira vitifolii*, an incurable pest of grapevines [1].</td></tr>
</table>

Table 2 Data was extracted for the following climate variables: precipitation, maximum and minimum temperature and soil moisture, over the time periods shown.

Climate variable	Period	Description
Precipitation (m)	Total growing season (Oct-Mar) rainfall. Summer rainfall (Dec-Feb)	Monthly precipitation (m day^{-1}) is the month-by-month average of the Bureau of Meteorology (BoM) Australian Water Availability Project (AWAP) Version 3 daily recalibrated rainfall at 0.05° resolution. AWAP monthly surfaces are created by reanalysis of station totals at the end of each month. The source data for the interpolations are daily observations of rainfall taken from the national climate databank of the BoM, known as the Australian Data Archive for Meteorology (ADAM). For most of the record the rain gauge network consists of between 5000 and 7500 stations. Daily measurements record the rainfall accumulated in the 24 hours to 9am on the date of observation.
Maximum and Minimum temperature (°C)	Average summer maximum (Dec-Feb)	Monthly minimum and maximum air temperatures are the month-by-month average of the BoM AWAP Version 3 daily temperatures at 0.05° resolution that are created at the end of each month. The source data for the interpolations are daily observations of temperature taken from ADAM. Temperatures are currently measured at about 750 sites across the country, but the size of the network contributing to AWAP surfaces varies through time [49]. Measurements (Stevenson screen) are recorded at 9am local time and show the minimum and maximum temperatures achieved in the previous 24 hours. Minimum temperatures are most likely to have occurred in the early morning on the same day as the observation. Since the maximum temperature is most likely to have occurred in the afternoon of the previous day, AWAP daily maximum temperature files are named with the date of the previous day.
Mean temperature (°C)	Average growing season (Oct-Apr)	Mean temperatures for each month were calculated as the average of the minimum and maximum.
Soil moisture	Average growing season (Oct-Apr)	Modelled estimates of soil moisture were developed for AWAP using the WaterDyn model of Raupach et al.[2] This model is a simple dynamic water balance model which determines the state of soil moisture in two layers. The soil moisture stores are defined with spatially varying depth and water holding capacity, and daily surfaces of AWAP Version 3 meteorology (precipitation, minimum and maximum temperatures, and solar radiation) [3] are used as model forcing. The water balance is computed in discrete cells without lateral water transfer (river routing). Monthly AWAP soil moisture data have been validated against long-term stream-flow measurements [2], and were recently compared to Australian water mass measurements from the Gravity Recovery And climate Experiment (GRACE) satellite with “remarkable” agreement [4]. Full details of the model are given in Raupach et al, [2] and in summary in Ummenhofer et al. [5]. In AWAP WaterDyn the mean monthly state of each soil moisture store is expressed as relative soil moisture, a proportion of the saturated capacity between 0 and 1.

Table 3 Sensitivity of DOY_M to climate variables for the common period 1985-2009 (upper) and full period (below) for all regions and sites in the study. Sensitivities calculated on first order differenced data. Sensitivity to average, minimum and maximum growing season temperature, summer maximum temperature, growing season rainfall, and soil moisture index from the upper and lower soil profile and yield, have been computed for each variable individually. Sensitivity is significant P<0.05 *, P<0.01 ** and grey shading.

Region	Variety	GST_{ave}	GST_{min}	GST_{max}	T_{max_djf}	GSR_{total}	$Soil_{upp}$	$Soil_{low}$	Yield
1985-2009	Unit	Days °C^{-1}				Days mm^{-1}	Days unit^{-1}		Days t/ha^{-1}
Mornington Peninsula	Pinot Noir	-10.3±6.7**	-11.0±8.0**	-8.1±5.5**	-2.2±3.3	0.04±0.04*	113.6±53.7**	57.6±35.8**	0.2±1.8
	Chardonnay	-15.3±7.8**	-18.4±8.6**	-11.1±6.9**	-3.2±4.1	0.03±0.05	127.7±73.9**	49.5±50.9	-0.4±1.7
Eden Valley	Shiraz (A)	-7.6±10.6	-1.1±13.2	-8.6±7.7*	-2.9±4.6	0.07±0.09	198.4±128.6**	47.0±60.1	9.6±7.4*
	Shiraz (B)	-12.4±11.1*	-9.2±13.8	-10.7±8.3*	-4.1±4.7	0.05±0.08	105.2±109.0	61.8±51.0*	4.7±2.8**
Margaret River	Cabernet Sauvignon	-18.0±8.0**	-15.5±8.6**	-18.1±7.3**	-14.7±5.1**	0.01±0.06	148.6±103.8**	209.3±94.9**	n/a
Rutherglen	Muscat a petit grains	-13.5±13.3*	-15.8±14.9*	-8.8±10.7	-3.7±7.0	0.06±0.12	158.8±210.1	70.4±70.1*	n/a
Central Victoria	Shiraz (A)	-8.6±4.7**	-6.5±6.3*	-7.0±3.4**	-3.8±2.0**	0.01±0.03	37.6±57.6	31.2±22.8**	0.5±1.9
	Shiraz (B)	-9.5±5.8**	-5.0±7.9	-8.7±3.9**	-4.6±2.3**	0.04±0.04*	73.7±63.6*	46.6±24.2**	0.1±2.5
	Marsanne	-6.2±5.9*	-4.4±7.2	-5.1±4.4*	-2.4±2.6	0.02±0.04	52.1±60.8	33.4±24.8*	1.8±2.1
	Riesling	0.0±12.9	2.9±14.6	-1.3±9.8	1.2±5.4	0.04±0.08	87.1±120.7	61.7±49.8*	5.2±4.6*
Full period									
Mornington Peninsula	As above								
Eden Valley	Shiraz (A)	-10.3±10.0*	-5.8±12.3	-10.2±7.5*	-4.2±4.2*	0.08±0.09	203.8±130.5**	48.6±46.0*	n/a
	Shiraz (B)	-12.7±9.9*	-9.5±11.9	-11.3±7.5**	-3.3±4.2	0.05±0.07	117.2±98.9*	63.2±37.8**	
Margaret River	Cabernet Sauvignon	-17.9±6.5**	-15.7±6.9**	-18.4±6.1**	-14.9±5.0**	0.01±0.07	127.5±115.0*	180.3±117.1**	
Rutherglen	Muscat a petit grains	-16.9±7.8**	-15.7±8.1**	-12.9±6.8**	-4.4±5.4	0.05±0.07	177.8±130.8**	48.0±41.9*	
Central Victoria	Shiraz (A)	-9.3±2.8**	-7.0±3.2**	-8.0±2.3**	-4.0±1.7**	0.01±0.02	38.3±43.5	25.9±15.5**	
	Shiraz (B)	-10.7±3.4**	-8.0±4.1**	-9.3±2.6**	-5.0±2.0**	0.01±0.03	59.9±54.4*	36.6±18.2**	
	Marsanne	-8.3±3.3**	-6.0±3.7**	-7.4±2.7**	-3.0±2.0**	0.02±0.02	64.2±45.2**	29.7±16.6**	
	Riesling	1.5±10.2	2.7±12.0	0.6±7.8	1.7±4.5	0.03±0.07	67.2±110.1	26.7±40.8	

Table 4 Trends in driving variables and response variables (decade^{-1}) for the period 1985-2009 (upper) and observed series (below) for all of the regions and sites in the study. Driving variables: average, minimum and maximum growing season temperature, summer maximum temperature, growing season rainfall, and soil moisture index from the upper and lower soil profile, and yield. Response variables: Day of year at maturity. Significant trends: P<0.05 *, P<0.01 ** and grey shading.

Site description		Potential driving variables								Response variable
Region	Variety	GST_{ave}*	GST_{min}	GST_{max}	T_{max_djf}	GSR_{total}	$Soil_{upp}$	$Soil_{low}$	Yield*	DOY_M*
1985-2009	Unit	°C decade^{-1}				mm decade^{-1}	Unit decade^{-1}		t ha^{-1} decade^{-1}	Days decade^{-1}
Mornington Peninsula	Pinot Noir	0.23±0.31	0.21±0.27	0.26±0.40	0.47±0.62	-66.7±58.5*	-0.06±0.04**	-0.07±0.06*	-2.2±1.5**	-15.7±5.9**
	Chardonnay	0.25±0.34	0.22±0.29	0.29±0.43	0.39±0.67	-78.2±62.0*	-0.06±0.04**	-0.08±0.06*	-0.3±2.5	-13.8±7.7**
Eden Valley	Shiraz (A)	0.31±0.35	0.13±0.32	0.49±0.42*	0.65±0.71	25.0±47.0	0.01±0.03	-0.03±0.06	-0.9±0.5**	-3.9±7.6
	Shiraz (B)	0.33±0.33*	0.13±0.30	0.53±0.41*	0.70±0.70	17.5±52.9	0.00±0.03	-0.04±0.07	-2.1±1.1**	-7.9±8.0
Margaret River	Cabernet Sauvignon	-0.02±0.27	-0.39±0.27**	0.34±0.30*	0.40±0.39*	-16.5±47.9	-0.01±0.03	-0.02±0.02	n/a	-0.6±6.9
Rutherglen	Muscat	0.53±0.44*	0.36±0.39	0.70±0.56*	0.86±0.84*	-22.5±53.9	-0.01±0.03	-0.08±0.08*	n/a	-1.6±13.4
Central Victoria	Shiraz (A)	0.41±0.35*	0.17±0.32	0.64±0.46**	0.93±0.70*	-36.3±56.8	-0.02±0.03	-0.10±0.08*	-3.1±1.3**	-8.3±5.3**
	Shiraz (B)	0.41±0.35*	0.17±0.32	0.64±0.46**	0.93±0.70*	-36.3±56.8	-0.02±0.03	-0.10±0.08*	-5.8±1.9**	-12.5±6.4**
	Marsanne	0.41±0.35*	0.17±0.32	0.64±0.46**	0.93±0.70*	-36.3±56.8	-0.02±0.03	-0.10±0.08*	-1.5±1.3*	-8.4±5.5**
	Riesling	0.21±0.41	0.06±0.39	0.37±0.54	0.82±0.89	-15.2±69.3	-0.01±0.04	-0.05±0.10	-6.9±1.3**	-7.2±11.0
Full period										
Mornington Peninsula	As above									
Eden Valley	Shiraz (A)	0.15±0.24	0.05±0.22	0.25±0.29	0.15±0.52	2.2±31.6	0.00±0.02	-0.03±0.05	n/a	-2.4±5.4
	Shiraz (B)	0.14±0.22	0.05±0.19	0.23±0.28	0.17±0.49	2.1±32.9	0.00±0.02	-0.01±0.06		-2.3±5.7
Margaret River	Cabernet Sauvignon	-0.02±0.21	-0.34±0.22**	0.29±0.23*	0.35±0.29*	-1.6±30.8	0.00±0.02	-0.01±0.01		0.5±5.1
Rutherglen	Muscat	0.08±0.12	-0.02±0.12	0.18±0.15*	0.10±0.20	-11.5±15.5	0.00±0.01	-0.01±0.03		-4.0±3.7*
Central Victoria	Shiraz (A)	0.14±0.09**	0.10±0.09*	0.19±0.12**	0.16±0.17	-16.7±15.3*	-0.01±0.01	-0.02±0.02		-4.0±1.5**
	Shiraz (B)	0.13±0.14	0.09±0.13	0.17±0.17	0.19±0.24	-14.5±20.5	-0.01±0.01	-0.02±0.03		-4.5±2.5**
	Marsanne	0.14±0.09**	0.10±0.09*	0.19±0.11**	0.16±0.16	-16.4±14.9*	-0.01±0.01	-0.02±0.02		-3.8±1.5**
	Riesling	-0.03±0.31	-0.03±0.26	-0.03±0.41	0.03±0.67	-2.9±43.4	0.00±0.03	-0.02±0.07		-3.8±7.1

*Note that more rapid declines in yield occurred in blocks which were reported as not thriving (Shiraz (B) and Riesling sites from Central Victoria (Supplementary Table 1)). **Trends will differ slightly from those reported in the previous study [6] as some years records were eliminated so the data could be normalised for multivariate modelling of trends.

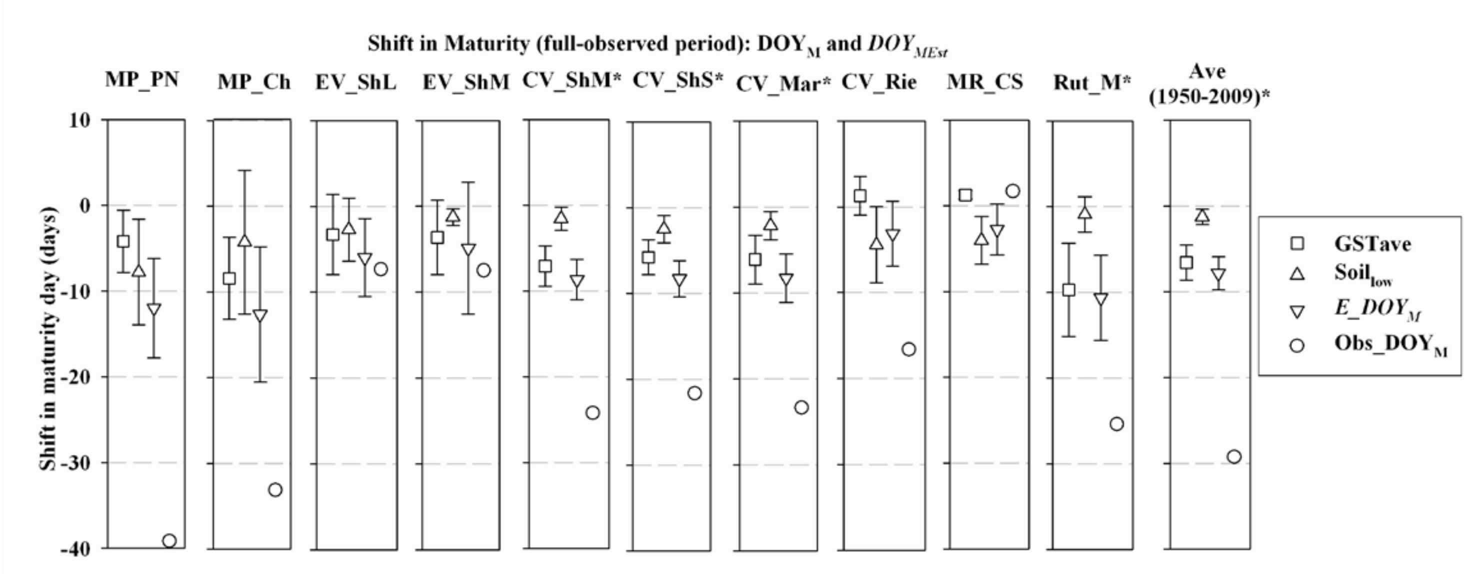


Figure 1 Comparing the observed shift with the modelled shift in maturity day for all of the blocks for the full period of observation. Observed shift in DOY$_M$ (circle), the individual contribution from the separate drivers GST$_{ave}$ (square) and Soil$_{low}$ (upright triangle), and the estimated modelled shift (DOY_{MEst}) (downward triangle), (See Table 1 for non-abbreviated description of regions and sites). Average shift calculated from sites noted with an asterisk.

Table 5 The variance explained (R^2) by the reconstructed series (DOY_{MEst}) compared to the observed series (DOY_M). Models were analysed over the observed period and also the period 1985-2009. Comparison of the model created with GST_{ave} alone, climate variables (GST_{ave} and $Soil_{low}$,) and for the 1985-2009 period, climate and crop-yield (GST_{ave}, $Soil_{low}$ and crop-yield).

		Observed period		1985-2009		
Region	Variety	GST_{ave}	Climate	GST_{ave}	Climate	Climate Crop-yield
Mornington Peninsula	Pinot Noir	0.31	0.34	0.29	0.43	0.33
	Chardonnay	0.56	0.62	0.56	0.62	0.53
Eden Valley	Shiraz (L)	0.12	0.23	0.12	0.19	0.21
	Shiraz (M)	0.24	0.22	0.32	0.37	0.5
Margaret River	Cabernet Sauvignon	0.39	0.51	0.31	0.53	na
Rutherglen	Muscat a petit grains	0.26	0.27	0.37	0.43	na
Central Victoria	Shiraz (M)	0.46	0.52	0.46	0.62	0.71
	Shiraz (S)	0.43	0.59	0.41	0.68	0.65
	Marsanne	0.34	0.44	0.26	0.51	0.59
	Riesling	0.006	0.24	0.13	0.05	0.76

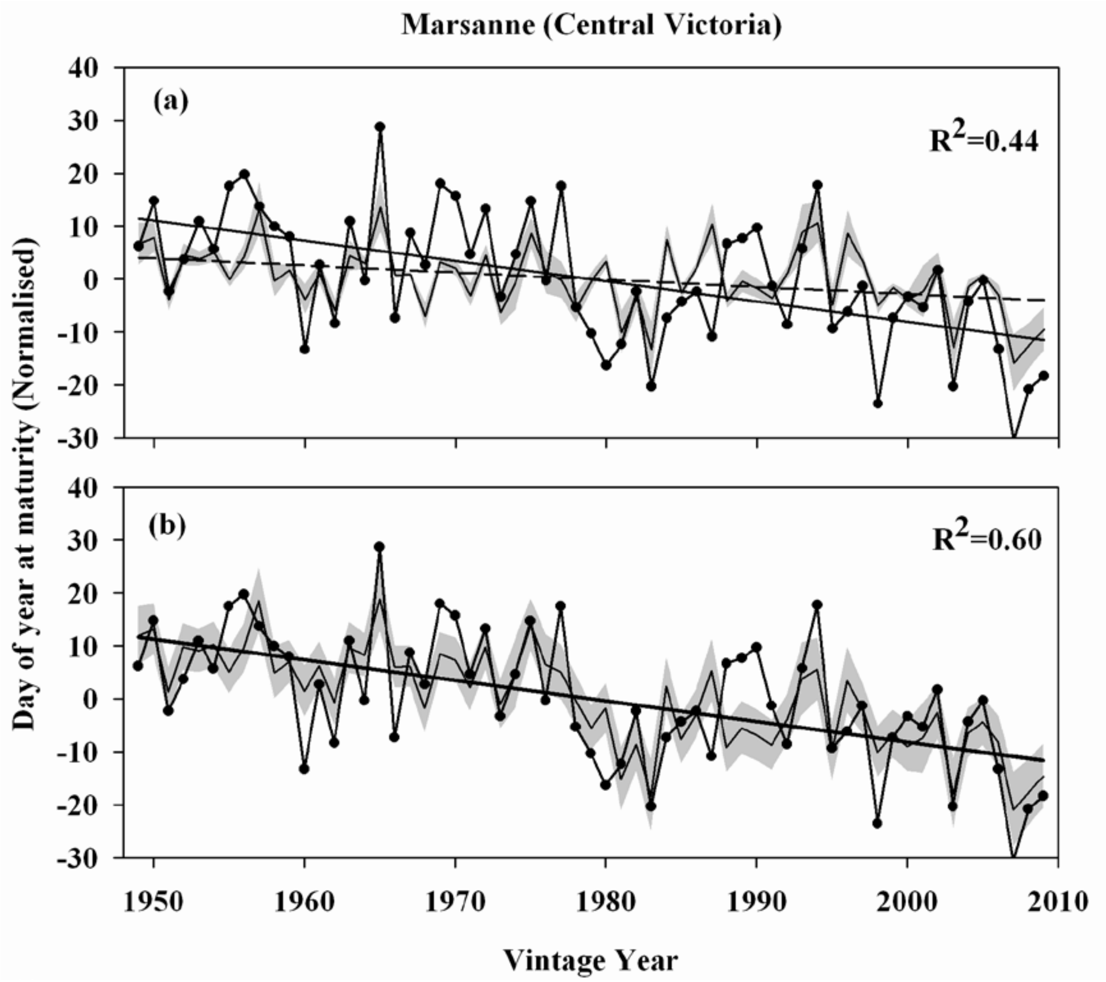


Figure 2 Time series of day of year to maturity (DOY_M) for Marsanne (Central Victoria) (a) DOY_M (black dots) (trend: black line) overlaying time-series *DOY_{MEst}* using GST_{ave} and $Soil_{low}$ (grey band, 95% confidence interval indicated by band width, trend: dashed line) and (b) DOY_M (black dots) (trend: black line) overlaying *DOY_{MEst}* modelled using GST_{ave} and $Soil_{low}$ and the 1979 step change (management) (grey band 95% confidence interval of the model, trend: dashed line).

1. Granett, J., Walker, M.A., Kocsis, L. & Omer, A.D. Biology and management of grape phylloxera. *Annual Review of Entomology* 46, 387-412 (2001).

2. Raupach, M.R. et al. Australian Water Availability Project (AWAP): CSIRO Marine and Atmospheric Research Component: Final Report for Phase 3 (2009).

3. Jones, D.A., Wang, W. & Fawcett, R. High-quality spatial climate data-sets for Australia. *Australian Meteorological and Oceanographic Journal* 58, 233-248 (2009).

4. García-García, D., Ummenhofer, C.C. & Zlotnicki, V. Australian water mass variations from GRACE data linked to Indo-Pacific climate variability. *Remote Sensing of Environment* doi:10.1016/j.rse.2011.04.007 (2011).

5. Ummenhofer, C.C. et al. Indian and Pacific Ocean influences on southeast Australian drought and soil moisture. *Journal of Climate* DOI:10.1175/2010JCLI3475.1 (2010).

6. Webb, L.B., Whetton, P.H. & Barlow, E.W.R. Observed trends in winegrape maturity in Australia. *Global Change Biology* 17, 2707-2719 (2011).

Appendix 5: Managing grapevines through severe heat: A survey of growers after the 2009 summer heatwave in south-eastern Australia.

L. Webb[1,2], J. Whiting[3], A. Watt[1], T. Hill[1], F. Wigg[1], G. Dunn[1], S. Needs[1] and E.W.R. Barlow[1]

[1]School of Agriculture and Food Systems, University of Melbourne, Parkville Victoria. [2]Centre for Australian Weather and Climate Research, a partnership between CSIRO and the Bureau of Meteorology, Aspendale, Victoria. [3]John Whiting Viticulture Consulting, PO Box 10, Golden Square Vic. 3555

Corresponding author's email: leanne.webb@csiro.au

Abstract

A survey of 92 vineyards, representing ten winegrowing regions in south-eastern Australia, soon after exposure to a severe heat-wave, revealed variation in the reported heat-related impact. This variation was observed between regions, within regions and within vineyards. Notably the estimates of losses were not always related to the amount of heat above a certain threshold but to the management practices employed in the lead-up and through the event.

Applicable and achievable recommendations for managing severe heat events have resulted from this assessment. We believe this method of capturing information from the diverse knowledge-base of managers is a very effective way to reveal potential adaptive capacity to a changing climate.

Introduction

An exceptional heatwave occurred in south-eastern Australia during late January and early February 2009. Many records were set for high day-time and night-time temperatures as well as for the duration of extreme heat (National Climate Centre 2009). At this time most of the south-eastern Australian winegrape crop was in the veraison (berry softening and commencement of sugar accumulation) or post-veraison stage of its phenology (McIntyre et al. 1982). The impacts of the heatwave on vineyards appear to be unprecedented, with significant heat-stress related crop losses at some sites.

Global average surface temperature has increased by approximately 0.7°C since the beginning of the 20th Century. The warming has been associated with more heatwaves, changes in precipitation patterns, reductions in sea ice extent and rising sea levels globally (IPCC 2007). Increases in heatwave occurrences in eastern Australia and South Australia since the 1950s have been measured (Deo et al. 2007) and are projected to increase in future (Alexander and Arblaster 2009).

By conducting a study of intra- and inter-regional variation of winegrape vineyard impact and management response associated with the 2009 heatwave in south-eastern Australia, successful management options were revealed that significantly reduced the impact. This survey of real-time responses to a severe heatwave supports and validates recommendations for management options identified during some recent workshops held in

Australia (Hayman et al. 2009), and at the same time quantifies the success of such strategies. As increases in the frequency of extreme hot days (>35°C) in the growing season are projected to eliminate winegrape production in many areas of the United States (White et al. 2006) these practices may become more critical to ongoing profitable wine production in this country and globally.

The Heatwave

According to the National Climate Centre (2009) there were two major periods of exceptionally high temperatures, 27–31 January and 6–8 February. On 27–31st January, 2009 in southern South Australia, and much of central, southern and western Victoria, maximum temperatures reached their highest levels since at least 1939 (Figure 2). The extreme heat on the 7th February, where record high temperatures for February were set for over 87% of Victoria, also affected the southern fringe of New South Wales and eastern South Australia (Figure 3). Renmark in the Riverland winegrape growing region set a February record (48.2°C). In addition to its peak intensity, the heatwave was also notable for its duration, with slightly lower, but still very high, temperatures persisting in many inland areas through the intervening period (1–5 Feb). Adelaide (South Australia) ultimately had nine consecutive days above 35°C, surpassing the previous record of eight consecutive days above 35°C set in March 2008; that is, two record heatwaves in twelve months.

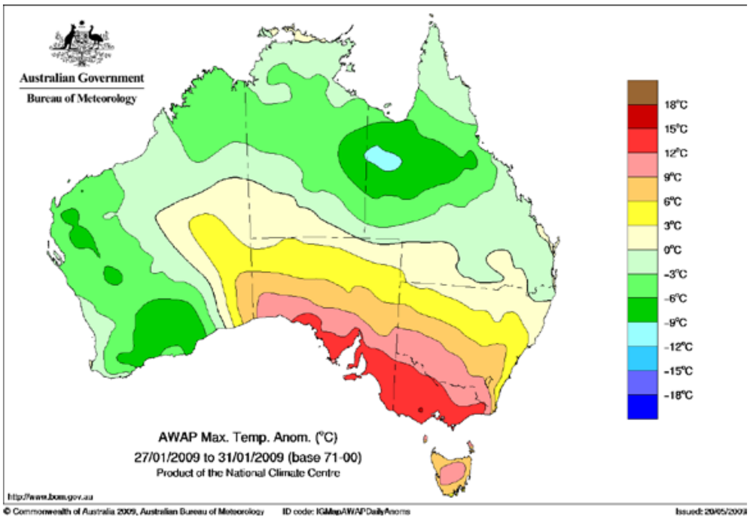


Figure 2 Maximum temperature anomalies (differences from the 1971–2000 average) for the period 27–31 January 2009

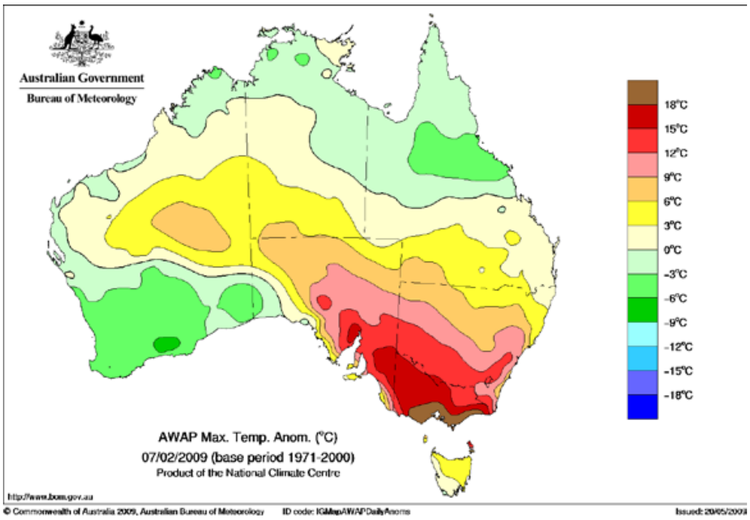


Figure 3 Maximum temperature anomalies (differences from the 1971–2000 average) for 7 February 2009

Across the winegrowing regions the heatwave varied in intensity, duration and also diurnally as can be seen by comparing records from Mildura (Murray Darling/Swan Hill region) where twelve consecutive days above 40°C occurred with those from Cerberus (Mornington Peninsula) with two heat-spikes and Launceston (Tasmania) where one spike in temperature was observed (Figure 4). See Table 2 for locations of sites and regions.

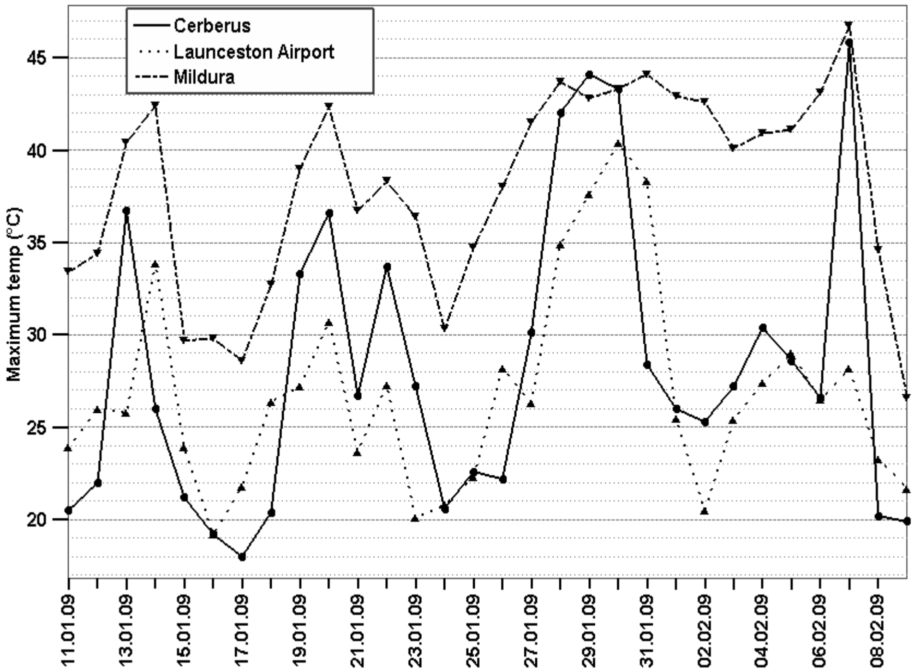


Figure 4 Daily maximum temperatures (°C) for Mildura (Murray Darling/ Swan Hill), Cerberus (Mornington Peninsula) and Launceston Airport (Northern Tasmania) over the period of the heatwave (See: http://www.bom.gov.au/climate/dwo/index.shtml)

The heatwave was also accompanied by very dry conditions, both during and in the weeks leading up to the event. Further, the south-eastern region of Australia had been subject to a protracted drought with below average rainfall experienced for the 12 years since 1996 (Australian Bureau of Meteorology 2008a). Not only were soil moisture reserves low in winegrowing regions without access to public irrigation schemes, but growers' decisions to irrigate may have been influenced because of reduced allocations of irrigation water from these schemes and/or because on-farm storages were often low or nil (Webb et al. 2008).

On the 7th February 2009 catastrophic bushfires afflicted some of the heatwave-affected winegrape growing regions that were also affected by the heatwave (Karoly 2009). While smoke from bushfires can adversely affect winegrapes (Kennison et al. 2007) this study focussed solely on heat impacts to vineyards.

The Survey

An assessment of vineyard responses and impact was undertaken by interviewing managers of properties from selected winegrowing regions located within the affected areas: Tasmania, Mornington Peninsula, Yarra Valley, Coonawarra, McLaren Vale, Barossa Valley, Heathcote, Rutherglen, and Murray Darling/Swan Hill, Riverland (Figure 5 and Table 2).

Figure 5 Winegrowing regions in south-eastern Australia (see inset map) that were selected for assessment (hatched). Other registered winegrape growing regions (not assessed) are depicted by the solid grey. State and territory boundaries are marked with the grey lines.

The regions surveyed represent the full range of temperatures (see Mean January Temperature (MJT) (Smart et al. 1980)) (Table 1) in which most winegrapes are grown in Australia. Furthermore, these regions represent a broad range of production end-point categories, from low yielding icon and super premium wine production to higher yielding bottled premium wines or bulk wine production. The vineyard operators employ a diverse range of management practices to enable the production of the desired product in the climate typical of the region (Smart and Robinson 1991).

The survey, undertaken within two to six weeks of the heatwave (Table 1), was designed to gain an understanding of the perceived extent of damage and the management practices implemented. Ten vineyards were selected randomly from within each of the ten regions (92/100 surveys completed) with vineyard managers being interviewed on site. They were asked a series of questions that addressed four specific categories: weather awareness, vineyard impact, management strategies implemented, and a post-event evaluation of the strategies employed.

We noted that the obvious effects on grape vines included stalled development, leaf burn, leaf drop, berry sunburn, berry ‘bagging’ and berry shrivel. Photos were taken, with the permission of the managers, to document some examples of the heat-stress damage (e.g. Figure 6). Growers were asked to estimate the losses that they attributed to heat-stress, both in terms of yield loss and also the scale of damage noted on the bunches. While there was an acknowledgement that it was sometimes difficult to attribute the losses to the heat alone, as other factors affected the crop (e.g. poor fruit-set due to wet conditions in spring in some regions), most growers provided this information with some degree of confidence. The scale of damage (average percentage of bunch affected) was also more complex as in some regions within one panel of a trellis every level could be observed. Again the growers estimated this figure as well as possible.

Table 2 Regions surveyed, Mean January Temperature (MJT) of region, weather station used to represent the region for this survey, dates (in 2009) that the heatwave event occurred and the period when the survey interviews were conducted.

Region Surveyed	MJT (°C)*	Weather Station (number)	The hot event	Survey dates
Tasmania	16.2	Launceston Airport (091311)	28–30th Jan	12–13th Mar
Mornington Peninsula	18.6	Cerberus (086361)	28–30th Jan, 7th Feb	20–23rd Feb
Yarra Valley	18.2	Coldstream (086383)	28–30th Jan, 7th Feb	24th Feb, 6th Mar
Coonawarra	19.3	Coonawarra (026091)	27–30th Jan	12–13th Mar
McLaren Vale	20.7	Noarlunga (023885)	27th Jan–1st Feb, 6th–7th Feb	3–4th Mar
Barossa Valley	21.4	Nuriootpa (023373)	27th Jan–1st Feb, 6th–7th Feb	2–3rd Mar
Heathcote	21.0	Bendigo Airport (081123)	28th Jan–1st Feb, 7th Feb	22nd Feb, 25th Feb
Rutherglen	22.5	Rutherglen Res.St. (082039)	28th Jan–1st Feb, 5th–7th Feb	4–5th Mar, 11th Mar, 15th Mar
Murray Darling/ Swan Hill	24.3	Mildura Airport (076031)	27th Jan–7th Feb	4–5th Mar
Riverland	23.6	Renmark Aero (024048)	27th Jan–7th Feb	6–7th Mar

*Averaged by region. Calculated by the principal author using spatial analysis (ESRI 2007) of digital climatology 1976–2005 provided by the Australian Bureau of Meteorology.

The experimental design was geared to gaining information as close to the event as possible. We wanted to observe the evidence of the impacts before this was removed at harvest and also the growers’ best possible recollections. This project used an inductive methodology where a qualitative survey instrument was developed, data collected and patterns observed from which tentative hypotheses were developed around impacts of the heatwave. In the social science field this is known as a grounded theory approach (Strauss and Corbin 1998).

It is noted that these trends were assessed from a small sample of vineyards from each region (typically <5–10% of the total). Attempts were made to limit bias by sampling (using a random number generator) from an alphabetical list of vineyards/wineries accessed from regional industry associations. We attempted to include a similar proportion of both larger and smaller properties from each region. Where people declined to be surveyed, the next vineyard on the list was approached, however, we cannot be sure whether perhaps worse, or maybe less, affected wineries tended not to respond. As such the outcomes should be considered within this context.

Figure 6 Examples of some of the impacts of the 2009 summer heatwave observed across the winegrowing regions of south-eastern Australia. a) shoot tip burn (Pinot Noir) b) leaf burn (Shiraz) c) sunburn on Chardonnay berries d) shiraz berry desiccation.

Results

Nearly everyone reported they had ample warning of the event and were satisfied with the weather information they can access. In a few cases the managers found the event was either more severe or of longer duration than expected, even given the forecast. Where two distinct hot temperature spikes were recorded, it was often the initial spike that caused most damage. Most (intuitively) believed that the combination of the intensity of the heat and the duration contributed to the impact.

The extent of the crop-loss (as estimated by the vineyard managers) was found to vary between regions ($P<0.01$), within regions ($P<0.01$) and within vineyards (Figure 7). The reported scale of damage (% of bunch affected) also varied by region (P<0.01) (Figure 7) and within regions (P<0.01) with many managers also noting that there was delayed or stalled development.

Where relatively higher levels of damage were reported in the properties surveyed (e.g. Mornington Peninsula, McLaren Vale and Rutherglen), several circumstances were reported:

- these events were unprecedented and for this reason there was an element of surprise with regard to the severity of the heat event and hence the management response undercompensated;
- in cooler regions, e.g. Mornington Peninsula, the management practices were typically geared to exposing fruit in order to minimise disease pressure, the opposite strategy to managing for extreme heat;
- some of the crops were ‘dry-grown’ so managers had no access to supplementary irrigation and/or
- water was not accessible due to the continuing long term drought in south-eastern Australia rendering some management options unavailable.

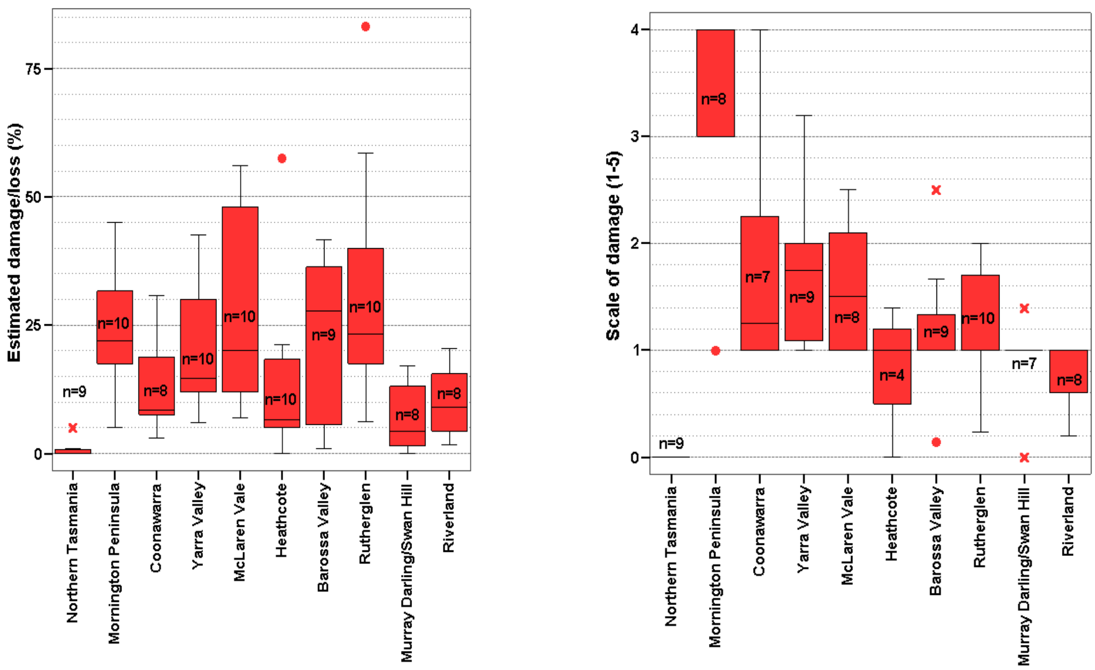


Figure 7 Boxplots[6] indicating (left) the estimated extent of damage and (right) the estimated scale of damage as it varied by region. Scale of damage categories: 0=no damage, 1=20%, 2=40%, 3=60%, 4=80% and 5=100% berries affected in a bunch. n = number of survey responses.

Tasmanian vineyard managers reported negligible impacts despite record temperatures. These temperatures were, however, lower than recorded on

[6] Summary plot based on the median, quartiles, and extreme values. The box represents the interquartile range which contains 50% of values. The whiskers are lines that extend from the box to the highest and lowest values, excluding outliers (dots) and extremes (crosses). A line across the box indicates the median.

the mainland, and possibly below damage ‘threshold’ levels. Furthermore, at the time of the heatwave, berries were at the pea size stage of development, and shoots were still elongating. So while shoot tip burn was observed in one vineyard that had no access to water, the Tasmanian grape crop was largely unaffected. (Due to the low levels of reported damage in this region results have been removed from some of the analysis. Effectiveness of management was less likely to influence results here than other factors such as phenological stage or reduced exposure to heat).

Paradoxically, low levels of damage were also reported in the Murray Darling/Swan Hill and Riverland regions, despite them experiencing the most extreme conditions. In this case it was mainly because current vineyard management already addresses regular exposure to high temperatures. Large canopies are grown, and water is managed to assist the vine’s capacity to cope in hot climates.

To test for a link between the heat exposure and the estimated losses, heat degree days were calculated for the period 23rd January to the 9th February, 2009, dates encompassing the heatwave period over all of the regions. Maximum temperatures recorded (Australian Bureau of Meteorology 2008) in excess of 35°C and 40°C were summed over the period to reflect each region’s heat load and highlight inter-regional variation (Figure 8). The regions, as previously described, experienced varying heat loads, with Tasmania (Launceston Airport) only recording 11.3°C summed heat degree days above 35°C for this period, while Murray Darling/Swan Hill received a total of 97.2°C heat degree days above 35°C, and for the Riverland the summation amounted to 100.4°C.

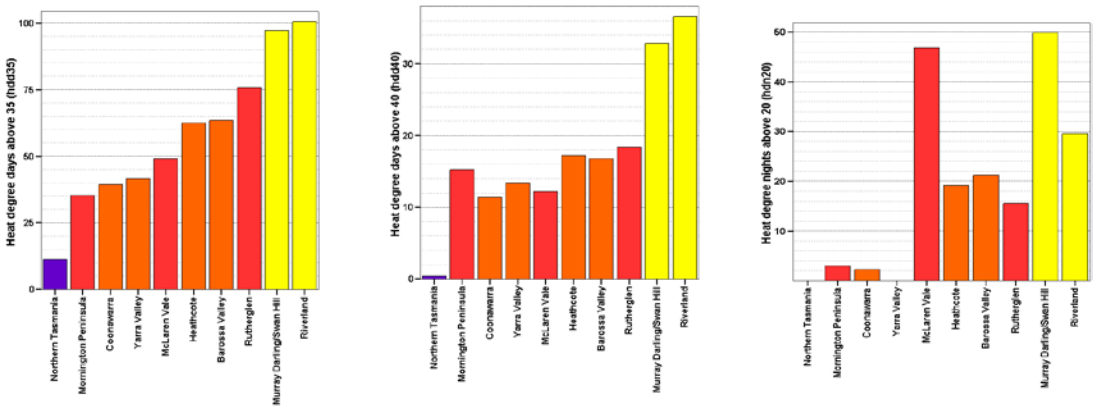


Figure **8** Heat degree days above 35°C (left) and 40°C (middle), and heat degree nights above 20°C (right) summed for the period 23rd January to 9th February 2009 and obtained from representative weather stations. Bar colours indicate the preliminary relative regional estimate of losses averaged over the vineyards (see (Webb et al. 2010) (Damage levels: Red= worst, Orange= medium, Yellow= lower and Purple=negligible).

When temperatures above 40°C were summed there was a similar degree of variation but in some cases the order of “heat load” total was changed compared with the heat summation between 35°C. This implies that some regions were exposed to a relatively larger temperature spike; when it got hot, it got really hot. The Mornington Peninsula for example reported a low temperature lead-up to the event, followed by a rapid heat spike (Figure 8).

Minimum temperatures (night-time) in excess of 20°C were summed and also show large regional differences (Figure 8). McLaren Vale, in particular, experienced relatively higher minimum temperatures (warm nights) compared to daytime maximums than other regions; although not a survey question it was frequently reported in this region.

One of the most interesting outcomes from this survey is that the estimates of losses were not always related to the amount of heat above a certain threshold. In a preliminary assessment of the data (Webb *et al.* 2010) the worst affected regions through to the least affected regions were subjectively assessed and ranked by the survey team. The colours of the bars (Figure 8) indicate these rankings. Tasmania shows low exposure and low damage, but Mornington Peninsula and the Yarra Valley had relatively low exposure and relatively high damage. As mentioned above, an initially unexpected result was the low levels of damage reported for the Riverland and Murray-Darling/ Swan Hill regions considering their heat loads.

One immediately obvious trend in the amount of damage reported was the variation with different row orientation and with the aspect of the canopy (Figure 9). The rows planted in a north-south (NS) orientation were more affected than rows planted east-west (EW) ($P<0.01$). Further, the western aspect of these NS rows was more affected than the east (Figure 9 and Figure 10). In EW oriented rows there was either no difference or the north side had more damage. There were also some observations of damage to the exposed ends and tops of canopies. Principal Component Analysis (PCA) indicates the variation in the damage estimation for a given row orientation is independent from any regional effect (data not shown).

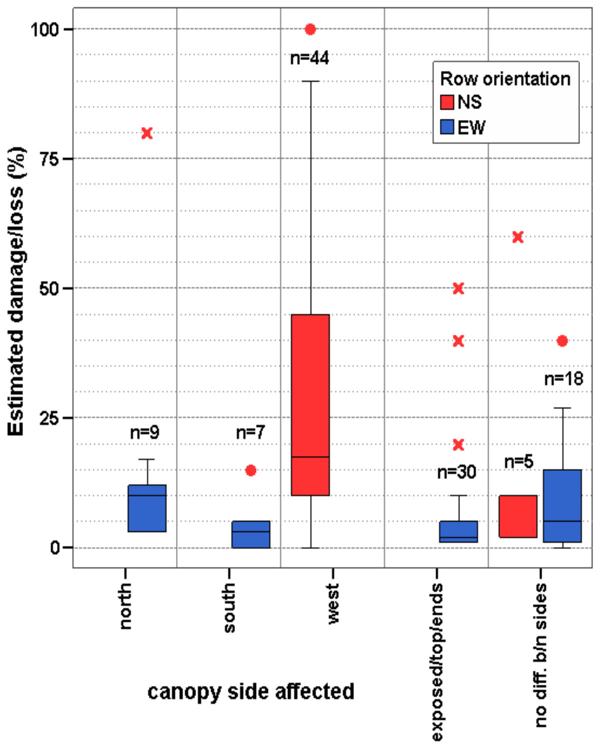


Figure **9** Estimated damage or loss reported for vines depending on their orientation: either north-south (NS), east-west (EW) and on the aspect of the canopy side (for the different row orientations). (NB. Blocks with poor access/availability of water have been removed from this dataset) (Tasmanian data is also not included as reduced impact in this region is likely for other reasons).

Figure **9** Different levels of damage within one north-south oriented vineyard row: a) exposed berries on the western aspect of the canopy and b) exposed berries on the eastern aspect of the canopy.

The survey addressed watering in the vineyard, assessing the watering schedules normally practiced and how this was varied through the heat event. This included: application method, sources of water accessed, the method used for scheduling, whether any problems were evident through the event, how the water was applied (before/during/after) and what records were kept from the event.

Watering prior to the event and absence of issues with regard to access or availability of water was correlated with lower reported damage (Figure 11). Most of the growers irrigated using drippers. The few that had dry-grown vineyards typically experienced more damage, which is not surprising as they could not use the option to increase watering as a way of reducing the heat-stress. Notably, however, some dry-grown blocks received low levels of damage (Figure 11). These were generally older vines grown on deeper soils so possibly had larger root-systems able to access deep water sources. The method of scheduling irrigation varied but the damage levels were not dependent on these. There was possibly less damage overall where a more technical method of water scheduling was used (this may also be regionally linked and therefore a canopy/trellis effect also underlies this result). The source of water also showed little influence upon the level of damage reported (data not shown).

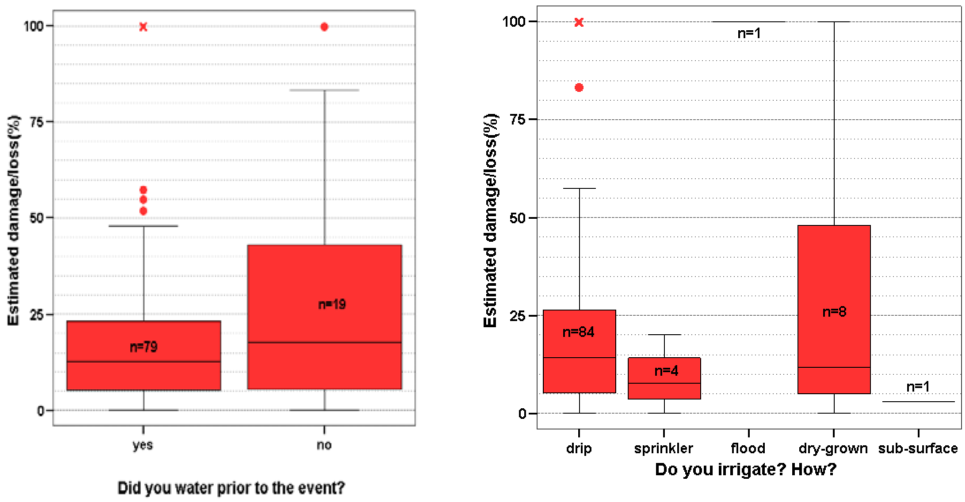


Figure 10 Boxplot of the estimated damage/loss (%) in relation to watering systems and availability. Damage is reported by vineyard block (not farm), as some farms used more than one system. When grower's responses varied with blocks in their vineyard these were counted more than once.

The estimated extent of damage did not vary for the grape colour or grape varieties surveyed (data not shown), though some respondents suggested varieties with larger berries and thinner skins being more affected. The lower number of replicates of these varieties, the different stages of development and different trellis types in the different regions may have disguised any trends. There was, however, some evidence of a difference in damage when comparing vines grown on different trellis. Vertical Shoot Positioned (VSP) vines, where the canopy is lifted into a vertical position once the wood of the shoots starts maturing, were more affected than the trellis where the grape bunches were more protected by the canopy (e.g. the 2-wire T-trellis system commonly used in the hotter regions). For vines with no problems with water access or availability there was a significant effect of phenological stage on the estimation of damage or loss ($P<0.05$), with vines at the veraison (early to late veraison) more affected than otherwise.

The growers were asked how they perceived grape quality may have been affected. Responses varied with some in the Yarra Valley mentioning acid dropping, and Heathcote and Rutherglen noted some flavour impacts. As most of the grapes had not been harvested at the time of the survey these comments were speculative.

Discussion

In January and February 2009 the occurrence of a severe heatwave effectively set up an extensive natural experiment whereby vineyards in many different winegrowing regions were exposed to varying intensity and duration of extreme heat. We have documented and compared the observed impact of the heatwave events and management responses made by 92 winegrowers across ten selected regions. Variation in management strategies, either traditional approaches or reactive management, highlights current best practice methods for managing extreme heat events in future.

The estimates of losses were not always related to the amount of heat above a certain threshold. We found losses were, in most cases, more influenced by the regional or inter-regional management strategies and viticultural practices employed by the managers participating in the survey.

Over *all* of the regions, four vineyard variables became apparent as having a major influence on the levels of damage reported:

1. Adequate water application was critical to reduction of heat-stress impact

Watering the root zone to full capacity prior to the event and then maintaining this moisture status as well as possible through the period of hot weather was the main strategy employed to minimise damage across regions. In cases where water was limiting, causing the vines to shut-down (Flexas et al. 2004; Kriedemann and Smart 1969), the reduced latent heat loss (through evaporation) compounded the high heat-load of the berries making damage more likely.

Vines grafted to drought–tolerant rootstock tended to perform better than drought sensitive rootstocks or own rooted vines (1103 Paulsen, 110 Richter, 140 Ruggeri and Ramsey, were noted as performing well while Schwarzmann and 101–14 suffered badly) as the typically more extensive root systems could potentially transport the required volumes of water to assist with hydrating and cooling the canopy (Dry 2007). In contrast, greater heat-stress damage was reported where impediments to root growth were evident.

Vines yielding larger crops require more water (McCarthy et al. 1992). Increasing the water application with consideration of, and compensation for, any higher cropping level reduced damage.

2. Poor canopy cover and/or bare inter-row increased exposure of the berries to radiation impact

Exposed berries were most affected due to the addition of radiant energy/heat to the berries already heated by the ambient temperature. Encouraging good canopy growth from early in the season, therefore ensuring leaf-canopy shading of potentially exposed fruit, was important in reducing damage.

Modified use of fruiting wires can offer improved protection for otherwise exposed fruit. For example, a ‘lazy-lift’ of fruiting wires on the west side of north-south oriented rows ensured the leaf-canopy protected the fruit-zone from direct radiation. Similarly, preventing downward rolling of the canopy by appropriate positioning of foliage wires can assist in reducing fruit exposure with some trellis designs.

Where the vineyard inter-row was bare, there was evidence of radiation from the heated soil affecting berries lower in the canopies at some sites. Under-vine mulch and inter-row swards or cover crops reduced this impact.

3. Vineyards with east-west row orientation were generally less severely impacted than those with north-south row orientation

In vineyards with east-west oriented rows the berries typically received little direct radiant energy/heat as the sun passed over the top of the canopy and did not shine directly on the canopy sides. On north-south oriented rows, in the hot afternoons, the west aspect received direct radiant energy/heat. The combination of this radiant input on already heated berries resulted in higher heat-loads and susceptibility to damage.

4. Some phenological stages were more vulnerable to damage

Grapes in the pre-veraison stage (or pea stage) (McIntyre et al. 1982) at the time of the heatwave generally escaped major damage. Grapes at the veraison stage at the time of the event were more impacted than most.

Post veraison grapes were reported to have lower damage. This might be linked to those grapes tending to be grown in the hotter districts (more advanced phenology) and therefore being on different trellis and experiencing different watering regimes. It may be worth noting, however, that different internal water transport mechanisms would operate as the berry develops through the veraison and post-veraison period (Greenspan et al. 1994). Water transport out from the berry post-veraison is not as responsive. This factor could also be implied with our results.

As a general rule some of the management options are short-term or more reactive or tactical and can be applied (providing the grower is ready) as a heat wave is forecast (e.g. extra water if available), and some are more strategic or longer-term proactive changes to management that must be implemented well in advance (e.g. pruning level, radiation protection). Some are required to be implemented in the vineyard planning stage so may not be amenable to management action but will govern the overall responses (e.g. soil, site and climate) (Figure 12).

It is possible that some regions may have been more vulnerable due to the cool conditions prior to the event. Some plant secondary metabolites (mainly phenolic compounds, flavonoids, and hydroxycinnamate esters) accumulate in the vacuoles of epidermal cells in response to UV-B irradiation and protect plants from further damage from subsequent or intense radiation (and act in the same manner as a sunscreen) (Frohnmeyer and Staiger 2003). Vineyards that were not ‘pre-conditioned’, due to cooler November and December temperatures, may have had reduced levels of these compounds and therefore less protection from radiation, consequently suffering increased damage (Downey et al. 2006).

Where leaves were damaged, desiccated, or entirely lost due to heat-stress induced lack of water (Thorne et al. 2006), subsequent ripening of the berries would have been impacted (Kliewer and Dokoozlian 2001). Stalled or delayed sugar accumulation was observed by many of the vineyard managers throughout all of the regions. Up to three weeks delay was noted in regions with a relatively cool lead-up to the heat event (e.g. Mornington Peninsula, Coonawarra). A lack of acclimation may have contributed to these increased delays in ripening, as consistently higher temperatures throughout a growing season have been shown to produce higher thermostability of photosynthesis functionality in grapevine leaves (Zsofi et al. 2009).

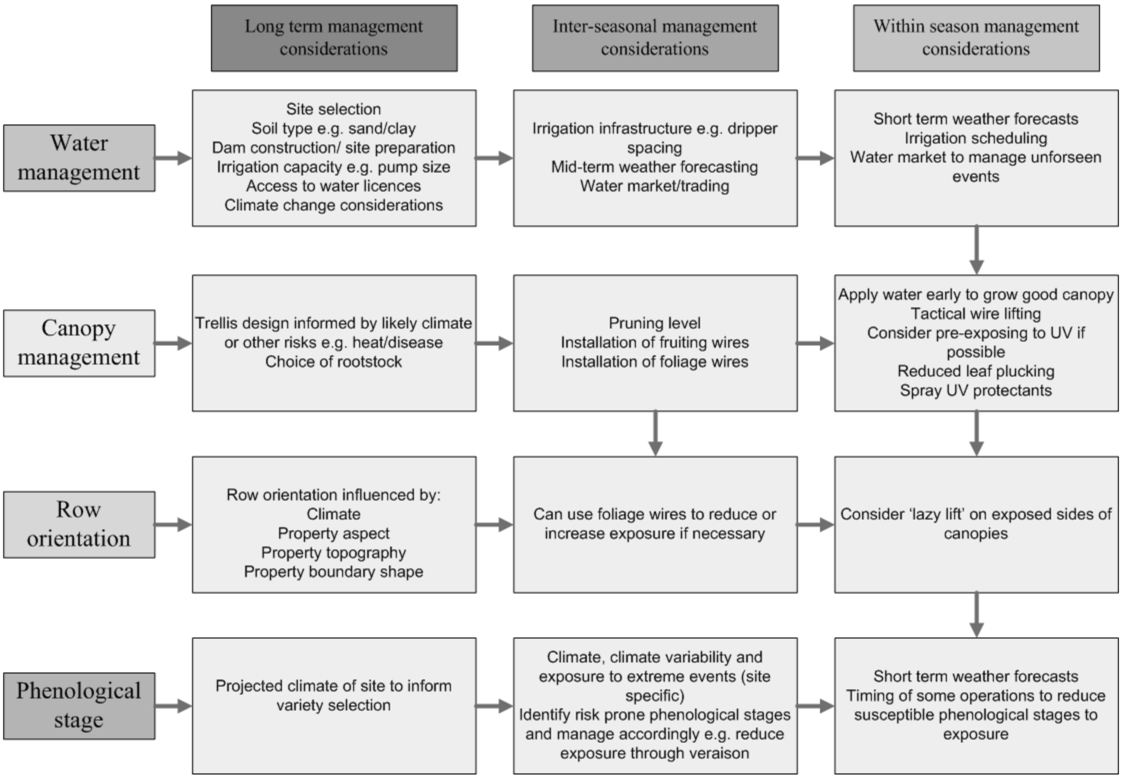


Figure **12** Timeframes of management options

Significant night-time stomatal conductance and transpiration is associated with higher daytime evapotranspiration values and the driving gradient between the leaf and the atmosphere at night (Snyder et al. 2003). Warm nights were experienced in all regions implying possible night-time water loss. McLaren Vale, a region with reported high levels of impact, experienced exceptionally high over-night temperatures which may have increased water demand. If not factored in to the irrigation budget this may have contributed to the heat-stress. While no studies have yet reported or quantified water loss at night in grapevines, with warm nights projected to increase (Alexander and Arblaster 2009) it may be prudent to re-evaluate water budgeting to incorporate night-time losses.

Other useful strategies mentioned by the managers are noted for consideration and perhaps further investigation:

- grapevine nutrition and overall health were deemed important to withstanding the added stress of an extreme heat event;
- physical barriers to UV radiation (e.g. kaolin clay sprays used in apple production (Glenn et al. 2001)) require further evaluation;
- having a diesel-powered back-up for electric irrigation pumps can be important due to the increased possibilities of power cuts during severe heat events.

Throughout the ten regions surveyed there is a range of management practices employed with regard to fruit exposure, and to sophistication of water management. These have evolved in response to the more typical risks to which the vineyards are exposed such as high temperatures in the more northern vineyards and disease pressure in the more southern vineyards. It must be emphasised that a major shift in management in response to this heatwave (e.g. reduction to fruit exposure) may predispose the crop to other risks in more typical seasons, with similar magnitudes of losses. Adjusting viticultural management will be, even more than previously, a risk minimisation exercise. Questions of fruit exposure vs. non-exposure, the cost of water security, rootstock, vine training and trellising, and choice of row orientation may need to be re-evaluated being mindful of more typical climate variability, but with due consideration of a hotter projected climate.

Conclusion

Capturing the observations and management decisions made by a significant cross-section of winegrape industry practitioners soon after a severe heatwave has proved extremely informative. Their depth of knowledge, both intuitive and technical, has revealed diverse approaches that ameliorated the impact of the heatwave. Documenting these, as their effectiveness varied across and within regions and even vineyards, allows the industry to identify the management strategies that, going forward, may assist this important sector and other horticultural enterprises to cope in an increasingly challenging environment.

Acknowledgements

We wish to thank all the vineyard managers who so willingly participated in the interviews during a busy time of the season. We also wish to thank Graeme Russell (Macquarie University) who assisted with development of the survey questionnaire, Adam Peitch (CCW, Riverland) and Ian Smith (CSIRO Marine and Atmospheric Research) for helpful suggestions. Thanks also to Grape and Wine Research and Development Corporation (GWRDC) for funding the project.

This information was presented at the 14th Australian Wine Industry Technical Conference, 4-7 July 2010, Adelaide, South Australia.

Please access the full report using the following link:
http://www.landfood.unimelb.edu.au/vitum/Heatwave.pdf

Bibliography

ALEXANDER, L.V., and ARBLASTER, J.M. (2009) Assessing trends in observed and modelled climate extremes over Australia in relation to future projections. *International Journal of Climatology* 29: 417-435. http://dx.doi.org/10.1002/joc.1730

AUSTRALIAN BUREAU OF METEOROLOGY (2008a) SPECIAL CLIMATE STATEMENT 16 Long-term rainfall deficiencies continue in southern Australia while wet conditions dominate the north. http://www.bom.gov.au/climate/current/statements/scs16.pdf

AUSTRALIAN BUREAU OF METEOROLOGY (2008b) Bureau of Meteorology website. Australian Government. http://www.bom.gov.au/climate/

DEO, R.C., MCALPINE, C.A., SYKTUS, J., MCGOWAN, H.A., and PHINN, S. (2007) On Australian heat waves: Time series analysis of extreme temperature events in Australia, 1950 - 2005. In *MODSIM 2007 International*

Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand. Oxley, L. and Kulasiri, D. (eds.), pp. 626-635. http://www.mssanz.org.au/MODSIM07/papers/10_s61/OnAustralianHeat_s61_Deo_.pdf

DOWNEY, M.O., DOKOOZLIAN, N.K., and KRSTIC, M.P. (2006) Cultural practice and environmental impacts on the flavonoid composition of grapes and wine: A review of recent research. *American Journal of Enology and Viticulture* 57: 257-268.

DRY, N. (2007) *Grapevine rootstocks. Selection and management for South Australian vineyards.* Adelaide, SA: Lythrum press in association with Phylloxera and Grape Industry Board of South Australia.

ESRI (2007) ArcINFO GIS mapping software. http://www.esri.com/software/arcgis/arcinfo/about/features.html

FLEXAS, J., BOTA, J., CIFRE, J., ESCALONA, J.M., GALMES, J., GULIAS, J., LEFI, E.-K., MARTINEZ-CANELLAS, S.F., MORENO, M.T., RIBAS-CARBO, M., RIERA, D., SAMPOL, B., and MEDRANO, H. (2004) Understanding down-regulation of photosynthesis under water stress: future prospects and searching for physiological tools for irrigation management. *Annals of Applied Biology* 144: 273-283.

FROHNMEYER, H., and STAIGER, D. (2003) Ultraviolet-B radiation-mediated responses in plants. Balancing damage and protection. *Plant Physiology* 133: 1420-1428. http://www.plantphysiol.org

GLENN, D.M., PUTERKA, G.J., DRAKE, S.R., UNRUH, T.R., KNIGHT, A.L., BAHERLE, P., PRADO, E., and BAUGHER, T.A. (2001) Particle film application influences apple leaf physiology, fruit yield, and fruit quality. *Journal of the American Society for Horticultural Science* 126: 175-181. http://www.ars.usda.gov/SP2UserFiles/person/2017/Particle%20film%20application%20influences%20apple%20leaf%20etc.pdf

GREENSPAN, M.D., SHACKEL, K.A., and MATTHEWS, M.A. (1994) Developmental changes in the diurnal water budget of the grape berry exposed to water deficits. *Plant, Cell and Environment* 17: 811-820. http://dx.doi.org/10.1111/j.1365-3040.1994.tb00175.x

HAYMAN, P., MCCARTHY, M.G., and GRACE, W. (2009) Assessing and managing the risk of heatwaves in SE Australian wine regions. *Australian and New Zealand Grapegrower and Winemaker* 543: 22-24.

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. SOLOMON, S., QIN, D., MANNING, M., CHEN, Z., MARQUIS, M., AVERYT, K.B., TIGNOR, M. and MILLER, H.L. (eds.): Cambridge University Press, Cambridge, pp. 18. http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf

KAROLY, D.J. (2009) The recent bushfires and extreme heatwave in southeast Australia. *Bulletin of the Australian Meteorological and Oceanographic Society* 22: 10-12.

KENNISON, K.R., WILKINSON, K.L., WILLIAMS, H.G., SMITH, J.H., and GIBBERD, M.R. (2007) Smoke-derived taint in wine: effect of postharvest smoke exposure of grapes on the chemical composition and sensory characteristics of wine. *Journal of Agriculture and Food Chemistry* 55: 10897-10901.

KLIEWER, W.M., and DOKOOZLIAN, N.K. (2001) Leaf area/crop weight ratios of grapevines: Influence on fruit composition and wine quality. In *Proceedings of the ASEV 50th Anniversary Annual Meeting*. RANTZ, J.M. (ed.) Seattle, Washington, June 19-23: American Society of Enology and Viticulture, pp. 285-295.

KRIEDEMANN, P.E., and SMART, R.E. (1969) Effects of irradiance, temperature and leaf water potential on photosynthesis of vine leaves. *Photosynthetica* 5: 15-19.

MCCARTHY, M.G., JONES, L.D., and DUE, G. (1992) Irrigation-Principles and Practices. In *Viticulture Volume 2: Practices*. Coombe, B.G. and Dry, P.R. (eds). Adelaide: Winetitles, pp. 104-128.

MCINTYRE, G.N., LIDER, L.A., and FERRARI, N.L. (1982) The chronological classification of grapevine phenology. *American Journal for Enology and Viticulture* 33: 80-85.

NATIONAL CLIMATE CENTRE (2009) Special climate statement: The exceptional January-February 2009 heatwave in south-eastern Australia. *Bulletin of the Australian Meteorological and Oceanographic Society* 22: 13-19. http://www.bom.gov.au/climate/current/statements/scs17d.pdf

SMART, R.E., ALCORSO, C., and HORNSBY, D.A. (1980) A comparison of winegrape performance at the present limits of Australian viticultural climates-Alice Springs and Hobart. In *The Australian Grapegrower and Winemaker*. Vol. 184 Adelaide: Winetitles, pp. 28 and 30.

SMART, R.E., and ROBINSON, M. (1991) *Sunlight into Wine. A handbook for winegrape canopy management.* Adelaide: Winetitles.

SNYDER, K.A., RICHARDS, J.H., and DONOVAN, L.A. (2003) Night-time conductance in C3 and C4 species: do plants lose water at night? *J. Exp. Bot.* 54: 861-865. http://jxb.oxfordjournals.org/cgi/content/abstract/54/383/861

STRAUSS, A., and CORBIN, J. (1998) *Basics of Qualitative Research.* Thousand Oaks: Sage Publications.

THORNE, E.T., STEVENSON, J.F., ROST, T.L., LABAVITCH, J.M., and MATTHEWS, M.A. (2006) Pierce's disease symptoms: Comparison with symptoms of water deficit and the impact of water deficits. *American Journal of Enology and Viticulture* 57: 1-11. http://www.ajevonline.org/cgi/content/abstract/57/1/1

WEBB, L., DUNN, G., and BARLOW, E.W.R. (2008) Water allocation scenarios in key regions within the Murray Darling Basin for the 2008/09 season and beyond. South Australia: GWRDC. http://www.gwrdc.com.au/webdata/resources/files/Mod6-Water2008-09AndBeyond.pdf

WEBB, L., WHITING, J., WATT, A., HILL, T., WIGG, F., DUNN, G., NEEDS, S., and BARLOW, E.W.R. (2010) Managing extreme heat in the vineyard-some lessons from the 2009 summer heatwave. In *Managing Climate*

Change: Papers from the GREENHOUSE 2009 Conference. JUBB, I., HOLPER, P.N. and CAI, W. (eds). Melbourne: Springer/CSIRO Publishing, pp. 123-135.

WHITE, M.A., DIFFENBAUGH, N.S., JONES, G.V., PAL, J.S., and GIORGI, F. (2006) Extreme heat reduces and shifts United States premium wine production in the 21st Century. *Proceedings of the National Academy of Sciences* 103: 11217-11222.

ZSOFI, Z., VARADI, G., BALO, B., MARSCHALL, M., NAGY, Z., and DULAI, S. (2009) Heat acclimation of grapevine leaf photosynthesis: mezo- and macroclimatic aspects. *Functional Plant Biology* 36: 310-322.

Appendix 6: Comparison of temperature and rainfall projections for selected world winegrowing regions.

L. B. Webb[1,2], I. Watterson[2], J. Bhend[2], and P.H. Whetton[2]

1. School of Land and Environment, University of Melbourne, Parkville Victoria, Australia

2. CSIRO Climate Adaptation National Research Flagship, Melbourne, Victoria, Australia.

Corresponding author:

L. B. Webb Tel: +613 92394549, Fax: +613 92394444, e-mail: leanne.webb@csiro.au

Abstract

Calculations of estimated projected warming and changes to precipitation for 35 selected wine regions of the world are presented here. In this study 23 CMIP3 global climate models are employed and estimates for the median, 10th percentile and 90th percentile of model results are assessed. Projected climate by 2030 and 2070, resulting from climate model pattern scaling forced using A1B and A1FI emission scenarios are considered. The time-frames and greenhouse gas forcings were selected so as to approximately equate to global average warmings of 1, 2 and 3°C.

Warming is projected for all of the regions studied with greater warming in the Northern Hemisphere continental regions and less for the Southern Hemisphere and coastal regions. Annually, projections for rainfall vary across regions with indications of a likely wetter future some higher latitude regions (e.g. New Zealand; Mosel and North Oregon) and also Chinese vineyards. Other regions in Southern Europe, Australia and South Africa have a drier future climate projected. Winter rainfall is projected to decrease in Chile, Greece, Australia and Spain, with other European regions and the American regions studied here likely to have slight increases in winter rainfall. For summer rainfall China is the only region likely to experience a wetter climate. Comparisons of the relative climate changes are discussed.

Future climate for 2030 and 2070 are compared and contrasted with current climate conditions among the different regions. Under a 2°C global warming for instance, projected summer climate for Mosel in Germany, a region famous for producing Riesling, is likely to be warmer than the current average summer in Bordeaux, France, renowned for production of Cabernet Sauvignon. Implications for viticultural management, particularly suitability of varieties, will be an important issue when planning future vineyard developments. The regional inter-comparison made available here informs potential options whereby future climates can be easily compared to current climates across regions.

Introduction

Winegrapes *Vitis vinifera L.* are planted across five continents of the globe. In 2009 the total global area dedicated to vineyards was 7,660,000 hectares, with the greatest percentage of plantings in Europe. The global vineyard footprint decreased in 2009 by 1%, or 70000ha. The USA (-9.3%), Europe (-

6%) and Oceania (Australia and New Zealand) contributed to the global decline, while Argentina, Chile and China have expanding industries (OIV 2010) (Figure 1). In recent decades a rapid globalisation of world wine markets has occurred with the volume of exports as a proportion of world wine production rising from 15 to 25 percent between 1988-90 and 2001 (Anderson & Nelgen 2011).

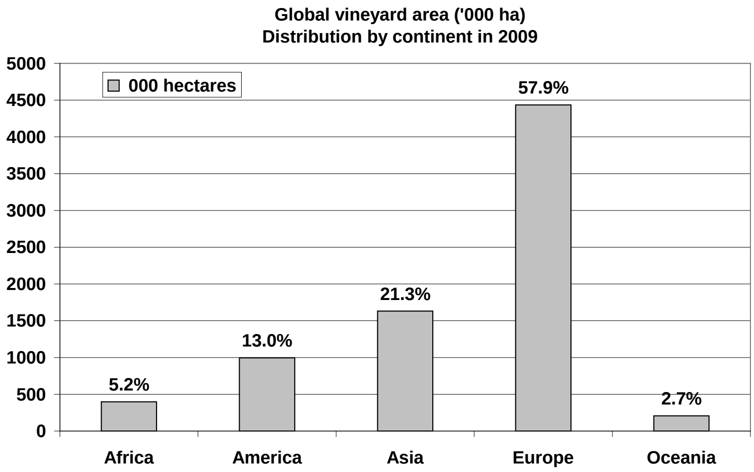


Figure 1 Vineyard area distribution by continent in 2009 (OIV 2010)

Winegrowing regions around the world have developed reputations over the past decades and even centuries for production of different wine styles. The winegrape industry is intimately wedded to the concept of *terroir:* matching premium grape varieties to select combinations of climate and soils to produce unique wines of distinctive styles (Seguin 1986). It is well known that different winegrape varieties have different genetically determined phenology, or annual developmental phases (Schwartz 2003), which results in very different times of harvest (Gladstones 1992, Kerridge & Antcliff 1996). Matching of the phenology of the different varieties to a particular climate is a fundamental aim for every vineyard manager (Jones & Davis 2000). This ensures that the ripening temperature regime is suitable for the development of flavours and aromas to produce a desired wine style. A number of past studies have investigated matching of varieties to climate for California (Amerine & Winkler 1944), Australia (Gladstones 1992), European grape growing regions (Jackson & Cherry 1988, Kenny & Shao 1992), and in Canada (Jones *et al.* 2004).

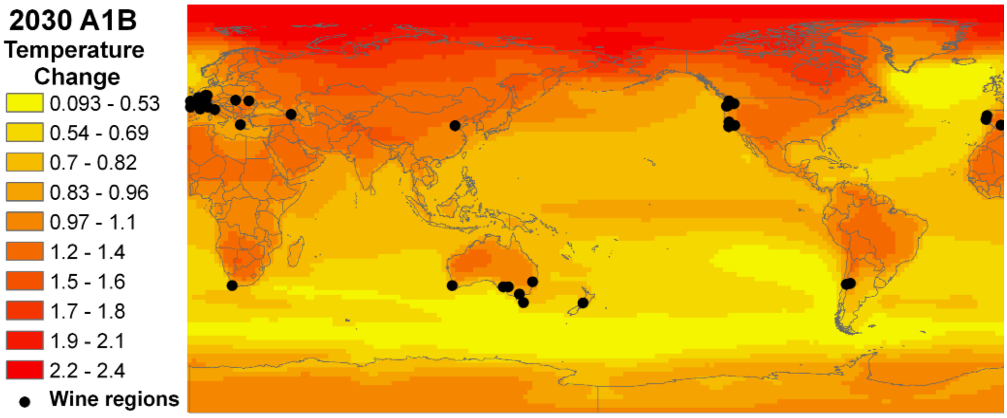
Since the Industrial Revolution, around 1750, the atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased by 35%, 148% and 18%, respectively (IPCC 2007). The Earth's average surface temperature has increased by approximately 0.7˚C since the beginning of the 20th Century. Most of the warming since 1950 is very likely due to increases in atmospheric greenhouse gas concentrations due to human activities, and with emissions of greenhouse gases (GHG's) likely to continue and even increase in future, further warming of the climate system is likely (IPCC 2007).

The winegrape industry around the world is alert to the effects of global warming and the associated changes to precipitation patterns because these changes alter the *terroirs* directly (Seguin & de Cortazar 2005). Evidence suggests that as climates warm, winegrape phenology progresses more swiftly and grapes ripen earlier (Le Roy Ladrie 1988, Chuine *et al.* 2004, Jones *et al.* 2005a, Seguin & de Cortazar 2005, Webb *et al.* 2011b). Negative impacts on winegrape quality as a result of ripening in a warmer climate during a warmer part of the year have been quantified for Australia (Webb *et al.* 2008a, 2008b) and globally (Jones *et al.* 2005b). These results can be explained by the rate of change in fruit composition being strongly influenced by temperature, with higher temperatures increasing the speed of sugar development, hastening acid degradation, and altering flavour compounds (Coombe & Iland 2004, Lund & Bohlmann 2006, Conde *et al.* 2007, Zamora 2007). It is for these reasons that interest in growing varieties better suited to a particular site in a warmer future climate is increasing (Webb *et al.* 2011a).

To maintain growth of varieties suited to a warmer projected climate sourcing varieties being successfully managed in warm to hot climates, using a 'climate analogue approach', is recommended for some regions (Jones 2007, Webb *et al.* 2007). Again, past studies have addressed this approach. Schultz (2000) used the Huglin Index (Huglin 1986) to illustrate the impact of climate change on varietal suitability with a spatial assessment. Kenny and Harrison (1992) examine possible geographical movement of core viticultural sites in Europe, and an Australian analysis also illustrated potential shifting varietal suitability (Webb *et al.* 2007). These analyses have all been limited to the study of one region. With markets for wine becoming more globally competitive (Anderson & Nelgen 2011), comparison of the worlds winegrowing regions, as they are affected by the changing climate, is therefore deemed appropriate.

Critical to this competitor analysis of major global wine regions is that the projected shifts in both temperature and rainfall will not be spatially uniform. Some winegrowing regions of the globe will warm faster than others, and some are likely to get wetter while others are likely to get drier in an enhanced greenhouse world (IPCC 2007) (Figure 2). Another factor to consider is that the baseline climate also varies across winegrowing regions of the world with both warmer and cooler winegrowing regions producing quality wine. This global projection analysis offers winegrowing practitioners a chance to assess the spatial variability of the changing climate as it affects their industry. These results can be considered separately for each region in the context of the former studies on varietal suitability, but of potentially more interest is the global inter-comparison of projected changes. Relative differences in shifts for various regions expose both more vulnerable and more resilient winegrowing regions of the world. Regional comparisons of current climate with future climate conditions may inform adaptation potential.

Here, we present the first study to focus on the spatial variation of projections of climate change, for temperature, and for the first time, rainfall, likely to occur across the world's wine regions out to 2030 and 2070 incorporating information from more than one climate model. In the first global study of impacts of temperature change on different wine regions of the world warming temperature trends resulting from running the HadCM3 model were calculated (Jones *et al.* 2005b). There exists, however, a range of responses forced by rising greenhouse gas concentrations among the various global climate models. Given the spread of model results for many cases, it is clear that there is considerable uncertainty in such projections, even for a particular forcing scenario (Watterson 2008).The motivation to use several models for prediction is based on the experience from many applications that the combined information of many models performs better than a single model (Jun *et al.* 2008). This assessment of climate projections uses 23 different climate models to address the issue of variation in the output of global climate models (Watterson 2008, Watterson & Whetton 2011).



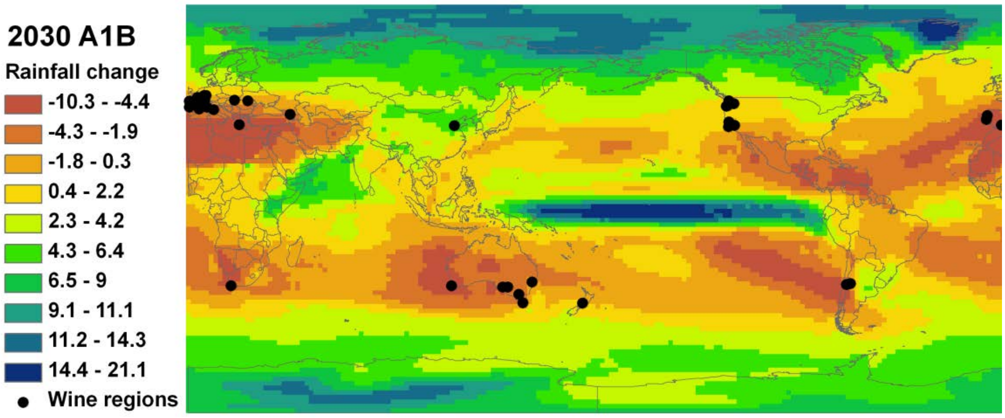


Figure 2 Projected annual temperature change (°C) (top), and annual rainfall change (%) (bottom) by 2030 (A1B emission scenario) as it varies spatially across the globe. Results depicted indicate the median of 23 CMIP3 climate models (Watterson & Whetton 2011). Blue circles indicate wine growing sites assessed in this analysis.

Global emissions uncertainty is addressed by considering a selection of possible emission scenarios outlined in the Intergovernmental Panel for Climate Change special report on emissions scenarios (IPCC SRES) (Nakićenović & Swart 2000). The announcement of the aspirations in the Copenhagen Accord (COP 15) whereby prevention of "dangerous anthropogenic interference with the climate system…. recognising the scientific view that the increase in global temperature should be below 2 degrees Celsius" (http://unfccc.int/files/meetings/cop_15/application/pdf/cop15_cph_auv.pdf), and also with the knowledge more than 100 countries have adopted this global warming limit of 2°C or below (relative to pre-industrial levels) (Meinshausen *et al.* 2009), implies that the SRES scenarios may become redundant in future. A sensitivity analysis rather than scenario analysis will remain relevant if mitigation of greenhouse gas emissions do not follow the SRES pathways. For this reason the SRES scenarios were carefully chosen to estimate global average warming of 1, 2 and 3°C warming (1°C_{gaw}, 2°C_{gaw}, 3°C_{gaw}). Thus, projection results could be viewed to be independent of GHG emissions uncertainty.

Method

Regions

More notable winegrowing regions of the world (Johnson 1989) were selected for this analysis. Many of these regions have been assessed in previous studies of climate impacts on wine regions of the world (Jones *et al.* 2005b, Webb *et al.* 2008a), furthermore we attempted to capture the most important production areas (Anderson & Nelgen 2011) (Figure 3 and Table 1).

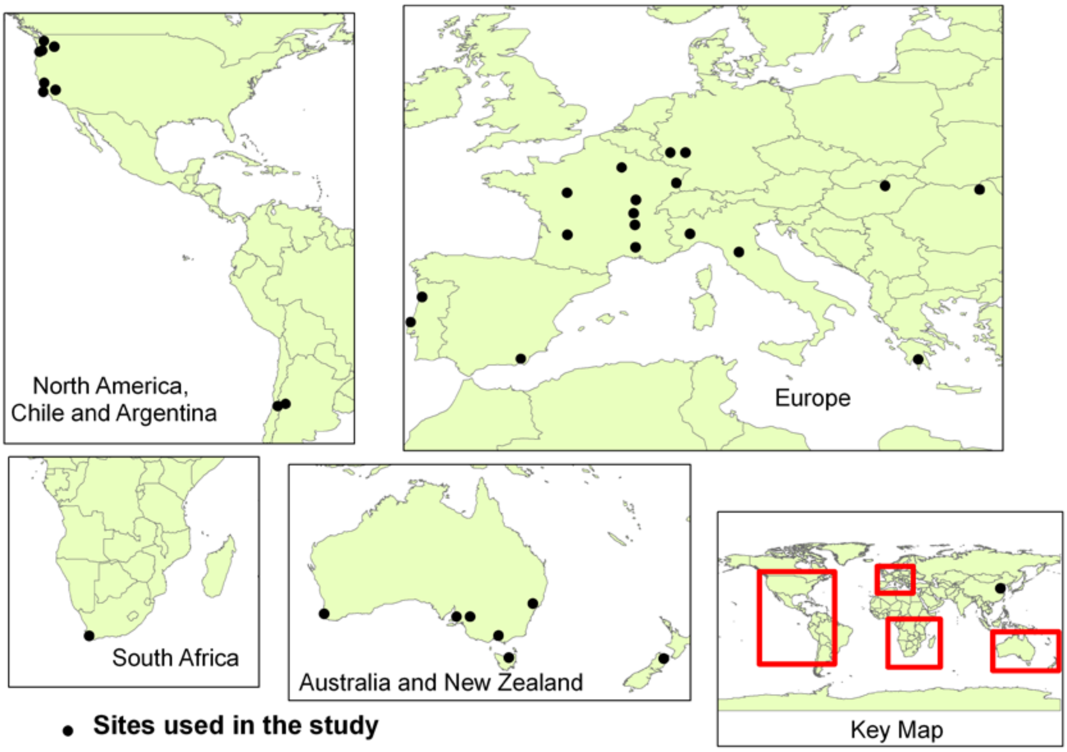


Figure 3 Sites used in this study. The Shandong (China) site is indicated in the key map.

Projections

Patterns of change taken from simulations of 23 CMIP3 models (Watterson & Whetton 2011), using a method of estimating distributions and “probability density functions” (PDFs) for forced change, are employed here to generate changes in temperature and precipitation at locations over the globe. The patterns are scaled in this assessment to represent various plausible future climates. By using this technique the range of responses, forced by changes in greenhouse gas concentrations, resulting from these global climate models are considered. This methodology has previously been used for calculating projections for Australia (CSIRO and Australian Bureau of Meteorology 2007).

Global warming estimates and representative ranges have been documented in the IPCC SRES (Nakićenović & Swart 2000) (Figure 4). By 2030 given an A1B emission scenario the globe is estimated to warm by 0.9°C (0.5-1.4°C) (CSIRO and Australian Bureau of Meteorology 2007). By 2070, under the A1B scenario, global average warming of 2.1°C (1.3-3.4°C) is estimated. Given a higher emission scenario (A1FI) by 2070 global average warming of 2.9°C

(1.7-4.6°C) is estimated (Figure 4). In displaying the results for these storylines and timeframes we demonstrate how a global average warming of approximately 1°C, 2°C and 3°C may translate to for selected wine regions of the world and how this may vary regionally.

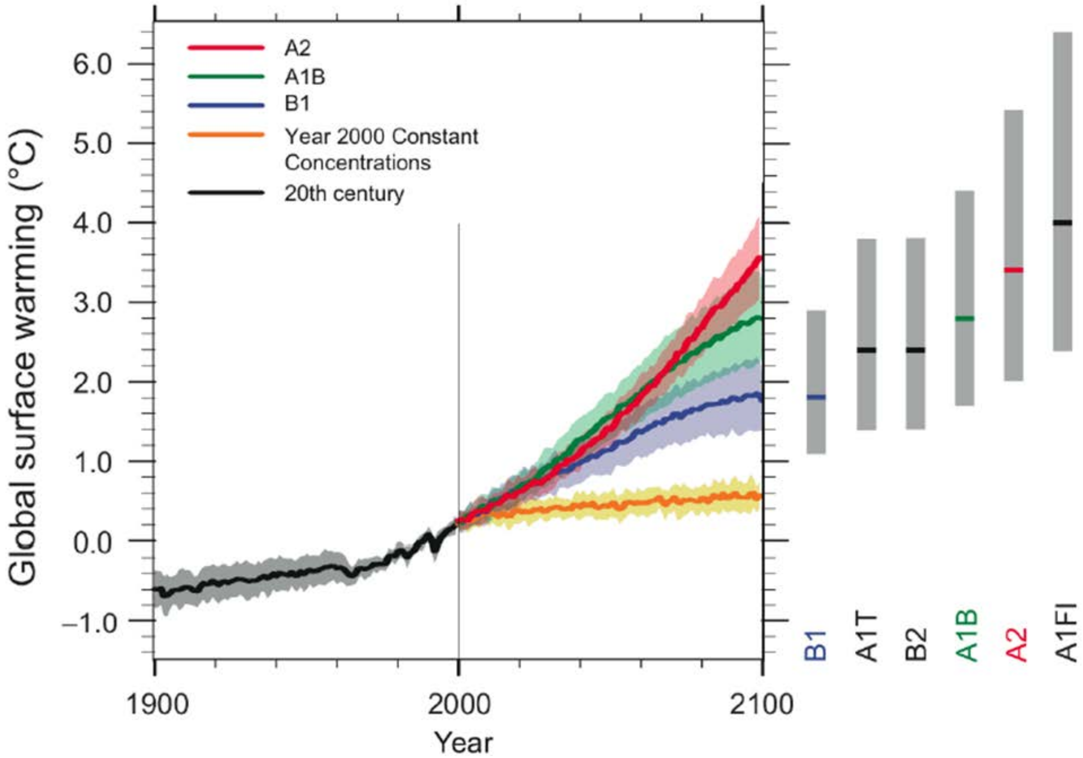


Figure 4 Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios. The assessment of the best estimate and likely ranges in the grey bars includes the Atmosphere and Ocean Global Climate Models (AOGCMs) in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints (IPCC 2007).

Projected changes in climate variables include ranges of uncertainty. A component of the uncertainty is due to different regional responses to global warming in different climate models. As a result, the low (high) scenarios of several climate variables (e.g. temperature and rainfall) *should not be combined* to create best case (worst case) climate change scenarios. This is because since such a combination might not actually be realisable in any individual model. Scenarios that are consistent between climate variables should be derived from the output of *individual* climate models. Model-specific scenarios are critical for detailed risk assessments, for which multiple variables are important. The utility of the projections presented in this report is in providing an overview of the likely changes in a wide variety of climatic aspects for selected World wine regions.

Baseline climatology and periods of measurement

Baseline climate of 1980-1999 is used for this analysis as the projections are calculated from this baseline period (Watterson & Whetton 2011). Internal climate variability is estimated here by calculating the 90 percent confidence interval of the climate for the period 1980-1999.

Results

Temperature and precipitation projections are listed for all of the sites studied for the period 2070, A1FI emission scenario (2070_A1FI), or ~3°C_{gaw} (Table 1). From this table the variation in the rate of warming and change to precipitation can be noted. There is more warming apparent in the continental sites in the Northern Hemisphere with the Russian site warming by 3.8°C (2.6-5.4°C) by 2070_A1FI. Southern Hemisphere and or coastal regions are likely to warm at a slower rate. By 2070_A1FI Marlborough in New Zealand is projected to warm by 2.2°C (1.5-3.2°C) (annual). Annual temperatures for Launceston in Northern Tasmania are projected to warm at the slowest rate of the sites selected for this study. By 2070_A1FI Launceston is projected to warm by 2.0°C (1.3-3.0°C).

Some winegrowing regions are projected to have reduced annual rainfall in future, while in others annual rainfall may increase. Greece is the region with the greatest projected drying of 21.9% (39% to 8% drier) by 2070_A1FI. Spain also has a projected declining rainfall outlook. In Australia, the Margaret River is the site where the greatest drying is projected 20.7% (40% to 3%) by 2070_A1FI (Table 1).

Regions in the higher latitudes (both Northern and Southern Hemispheres) may have a wetter climate in future. For the Shandong region of China all models are indicating a wetter future climate, 17% wetter (1-38%). The median of the model projections for the more northern sites in the USA also indicate a wetter future climate. Central Washington, for instance, may be 6% wetter in future (model ranges between 5% drier to 18% wetter). For all of the French vineyard regions a drier future is indicated: Champagne (2% drier), Burgundy (6% drier) and Bordeaux (10% drier) (Table 1).

The pattern of spatial variation in annual warming and rainfall change is illustrated for 2030 forced with the A1B emission scenario (2030_A1B) (1°C_{gaw}) (Figure 2).

Table1 Winegrowing regions selected for assessment, representative towns and their location (latitude and longitude used for the calculations) are listed. Baseline climatology for both temperature and rainfall (annual average 1980-1999) are shown. Climate projections for temperature and precipitation (annual) calculated for the period cantered on 2070_A1FI are presented for each site. The 10th percentile, the median (50th percentile) and the 90th percentile of the 23 CMIP3 models described in Watterson & Whetton (2011) are given for each site to indicate the range of output generated by these models.

				Temperature				Precipitation			
Region	Town	Latitude	Longitude	Ann. ave	10	50	90	Ann. ave	10	50	90
Spain Rioja	Rioja	36.93	2.45	18.0 ± 0.8	2.08	3.50	4.79	484.0 ± 183.1	-39.63	-21.91	-7.09
USA Sth California	Fresno	36.73	240.23	17.9 ± 1.2	2.27	3.33	4.69	264.7 ± 173.5	-28.00	-2.57	28.33
South Africa	Stellenbosch	-33.93	18.85	17.2 ± 0.7	1.60	2.44	3.58	589.9 ± 136.4	-32.14	-16.91	-3.70
Aust. Riverland	Loxton	-34.45	140.57	16.9 ± 0.8	2.00	2.91	4.10	212.8 ± 85.9	-35.11	-10.69	12.24
Aust. Barossa Valley	Nuriootpa	-34.47	138.25	16.8 ± 0.8	1.91	2.77	3.90	398.1 ± 121.9	-34.46	-12.06	8.64
Argentina	Mendoza	-32.88	291.17	16.4 ± 0.8	2.09	2.97	4.06	178.3 ± 88.3	-34.43	-12.78	8.67
Portugal Sth.	Caldas da Rainha	39.4	350.87	16.3 ± 0.7	1.39	2.50	3.92	845.5 ± 356.1	-38.98	-20.33	-3.82
Aust. Hunter Valley	Muswellbrook	-32.27	151.25	16.1 ± 0.9	2.22	3.32	4.77	850.1 ± 363.5	-29.31	-6.17	15.81
Aust. Margaret River	Margaret River	-33.95	115.75	15.9 ± 0.9	1.69	2.44	3.40	823.5 ± 217.9	-39.63	-20.72	-2.96
Portugal Nth.	Porto	41.13	351.4	15.3 ± 0.7	1.30	2.42	3.85	1147.2 ± 307.1	-33.51	-16.52	-1.23
Aust. Yarra Valley	Yarra Valley	-37.65	145.37	14.4 ± 0.8	1.82	2.64	3.70	754.9 ± 217.8	-27.17	-11.91	1.26
USA Coastal California	Napa	38.3	237.72	14.3 ± 1.1	2.21	3.19	4.42	778.2 ± 564.4	-22.53	0.01	26.43
China (Shandong)	Shandong	36.67	117.02	14.1 ± 0.8	2.47	3.65	5.19	560.5 ± 260.2	0.97	17.33	38.21
USA Nth. California	Sonoma	36.28	237.55	13.9 ± 0.9	2.00	2.91	4.09	907.1 ± 609.2	-26.58	-0.61	30.06
Greece	Sparti	37.07	22.43	13.8 ± 0.8	2.06	2.98	4.14	695.3 ± 267.4	-38.71	-21.94	-8.34

				Temperature				Precipitation			
Region	Town	Latitude	Longitude	Ann. ave	10	50	90	Ann. ave	10	50	90
S. Rhone Valley	Chateauneuf du Pape	44.05	4.82	13.7 ± 0.9	2.25	3.37	4.88	796.4 ± 295.1	-19.65	-8.31	2.01
Fr. Bordeaux	Bordeaux	44.83	0.57	12.9 ± 1.1	2.07	3.23	4.77	804.7 ± 191.1	-21.85	-10.10	0.01
Chile	Santiago	-33.42	289.45	12.8 ± 0.6	1.83	2.61	3.58	342.1 ± 323.2	-36.78	-15.99	4.48
Italy (Chianti)	Firenze	43.77	11.25	12.6 ± 0.7	2.30	3.46	5.02	718.0 ± 232.2	-21.40	-7.96	4.09
Italy (Barolo)	Asti	44.9	8.2	12.5 ± 0.7	2.22	3.38	4.93	999.0 ± 340.3	-19.98	-7.31	3.87
Aust Nth. Tasmania	Launceston	-41.43	147.13	11.8 ± 0.8	1.31	2.03	2.98	645.1 ± 173.2	-17.98	-6.50	4.51
Fr. Loire Valley	Angers	47.47	0.55	11.8 ± 1.2	1.70	2.83	4.42	666.3 ± 191.5	-15.75	-4.06	7.18
USA East Washington	Seattle	47.6	237.68	11.5 ± 0.9	2.25	3.38	4.88	1035.8 ± 299.3	-4.92	6.41	19.23
USA Nth Oregon	Portland	45.52	237.33	11.0 ± 1.1	1.91	2.91	4.20	1094.1 ± 405.0	-6.98	5.79	20.06
Southern Oregon	Roseburg	45.22	236.67	10.8 ± 1.0	1.89	2.84	4.05	1219.7 ± 478.4	-9.56	4.00	18.69
Russia (Georgia)	Tbilisi	41.7	44.78	10.4 ± 1.2	2.58	3.79	5.37	546.5 ± 170.5	-20.51	-7.12	5.04
Fr. Burgundy-Cote	Beaune	47.02	4.83	10.3 ± 1.1	2.13	3.26	4.75	781.1 ± 238.1	-16.40	-5.67	4.39
Fr. Champagne	Epernay	49.03	3.95	10.3 ± 1.2	1.93	3.02	4.52	689.2 ± 181.0	-13.73	-2.48	8.43
USA Central Washington	Sunnyside	46.32	240	10.1 ± 1.3	2.22	3.44	5.11	187.2 ± 68.1	-5.31	6.14	18.84
Hungary	Eger	47.9	20.37	9.9 ± 1.2	2.33	3.47	4.95	499.9 ± 178.8	-13.28	-1.74	10.28
Ger. Rhine Valley	Rudesheim	49.97	7.92	9.6 ± 1.2	1.87	2.94	4.45	672.3 ± 168.7	-7.99	2.33	13.01
Ger. Mosel Valley	Bernkastel	49.95	6.98	9.4 ± 1.3	1.75	2.85	4.47	813.8 ± 200.7	-8.49	2.07	12.86
Fr. Alsace	Colmar	48.07	7.35	9.1 ± 1.2	1.99	3.07	4.53	950.8 ± 227.7	-11.11	-1.26	8.43
Romania	Suceava	47.65	26.25	8.5 ± 1.5	2.39	3.60	5.21	523.7 ± 176.0	-15.15	-1.80	12.54
New Zeal. (Marl.)	Marlborough	-41.57	173.42	7.6 ± 1.0	1.49	2.24	3.23	1355.0 ±236.9	-6.92	2.33	11.38

1

Projected climate for 2030_A1B (~1°C_{gaw}), 2070_A1B (~2°C_{gaw}) and 2070_A1FI (~3°C_{gaw}) is graphically represented for a selection of the sites in the study (Figure 5, Figure 6 and Figure 7). In these graphs the coolest region (annual temperature) is shown on the bottom progressing to the warmest (annual temperature) on top. It is interesting to compare the warming with the variability in the temperature (90% confidence interval is given by the black error bars on the plots). In all cases the warming by 2030_A1B remains within the range of the baseline climate variability. By 2070_A1B this is not the case. The range of projected climate falls outside the range of experience (1980-1999), and even more so by 2070 if higher emissions are driving the warming (A1FI) (Figure 5).

With regard to annual rainfall, in all cases except for the Margaret River (Aust.), the projected change is not outside the range of the variability experienced over the period 1980-1999, even out to 2070_A1FI (~3°C_{gaw}). This is perhaps more of a comment on the inter-annual variability of rainfall than on the likely impacts of a future wetter or drier climate (Figure 5).

What may be of more relevance when considering the impact of a changing climate on this deciduous plant, is the change to summer temperature and rainfall. It is in this period when the grapes are on the vine and going through the process of ripening (Figure 6). Comparing across the regions it can be noted that the current climate (1980-1999) of Bordeaux may become as warm as some of the hotter years experienced in the Rioja region of Spain by 2070 (~2°C_{gaw}), Mosel (Germany) may be as warm as the Margaret River region of Australia or Bordeaux in France. The Barossa region of Australia may also be similar to Rioja or the Riverland region of Australia by 2070 (Figure 6).

For most regions over the summer period a drying of the climate is noted with European regions likely to experience the greatest reductions. The Shandong region of China is the one region where a likely wetter future summer climate is estimated here (Figure 6).

Winter temperatures are projected to warm in all regions (Figure 7). Average winter temperatures are not likely to fall below freezing in Georgia (Russia) by 2070 (A1FI). The winter climate in this region will likely resemble that (1980-1999) of the Mosel region (Germany) by 2070.

Winter rainfall is projected to increase slightly for the more northern European locations, USA regions and New Zealand. For the Australian sites a likely reduction in winter rainfall is projected (Figure 7).

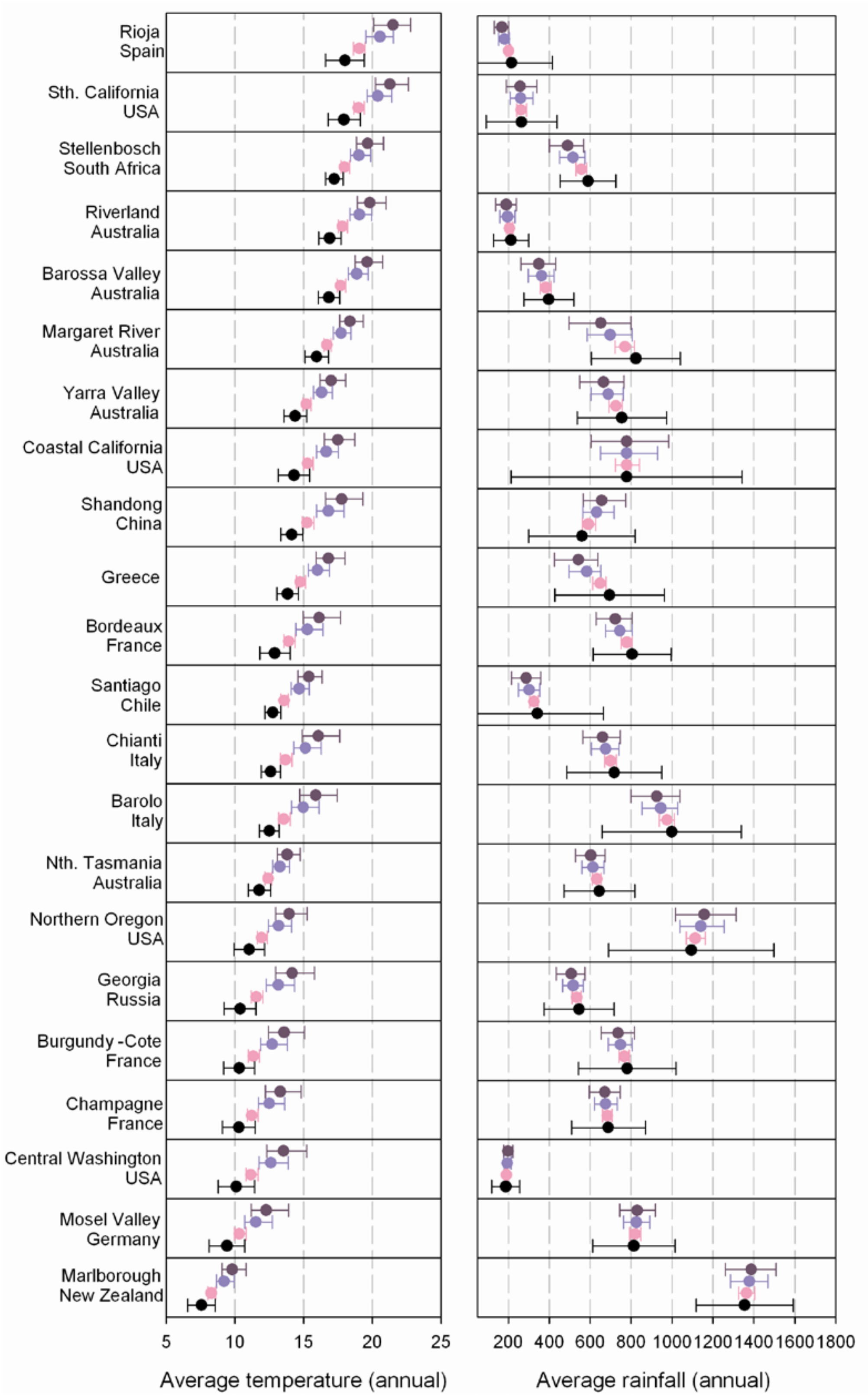


Figure 5 Average temperature and rainfall (annual) for selected wine-growing regions of the world for baseline climatology (1980-1999) (black), and projected climate: 2030 A1B (pink); 2070 A1B (mauve); and 2070 A1FI (purple). Baseline climate error bars indicate 90% confidence interval. Projected climate error bars indicate from the 10th percentile to the 90th percentile of model output.

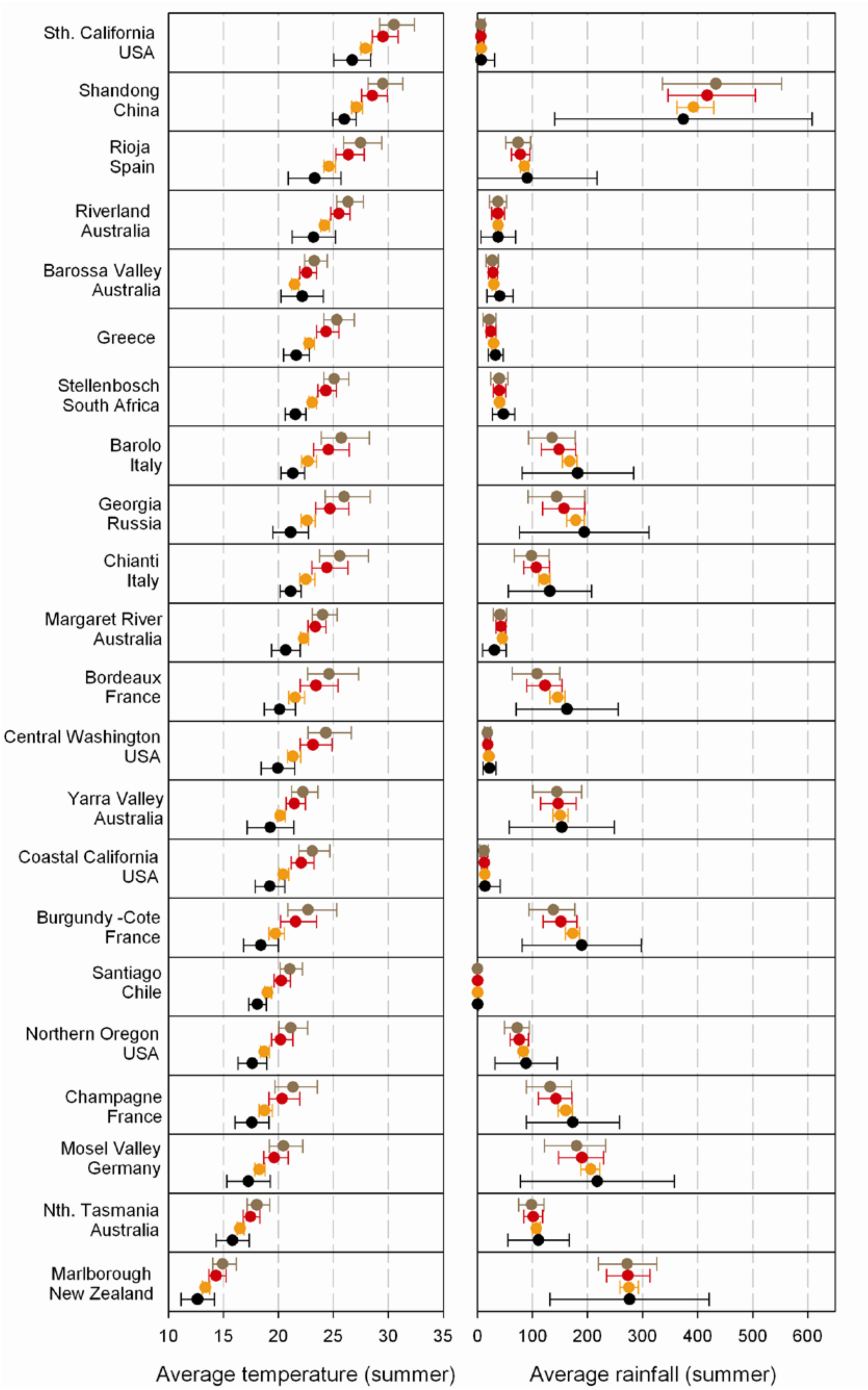


Figure 6 As for Figure 2 but for summer. Also baseline climatology (1980-1999) (black), and projected climate: 2030 A1B (gold); 2070 A1B (red); and 2070 A1FI (brown).

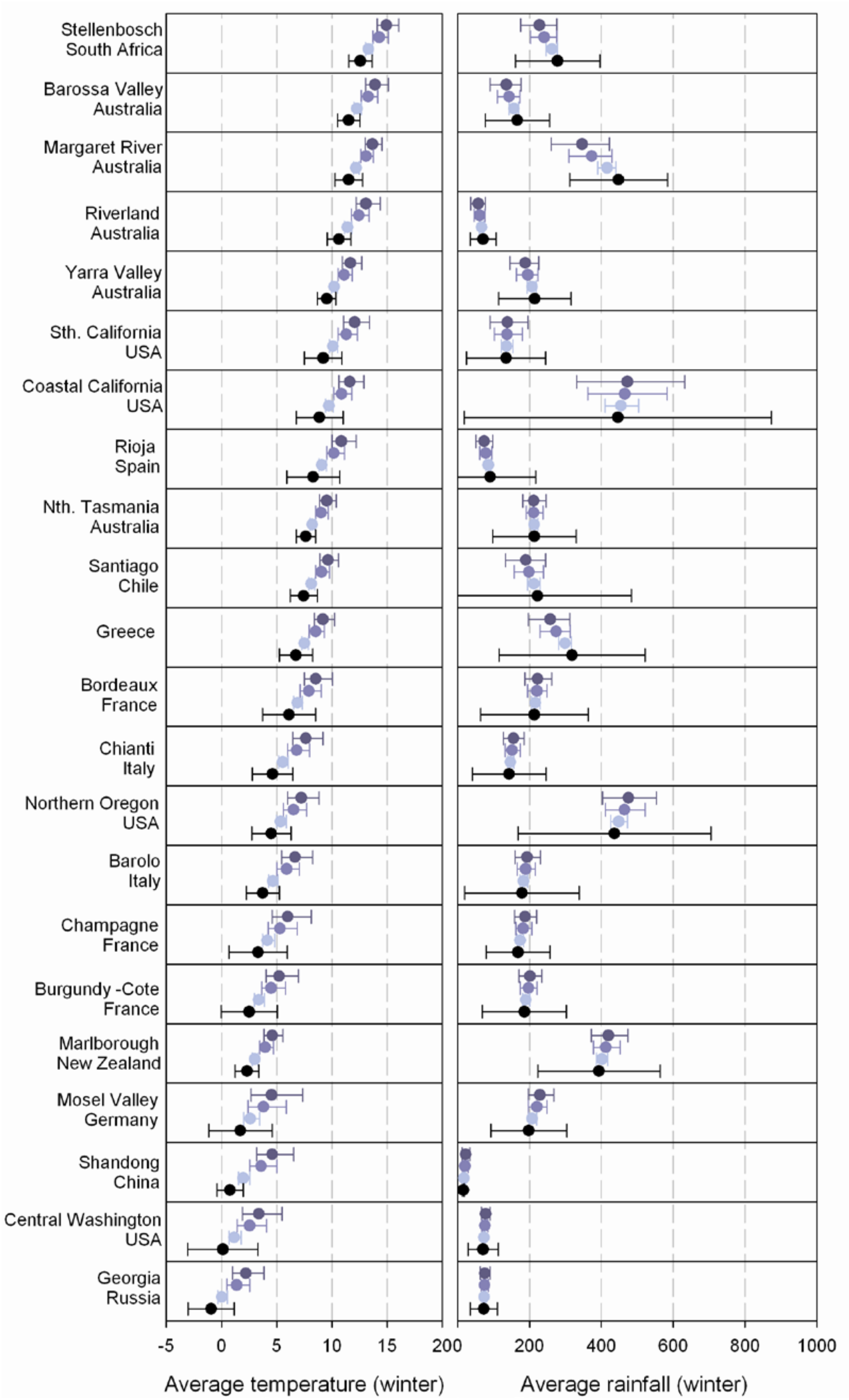


Figure 7 As for Figure 2 but for winter. Also baseline climatology (1980-1999) (black), and projected climate: 2030 A1B (light blue); 2070 A1B (mid blue); and 2070 A1FI (dark blue)

Discussion

It is interesting to compare the projected climate of some sites with the current climate of others. Inter-regional climate and projected climate comparison shows New Zealand's (Marlborough) annual average temperature will become warmer than Mosel Valley (Germany) (2070_A1FI), though Marlborough will remain a much wetter climate. Bordeaux may become as warm as the Margaret River (Australia) and also experience very similar annual rainfall to the current climate of the Margaret River region in future. For the summer period by 2070, Mosel (Germany) famous for cool climate Riesling production may be as warm as the Margaret River region of Australia or Bordeaux in France, both renowned for production of Cabernet Sauvignon. Barolo (Asti, Italy) can be compared with Spain, or even the Central Valley in California (Fresno), though the rainfall is slightly higher in the Asti region.

The decreasing suitability for production of current varietal selections in some regions may need to be addressed. To maintain consistency in wine styles (so called typicity), the industry will need to consider altering the balance of varieties growing in specific areas to better match future growing season conditions (Schultz 2000). Future planning strategies should consider introduction of alternative varieties currently grown in hotter regions of the world. Varieties crushed in Spain or Portugal or other hot wine growing regions of the world today could be considered for sites, such as in the Barolo region of Italy, that will achieve similar growing conditions in future climates. A recent report comprehensively provides information about access to alternative grapevine varieties from around the world that may assist growers with this adaptation option (Dry 2010).

For regions currently considered at the hot limit for winegrape cultivation, or as we move further into the century with greater warming projected, there may be no conventional 'hotter-suited' varieties to source (Webb *et al.* 2007). For these regions (and time-frames) particularly, though with probable benefits for all regions, there remains a very high potential to exploit genetic variability of grapevine material in order to moderate effects of climate change using both conventional breeding and genetic modification of grapevines (Webb *et al.* 2011a).

Some breeding programs have been developed in Australia with the aim of breeding wine grape varieties that ripen later in the season and are able to maintain a good sugar to acid balance (Clingeleffer 1985). More recently in a comprehensive study of the challenge of adapting phenological stages to a warmer climate, Duchene *et al.* (2010) examined the phenological timing of Riesling and Gewurztraminer, their actual progeny, and some 'virtual' progeny, in Alsace France. In their study, while they could not fully compensate for some of the more extreme warming scenarios with their breeding program, they demonstrated clearly the potential adaptive benefit from exploiting the genetic variation in phenological response using breeding.

The potential for viticulture can be expected to increase in some cooler regions, where in the present day climate there may be temperature limitations (Ashenfelter & Storchmann 2010). For example, potential exists to plant some varieties that would have difficulty ripening in present climates, in some of the cooler regions. Cautious and considered replanting may begin to take place in some of the warmer macroclimates of regions such as this (Becker 1977).

Winegrape varieties that ripen later than 'ideal' under current climate conditions, but with the overall 'best' phenological suitability for future climate conditions may prove advantageous in the long term. However, this may incur opportunity costs earlier on as the variety will not be optimal for current conditions. Some mix of strategies could be recommended in adapting a site to projected climate shifts (Webb *et al.* 2010). Perhaps some form of transition planting of later ripening varieties with the vineyard being modified in stages could spread the climate risk. Alternatively, keeping the earlier ripening varieties may have some advantages in that the crop potentially avoids late summer heatwaves and exhibits improved water use efficiencies.

The flexibility of using alternative varieties are more limited in some countries than others. French, Italian and German legislation allows for only certain grape varieties to be grown in certain regions for wines produced to be awarded the regional quality classification (Johnson 1989), for example, the Appellations Contrôlées system (France), and the Denominazione di Origine Controllata (Italy). These may restrict adaptation potential in Europe but there are no such legislative restrictions in Australia, South Africa and USA.

In the instances where winters become too warm and the chilling requirement of vines is not met (Darbyshire *et al.* 2011) bud-break can become uneven or protracted (Lavee & May 1997). In these cases chemical dormancy breakers (Shulman *et al.* 1983) may offer some adaptive measures. Certain varieties like Cabernet Sauvignon and Sauvignon Blanc are currently cane-pruned in cooler climates due to low basal bud fertility. Warming in these regions will improve basal bud fertility allowing less expensive spur pruning to be practised (Tassie & Freeman 1992).

Some regions may benefit from more mild winter temperatures in future climates. Georgia, Russia has a current average winter temperature of below zero. Freezing conditions can adversely affect vines. In some regions vines are actually buried over the winter period to protect them from freezing (Fennell 2004). With a warming climate these conditions will be moderated potentially reducing the necessity to protect the vines.

If growers do not wish to change varieties but do want to remain within a particular region some other adaptation options exist. Cooler or more elevated sites can be selected. It is interesting to note that many of the more elevated sites in the world may currently be used for forestry or remain un-cleared. These sites may therefore have higher risks of bushfires and subsequent risk of exposure to smoke. Exposure of grapes to bushfire smoke can cause irreversible quality impacts to winegrapes (Kennison *et al.* 2007).

The other option available to wine production in attempting to maintain a suitable climate for growing a particular variety is to move to higher latitudes. In the Northern Hemisphere there is far more potential to exploit the adaptive option of a pole-ward shift in location than in the Southern Hemisphere due to the situation of land masses on the globe. In Australia and South Africa for instance, many of the sites for vineyard production are already in the more southerly locations on the continent.

The impact of rainfall change is region and season specific with some regions likely to be drier in future and others wetter. Where the climate may be wetter in future, e.g. China, there is of course greater risk fungal disease pressure, and therefore associated costs of disease control (Magarey *et al.* 1994). Many regions, of course may experience reduced disease pressure if rainfall declines.

Availability of moisture to grapevines has been found to affect the timing of maturity in a recent Australian study (Webb *et al.* under review). Where drying as well as warming is anticipated in future climate the impact on timing of maturity and therefore the decrease in suitability of a variety for a region may be exacerbated.

Conclusion

The climate conditions for world wine growing regions are projected to change. The impacts of the shifts in climate are unique to each region due to the spatial variability of the projections. Some regions may benefit from these changes with a milder future climate, better suited to winegrape growing, being anticipated. Other regions may need to consider a shift in the varietal mix to produce the best wine in future climates. Still other regions may have increased pressure from diseases. Where the climate is already at the hot end of the growing spectrum it remains to be seen as to whether grapes will be produced at these sites in future climates. As a result of this analysis each region can now assess their relative strengths and weaknesses that going forward, will inform potential adaptation options.

Acknowledgements

This work was partly funded by the CSIRO Climate Adaptation National Research Flagship and also by the Australian Grape and Wine Research and Development Corporation.

Bibliography

Amerine MA, Winkler AJ (1944) Composition and quality of musts and wines of California grapes. *Hilgardia,* **15**, 493-674.

Anderson K, Nelgen S (2011) *Global wine markets, 1961-2009: a statistical compendium.* University of Adelaide Press, Adelaide, SA.

Ashenfelter OC, Storchmann K (2010) Measuring the Economic Effect of Global Warming on Viticulture Using Auction, Retail, and Wholesale Prices. *Review of Industrial Organization,* **37**, 51-64.

Becker NJ (1977) Selection of Vineyard sites in cool climates. In 'Third Australian Wine Industry Technical Conference.' Albury, NSW (Eds pp. 12-18. (The Australian Wine Research Institute.).

Chuine I, Yiou P, Viovy N, Seguin B, Daux V, Ladurie ELR (2004) Historical phenology: Grape ripening as a past climate indicator. *Nature,* **432**, 289-290. http://www.nature.com/nature/journal/v432/n7015/suppinfo/432289a_S1.html

Clingeleffer PR (1985) Breeding grapevines for hot climates. *The Australian Grapegrower and Winemaker,* **256**, 99,101-102,104.

Conde C, Silva P, Fontes N*, et al.* (2007) Biochemical changes throughout grape berry development and fruit and wine quality. *Food,* **1**, 1-22.
Coombe BG, Iland P (2004) Grape berry development and winegrape quality. In: *Viticulture Volume 1 - Resources. 2nd edition* (eds Dry PR, Coombe BG), pp. 210-248. Winetitles, Adelaide, South Australia.
CSIRO and Australian Bureau of Meteorology (2007) *Climate change in Australia, Technical report.* CSIRO and Bureau of Meteorology through the Australian climate change science program, Melbourne, Australia. http://www.climatechangeinaustralia.com.au/resources.php (Accessed 1/5/09)
Darbyshire R, Webb L, Goodwin I, Barlow S (2011) Winter chilling trends for deciduous fruit trees in Australia. *Agricultural and Forest Meteorology,* **151**, 1074-1085. http://www.sciencedirect.com/science/article/B6V8W-52MPW75-1/2/da3dcb859674360f6292b94259249de2
Dry P (2010) *Alternative Varieties- Sourcing key viticultural, wine and market information.* Grape and wine research and development corporation. http://www.gwrdc.com.au/webdata/resources/factSheet/AlternativeVarieties.pdf
Duchêne E, Huard F, Dumas V, Schneider C, Merdinoglu D (2010) The challenge of adapting grapevine varieties to climate change. *Climate Research,* **41**, 193-204.
Fennell A (2004) Freezing tolerance and injury in grapevines. In: *Adaptations and Responses of Woody Plants to Environmental Stresses.* (ed Arora R), pp. 201-235. Hawthorn Press, Binghamton, NY.

Gladstones J (1992) *Viticulture and Environment.* Winetitles, Adelaide.
Huglin P (1986) *Biologie et ecologie de la vigne.*, Lausanne, Switzerland.
IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge. http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf
Jackson DI, Cherry NJ (1988) Prediction of a district's grape-ripening capacity using a Latitude Temperature Index (LTI). *American Journal for Enology and Viticulture,* **39**, 19-28.
Johnson H (1989) *The World atlas of wine.* Mitchell Beazley Publishers., London.
Jones GV (2007) Climate change and the global wine industry. In 'Thirteenth Australian wine industry technical conference'. Adelaide, SA (Eds Blair R, Williams P, Pretorius S) pp. 91-98. (Australian wine industry technical conference Inc.).
Jones GV, Davis RE (2000) Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. *American Journal for Enology and Viticulture,* **51**, 249-261.
Jones GV, Duchene E, Tomasi D*, et al.* (2005a) Changes in European winegrape phenology and relationships with climate. In 'Proceedings for the XIVth GESCO Viticulture Congress'. Geisenheim, Germany. (Eds Schulz HR, et al.) pp. 55-61.
Jones GV, Snead N, Nelson P (2004) Geology and wine 8. Modeling viticultural landscapes: A GIS analysis of the terroir potential in the Umpqua Valley of Oregon. *Geoscience Canada,* **31**, 167-178.

Jones GV, White MA, Cooper OR, Storchmann KH (2005b) Climate change and global wine quality. *Climatic Change,* **73**, 319-343.
Jun M, Knutti R, Nychka DW (2008) Spatial Analysis to Quantify Numerical Model Bias and Dependence. *Journal of the American Statistical Association,* **103**, 934-947. http://pubs.amstat.org/doi/abs/10.1198/016214507000001265
Kennison KR, Wilkinson KL, Williams HG, Smith JH, Gibberd MR (2007) Smoke-derived taint in wine: effect of postharvest smoke exposure of grapes on the chemical composition and sensory characteristics of wine. *Journal of Agriculture and Food Chemistry,* **55**, 10897-10901.
Kenny GJ, Shao J (1992) An assessment of a latitude-temperature index for predicting climate suitability for grapes in Europe. *Journal of Horticultural Science,* **67**, 239-246.
Kerridge GH, Antcliff AJ (1996) *Winegrape varieties of Australia.* CSIRO Publishing, Collingwood, Victoria.
Lavee S, May P (1997) Dormancy of Grapevine buds- facts and speculation. *Australian Journal of Grape and Wine Research,* **3**, 31-46.
Le Roy Ladrie E (1988) *Times of feast, times of famine. A history of climate since the year 1000.* Farrar, Stratus and Giroux by arrangement with Doubleday and Company, Inc., USA.
Lund ST, Bohlmann J (2006) The Molecular Basis for Wine Grape Quality-A Volatile Subject. *Science,* **311**, 804-805.
Magarey PA, Wachtel MF, Emmett RW (1994) Disease Management - overview. In: *Diseases and Pests. Grape Production Series. Number 1.* (eds Nicholas P, Magarey P, Wachtel M), pp. 75-80. Winetitles, Adelaide.
Meinshausen M, Meinshausen N, Hare W*, et al.* (2009) Greenhouse-gas emission targets for limiting global warming to 2[thinsp][deg]C. *Nature,* **458**, 1158. http://dx.doi.org/10.1038/nature08017
http://www.nature.com/nature/journal/v458/n7242/suppinfo/nature08017_S1.html
Nakićenović N, Swart R (2000) *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge.
OIV (2010) OIV summary on the global situation of the vine and wine industry in 2009. In '33rd World Congress of Vine and Wine'. Paris (Eds pp.
Schultz HR (2000) Climate change and viticulture: A European perspective on climatology, carbon dioxide and UV-B effects. *Australian Journal of Grape and Wine Research,* **6**, 2-12.
Schwartz M (2003) *Phenology: An integrative environmental science.* Kluwer Academic Publishers, Netherlands.
Seguin B, de Cortazar IG (2005) Climate warming: consequences for viticulture and the notion of *'terroirs'* in Europe. *Acta Horticulturae,* **689**, 61-71.
Seguin G (1986) '*Terroirs*' and pedology of wine growing. *Cellular and Molecular Life Sciences,* **42**, 861-873.
Shulman Y, Nir G, Fanberstein, Lavee S (1983) The effect of Cyanamide on the release from dormancy of grapevine buds. *Scientia Horticulturae,* **19**, 97-104.

Tassie E, Freeman BM (1992) Pruning. In: *Viticulture, Volume 2. Practices* (eds Coombe BG, Dry PR). Winetitles, Underdale, South Australia.

Watterson IG (2008) Calculation of probability density functions for temperature and precipitation change under global warming. *Journal of Geophysical Research,* **113**, D12106.

Watterson IG, Whetton PH (2011) Distributions of decadal means of temperature and precipitation change under global warming. *Journal of Geophysical Research,* **116**, D07101. http://dx.doi.org/10.1029/2010JD014502

Webb L, Clingeleffer PR, Tyerman S (2011a) The genetic envelope of winegrape vines: potential for adaptation to future climate challenges. In: *Crop adaptation to climate change* (eds Yadav SS, Redden B, Hatfield JL, Lotze-Campen H), pp. 464-481. John Wiley & Sons, Inc., Iowa, USA.

Webb L, Dunn G, Barlow EWR (2010) Winegrapes. In: *Adapting agriculture to climate change: Preparing Australian agriculture, forestry and fisheries for the future.* (eds Stokes CJ, Howden SM), pp. 101-118. CSIRO Publishing, Melbourne.

Webb L, Whetton P, Barlow EWR (2007) Shifting Viticulture Suitability. *Australian and New Zealand Grapegrower and Winemaker,* **August**, 43-47.

Webb L, Whetton P, Barlow EWR (2008a) Climate change and wine grape quality in Australia. *Climate Research,* **36**, 99-111.

Webb L, Whetton P, Barlow EWR (2008b) Modeling the relationship between climate, winegrape price, and winegrape quality in Australia. *Climate Research,* **36**, 89-98.

Webb LB, Whetton PH, Barlow EWR (2011b) Observed trends in winegrape maturity in Australia. *Global Change Biology,* **17**, 2707-2719. http://dx.doi.org/10.1111/j.1365-2486.2011.02434.x

Webb LB, Whetton PH, Bhend J, Darbyshire R, Briggs PR, Barlow EWR (under review) The fingerprint of climate change: Attribution analysis of trends in winegrape maturity. *Nature Climate Change,*

Zamora F (2007) Phenolic maturity as a criteria for choosing the best winemaking strategy. In 'Global warming: new oenological challenges. Les XIXes entretiens scientifiques'. Margaux, France (Eds pp. 27-34. (Lallemand).

Appendix 7: Sustainability practices and programs in New World vineyards of the Mediterranean biome

Contributors:

Leanne Webb, University of Melbourne and CSIRO, PMB 1 Aspendale, Victoria, Australia

Olga Barbosa, Instituto de Ciencias de la Tierra y Evolución Universidad Austral de Chile, Valdivia & Institute of Ecology and Biodiversity (IEB), Chile

Isabel Granillo Especialista de Conservación. The Nature Conservancy, Ave. de la Marina S/N, Tercer piso, Oficina 2, Ensenada, Baja California, México, C.P. 22800

Jonathan Green, Winemakers' Federation of Australia, PO Box 2414 Kent Town, South Australia, Australia 5071

Inge Kotze WWF South Africa, WWF's Biodiversity and Wine Initiative, P.O.Box 23273 Claremont, 7735, South Africa

Kimberly A. Nicholas, Lund University Centre for Sustainability Studies, PO Box 170, SE 22100, Lund, Sweden

Liz Spence, The Nature Conservancy, 201 Mission St. 4th Floor, San Francisco, CA 94105

Josh Viers, Dept. of Environmental Science & Policy, University of California, One Shields Ave., Davis, CA 95618, USA

John Williams, Dept. of Environmental Science & Policy, University of California, One Shields Ave., Davis, CA 95618, USA

Introduction

In January 2011, the 2nd International Biodiversity and Vines Workshop (Vinecology) was held in Davis, California. The conservation planners and scientists who attended came from the New World Mediterranean winegrowing regions of South Africa, Chile, the United States, Mexico, and Australia. These regions share similar climatic and environmental contexts. The Mediterranean biome is characterised by its climate – warm-dry summers and cool-wet winters – and its endemic biodiversity, which has been recognised as a priority for global biodiversity conservation efforts.

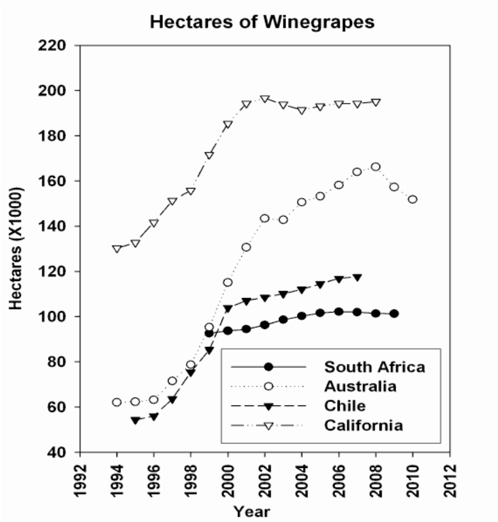


Figure 1 Hectares of winegrapes, 1995-2010 from some New World winegrowing regions included in the Mediterranean biome. (Australian statistics (ABS 2010). Vinos de Chile statistics of Wines of Chile (2011). South African Wine Industry Information and Systems (SAWIS), South African Wine Industry Statistics, June 2010. (www.sawis.co.za). NB: Baja California (Mexico) fewer than 3000 hectares currently under cultivation).

Despite the recent plateau in vineyard development in some of the New World winegrowing regions located in the Mediterranean biome (Figure 1), vineyards still contribute substantially to these landscapes. Here we document the current state of knowledge and program approaches regarding biodiversity and ecosystem services as they relate to vineyard plantings in these countries.

Vinecology participants believe better management of biodiversity and underlying ecosystems within vineyard landscapes can be achieved by working together and learning from both shared and varying experiences. This will ensure productive agricultural sectors are sustained while also protecting and conserving the Mediterranean biome - one of the most diverse, yet poorly protected biomes on earth.

Ecosystem Services and Biodiversity

Ecosystem services are the benefits that people derive from ecosystems. A well managed and maintained natural system provides numerous free services and benefits to the producers and broader society (Millennium Ecosystem Assessment 2005). These services can be divided into:

Provisioning services such as clean water and biomass for food, fuel, and fibre;

Regulating services, such as carbon sequestration and pest and disease control;

Supporting services, such as nutrient cycling and primary production; and

Cultural services, such as recreational, aesthetic, and spiritual experiences.

Mediterranean ecosystems are currently under great threat. These ecosystems are very special due to their high biodiversity, with many endemic populations of plant species (i.e. plants that occur only in this region) (Cowling *et al.* 1996). They are also threatened with a conversion rate higher than that for tropical forests. More than 41% of their original area is already converted. Of the area remaining globally, only 5% is protected by formal recognition as a nature reserve (Hoekstra *et al.* 2005).

While many wine producing regions are introducing ‘sustainability’ programs, these vary in their definition of sustainability. The majority of these programs are focused on general practices that reduce a vineyard’s environmental impact by conserving energy or reducing carbon dioxide emissions. Few, however, make explicit connections to conservation outcomes on the landscape. If sustainability certification programs are to have a positive effect on vineyard landscapes, they must also relate management practices to habitat quality, biodiversity, and ecosystem function.

Conservation scientists need to communicate to growers about the benefits of these actions to make the connection between conservation and farming practices more clear. Conservation extension programs within the industry, such as the South African WWF Biodiversity & Wine Initiative in cooperation with winegrowers and land-owners, have already demonstrated how increased awareness of the natural systems’ roles and functions can result in producers adopting sustainable and biodiversity-friendly agricultural practices.

Vineyard practices can be directed to conserve biodiversity in several ways, including:

- The maintenance or restoration of remnant native vegetation on land not directly used for production purposes (e.g., through removal of invasive species and the maintenance of river corridors and wetlands).
- Ensuring that cover crops planted between the vines and windbreaks between the production blocks are, at a minimum, non-invasive exotic species, and preferentially, well-adapted indigenous species.
- Focused integrated pest management strategies to promote minimal and efficient use of chemicals and fertilisers to reduce broader ecosystem impacts.
- The efficient use and management of natural resources such as water and soil– including water re-use, effective wastewater treatment and disposal, and erosion protection.
- Maintaining and restoring river flows, riparian buffers and corridors and native riparian and wetland vegetation as important free provisioning and regulatory services.

Vineyards can also play an important ecological role within a broader regional landscape context. This can be done by reconnecting fragments of remaining natural areas through the establishment of vegetation corridors and functional habitat linkages. These habitats not only provide refuge for native wildlife, which have been shown to keep alien species at bay, but also provide benefits to microclimatic conditions in vineyards by reducing wind velocities as well as for other ecosystem services.

Description of environmental programs in winegrowing regions

Environmental assurance schemes allow winemakers and winegrape growers to receive formal certification of their practices according to recognised standards. Standards include monitoring for legal compliance to relevant environmental, health and safety legislation, and the minimisation and efficient use of electricity, water, fertilisers, chemicals, wastewater treatment, and solid waste reduction and recycling.

At an international scale guidelines for sustainability programs for the wine sector have been developed, including the Sustainable Vitiviniculture Code (International Organisation of Vine and Wine 2008), and the Global Wine Sector Sustainability Principles Project (International Federation of Wine and Spirits 2006). These international guidelines represent an attempt to define what sustainability means for the wine sector at an international scale and reflect a consensus from member nations. Membership includes most wine producing countries in either or both of the above organisations; hence this bodes well for further refinement on defining sustainability for the wine sector.

In each country these schemes vary, but the overall intention of compliance is to increase the sustainability of practices undertaken by industry practitioners. The majority of the programs are independently audited for compliance before certification is given. The certification provides a means for businesses to demonstrate their compliance with specified environmental standards through a process of monitoring, management and verification.

Benefits from membership in these schemes include: best practice guidelines for on-farm management practices, producer training to implement these guidelines effectively, and producer participation in on-farm land stewardship agreements to set aside natural areas for long-term conservation, environmental education and eco-tourism activities.

Progress of the implementation of environmental programs

The New World Mediterranean wine-producing regions are at various stages of implementation of environmental sustainability programs. We have compiled a brief description of these with links to relevant websites that provide some more detailed information (Table 1).

Table 1 New world wine producing countries from the Mediterranean biome inter-country comparison of ecology and biodiversity initiatives integrated with viticulture and winemaking enterprises.

		Sustainable Practices in Viticulture			
	Certification Programs	Participation/ Status	Trends	Reporting compliance	Other programs
Australia	Entwine Australia is the flagship national sustainability program: 3rd party holistic environmental management certification (that includes biodiversity management requirements and action planning), plus carbon, water, waste, land management accounting and benchmarking. See http://www.wfa.org.au/entwineaustralia/default.aspx	Participation of the scheme is voluntary. 45% of the Australian crush was involved in Entwine in 2011; Growers and winemakers meet environmental standards through a process of monitoring, management and verification.	Membership growing steadily, initial adoption by larger operations and leading premium brands, growth in coming year mainly expected from family-owned wine exporting operations	Members report on natural resource performance indicators and greenhouse emissions each year. The scheme is independently audited. Membership is not required for export, but this is under consideration	Organic and biodynamic farming is growing in Australia. Members of these programs will be eligible for Entwine membership where operators can demonstrate an auditable holistic management focus that goes beyond chemical use constraints.
México	None See http://www.vidyvino.org/	Some proposals for efficient water uses in vineyards	Interest by some growers		Not existent at this time
United States (California) NB Oregon not included, not Med Biome.	Vineyard development ordinances are strictest in Napa and Sonoma counties (ordinances on slope, grading, floodplain management, oak trees and groundwater). A variety of programs at regional/county level. 3 major programs--Lodi Rules, Napa Green and "SIP" Central Coast Vineyard Team. One state-wide California Code of Sustainable Wine Production (CCSW) See http://www.lodiwine.com/certified-green/lodi-rules-for-sustainable-winegrowing	CCSW 62% of wine, 68% of acres. CCSW certification has ~40 vineyards/wineries certified to date.	Overall fragmentation of certifications creates confusion among consumers. Even though the state-wide code has good representation, the state-wide certification has not been as successful in terms of grower participation in its first year.	CCSW requires annual self-assessment verified by approved 3rd party auditor	Trout Unlimited's "Water and Wine" program, Fish Friendly Farming focused on conservation in North Coast watersheds. Areas under future climate change scenarios overlaid with biodiversity priority areas to represent likely areas of conflict
Chile	Chile's Sustainability Code (CSC) (social context, energy reduction, waste management and environmental management in vineyards) defines minimum standards for sustainable management but does not include specific guidelines for biodiversity management neither within the vineyards nor in the surrounding area. The Wine, Biodiversity and Climate Change Scheme, currently working with several wineries, is an academic initiative that has established biodiversity friendly management practices in vineyards and aims to engage Chilean wine industry on	50% of wineries have registered CSC scheme and are currently at various stages in levels of achievement for certification. In addition, more than 10 big wineries (ca 40% of national industry) have joined the Wine, Biodiversity and Climate Change Scheme and have already	CSC is in its first year implementation, whereas the Wine, Biodiversity and Climate Change Scheme has been running for 3 years	Members of the CSC reports to Wines of Chile through independent audits. In the Wine, Biodiversity and Climate Change Scheme they are audited by the scheme but it is under evaluation with the possibility of creating a national certification scheme	Other schemes include organic and biodynamic and are independently audited by international certification companies

	biodiversity conservation. See www.vccb.cl or http://www.sustentavid.org/	implemented required standards.			
South Africa	The scheme for the Integrated Production of Wine (IPW) is an industry wide minimum standard for environmental sustainability. Furthermore this scheme includes comprehensive guidelines on managing the surrounding natural areas (biodiversity) and resources available in the natural environment (for example: soil and water resources). The WWF Biodiversity and Wine Initiative builds on the industry wide minimum compliance (IPW) to lead best practice within the industry focused on continual improvement and sound management of the natural systems as the foundation for farming sustainably. www.swsa.co.za (Sustainable Wines South Africa); www.bwi.co.za (WWF South Africa's Biodiversity and Wine Initiative)	BWI members (220 BWI members of the 605 wineries i.e. 33% of industry accredited by WWF Biodiversity and Wine Initiative as operating at best practice); Integrated Production of Wine - 98% (based on crush tonnage) of the South African wine industry is certified by the industry wide certification.	In 2011, South Africa launched the Sustainability seal which integrates all relevant environmental standards as the industry wide benchmark for compliance and management of environmental risk within the vineyard and cellar and surrounding environment.	The IPW is independently audited to ensure legal compliance as a minimum industry benchmark including all legislative aspects relevant to the management of vineyards and cellars (wineries) as well as best practice for managing associated environmental risks within vineyard and cellar management.	The sustainability seal provides the industry benchmark – further best practice certification that then builds on this industry wide compliance includes organic, biodynamic or biodiversity best practice accreditation. Integrated Production of Wine (formal industry wide certification program (98% of industry registered and certified (industry audited)

South Africa and Australia are relatively advanced in the development and implementation of a national certification program, with consistent benchmark standards in place and strong producer adoption across the industry. The South African wine industry has already achieved industry-wide compliance, measured against a broad spectrum of minimum environmental standards, which are now the benchmark requirement for their winemakers who wish to export wine (see Table 1 for more details). The United States (California) maintains a regional portfolio of schemes. Chile has just launched its program and is in the first year of implementation, although a voluntary conservation-focussed scheme has existed for three years. In Chile it was demand from the international, especially European, wine market that spurred the development of regulations. México is in an early planning and development phase of a vineyard conservation scheme, with particular interest in efficient water use.

Some aspects of programs will become common to all regions, such as the carbon accounting tool, which was collectively developed to ensure that one international standard and methodology is consistently applied. Other aspects such as integrated pest management, and the management of specific environmental issues within the vineyard and winery vary and are formulated within a country- and climate-specific context.

Members of the Australian sustainability accreditation program ‘Entwine Australia’ must demonstrate performance on a range of matters pertinent to sustainability. An environmental action plan is developed at commencement with the program, and outcomes are audited each year to maintain certification. For example, on the biodiversity topic, Entwine members must address the management needs of natural habitat areas on their vineyard and winery properties such as natural bushland, waterways and wetlands, through actions such as removing weeds and feral animals and protecting areas from livestock. Biodiversity is also addressed within the production part of the vineyard by assessing the opportunity to utilise native plants between vine rows and in wind breaks around the property.

A participant in the Entwine Australia program, Streicker Wines Bridgeland vineyard in Western Australia’s Margaret River region, identified through their environmental action planning process that the biodiversity management priority was to protect the legacy of some relatively unspoilt native forest and riparian areas on the property. Commenting on their membership of the program Brian Lowrie, Director of Operations, stated that:

"We looked to the Entwine Australia program as a way of formalising our commitment to protecting the environment and maintaining currency with market trends and consumer preferences. Certain consumer segments are beginning to question companies’ green credentials and are looking to purchase products from companies who demonstrate a genuine commitment to adopting sustainable practices and protecting the environment."

A map of the environmental action plan for the Bridgeland vineyard is provided (Figure 2).

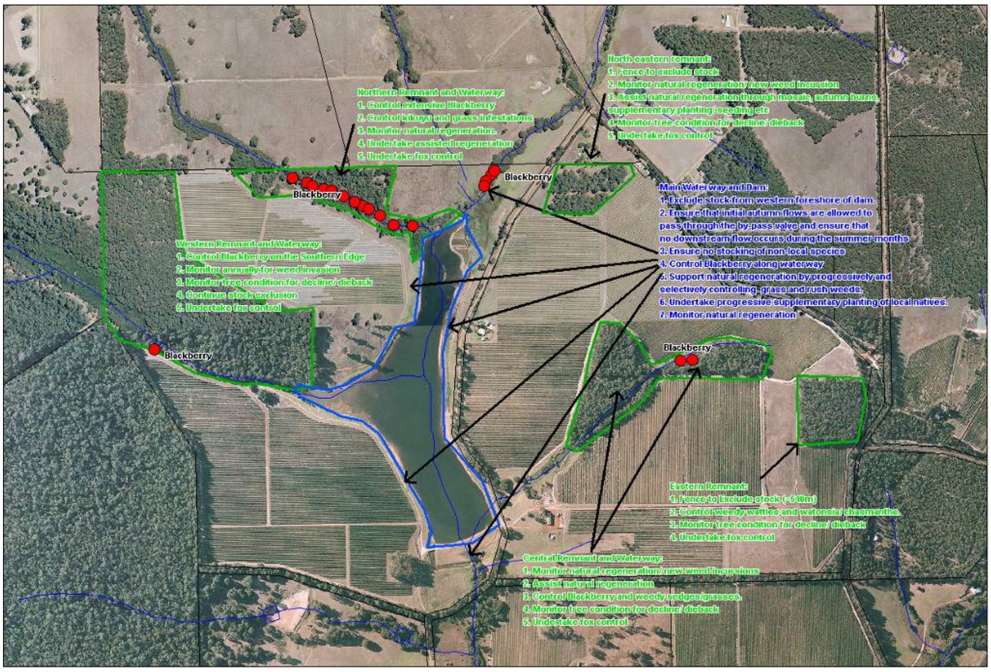


Figure 2 Streicker Wines Bridgeland vineyard, Margaret River. Environmental action plan.

Vinecology: The Next 25-50 Years

Wine is recognised for its sensitivity in reflecting the climate under which it was cultivated, and vineyards thrive in specific climate regions of the world. Climate changes will alter the timing of ripening (Webb *et al.* 2007), the chemical composition of fruit at harvest (Nicholas *et al.* in press), and potentially the suitability of traditional varietals or even continued fine wine production in some regions (White *et al.* 2006).

Climate change also interacts with the issues of biodiversity and ecosystem services, as native species may be limited in their ability to shift with the climatic conditions suitable to them, and new climate regimes might encourage vineyard expansion into biologically sensitive areas, particularly coastal regions and hillsides.

Vineyard managers have a number of options for changing management to adapt to some degree of climate change (Webb *et al.* 2010). However it is also important to include ecosystem services in the planning process when considering adaptation to climate changes to improve the overall outcome. For example, careful management of winery wastewater may ensure waterways and riparian regions retain their biodiversity and ecological health (Kumar *et al.* 2009). This will become increasingly important as water availability is likely to decrease and demand is likely to increase in latitudes suitable for wine-growing (IPCC 2007). Well-functioning ecosystems that support a healthy flow of ecosystem services are more likely to enhance the overall resilience of a system to projected climate changes.

There is currently a strong and growing trend towards industry certification and a growing awareness of the importance of the issue of environmental sustainability. The Vinecology network aims to support the transfer of scientific information, and generate greater global industry engagement in sustainability programs that are aligned with producer benefits and consumer expectations. Enhanced collaboration between non-governmental organisations, conservation scientists and wine sector leadership will assist with definition of these conservation goals and opportunities.

Ecosystem service protection is a common goal for users of sustainable landscapes. Wine industry practitioners can play a strong leadership role for other land-users by protecting Mediterranean ecosystems, at the same time as sustaining a more resilient industry into the future.

Acknowledgements

We gratefully acknowledge The Nature Conservancy, in particular Mark Reynolds and Liz Spence for providing the vision, enthusiasm and hard work necessary to make the workshop a success.

References

ABS (2010) *Australian Wine and Grape Industry, cat. no. 1329.0,*

Canberra, Australian Bureau of Statistics.

Cowling RM, Rundel PW, Lamont BB, Arroyo MK, Arianoutsou M (1996) Plant diversity in Mediterranean-climate regions. *Trends Ecol Evol,* **11**, 362-366.

IPCC (2007) *Intergovernmental Panel on Climate Change, Climate Change 2007: The Physical Science Basis, Summary for Policymakers.* WMO, UNEP. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/spm.html [2011, August 1]

Hoekstra JM, Boucher TM, Ricketts TH, Roberts C (2005) Confronting a biome crisis: global disparities of habitat loss and protection. *Ecology Letters,* **8**, 23-29.

International Federation of Wine and Spirits (FIVS) (2006). Global Wine Sector Environmental Sustainability Principles. [Online]. Available: http://fivs.org/wm/strategicInitiatives/fivsForesee.htm [2011, August 1]

International Organisation of Vine and Wine (OIV) (2008). Sustainable Vitiviniculture Code. [Online]. Available:

http://www.wfa.org.au/resources/5/PDF_Resources/Resources/OIV%20Sustainable%20Vitiviniculture%20Guide.pdf [2011, August 1]

Also see :(http://www.powershow.com/view/113c79-ZWRjO/International_Organisation_of_Vine_and_Wine_flash_ppt_presentation) [2011, August 1]

Kumar A, Arienzo M, Quayle W*, et al.* (2009) *Developing a Systematic Approach to Winery Wastewater Management.* FINAL REPORT to GRAPE AND WINE RESEARCH & DEVELOPMENT CORPORATION, Project Number: CSL05/02. http://www.gwrdc.com.au/webdata/resources/project/CSL_05-02.pdf

Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-being: Synthesis Report.* Island Press, Washington, DC.

Nicholas KA, Matthews MA, Field CB, Lobell DB, Willits NH (in press) Effect of vineyard-scale climate variability on Pinot noir phenolic composition. *Agricultural and Forest Meteorology,* Webb L, Dunn G, Barlow EWR (2010) Winegrapes. In: *Adapting agriculture to climate change: Preparing Australian agriculture, forestry and fisheries for the future.* (eds Stokes CJ, Howden SM), pp. 101-118. CSIRO Publishing, Melbourne.

Webb L, Whetton P, Barlow EWR (2007) Modelled impact of future climate change on phenology of wine grapes in Australia. *Australian Journal of Grape and Wine Research,* **13**, 165-175.

White MA, Diffenbaugh NS, Jones GV, Pal JS, Giorgi F (2006) Extreme heat reduces and shifts United States premium wine production in the 21st Century. *Proceedings of the National Academy of Sciences,* **103**, 11217-11222.

Appendix 8: Extended heatwave survey report and heatwave DVD.