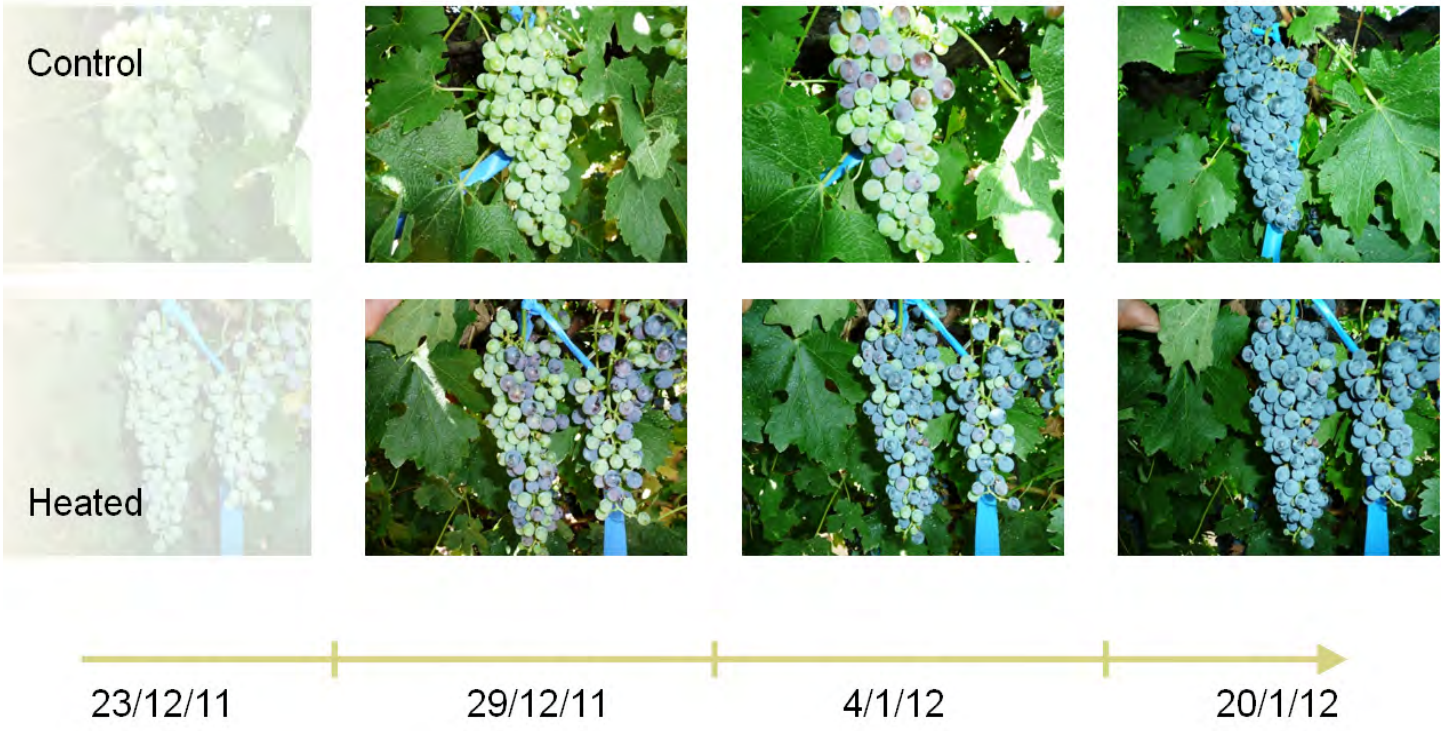
Strategies to maintain productivity and quality in a changing environment-Impacts of global warming on grape and wine production



FINAL REPORT to
GRAPE AND WINE RESEARCH AND DEVELOPMENT CORPORATION

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Front cover:
The effect of warming by 2 °C above ambient on veraison of Cabernet Sauvignon grapes at Irymple, Victoria in the 2011–2012 growth period.

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Executive Summary

This project tested the potential impact of a warmer climate on grape production and quality in a field experiment near Mildura in NW Victoria. Open top heated chambers (OTC) were installed in fully established vineyards of Chardonnay, Cabernet Sauvignon and Shiraz. Temperature in heated chambers was maintained at 2 °C above ambient temperature. Vines growing in heated chambers were compared to vines growing in unheated chambers and vines growing outside the chambers. Vine development, leaf functioning, fruit growth, fruit quality and yield were closely monitored throughout the season. Wine made from fruit grown in heated and unheated chambers was analysed and its quality was assessed.

Open top chambers (OTC) were used in this project to simulate climate warming to ~2°C above ambient.

- Heating accelerated bud burst by 3 – 12 days, cap fall by 5-10 days and veraison by 5-12 days. Heating delayed leaf fall.
- Modelling that indicated a significant advance in phenology with a relatively small increase in the average daily temperature is therefore confirmed.
- Leaf canopy function was similar in heated and unheated vines; there was no difference in stomatal conductance or leaf temperature in response to heat.
- Heating increased the rate of ripening. This was most noticeable for the early ripening Chardonnay in both seasons and for Shiraz and Cabernet Sauvignon in the second season.
- The influence of temperature on flavonols and tannins remains unclear.
- Yields were variable in 2011 due to differential impacts of disease following unseasonal wet weather. No significant impact was seen in 2012. It is premature to draw conclusions regarding the impact of warming on yield.
- This work demonstrates to industry the likely future vineyard environment they will have to manage, although such a future will likely include increased atmospheric CO_2.
- This project successfully tested injection of CO_2 into open top chambers (OTC). This capability enables investigation of the impact of elevated temperature and CO_2 and their interactions on vine performance and wine quality.

Short term heatwave (>5 °C) impacts in OTC at distinct phenological stages.

- Leaf function measures indicated that vines suffered moderate heat stress depending on phenology. Heatwave at fruit-set increased stomatal conductance and transpiration, which prevented any impact on leaf temperature or photosynthesis. Later heatwaves caused stomatal closure, leading to increased leaf temperature and reduced photosynthesis.
- Well watered vines readily adapt to heat events of limited duration. Detrimental effects may be mitigated by irrigation management.
- Sugar and acid are relatively resilient to short-term extremes of temperature.

- Impacts on anthocyanin, tannin and flavonol composition were inconsistent making it difficult to identify clear trends from this limited data set.

Study tours to evaluated management strategies in hot production regions.

- Adaptive response to excessive temperature and heat stress in California is restricted to additional irrigation. This may have negative implications for wine quality and increase water costs.
- Southern Italian viticulture relies on low crop loads and adapted local varieties that appear well suited to Australia and many are already planted here.
- North African wine regions rely on a low input viticulture often resulting in sub-standard wines, mainly from lack of private investment not climate.

Desktop studies were undertaken to assess management strategies with the potential to mitigate the detrimental effects of warming.

- Use of weather monitoring and forecasting together with best practice irrigation scheduling has the potential to mitigate plant water stress during heat waves and maintain fruit and wine quality of a high standard.
- An increase in temperature, which causes income to fall, is expected to decrease the wealth earned from investing in viticulture and is expected to decrease the value of the land.
- Relocating to a better micro climate may be an option for some growers but growers will make this decision based on a complex combination of production, financial, human and market considerations.

Recommendations and future directions

- Delays in establishing infrastructure led to a 3 season project reduced to 2 seasons, one of which was atypical because of record rainfall and high disease pressures, and yield and quality loss. There are some general indications of what might be expected in a warmer climate, but it is difficult to draw conclusions from such a limited data-set. It is recommended this work be continued for 2 additional seasons.
- Beyond a two year extension of the current work it is recommended to include investigations of the effect of elevated CO_2 and its interaction with elevated temperature on vine productivity.
- A comprehensive evaluation of grape varieties and rootstocks that are well adapted to hot and dry environments should be pursued locally and through international collaboration.
- Increase in temperature leading to a fall in income and a decrease in land value will make a relocation of the industry economically unviable. Strategies will be needed to assist the industry adapt to conditions in current production areas.
- Inconsistencies in fruit composition indicate the complexity of grape composition in response to environmental and management factors. This area is still poorly understood and requires a coordinated research effort.

Background

The anticipated increased temperature in viticultural production areas due to climate change has been predicted to result in decreased yields and decreased grape and wine quality. Currently, such predictions are largely based on anecdotal reports of the ideal climatic ranges for different grape cultivars and have not been tested experimentally.

Unlike livestock and annual crop production, perennial horticulture cannot easily relocate with changing environmental conditions because it requires an extensive infrastructure ranging from an irrigation distribution network, to processing capacity, and other service industries. In most Australian winegrape production areas this infrastructure is well established and relocation would involve social, economic and environmental costs that may jeopardise the viability of the Australian wine industry and threaten its ongoing contribution to the Australian economy.

This project explored the question of the impact of a warmer climate on winegrape production in Sunraysia, a major wine growing region in north-west Victoria. The main component of this project was a field based experiment which investigated the impact of a sustained temperature increase of ~2°C on the performance of major commercial grape varieties. A second component explored potential strategies to overcome or mitigate the effect of warming. Both components are presented as separate chapters. The specific objectives of the project are listed below and each is addressed throughout the report. Agreed outcomes and annual performance targets are listed in Tables 1 to 3.

Objectives

1. Quantify the response of Shiraz, Cabernet Sauvignon and Chardonnay vines in warm production areas to the effects of elevated temperatures anticipated under climate change projections. see
2. Investigate the ability of warm inland regions to maintain fruit quality and wine end use under an elevated temperature scenario.
3. Investigate the "tipping points" at which extreme heat events permanently impact on vine physiology and fruit composition to define damage thresholds.
4. Explore management strategies for wine grape producers to respond to increased temperature and increased frequency of extreme heat events.
5. Communicate the outcomes of objectives 1-4 to the warm inland regions of Australia.

Table 1: Performance targets 2009-2010

Outputs	Due date	Performance target
Project commenced.	30/07/2009	Contract executed, staff appointed.
Knowledge of current wine industry practice in hot production areas.	30/08/2009	Tour of Central Valley (California) to document current hot production viticulture practice.
Input and directions for project from industry reference group.	30/10/2009	First meeting convened with industry advisory panel.
International collaboration with hot climate viticultural regions.	30/12/2009	International collaboration with hot climate viticultural regions established and proposed activity provided to GWRDC.
Knowledge of vine response and impact on fruit and wine quality.	30/12/2009	Field trial established and first year of field work completed.

Table 2: Performance targets 2010-2011

Outputs	Due date	Performance target
Knowledge of current wine industry practice in hot production areas	30/08/2010	Tour of hot production areas in southern Europe, Middle East and North Africa.
Input and directions for project from industry reference group.	30/10/2010	Meet with industry reference group,provide update on project and seek input.
Industry informed about the project.	30/12/2010	Industry journal article prepared on project work and study tour outcomes. Field day held at trial site.
Knowledge generated from international collaboration with hot climate viticulture.	30/12/2010	Outcomes of international collaboration with hot climate viticultural regions submitted to GWRDC.
Knowledge of vine response and impact on fruit quality and wine end use under elevated temperature scenario.	30/06/2010	Second year of field work completed. Data sets on response of grapevines to increased temperature collected and analysed. Wine quality from 2009-10 season evaluated.

Table 3: Performance targets 2011-2012

Outputs	Due date	Performance target
Communicate project outcomes to industry.	30/12/2011	Draft and submit article to industry publication and scientific journal. Field day held at trial site. Fact sheet with key findings targeted at warm climate irrigated region including management strategies to cope with higher temperature and extreme heat events.
Knowledge of vine response and impact on fruit quality and wine end use under elevated temperature.	30/06/2012	Third year of field work completed and data analysed. Wine quality from 2010-11 season evaluated.
Interim final report.	30/03/2012	Interim final report submitted to GWRDC.
Final report to GWRDC.	30/06/2012	Analysis, tabulation and interpretation of 3 years data. Results written up in final report format.

Chapter 1

Impacts of global warming on grape and wine production - experimental section

1.1 Introduction

Despite controversy in the media there is a scientific consensus that the earth's climate is warming and will continue to do so. The best case scenario, based on rapid global adoption of new technologies to mitigate CO_2 emissions, suggests a rise of between 1.1 and 2.9 °C (IPCC, 2007). Even conservative estimates indicate a rise of over 2 °C (Schmittner et al., 2011). It is therefore likely that Australian viticulture will be subjected to increasing air temperatures over the next 30-50 years. Predictions of the impact of such warming on viticulture vary, but include decreases in both production and wine quality. Analyses of vintage records suggest that climate warming is already having an effect on phenology, with harvest dates advancing and vintages becoming shorter over the past 30 years (Webb et al., 2011; Petrie & Sadras, 2008). Unfortunately it is difficult to disentangle the impact of past warming from other factors, such as consumer wine preferences, changes in viticultural practice and natural year to year variation in weather. Only direct field manipulation of air temperature over multiple seasons is able to definitively determine the potential impacts of future climate warming. This is what we attempted to achieve at the DPI research facility in Mildura to examine the impact of future climate warming on warm climate viticulture.

This chapter presents the results and outcomes from a field experiment conducted at DPI near Mildura in north-west Victoria. The experiment employed a field-based system to alter the atmospheric temperature around established vines. The approach selected utilised an Open Top Chamber (OTC) whose assembly is described below. The effect of warming on the grape cultivars Chardonnay, Cabernet Sauvignon and Shiraz was investigated and its effects on vine performance, grape and wine quality will be presented and discussed.

1.2 Methods

1.2.1 Site

The vineyard at the Victorian Department of Primary Industries Irymple site, in the Sunraysia region, was utilised for all the field work activities that were undertaken as part of the project.

Three *Vitis vinifera L.* varieties were used, representing the three most widely planted varieties in the warm climate regions, Shiraz, Cabernet Sauvignon and Chardonnay. The vineyard contained an entire block of each variety, allowing the varieties to be separately managed, matching local commercial practice (Figure 1.1). The Chardonnay vines were planted in 1995 on Ramsey (*Vitis champinii)* rootstock and trained to a two-wire vertical trellis at 1.2 and 1.6 m in height.. The Shiraz and Cabernet Sauvignon vines were established in 1998 on Ruggeri (*Vitis berlandieri* $\times$ *Vitis rupestris)* and Paulsen (*Vitis berlandieri* $\times$ *Vitis rupestris)* rootstocks respectively and trained to a two-wire vertical trellis at 1.35 and 1.75 m in height. Row width was 3 m in each case, whereas vine spacing was 2.44 m for Chardonnay, but 1.8 m for Shiraz and Cabernet Sauvignon. Winter pruning of all vines was by mechanical hedging to approximately 40 cm width.



Figure 1.1: Aerial photograph of Chardonnay, Shiraz and Cabernet vineyards (outlined in blue) located at the Victoria Department of Primary Industries Irymple site. Yellow lines indicate the location of the three phase power supply.

The soil for each block was similar ranging from a light sandy clay loam to a sandy loam in the surface layer to a depth of 60 cm to a sandy clay loam at 60-150 cm depth (Table 1.1).

Prior to the installation of the warming chambers and choice of control sites, each block was assessed to eliminate any locations and/or vines with irregularities which may have led to inconsistent performance and/or influence the treatments to be applied. However, a vine showed signs of the viral disease Australian Grapevine Yellows (AGY) mid way through the 2011 season. This vine was excluded from the trial in the 2012 season by relocating the chamber to the current site.

1.2.2 Experimental design

Open top chambers were established in each varietal block, with each chamber encompassing a single 5.4 m panel of vines (two individuals for Chardonnay, three for the red varieties). Further panels were assigned as non-chamber controls. Three replicates for each treatment/control were assigned to random positions within each block. Treatments were:

Table 1.1: Soil profile information for the Irymple Shiraz, Cabernet S. and Chardonnay sites from a soil survey conducted in 1993. SL = sandy loam; SCL = sandy clay loam; LSCL = light sandy clay loam (Wetherby, 1993).

Variety	Depths (cm)	Texture class	Surveyor's Comment
Cabernet S	0-30	LSCL	fine carbonate in sandy loam to clay loam
	30-60	LSCL	
	60-150	SCL	
Shiraz	0-20	SL	fine carbonate in sandy loam to clay loam
	20-60	SL	
	60-120	SCL	
	60-120	SCL	
Chardonnay	0-30	SL	fine carbonate in sandy loam to clay loam
	30-60	SCL	
	60-150	SCL	

- Atmospheric warming (approximately 2 °C above ambient)
- Fan only control (chamber and fan system installed, but no heating system used)
- Non-chamber control (no chamber or fan infrastructure installed)

Soil moisture was monitored in all replicates. A single 1 m access tube was installed at each replicate site, including the non-chamber controls. Soil moisture was measured at approximately 7 day intervals, using a Diviner 2000 (SENTEK, Sentek Sensor Technologies 77 Magill Road Stepney SA 5069 Australia). Atmospheric conditions were monitored with a HOBO Micro Station (H21-002) (Onset Computer Corporation 470 MacArthur Bvld. Bourne MA 02532) system in every replicate. The HOBO Micro Station was set to log air temperature, soil temperature and relative humidity at 15 minute intervals. The air temperature/humidity sensor (S-THB-M002) was placed between the two cordon wires at 1.4-1.5 m and enclosed in a Solar Radiation Shield (RS3) and the soil temperature sensor (S-TMB-M002) was buried at a 10 cm depth under the drip-line at the mid point between two vines.

1.2.3 Open topped chamber design

Simulated climate warming was provided using an Open Top Chamber system (OTC). Other systems were deemed to cause too great an impact on other environmental parameters, such as humidity, UV radiation and CO_2 concentration (e.g. fully enclosed chambers) or provide warming by a means other than increasing air temperature (e.g. infra-red heat lamps) and therefore have too many potential artefacts to be an effective demonstration of the likely impact of warming on Australian viticulture.

The OTCs were 5.4 × 4.8 × 2.4 m (length × width × height) to encompass a whole panel of trellis, allow enough room to maintain the vines and minimise any blocking effect on received UV radiation at low solar angles (Figures 1.2A and 1.2B). Each was constructed using a tubular steel frame and had a single hinged doorway for access. Transparent cladding was provided by using Laser light™ corrugated Standard SunTuf Clear Greca (SKYGC) rigid plastic sheeting. The sheeting was highly UV absorbent, but the choice of OTC height limited the periods

where significant UV radiation was blocked to those where the solar elevation angle was below approximately 30°.

The climate warming units worked on high volume, low velocity air movement principal, provided by a bespoke heating unit, manufactured by Affordable Airconditioning (Frewville, SA 5063). Each one consisted of a steel central module containing 3 phase triple 2.4kW finned heating elements (Stokes Appliance Parts, 24 Palmerston Road West, Ringwood 3134, Australia). with an axial Minitube (MTS354) continuously operating single phase fan (Fantech Pty Ltd, 52-54 Paringa Avenue Somerton Park, SA 5044) and a Satchwell (MN450, TAC Headquarters Malmo, Sweden) climate control module that regulated the temperature of the outflow air to achieve approximately 2 °C above the ambient vineyard temperature (Figure 1.2C). The external temperature sensor was placed 7.75m from the chamber wall in each heated treatment site. and the chamber temperature sensor was placed at a height of 1.4-1.5m from the soil surface (depending on variety). These sensors were entirely independent from the HOBO logging system. The central module was connected to a linear duct system which directed the warmed air to the soil surface to encourage efficient heating. The ducting was located directly below the canopy.

The fan-only control OTC contained a unit that was identical, except that no heating element was present, with a single phase fan unit only (Figure 1.2D).



Figure 1.2: Chamber installed at the Chardonnay trial site. B. Vine within a chamber. C. Climate warming unit utilised to achieve an increase of ambient air temperature by approximately 2 °C D. Fan-only control unit simulating the air movement in the heated chambers.

1.2.4 Vine phenology

The timing of budburst, anthesis, fruit-set, and veraison were determined in both full growing seasons covered by the project, 2010/11 and 2011/12 by method of repeated photographing whole vines and individual marked bunches throughout the season, followed by a retrospective assessment of EL stage (Coombe, 1995). The photographic catalogue consisted of weekly

canopy development photos, which expanded to bunch development once bunches had developed enough for tagging. Two bunches originating from the upper cordon were tagged at each treatment site for development photographs.

In the 2011-2012 season in addition to the photographic records a quantitative assessment of bud burst, flowering (perencent cap fall) and veraison were carried out in the field. Shortly before bud burst 50 spurs were labelled for each replicate vine and were assessed using the Merbein Bunch count method (Antcliff et al., 1972). Beginning shortly before anthesis the percentage cap fall of each labelled spur was scored weekly until berry set. Beginning at berry softening the percentage veraison (colouring) was recorded for each bunch of the previously labelled indicator spurs. The information was entered into a spreadsheet and the mean percentage of bud burst, cap fall and veraison were calculated for each sampling date and treatment. The dates of 50% bud burst, capfall and veraison respectively for each variety and treatment were determined by interpolation between the sampling dates.

In the 2010/11 season the Sunraysia region had 899 mm rainfall (Bureau of Meteorology, 2012). This was a record for the region and resulted in a large incidence of disease within the trial sites. Ineffective spray application up to the rain events in combination with a lack of airflow in the OTCs may have created an environment conducive to fungal infections.

1.2.5 Vine physiology

A limited assessment of vine canopy physiology was made in both seasons. Stomatal conductance during the 2010/11 season of all replicates within a variety was measured using a Leaf Porometer (SC-1, Decagon Devices Inc. 2365 NE Hopkins Court Pullman, WA 99163) on 26/11/10 for Cabernet Sauvignon and 20/12/11 for Shiraz, then on 8/3/11 for all three varieties. Three fully expanded, young, sunlit leaves were assessed in each chamber/control panel prior to midday on each occasion. During the 2011/12 season six fully expanded, young, sunlit leaves were assessed for each replicate in all three varieties prior to flowering, at fruit-set and prior to harvest.

Leaf gas exchange was measured at canopy closure in both seasons using a LiCor 6400 Portable Photosynthesis Analyzer (John Morris, Adelaide, SA). Two leaves were assessed in each replicate of all three varieties with assimilation under saturating light (A_{sat}), stomatal conductance, transpiration, water use efficiency, leaf temperature all being assessed. In addition an estimate of Rubisco activity ($V_{c\,max}$)was made from the Asat measurement using the C3 photosynthesis model (Farquhar et al., 1980) rearranged according Harrison et al. (2009).

Changes in canopy size were estimated using measurements of leaf area index (LAI) with a LiCor LAI2000 Plant Canopy Analyzer (John Morris Scientific, Keswick, SA). The measurement strategy involves using the 315° aperture cover. Each reading involved the centre of the 45° opening (22.5 °C) facing in the same direction away from direct sunlight: Cabernet Sauvignon and Chardonnay NW and Shiraz SW. The measurement consists of two ambient readings above the canopy and three readings taken 150mm from the soil surface against the outer post/chamber wall (depending on the treatment).

Fortnightly Ceptometer (AccuPAR LP-80, Decagon Devices, Inc. 2365 NE Hopkins Ct. Pullman, WA 99163) data was collected throughout the 2010/11 season. This involved a measurement sequence, using segmented measurements across the canopy at 90° to the cordon taking in the whole canopy. Each measurement site was equidistant from any vertical wooded structures with four cross-sections at each site for Shiraz and Cabernet Sauvignon and three for Chardonnay.

1.2.6 Pruning weight

At the end of the 2010-2011 growing season the pruning weight of vines of all treatments was assessed. Pruned shoots and canes of a one meter wide transect per replicate were collected and weighed. A sub-sample (ca 300 g) was taken from the pruned cane and shoot material, was weighed and after drying in an oven was re-weighed to determine its water content. The resulting moisture percentage was in turn used to determine the dry weight of all pruned shoots and canes.

1.2.7 Grape harvest procedure

A target vine was selected in each treatment plot. The central vine of each three in red varieties and the southern most vine of each panel in Chardonnay. Target vines were excluded from any berry sampling during the season. When grapes had reached maturity (texttildelow 24°Brix a one metre wide transect was harvested from the target vines and the number of bunches was recorded. The fruit was then transported in labelled buckets to the laboratory for weighing and a sub-sample of four bunches was taken for analysis. In the control and heated treatment sites the remaining fruit was harvested to be made into wine.

1.2.8 Assessment of fruit quality

Fruit material

Fruit was collected from Shiraz, Cabenet Sauvignon, and Chardonnay during three growth stages, Pea-sized Berries, Veraison, and Harvest. Six berries were removed from 20 bunches (total of 120 berries), at harvest an additional 6 berries were removed from each bunch (total of 240 berries). The grape berries were then used for analysis of pH, titratable acidity (TA) and total soluble solids (TSS, °Brix). A subsample of tree replicates of 20 berries were collected for berry weight. Subsequently skins were removed and skin weight recorded. Skin samples were then rapidly frozen in liquid nitrogen, ground to a fine powder and stored and -80 °C until analysed. Samples were then weighed to approximately 1.0 g (+/- 5%) in three replicates and weight recorded to four decimal places.

Total Soluble Solids

Berry juice Total Soluble Solids (TSS) (expressed as °Brix; grams of sucrose equivalents/gram of berry juice expressed as %) was measured after crushing and centrifuging the fresh berry sample at harvest. TSS was measured using a digital refractometer.

pH and Titratable Acidity

Acidity and pH of the juice were measured by titrating by 0.1N sodium hydroxide to an end point of pH 8.3 using a Radiometer combined electrode, a TIM850 Radiometer, TitraLab titrator and a SAC80 Radiometer sample changer (Radiometer analytical, Pacific Laboratory Products, Blackburn, VIC 3130).

Extraction, Purification and Analysis of Tannins from Grape Skins

Weighed out samples were extracted with 10 mL of 70% acetone/water (v/v) that contained 0.1% ascorbic acid to prevent oxidation of tannin. Samples were then vortexed for one minute and sonicated for 20 minutes. Following sonication, samples were centrifuged for 10 minutes (4,000 $\times$ g). Tannin extracts were then purified utilising liquid-liquid separation to remove any non-tannin material as described by Seddon & Downey (2008).

Following the removal of non-tannin material 100 μL of purified sample was transferred to 1.5 mL microfuge tube and dried down under vacuum. Dried down samples then underwent acid catalysed cleavage in the presence of excess phloroglucinol as described by Kennedy & Jones (2001). Samples were then analysed by Reverse-Phase High Performance Liquid Chromatography (RP-HPLC) as reported by Hanlin & Downey (2009).

Terminal subunit composition was determined utilising standard curves of catechin, epicatechin, and epicatechin-gallate. Whilst, extension subunits were quantified by utilising the catechin standard curve and conversion factors as reported by Kennedy & Jones (2001).

Anthocyanin and Flavonol Analysis in Grape Skin

Anthocyanin and flavonol composition were determined by High Performance Liquid Chromatography (HPLC). Grape skins samples (1.0g) were extracted with 10 mL of 50% methanol in water (v/v) (Downey & Rochfort, 2008). Each tube was then vortexed and sonicated for 20 minutes at room temperature (~24 °C. Following sonication each tube was vortexed again and centrifuged at 4,000 $\times$ g for 10 minutes. Subsequently 1.5ml of the supernatant was transferred to a 2 mL screw cap tube and centrifuged at 13,000 $\times$ g to remove any remaining cell debris prior to analysis. Following centrifugation, 200 μL of grape skin extract was transferred to a HPLC autosampler vial for analysis using a Wakosil™ analytical column (150 mm x 4.6 mm, 3 μm packing). The HPLC separation utilised a binary solvent gradient as described by Downey & Rochfort (2008). Anthocyanins are expressed as milligrams of malvidin-3-O-glucoside equivalents per gram of fresh berry skin, and flavonols are expressed as milligrams of quercetin-3-O-glucoside equivalents per gram of fresh berry skin.

1.2.9 Assessment of wine quality

Winemaking

Fruit for winemaking was harvested from the entire treatment area to ensure that adequate fruit was available for winemaking. Following harvest fruit was transported to the CSIRO experimental winery located in Merbein, Victoria. Wine was made according to the CSIRO standard winemaking practice (Gong et al., 2010). Fruit from each treatment was crushed and divided between three fermentation vessels. Wines underwent seven days of maceration during fermentation. Following fermentation to dryness, the wine underwent as series of steps including racking and cold stabilisation prior to bottling. Wines were then stored at 18 °C until required for post-bottling, analysis, sensory and descriptive analysis.

Spectrophotometric Analysis of wines

At various time points during the winemaking process and post bottling, 20 mL of wine was collected for spectrophotometric analysis. Wines were analysed utilising methods outlined by

Iland et al. (2004) for analysis of wine colour density and wine hue in the red wines and total hydroxycinnamates and total brown pigments in the white wine. In addition tannin, anthocyanin, iron reactive phenolics, and polymeric pigment concentration was determined utilising methods described by Harbertson et al. (2003). Prior to analysis wines were centrifuged at 4,000 $\times$ g to remove any solid material. This was particularly important for samples collected prior to bottling.

1.2.10 Heatwave events

Experimental design

An additional smaller OTC (5.4 $\times$ 2.4 $\times$ 2.4 m) was used to create short-term "extreme" heat events on a single panel of vines. This air warming unit used dual triple 2.4 kW finned heating elements with a continuously operating single phase fan unit (MTS302, Fantech Pty Ltd, 52-54 Paringa Avenue Somerton Park, SA 5044) Each extreme heat event generated was matched with an existing non-chamber control replicate used in objective 1. The heat events were typically five days in length and attempted to provide as much climate warming as possible to the treated vines. The warming generated was assessed with a HOBO system identical to those used in Objective 1 and set up in the same way.

Assessment of vine physiology in 2010 - 2011

Heatwave events were generated using the chamber at flowering, veraison and harvest in all three varieties (Table 1.2). Short-term effects were assessed using measurements of stomatal conductance (g_s) and by measurements of chlorophyll content of six young, fully expanded sun exposed leaves, using an CCM-200 Chlorophyll Content Meter (Opti-Sciences, Inc., 8 Winn Avenue Hudson, NH, 03051, USA).

Table 1.2: Dates of heatwave events in Chardonnay, Cabernet Sauvignon and Shiraz during the 2010-2011 season.

	Chardonnay	**Cabernet Sauvignon**	**Shiraz**
Pre-flowering	18 – 22-Nov-10	01 – 05-Dec-10	25 – 29-Nov-10
Pre-veraison	17 – 21-Dec-10	10 – 14-Jan-11	24 – 28-Jan-11
Pre-harvest	14 – 18-Feb-11	21 – 25-Feb-11	28-Feb – 04-Mar-11

Assessment of vine physiology in 2011 - 2012

A slightly different approach was taken in the 2011/12 season, with heatwaves only being generated in the Cabernet Sauvignon vines. The system was again run at flowering (14/11/11-21/11/11), veraison (16/01/12-20/01/12) and harvest (20/02/12-24/02/12), but more intensive short-term measurements were made. Stomatal conductance was measured using two cycles of six young, sun exposed leaves at each site of the heatwave treatment and control at multiple times of day (each day at 1030 and 1530) on multiple days during all three heatwaves In addition, leaf temperature effects were determined in individual leaves using a Fluke infra-red thermometer (Fluke Australia P/L, Melbourne, Vic) from 1030 and 1530 daily (4:1 of stomatal conductance

readings) and for the whole canopy using a FLIR B360 infra-red camera (FLIR Systems Inc., Wilsonville, Oregon, USA).

Chlorophyll fluorescence was assessed using a Walz MiniPAM system, as photosystem II efficiency and as dark adapted (approx. 1 hr) Fv/Fm. On each occasion gas exchange was measured as described under objective 1, but using eight leaves per chamber/control. Midday leaf- and stem- water potentials were measured in the latter two events (not at flowering) using a Plant Water Status Console (ICT International, Armidale, NSW) fitted with a Peak Hold Meter (MEA, Magill, SA) on eight leaves per chamber/control. Finally, pre-dawn leaf water potential and Fv/Fm were also measured, as described above, during the veraison heat event.

1.2.11 Assessment of fruit and wine quality

Fruit was collected from Shiraz, Cabernet Sauvignon, and Chardonnay during three growth stages, Pea-sized Berries, Veraison, and Harvest as per methods described in Section 1.2.8 on page 6. Fruit was then assessed for juice acidity Total Soluble Solids, pH and Titratable Acidity. Skins were removed from the berries and stored for analysis of Tannin, Anthocyanin and Flavonol content (Section 1.2.8).

1.3 Results and Discussion

Objective 1. Quantify the response of Shiraz, Cabernet Sauvignon and Chardonnay vines in warm production areas to the effects of elevated temperatures anticipated under climate change projections

1.3.1 Open top chambers (OTC) performance

The warming chambers were installed at various times during the latter half of the 2009/10 season and all 18 chambers were then run continuously until the end of the 2011/12 season, with the exception of a brief period each season to allow machine harvesting to occur on the rest of the row. Consequently, there were full two seasons of environmental data to assess chamber performance.

The temperature within the chamber tracked that outside the chamber with reasonable accuracy (Figure 1.3), with no evidence that sunlight hours impacted significantly on chamber performance. The chambers maintained a similar temperature differential to the external air on clear, sunny, warm days (the first eight days represented in Figure 1.3) as on cooler, cloudy days (the final six days represented in Figure 1.3). However, wind-speed did impact the minute to minute variation in air temperature, with greater variation in the temperature differential during periods of high wind (wind speed data not presented, but the final four days represented in Figure 1.3 represent a period of high wind speed). This was due to warmed air being blown out of the chamber faster than it could be replaced as the wind speed increased. The effect could have been reduced with a taller chamber, but this was not implemented due to the impact on light quality that would have occurred.

Although no diurnal effect on warming was observed when a limited subset of the data was examined (*e.g.* Figure 1.3), the season long averages demonstrated that the warming effect on the daily maximum temperature was approximately 25% greater than that on the daily minimum when the warming chambers were compared with the chamberless controls, suggesting that the warming was slightly less effective at night (Table 1.3). In contrast, the effect on mean daily maximum air temperature was similar or slightly less when compared with the fan only controls. Furthermore, there was generally no difference between the fan only controls and chamberless controls at night, but a small difference during the day, suggesting that the presence of the chamber itself, without active heating, had a small warming effect.

Table 1.3: Effects of warming treatments compared with fan only chambers and chamberless control plots on mean daily maximum and mean daily minimum air temperatures in the 2010/11 and 2011/12 seasons.

Season	Variety	Difference in Mean Daily Max °C		Difference in Mean Daily Min °C	
		v. Fan only	v. Chamberless	v. Fan only	v. Chamberless
2009–2010	Cabernet	1.6±0.8	2.4±0.9	2.0±0.8	1.9±0.8
	Chardonnay	1.2±1.0	1.8±0.9	0.9±0.6	0.9±0.7
	Shiraz	1.3±1.0	1.8±1.1	1.4±0.9	1.3±0.9
2010–2011	Cabernet	2.2±1.0	3.4±1.3	2.9±0.9	2.7±1.0
	Chardonnay	1.4±0.8	2.4±1.0	1.9±0.7	1.8±0.8
	Shiraz	2.0±0.7	2.8±0.8	2.1±0.7	1.9±0.7

The intended warming to be generated by the OTC system was 2-3 °C, replicating the atmo-

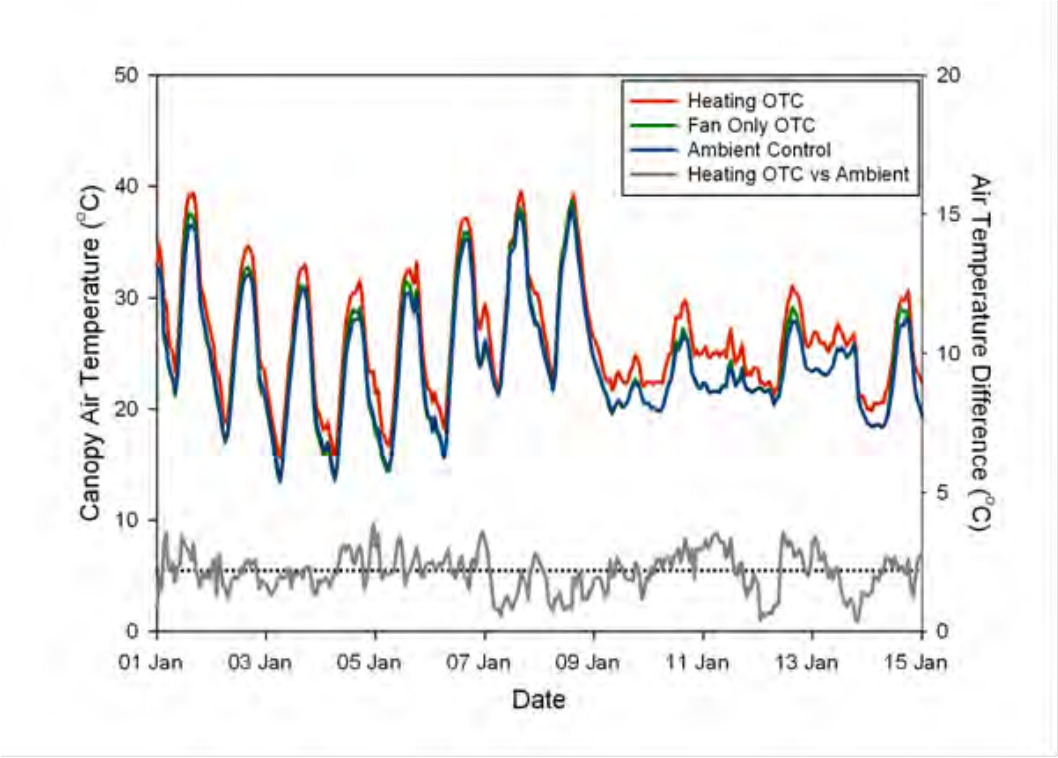


Figure 1.3: Mean air temperature of three warming chambers, three fan only control chambers and three non-chambered areas in Cabernet Sauvignon vines (left axis) and the mean air temperature between the warming chambers and the ambient controls (right axis).

spheric warming expected in Australia's viticultural regions circa 2050 (OzClim 2012). The actual warming over the course of the project varied by variety and season, the former presumably due to local microclimate and the latter due to the control sensor being repositioned in the 2011/12 season (Figure 1.4A). Consequently, the average warming in 2010/11 was 1.71 °C compared with 2.37 °C in 2011/12. Over the two seasons the average warming ranged from 1.65 °C in Chardonnay to 2.55 °C in Cabernet.

As no humidification was used, the warming treatments resulted in a decrease in relative humidity with all varieties (Figure 1.4B), also consistent with future climate scenarios. This in turn meant that vapour pressure deficit (VPD) was higher in the warming chambers (Figure 1.4C). Finally, the soil temperature monitoring suggested that at 10 cm depth the soil was also warmer in the heated chambers. There was a big difference between seasons, with the effect being much less than that on air temperature in 2010/11, but much higher in 2011/12. This was probably due to differences in the positioning of the heater air outflow in the second season to maximise air mixing, meaning the heater outflow was directed directly over the soil temperature sensor in 2011/12.

Minute to minute variation is indicated by the standard deviation bars on Figure 1.4 as the warming effect was calculated on a per-reading basis. This variation was limited, with one standard deviation averaging 52% of the mean value, so the actual warming achieved was generally close to the mean.

In addition, values for mean daily mean, maximum and minimum air temperatures are provided in Table 1.4 These demonstrate the difference in temperature between the two seasons, 2010/11 being a record wet season in the Mildura region, but by again examining the standard deviation values it can be seen that there was little difference in the variation between treatments or varieties in the seasonality observed. This is further evidence of the effectiveness of the warming chambers in tracking ambient temperature.

Table 1.4: Mean air temperature, mean daily maximum air temperature and mean daily minimum air temperature for the heated, fan only control and chamberless control plots during the 2010/11 and 2011/12 growing seasons, for Cabernet Sauvignon, Chardonnay and Shiraz grapevines.

Season	Variety	Difference in Mean Daily Max °C			Difference in Mean Daily Min °C			Difference in Mean Daily Min °C		
		Heated	Fan only	Control	Heated	Fan only	Control	Heated	Fan only	Control
2009–2010	Cabernet	21.9±6.9	20.0±7.1	19.7±6.9	29.3±6.1	27.7±6.1	26.9±6.1	15.0±4.9	13.0±4.9	13.1±4.9
	Chardonnay	21.0±7.3	19.9±7.1	19.7±7.0	28.9±6.4	27.6±6.1	27.1±6.0	13.8±5.1	13.0±5.0	12.9±5.0
	Shiraz	21.2±6.9	19.7±6.9	19.6±6.8	28.8±6.2	27.5±6.0	27.0±5.9	14.4±5.0	13.0±4.9	13.0±4.9
2010–2011	Cabernet	23.8±7.3	21.1±7.3	20.9±7.0	32.1±5.7	29.9±5.4	28.7±5.6	16.2±5.2	13.3±4.9	13.5±4.9
	Chardonnay	22.8±7.0	21.0±7.1	20.8±6.9	31.8±5.2	30.4±5.0	29.4±5.2	15.3±4.8	13.3±4.9	13.5±4.9
	Shiraz	22.8±7.2	20.6±7.0	20.6±6.9	31.1±5.4	29.2±5.1	28.3±5.3	15.2±5.1	13.1±4.8	13.3±4.8

By examining the differences between the chamberless control and the fan only control it was possible to determine effects caused directly by the use of the chamber (Tables 1.3 & 1.4). The difference between the controls was small, the chamber alone accounting for an average warming effect of between 0 and 0.3 °C, although this appeared to primarily occur during the day.

In summary, the chambers performed well, providing a climate warming scenario that was realistic and likely to be experienced by growers throughout Australia within the next 20 to 40 years, within the expected lifetime of many current plantings.

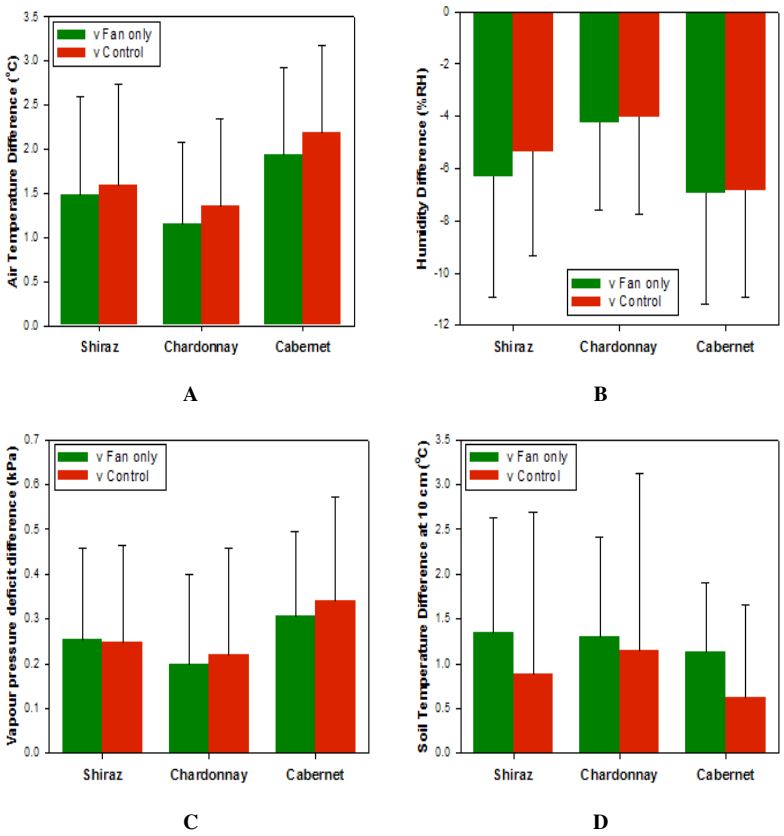


Figure 1.4: Whole season mean difference between warming chambers and chamberless controls for 2010/11 (green bars) and 2011/12 (red bars) ± standard deviation in a) air temperature, b) relative humidity, c) soil temperature at 10 cm depth and d) vapour pressure deficit for Shiraz, Chardonnay and Cabernet Sauvignon vines. Data were recorded at 10-15 minute intervals.

Leaf and canopy growth

During the establishment phase of the trial in 2009-2010 light interception of Cabernet Sauvignon was monitored using a Decagon ceptometer for a period of around six weeks (Figure 1.5). No statistically significant differences were seen between the imposed treatments.

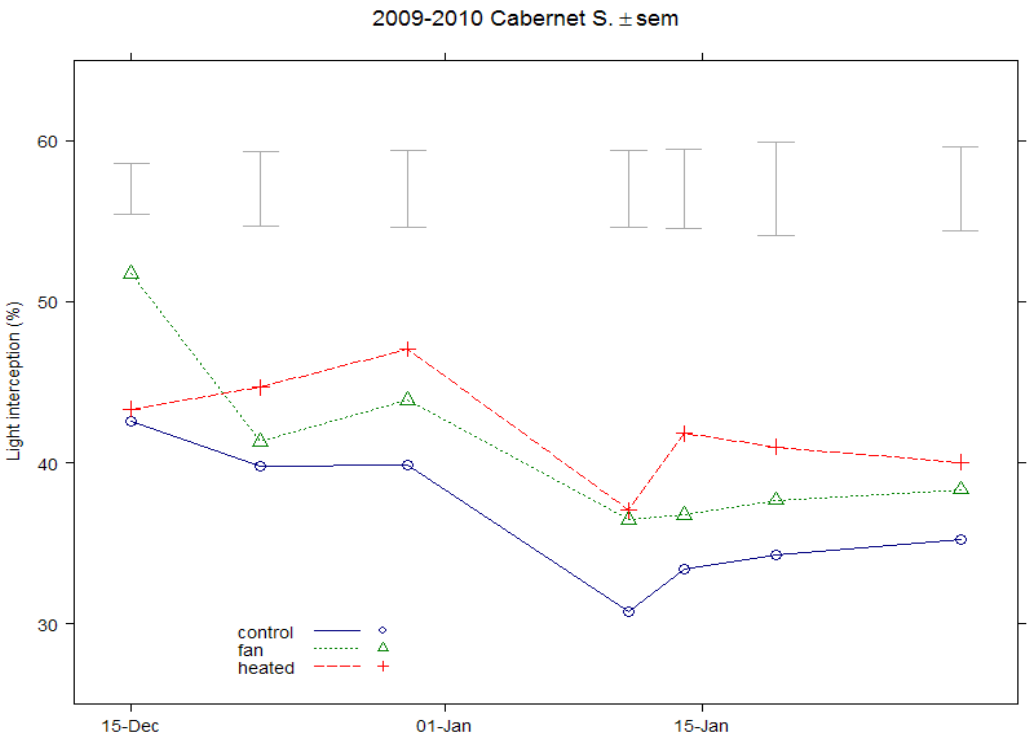


Figure 1.5: Percent light interception of heated and unheated OTC vines relative to control vines without a chamber during the 2009-2010 growing season. The variety under investigation was Cabernet S. Vertical bars represent the standard error of the mean difference (sem).

Light interception of all varieties was monitored throughout 2010-2011 when the experimental treatments were imposed to all varieties for the whole season (Figure 1.6). Differences between treatments were seen early in the season between mid September and mid November when heated treatments tended to develop more quickly with a larger leaf area than either control vines without a chamber or those in a chamber with a fan only. There was also in indication that toward the end of the season control vines defoliated more quickly than those in the chamber regardless of heating.

1.3.2 Apparent leaf area index

In the second full season of experimental treatments leaf area development was monitored using a LiCor canopy analyser rather than a ceptometer. The Licor instrument measured the seasonal development of the apparent leaf area index (ALAI) for each of the varieties under investigation (Figure 1.7). Results indicate that immediately after bud burst ALAI of vines growing in heated chambers developed more quickly resulting in a larger leaf area relative to the other treatments.

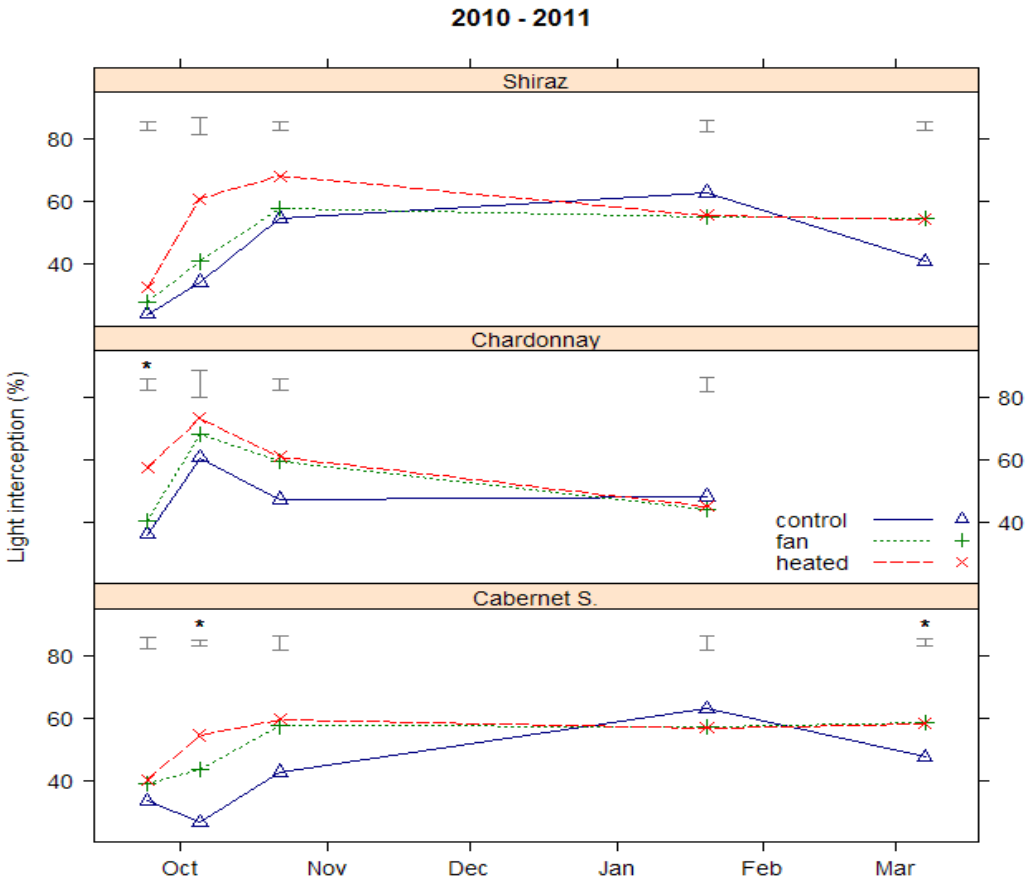


Figure 1.6: Percent light interception of heated and unheated OTC vines relative to control vines without a chamber during the 2010-2011 growing season. Shiraz, Chardonnay and Cabernet S were investigated. Vertical bars are standard error of the mean (sem); stars indicate statistically significant differences between treatments ($p<=0.05$).

The acceleration was most persistent in Cabernet S. lasting until around mid November while in Shiraz and Chardonnay it came to an end by early to mid November. After fruit set ALAI of all vines was similar for the remainder of the season regardless of treatment. Heating obviously accelerated bud development and thus boosted leaf area early in the season until around the time of lowering.

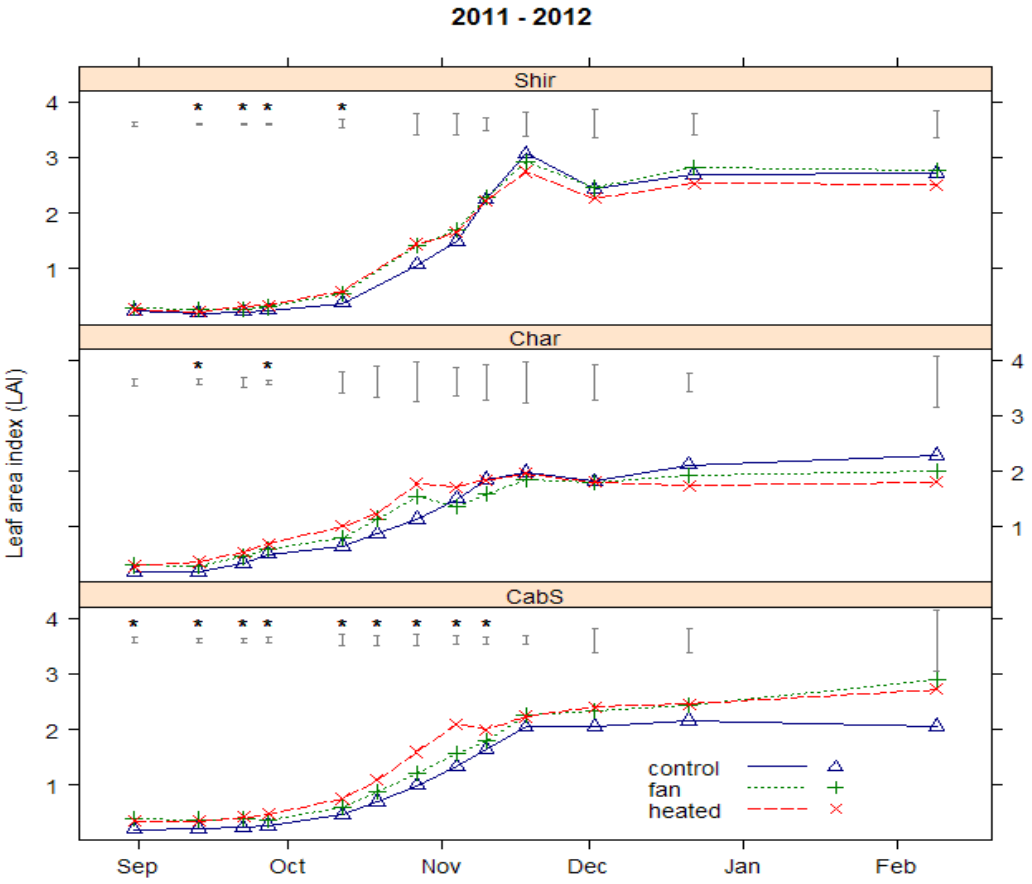


Figure 1.7: Apparent leaf area index (ALAI) of heated and unheated OTC vines relative to control vines without a chamber during the 2011-2012 growing season. Shiraz, Chardonnay and Cabernet S were investigated. Vertical bars are l.s.d; stars indicate statistically significant differences between treatments ($p<=0.05$).

1.3.3 Phenology

Photographic records

Photographs of key phenological stages were taken systematically at weekly intervals in both seasons as described in Section 1.2.4. Images of three key growth stages, namely, at around bud burst, flowering to set and at veraison are depicted in Figure 1.8 on page 18. Images of heated and unheated treatments for any given growth stage and variety are always depicted on the same date. The comparison clearly illustrate the considerable acceleration in vine development seen as a result of heating (~2.5 °C). For example, during bud burst the leaf canopy of heated vines had

filled in to a much greater degree than that of unheated control vines. At fruit set, heated vines had clearly visible berries while flower caps and stamens were still visible on control vines. The difference was even more apparent at veraison, when a large proportion of berries on heated red varieties had darkened whilst those of control vines were still green. Even on the white variety Chardonnay there was a clear difference in berry colour, size and appearance between heated and unheated treatments.

Photographic images of all varieties were also scored in accordance with the Eichhorn Lorenz (EL) scale as described by Coombe (1995) with the aim to provide a quantitative estimate of vine development under elevated temperature.

The time course of the EL stages of heated and control vines for each variety and season is depicted in Figure 1.9 on page 19. As was seen for the photographic images earlier the graphs illustrate the acceleration in growth seen as a result of heating. The phenological stages of heated vines were for most of the season clearly ahead of control vines except for a period well after harvest when heated vines retained green leaves for longer than control vines. The delay in leaf fall for heated over control vines seems to indicate that warmer temperatures prolonged leaf functioning late in the season.

1.3.4 Bud and bunch counts

The second season of the trial included detailed bud and bunch counts at key phenological events as described in section 1.2.4. The aim was to provide an accurate quantitative assessment of the course of key phenological events under the different temperature regimes. Result showed that for each variety heating had a marked influence on the course of key phenological events. Heating always accelerated bud burst in that at any given time after the first buds had opened there was a greater percentage of burst buds in heated as compared to unheated vines (Figure 1.10 top row). There was very little difference in the course of bud burst between control vines and those in a chamber with a fan only but no heating.

Heating also accelerated cap fall and veraison, such that at any time after the first caps began to fall or berries began to colour in the red varieties, their respective percentages were always much greater in heated than unheated vines (Figure 1.10 middle and bottom rows respectively). There was a small effect of the fan only chambers on capfall but not on veraison.

The delay in key phenological events of unheated relative to heated vines becomes even more apparent when the time difference of the heating and fan treatment for each variety is expressed relative to control vines (see Figure 1.11). Results show that heating accelerated bud burst by around 5, 12, and 2.5 days respectively for Cabernet, Chardonnay and Shiraz. It also showed that the unheated chamber with a fan had very little influence on bud burst relative to control vines except for Chardonnay where bud burst was slightly accelerated over control vines.

Heating accelerated cap fall by around 5, 10, and 10 days respectively for Cabernet, Chardonnay and Shiraz (Figure 1.11). The unheated chamber did not accelerate cap fall in Cabernet S but did so by a couple of days in Chardonnay and Shiraz.

Heating accelerated veraison by around 5, and 10 days respectively for Cabernet S and Shiraz but the unheated chamber did not (Figure 1.11). The course of veraison of Chardonnay was not evaluated.

Although there was only one season of bud counts and results varied between varieties a 2.5 °C temperature increase is likely to result in an advance in phenology by between 2.5 and 10 days depending on variety. The work demonstrated the validity of modelled temperature scenarios and their impact on vine phenology as proposed by Webb et al. (2007). To consolidate these findings and to further validate phenological simulation models it is desirable to continue the



Figure 1.8: Photographic record of the main phenological stages of heated OTC vines relative to control vines without a chamber during the 2011-2012 growing season. Shiraz, Chardonnay and Cabernet S were investigated.

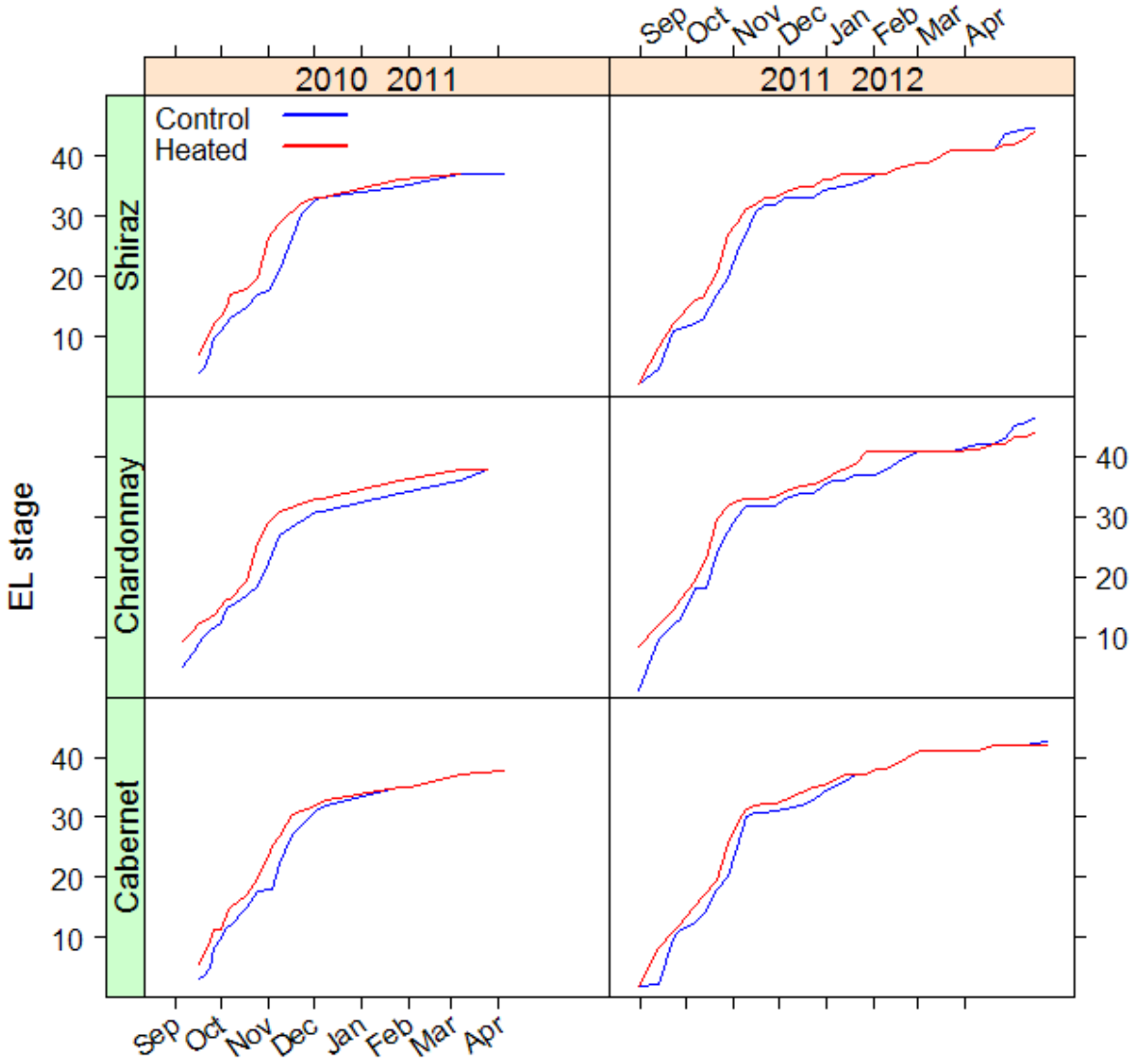


Figure 1.9: Phenological stages according to the EL scale (Coombe, 1995) of heated OTC vines relative to control vines without a chamber during the 2010-2011 and 2011-2012 growing seasons. Shiraz, Chardonnay and Cabernet S. were investigated.

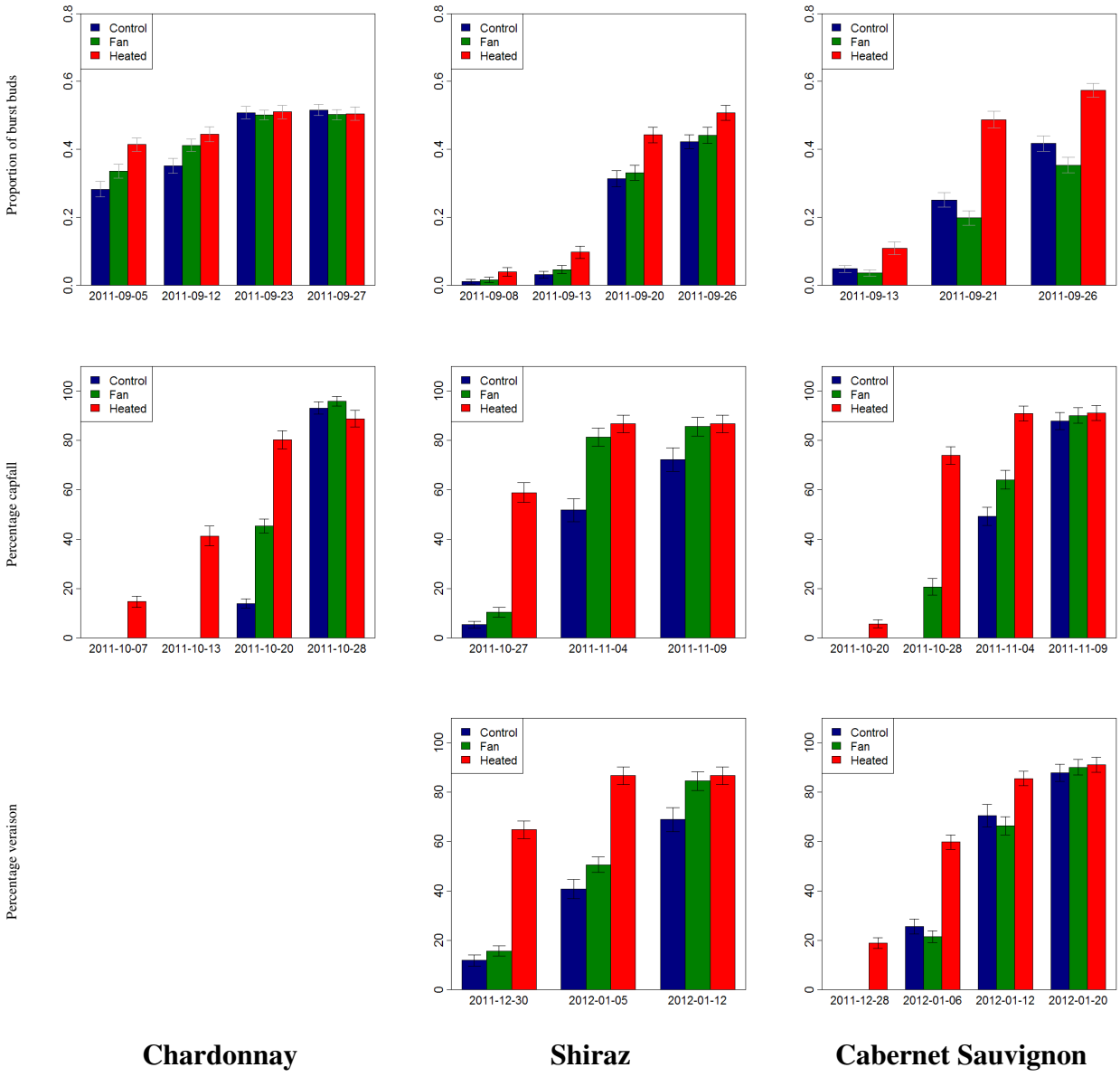


Figure 1.10: Percent bud burst(top row), cap fall (mid row) and veraison (bottom row) of heated and unheated (Fan) OTC vines relative to control vines without a chamber during the 2011-2012 growing season.

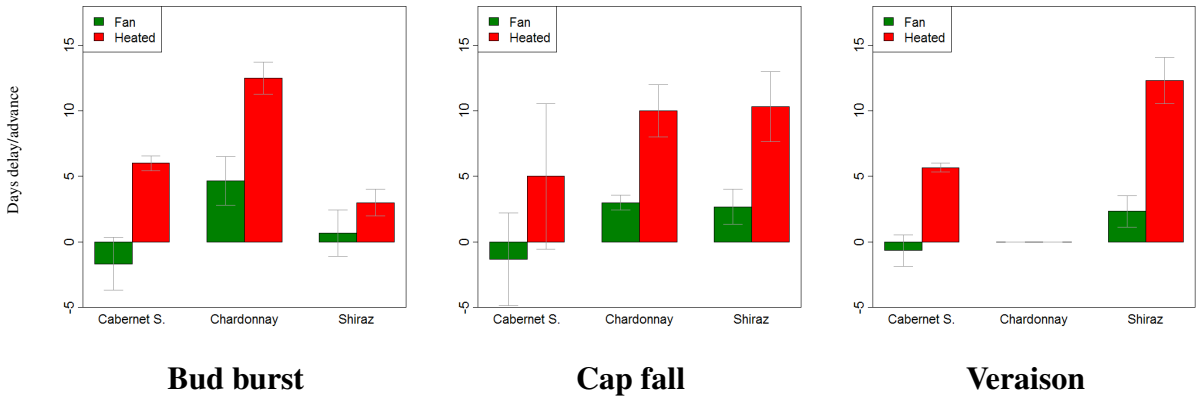


Figure 1.11: Days of delay or advance of bud burst, cap fall and veraison for unheated control vines without a chamber relative to unheated (Fan) OTC and heated vines within a chamber. Vertical bars are +/- standard error of the mean (SEM).

field assessment for a number of seasons.

1.3.5 Pruning weight

Pruning weigh ranged between 1.6 and 1.8 t ha^{-1} and the imposed treatments did not appear to have any influence on the accumulated pruning biomass regardless of variety (Figure 1.12). Pruning weight is a good indicator of vegetative vine growth throughout the season and results indicate that heating had no influence on the vines' capacity for vegetative growth.

1.3.6 Yield

Yields from the OTC's in 2010/11, heated or not, were generally lower than the ambient controls (Figure 1.13). However, this was not due to the temperature treatments *per se*, but to differential impacts of disease. A very high incidence of downy mildew was reported throughout South-Eastern Australia and this was also true of Sunraysia. The physical constraints of working in the chambers created difficulties in disease management, resulting in greater infection rates in OTC vines than in the ambient controls. It is interesting to note that in all three varieties the small impact on %RH of the warming treatment noted above was enough to significantly reduce the OTC disease impact, producing a higher yield in the heated OTCs than in the fan only OTCs in all three varieties.

Yield of all varieties and regardless of treatment were generally higher in the subsequent season (Figure 1.13). Yield of all varieties in fan only chambers tended to be higher relative to heated or control vines.

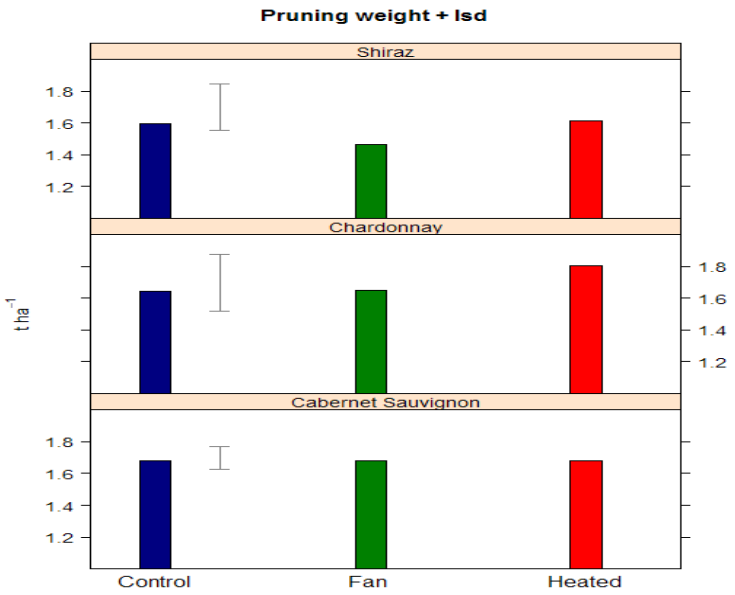


Figure 1.12: Pruning weigh (t ha^{-1} dry matter) of Shiraz, Chardonnay and Cabernet Sauvignon at the end of the 2010-2011 growing season. Vertical bars indicate l.s.d.. Treatments differences were not statistically significant.

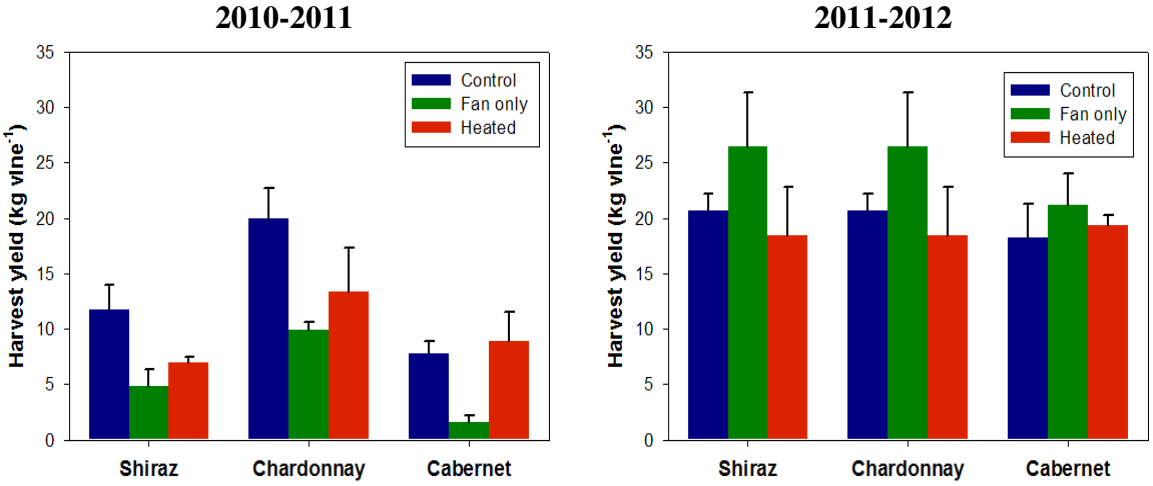


Figure 1.13: Harvest yield (kg vine^{-1}) of Shiraz, Chardonnay and Cabernet Sauvignon at the end of the 2010-2011 and the 2011-2012 growing seasons. Vertical bars indicate +SE. Treatments differences were not statistically significant.

1.3.7 Vine physiology

Stomatal conductance (g_s) is a widely used integrative measure of vine performance, sensitive to a wide range of factors that impact canopy function. Consequently, g_s was chosen to provide a broad assessment of treatment impact on leaf level physiology across the two seasons of fieldwork. During the 2010/11 season, measurements were limited, in part due to the lack of suitable weather conditions for measurement. In general there was little difference between the treatments, with the only significant impact being between control and heated Cabernet vines on 8/3/11 (Figure 1.14). As might be expected from previously published results (Costa et al., 2012) there were varietal differences, Cabernet typically having the lowest g_s.

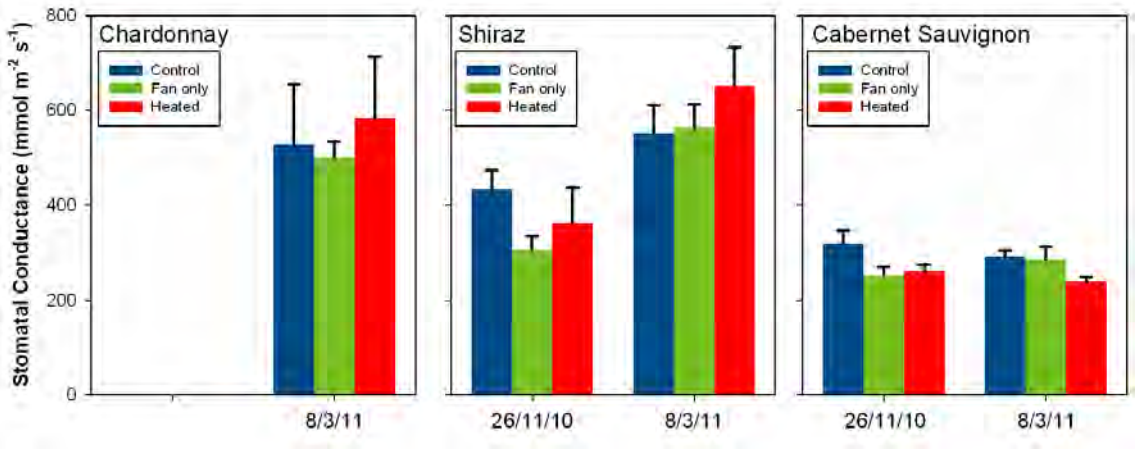


Figure 1.14: Stomatal conductance of sun exposed leaves from Chardonnay, Shiraz and Cabernet vines in ambient conditions, a fan only OTC or a heating OTC during the 2010/11 growing season. Bars are means of three sets of measurements +SEM, with each set of measurements consisting of 8-10 individual leaf level measurements.

It is difficult to draw conclusions from the 2010/11 g_s results due to the impact of disease during the season. Weather conditions during the growing season were extremely wet, for instance a single rain event produced more than double the typical growing season precipitation. Seasonal rainfall being 899 mm compared with the long-term average of 175 mm (Bureau of Meteorology, 2012). Disease pressure was high throughout the Sunraysia region, with downy mildew and Botritys having a high prevalence (Magary, 2011). The spray program for the OTCs was the same as the rest of the vineyard, but canopy penetration of spray was limited, due to the height required to clear the sides of the chambers. The result was a greater prevalence of disease in the OTCs than in the control sections of the vineyard. This was further complicated, by the warming and reduced humidity in the heating OTCs (see above) which in turn resulted in less disease in the heating OTCs than the fan-only control OTCs. Although as far as possible disease free leaves were chosen for all physiological measurements, on occasion this was not always possible and even where it was, impacts of disease elsewhere in the canopy on source-sink balance may have had an impact on the function of disease free leaves.

During the 2011/12 season, spraying within the OTCs was undertaken by hand, with schedules and sprays matched to the rest of the vineyard, with no significant occurrence of disease, or difference between treatments noted.

As during the previous season, there was no overall effect of the treatments on g_s during the 2011/12 season (Figure 1.15). However, the heated vines had significantly higher gs on the

first set of measurements after budburst in all three varieties. This may have reflected an initial response to the higher air temperatures, alternatively it may have been due to the faster development of the heated vines early in the season (see above). There were also some significant differences at individual measurement points, e.g. Shiraz on 5/12/11, but repeated measures ANOVA analysis did not indicate any season long effect of the treatments.

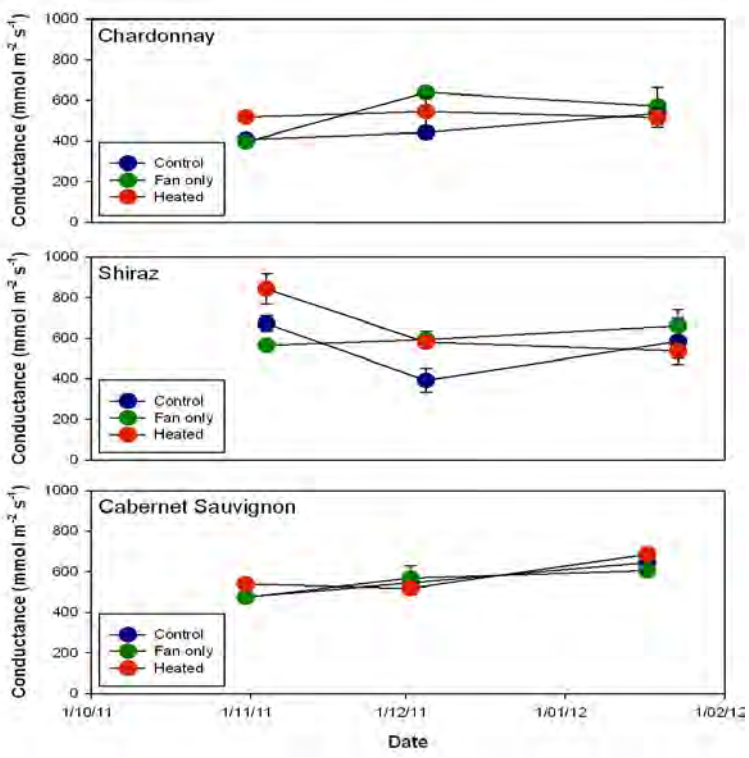


Figure 1.15: Stomatal conductance of sun exposed leaves from Chardonnay, Shiraz and Cabernet vines in ambient conditions, a fan only OTC or a heating OTC during the 2011/12 growing season. Points are means of three sets of measurements ±SE, with each set of measurements consisting of 8-10 individual leaf level measurements.

In both seasons a set of leaf gas exchange measurements were taken around canopy closure. Photosynthesis was not significantly affected by treatment in either season, was not significantly different between varieties in 2011/12 and was similar between seasons, despite the different weather conditions (Figure 1.16). The absolute values were typical of grapevines growing in the Sunraysia region with good nutrition (Edwards & Clingeleffer, 2011)).

The gas exchange measurements were used to estimate carboxylation activity ($V_{c\,max}$), thereby taking into account any differences in g_s. Although there was a significant impact of treatment in 2010/11 (Table 1.5) this was largely due to leaf temperature differences and the marginally significant difference in temperature adjusted $V_{c\,max}$ that remained was between the OTCs and control and was probably a result of the differential disease impact. There was no treatment effect on either $V_{c\,max}$ measure in 2011/12 (Table 1.6).

In fact leaf temperature was the only gas exchange parameter that was significantly altered by the warming treatment, and even then it was only significant in 2010/11. There were some varietal effects, with Chardonnay having a high transpiration rate and Cabernet a higher $V_{c\,max}$ in both seasons (Tables 1.5 and 1.6). Chardonnay also had a lower instantaneous water use efficiency as a result of the effect on transpiration, in line with previous observations (Bota et al., 2001).

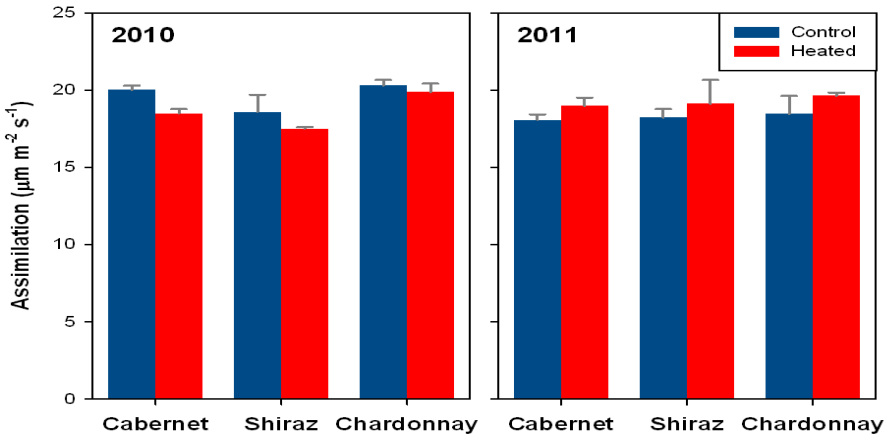


Figure 1.16: Photosynthesis under saturating light of fully expanded, sun exposed leaves of Chardonnay, Shiraz and Cabernet vines exposed to ambient of warmed environmental conditions (fan-only OTC data excluded for clarity). Bars are means of three sets of measurements +SE. Each set of measurement consisted of two individual leaf level measurements.

In summary, the leaf level measurements of canopy function all indicated no consistent difference between the warmed vines and the control vines. Given the limited extent of the warming and commonly observed ability for leaf physiology to acclimate to moderate warming (Tjoelker et al., 1999; Gunderson et al., 2010), these results suggest that even in warm climate regions commonly used winegrape varieties retain enough phenotypic plasticity for basic canopy function to remain unaffected.

Table 1.5: Leaf gas exchange parameters at canopy closure in the 2010-2011 season.

Variety	Treatment	A_{sat} μmol m^{-2} s^{-1}	g_s mmol m^{-2} s^{-1}	c_i ppm	E mol m^{-2} s^{-1}	Leaf T °C	A/g mmol mol^{-1}	A/E μmol mol^{-1}	$V_{c\,max}$ μmol m^{-2} s^{-1}	$V_{c\,max}$@25C μmol m^{-2} s^{-1}
Cabernet	Control	20.0±0.3	389±66	260±12	4.47±0.23	27.6±0.4	54.6±7.6	4.50±0.26	113±6	90.4±1.7
	Fan only	18.9±0.7	316±3	248±6	4.46±0.16	28.6±0.5	62.7±2.9	4.26±0.07	119±10	86.7±4.2
	Heated	18.5±0.3	272±13	239±4	4.29±0.18	29.2±0.1	69.0±2.9	4.33±0.17	124±2	86.3±2.1
Shiraz	Control	18.6±1.1	396±104	256±23	5.50±0.81	29.2±0.5	57.1±15.4	3.49±0.39	118±8	81.6±2.7
	Fan only	16.2±1.5	252±64	236±20	4.64±0.80	30.3±0.2	72.7±14.4	3.62±0.36	118±5	74.5±1.9
	Heated	17.5±0.1	313±39	257±11	5.42±0.28	30.2±0.4	57.7±6.6	3.28±0.15	116±7	73.7±2.0
Chardonnay	Control	20.3±0.4	417±12	264±2	5.10±0.18	28.8±0.3	51.0±0.5	4.00±0.06	120±3	86.8±2.4
	Fan only	20.6±0.6	479±16	271±4	6.12±0.31	29.9±0.1	45.5±2.9	3.38±0.18	121±4	84.1±2.7
	Heated	19.9±0.5	447±46	266±5	5.68±0.28	29.4±0.5	49.9±2.0	3.53±0.14	121±8	82.8±2.8
Anova	Variety	***	**	ns	**	***	*	***	ns	***
	Treatment	ns	ns	ns	ns	**	ns	ns	ns	*
	Interaction	ns	ns	ns	ns	ns	ns	ns	ns	ns

1.3.8 Conclusions, objective 1

The heated open top chambers very effectively maintained an atmospheric temperature approximately 2 °C above ambient for two full seasons, consistent with conditions expected around 2050. The non-heated chambers had a minimal effect on atmospheric temperature, acting as an effective control in this respect. The unusual weather conditions in the 2010/11 season led to differential disease impacts between the treatments, making the data interpretation more complex.

Table 1.6: Leaf gas exchange parameters at canopy closure in the 2011-2012 season.

Variety	Treatment	A_{sat} μmol m^{-2} s^{-1}	g_s mmol m^{-2} s^{-1}	c_i ppm	E mol m^{-2} s^{-1}	Leaf T °C	A/g mmol mol^{-1}	A/E μmol mol^{-1}	$V_{c\ max}$ μmol m^{-2} s^{-1}	$V_{c\ max}$@25C μmol m^{-2} s^{-1}
Cabernet	Control	18.1±0.4	266±3	240±1	3.90±0.03	25.8±0.1	69.0±0.3	4.66±0.04	99±3	92.4±2.1
	Fan only	19.1±0.5	325±43	251±11	4.34±0.33	25.8±1.0	61.1±7.0	4.45±0.28	102±8	94.5±1.6
	Heated	19.0±0.5	344±30	259±6	4.81±0.50	26.3±0.7	56.1±4.1	4.03±0.37	100±7	89.4±2.1
Shiraz	Control	18.2±0.5	273±32	236±10	5.81±0.32	30.2±0.5	68.4±6.7	3.15±0.08	131±5	84.1±3.6
	Fan only	19.0±0.8	320±37	247±6	6.20±0.68	30.3±0.6	61.2±4.6	3.11±0.21	131±6	83.0±2.6
	Heated	19.1±1.5	320±49	243±6	6.84±0.86	30.7±0.2	62.5±5.6	2.84±0.16	137±7	84.1±5.4
Chardonnay	Control	18.5±1.1	356±65	256±12	5.63±0.30	28.0±0.9	56.7±8.3	3.29±0.04	108±8	83.2±4.4
	Fan only	18.9±0.9	328±54	247±11	5.70±0.39	28.4±0.6	61.4±7.8	3.34±0.13	117±3	86.7±2.6
	Heated	19.6±0.2	383±30	253±3	6.27±0.33	28.7±0.9	56.9±1.3	3.20±0.15	120±9	87.2±1.2
Anova	Variety	ns	ns	ns	***	***	ns	***	***	*
	Treatment	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Interaction	ns	ns	ns	ns	ns	ns	ns	ns	ns

However, it also highlighted the reduction in disease that a small decrease in relative humidity can achieve, suggesting that future climates may have an impact in that respect.

The 2 °C warming had no impact on leaf level physiology, consistent with the existing literature on plant acclimation to this level of warming. In contrast, there was a significant impact on vine phenology. Data from measurement of leaf area index, Merbein bunch counts and photographic records clearly demonstrated earlier budburst in all three varieties as a result of climate warming. This did not impact the proportion of budburst *per se*, but only the timing. Anthesis and veraison were similarly advanced by 5-10 days.

No over-arching effect on canopy size, pruning weight or yield was observed, although the practicalities of the system limited replication to three plots per treatment per variety. Consequently, the warming appeared to impact only the timing of growth, not growth or production itself. However, a delay in leaf fall was also noted in the heated chambers, suggesting that greater post-harvest accumulation of storage reserves may have been occurring and this could have an impact over a number of years. Storage reserves were not estimated as part of this study, but samples were taken for future analysis.

Objective 2. Investigate the ability of warm inland regions to maintain fruit quality and wine end use under an elevated temperature scenario

1.3.9 Fruit and must quality indicators

Total soluble solids, or total dissolved solids, measured by digital refractometer and reported as °Brix, was measured in the fruit of Chardonnay, Shiraz and Cabernet Sauvignon at veraison (the onset of ripening) and harvest for 2 seasons, 2010-11 and 2011-12. Harvest date was based on the generally accepted level of maturity across industry of approximately 24 °Brix. Titratable acidity (TA) and pH were also determined at veraison and harvest by autotitrator for all three varieties in both seasons. Due to the advanced phenology in Chardonnay additional control samples were collected. A sample of fruit from the heated treatment was collected when the fruit reached veraison (defined as an increase in °Brix). At that time a comparative sample was collected from the control vines. When the control vines reached veraison another sample was collected from the control vines and also from vines in the fan only treatment. This sampling was repeated at harvest for Chardonnay. This sampling protocol was employed in both 2010-2011 and 2011-2012 for Chardonnay and for Shiraz and Cabernet Sauvignon at veraison and harvest.

Total soluble solids, titratable acidity and pH

Chardonnay In Chardonnay grapes, total soluble solids (°Brix) and pH increased and titratable acidity (TA) decreased during berry development (Figure 1.17 on page 28) consistent with previously published research (Winkler et al., 1974). In both seasons at veraison, °Brix was significantly greater in the heated treatment than in the control vines sampled on the same date. In 2010-11, °Brix was higher in the fan only treatment when the control reached veraison (Figures 1.17 and 1.18 on page 29). Fruit from the heated treatment reached veraison about two weeks before the controls in both 2010-11 and 2011-12, which was consistent with advanced phenology observations reported in Section 1.3.3. In both seasons, Chardonnay fruit from the heated treatment reached commercial maturity (~24 °Brix) ahead of the control or fan only treatment. In 2010-11, fruit from the heated treatment reached 24 °Brix about seven weeks before the control. This could be partly attributed to advanced phenology as a result of the heating treatment; however 2010-11 was an extremely wet season with a lot of late summer rainfall that delayed ripening across the whole region. In 2011-12, fruit from the heated treatment reached commercial maturity around 3-4 weeks ahead of the control and fan only treatments. In both seasons (2010-11 and 2011-12) TA was higher in the heated treatment at veraison and pH was commensurately lower. By harvest (24 °Brix) there was little difference in either pH or TA despite considerable differences in the harvest dates.

Shiraz In Shiraz grapes, °Brix and pH increased from veraison to harvest and TA decreased in both seasons (Figures 1.19 and 1.20). In 2010-11, Shiraz grapes from all treatments reached veraison at around the same time and were sampled on the same date. Upon complete analysis of the samples it was observed that fruit from the heated treatment had higher °Brix, consistent with the advanced phenology reported in early sections of this report. Fruit from all treatments (heated control and fan only) was harvested on the same date in 2010-11 and there was little difference between °Brix, TA or pH at harvest. In 2011-12, fruit from the heated treatment was harvested one week earlier than the control and fan only treatment. At this harvest date the fan only treatment had lower °Brix and pH than the control and the heated treatments. Interestingly, in both seasons TA was higher in the fan only treatment than in either the control or heated treatments at veraison. This difference wasn't observed at harvest.

Cabernet Sauvignon As was observed in Chardonnay and Shiraz fruit from this trial and from previous research, pH and °Brix increased between veraison and harvest and TA decreased (Figures 1.21 on page 32 and 1.22 on page 33). As observed in Shiraz, TA was higher in the fan only treatment in Cabernet Sauvignon grapes at veraison in both seasons, but there was no difference at harvest. It is uncertain what drives this difference and what impact it may have on the final wine. At harvest there was no difference in TA between treatments in either season studied (2010-11 and 2011-12). At harvest in both seasons, pH was slightly higher in the heated fruit than in the control and fan only in both seasons. While the differences weren't large, the pattern was similar in the Shiraz and Cabernet Sauvignon fruit and this is consistent with previous reports that fruit pH is generally higher at harvest in warm climates (Soar et al., 2007). In both seasons, sugar accumulation (°Brix) was advanced in the heated treatment compared to both the control and fan only treatment (Figures 1.21 and 1.22). This was more apparent in 2011-12 with the heated treatment about a week further advanced than the control.

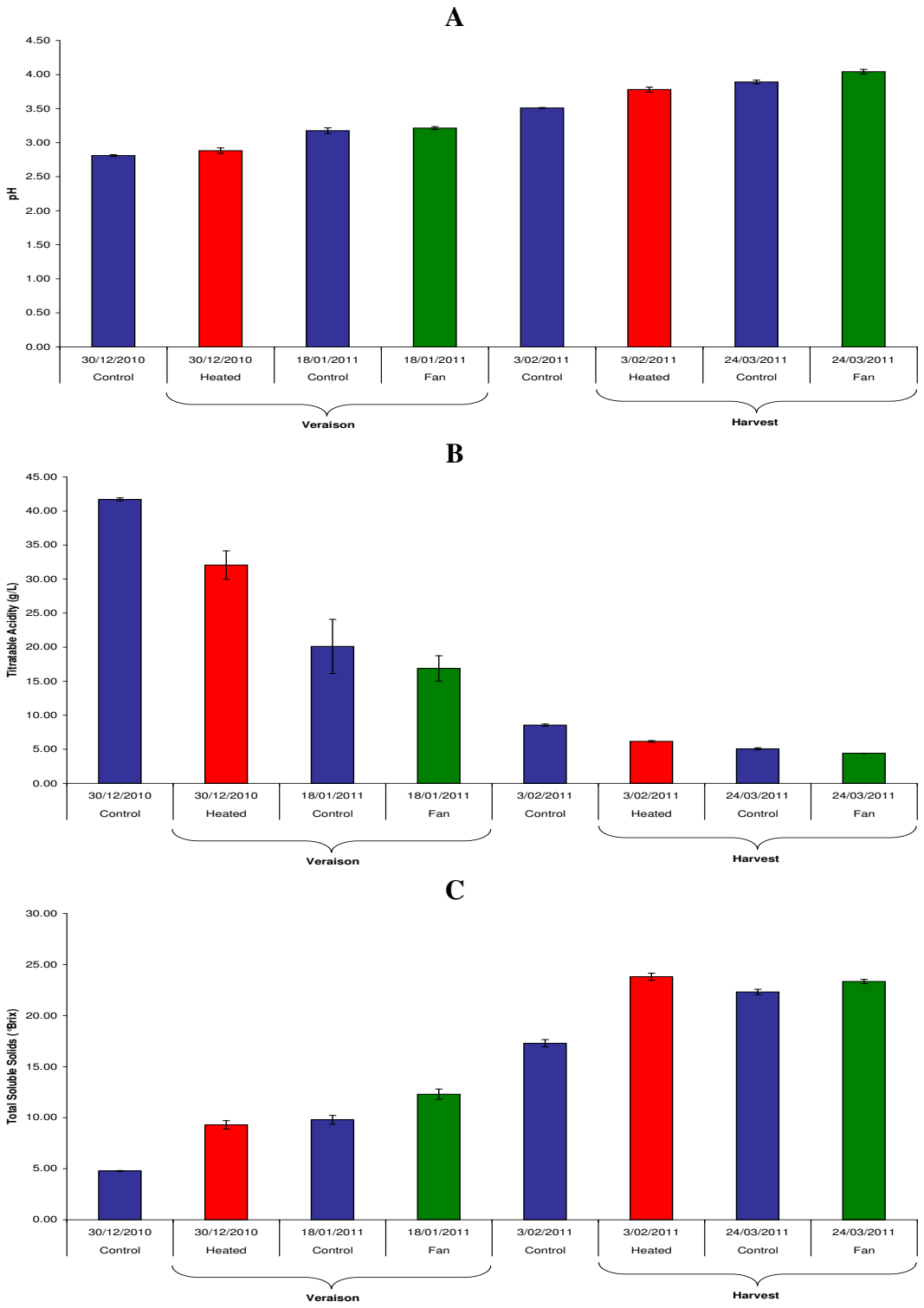


Figure 1.17: Chardonnay fruit collected at 2 developmental periods during the 2010-2011 growing season, from Control, Fan (Fan Only) and Heated treatment (Fan + Heater, +3 °C). A. pH, B. Titratable Acidity (g/L) and C. Total Soluble solids (°Brix).

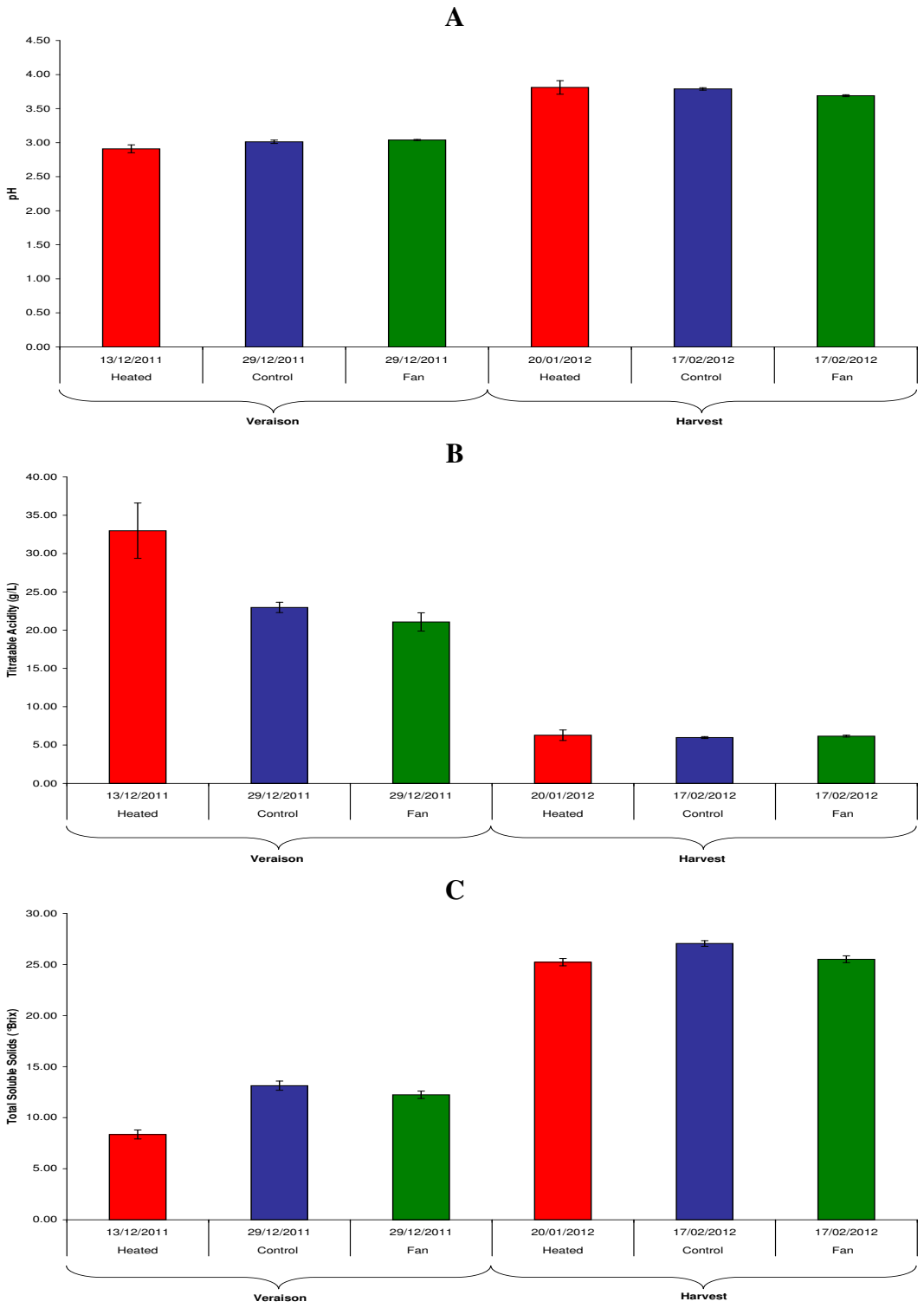


Figure 1.18: Chardonnay fruit collected at 2 developmental periods during the 2011-2012 growing season, from Control, Fan Only, and Heated (Fan + Heater, +3 °C). A. pH, B. Titratable Acidity (g/L) and C. Total Soluble solids (°Brix).

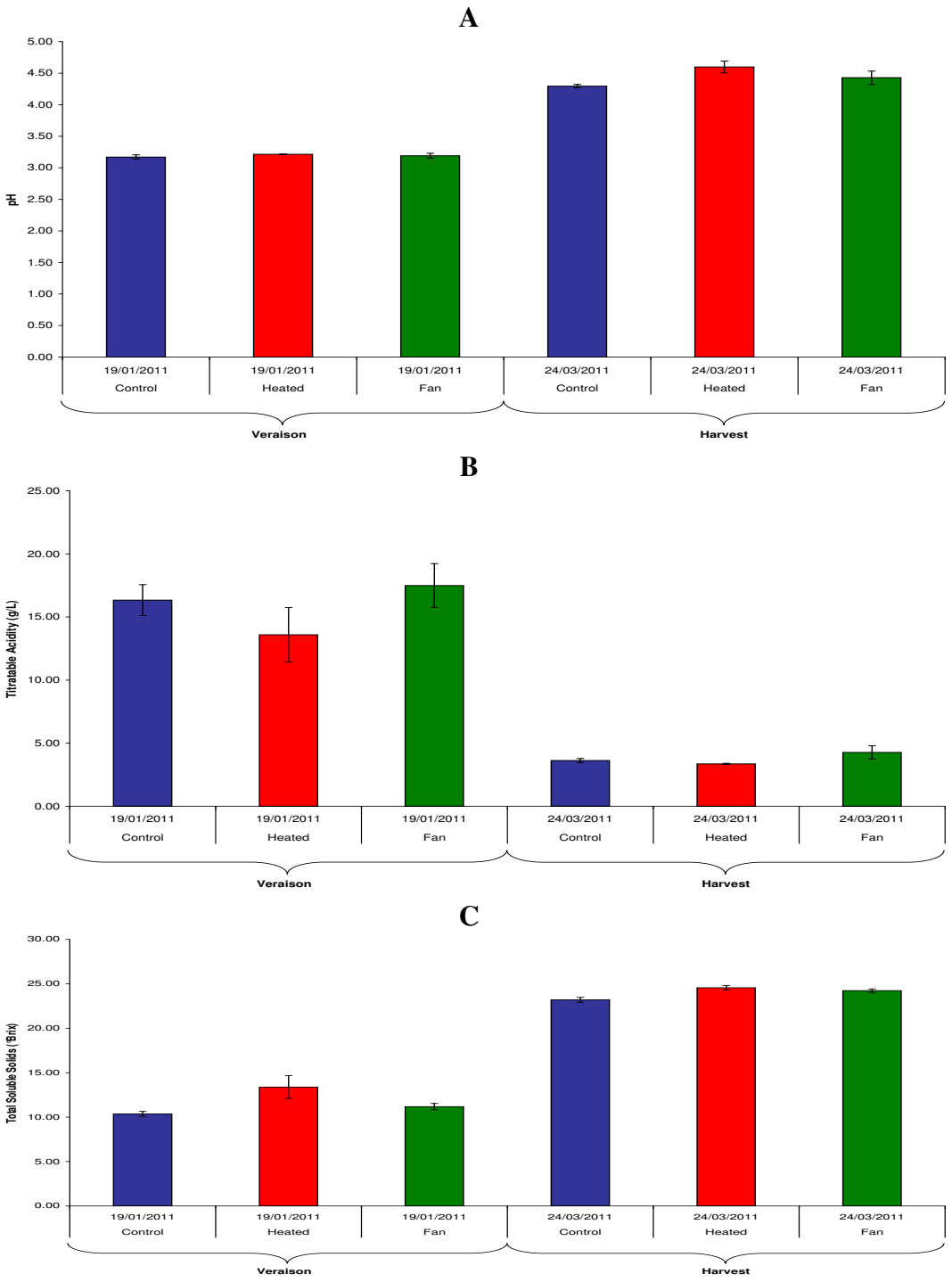


Figure 1.19: Shiraz fruit collected at 2 developmental periods during the 2010-2011 growing season, from Control, Fan (Fan Only) and Heated treatment (Fan + Heater, +3 °C). A. pH, B. Titratable Acidity (g/L) and C. Total Soluble solids (°Brix).

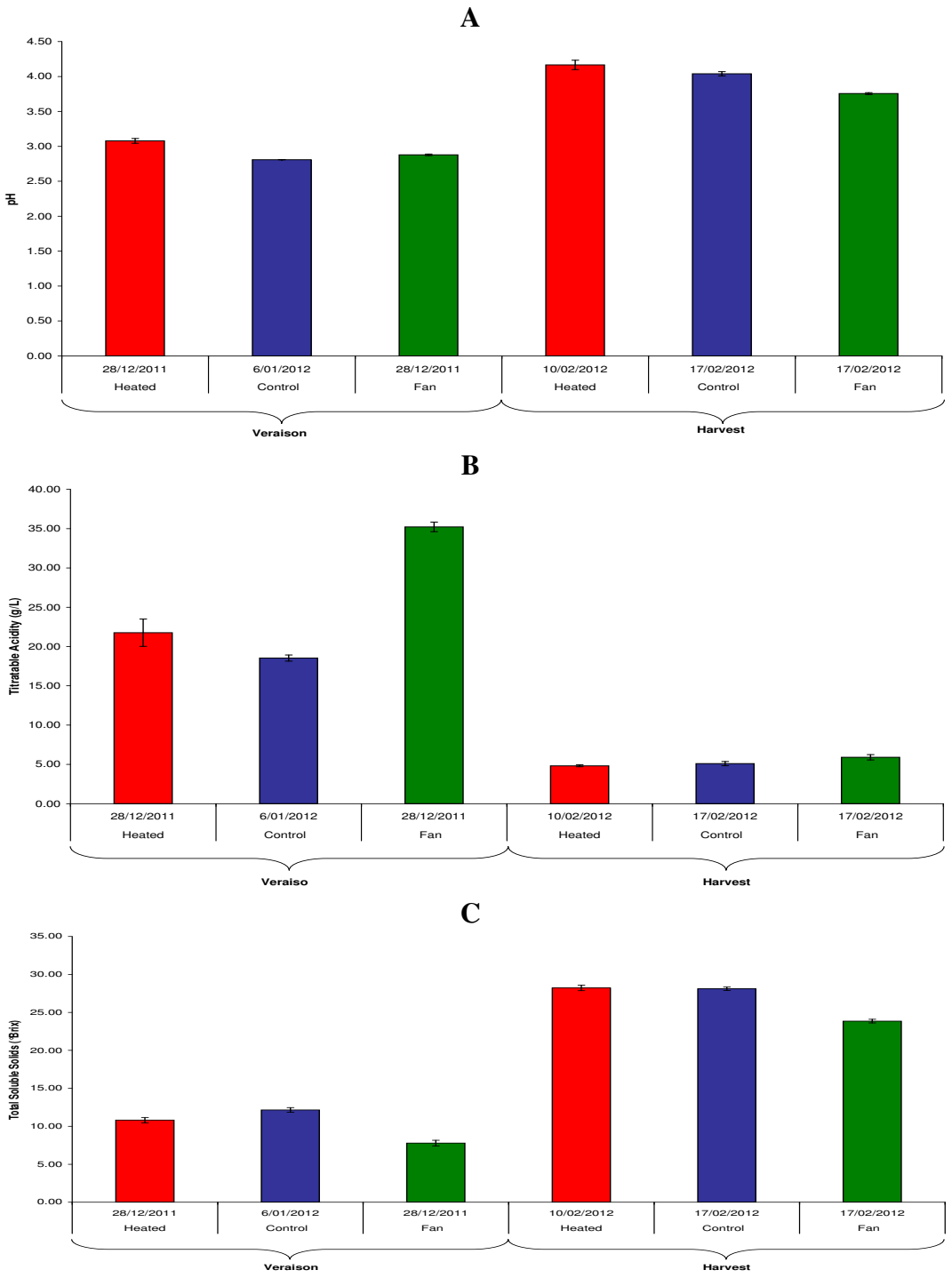


Figure 1.20: Shiraz fruit collected at 2 developmental periods during the 2011-2012 growing season, from Control, Fan (Fan Only) and Heated treatment (Fan + Heater, +3 °C). A. pH, B. Titratable Acidity (g/L) and C. Total Soluble solids (°Brix).

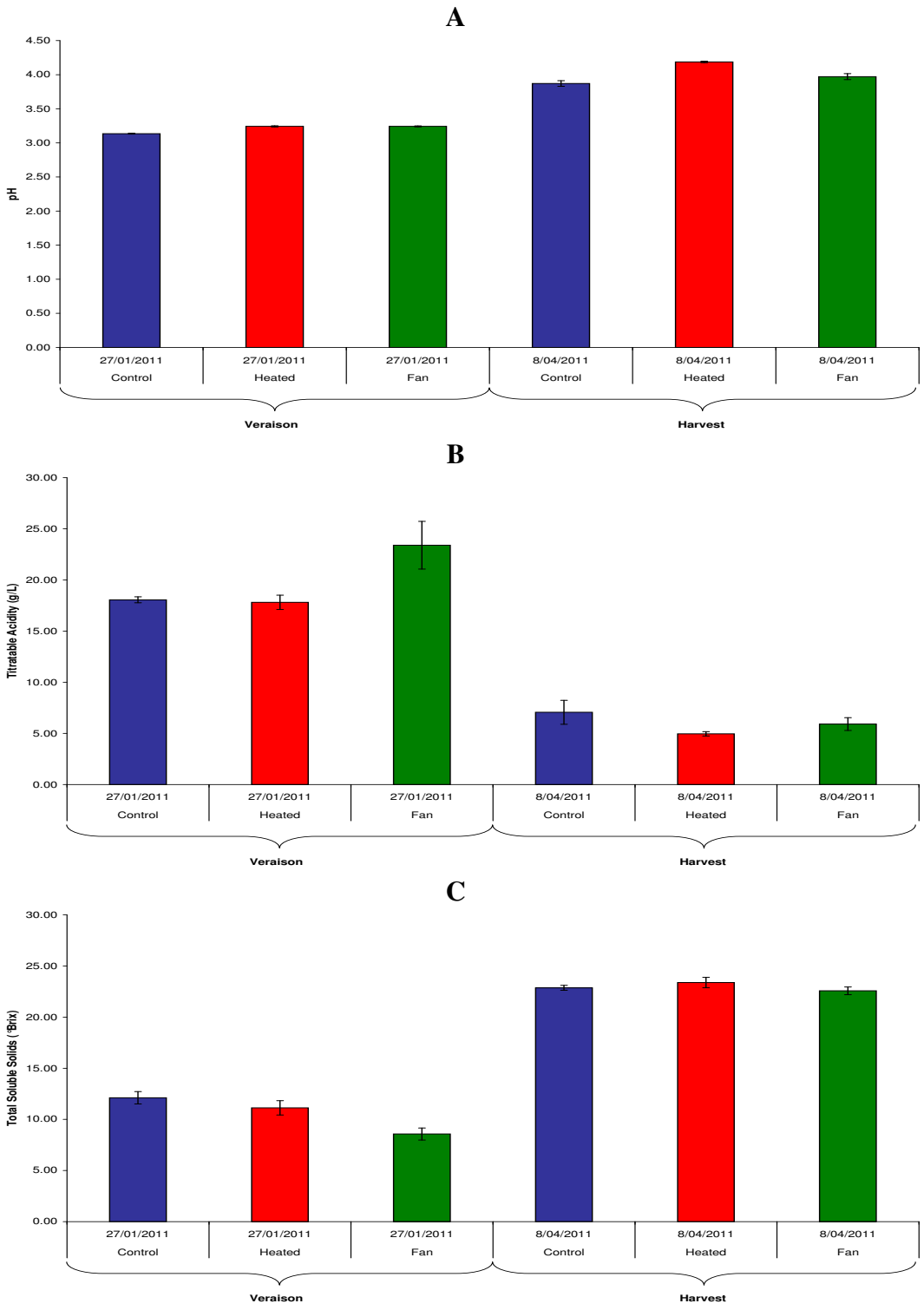


Figure 1.21: Cabernet S. fruit collected at 2 developmental periods during the 2010-2011 growing season, from Control, Fan (Fan Only) and Heated treatment (Fan + Heater, +3 °C). A. pH, B. Titratable Acidity (g/L) and C. Total Soluble solids (°Brix).

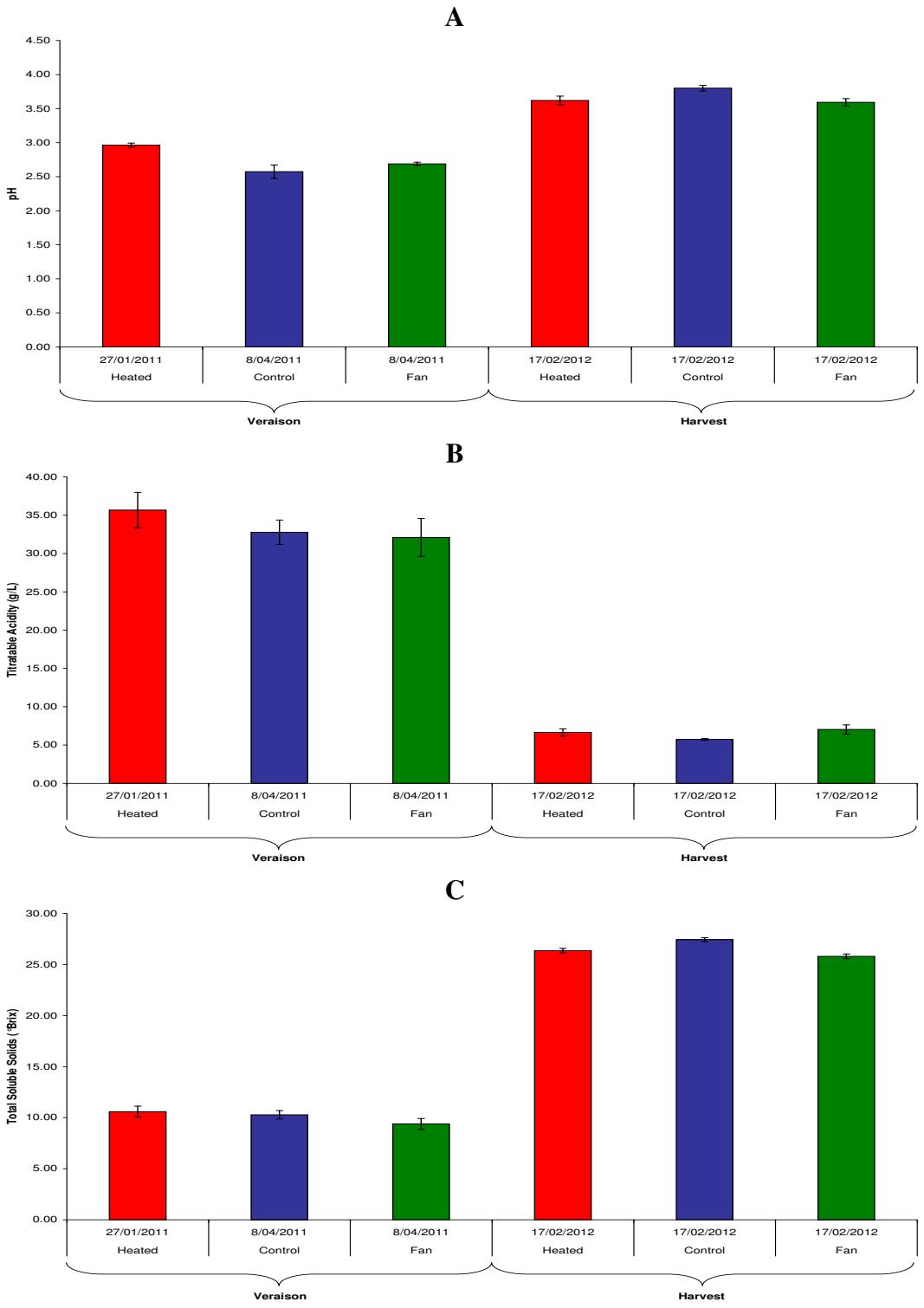


Figure 1.22: Cabernet S. fruit collected at 2 developmental periods during the 2011-2012 growing season, from Control, Fan (Fan Only) and Heated treatment (Fan + Heater, +3 °C). A. pH, B. Titratable Acidity (g/L) and C. Total Soluble solids (°Brix).

Fruit tannin, anthocyanin and flavonol content

Fruit from heated, control and fan only treatments were analysed for condensed tannins and flavonols in the skin of Chardonnay, Shiraz and Cabernet Sauvignon grapes at the pea-sized berry size, at veraison and at commercial harvest (~24 °Brix). Anthocyanins were also analysed in the Shiraz and Cabernet Sauvignon fruit at veraison and harvest.

Chardonnay

Total skin tannins In 2010-11, tannin concentration in Chardonnay grape skin was highest when berries were pea-sized and lowest at harvest for all treatments (Figure 1.23 on page 35). There was no difference in total skin tannin concentration between the control, fan only and heated fruit at any of the three sampling points.

The pattern in 2011-12 was slightly different (Figure 1.24 on page 36). In the control samples total tannin decreased from pea-sized berries towards veraison, but then increased at veraison before declining towards harvest. This pattern appears to be repeated in the fan only treatment; total tannins at pea-sized and veraison were similar and lower at harvest, while in the heated treatment the highest concentration was in pea-sized berries and this had decreased at veraison and then decreased further by harvest.

The pattern of accumulation in 2010-11 was similar to that observed in both Shiraz and Cabernet Sauvignon skin tannins previously (Hanlin & Downey, 2009). This pattern differed from earlier research that showed a peak in tannin accumulation around veraison then declining towards harvest (Downey et al., 2003a). It was hypothesised by Hanlin & Downey (2009) that these two patterns represented regional differences in tannin accumulation, likely driven by climate with the peak in tannin accumulation occurring earlier in berry development (*i.e.* around fruit-set or pea-sized berry) in the warmer regions and around veraison in cooler regions. The pattern of Chardonnay skin tannin accumulation in 2011-12 doesn't quite fit that hypothesis or the previous observations for the control and fan only fruit, but it does for the heated treatment.

These observations tend to support the notion that temperature was driving the different patterns of accumulation between the cooler McLaren Vale (SA) region and the warmer Sunraysia (Vic.) region.

Flavonols Flavonols in winegrapes have a role in protection against UV irradiation. Generally highly exposed fruit have a greater flavonol content than shaded fruit (Price et al., 1995; Haselgrove et al., 2000; Downey et al., 2004). This was reported across a number of varieties in a previous GWRDC-funded project (DNR 02/09). The effect of temperature on flavonol accumulation and synthesis has not been previously studied.

In 2010-11, the concentration of flavonols was relatively high early in berry development (pea-sized berries), had decreased by veraison and increased again by harvest in all treatments (Figure 1.23 on page 35). At harvest the flavonol concentration (mg/g FWT skin) was highest in the fan only treatment. Flavonol concentration was also high in the heated treatment, but variability between field and analytical replicates means this difference was not significant

In the following season (2011-12), the pattern of flavonol accumulation was different (Figure 1.24 on page 36) . In the control fruit, maximum concentration was observed around veraison, not fruit-set as previously reported (Downey et al., 2003b). At pea-sized berries in 2011-12 there was little difference between treatments, at veraison, the highest concentration was in the control fruit followed by fruit from the fan only treatment. At harvest in 2011-12, the highest flavonol

concentration was observed in the heated treatment, and the lowest concentration in the fan only treatment, although these differences were not significant.

While the data presented here is only for two seasons and not really enough to make broader generalisations, the indication is that flavonol biosynthesis in Chardonnay grape berry skin is not affected by temperature. It seems likely that light exposure, which has already been established as the major driver of flavonol biosynthesis, has a much greater effect than temperature. However, differences in leaf area and light interception (Sections 1.3.1 and 1.3.2) do not seem to be a good indicator of this.

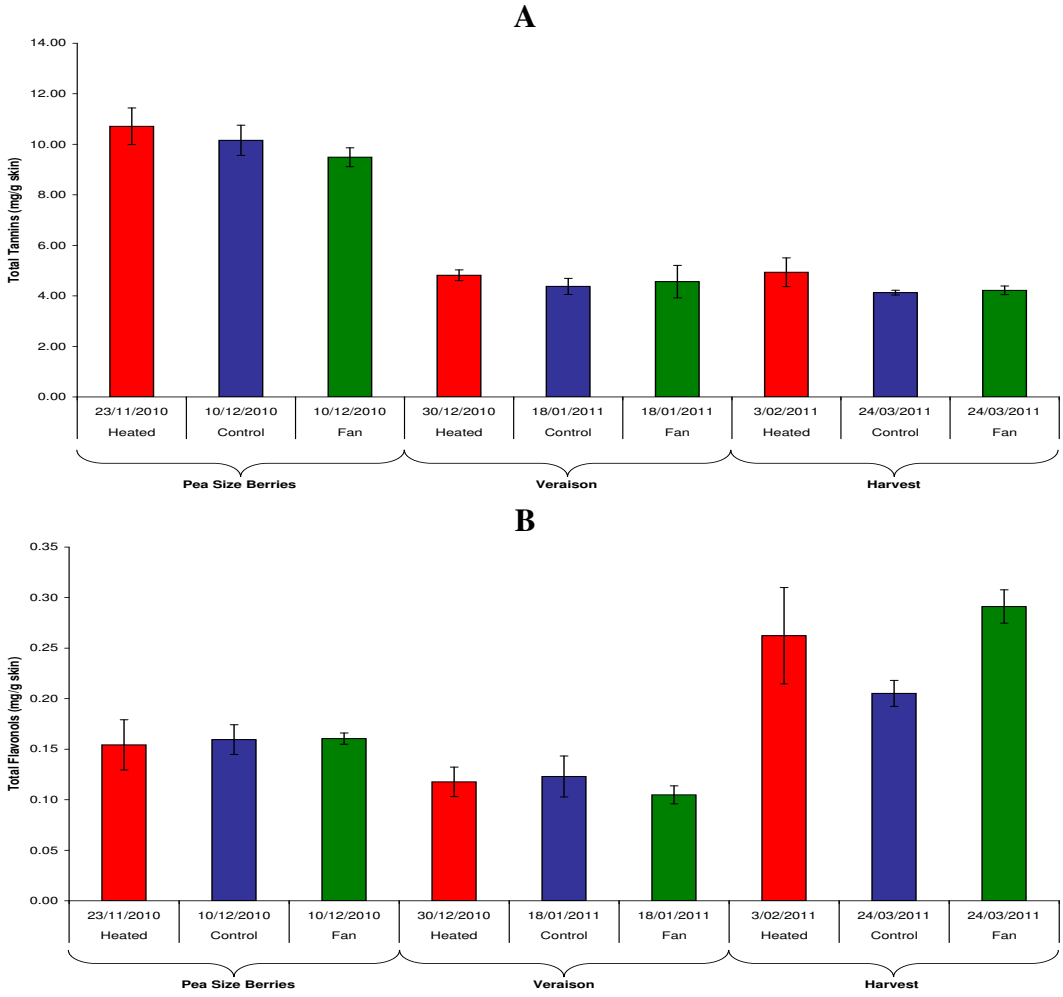


Figure 1.23: Chardonnay fruit collected at 3 developmental periods during the 2010-2011 growing season, from Control, Fan Only and Heated treatment (Fan + Heater, +3 °C). A. Total Tannin mg/g of skin expressed as catechin equivalents,and B. Total Flavonols mg/g of skin expressed as quercetin-3-glucoside equivalents).

Shiraz

Total skin tannins Total tannin concentration in Shiraz grape skin was lowest at harvest in both seasons consistent with previous research (Downey et al., 2003a; Hanlin & Downey, 2009). The

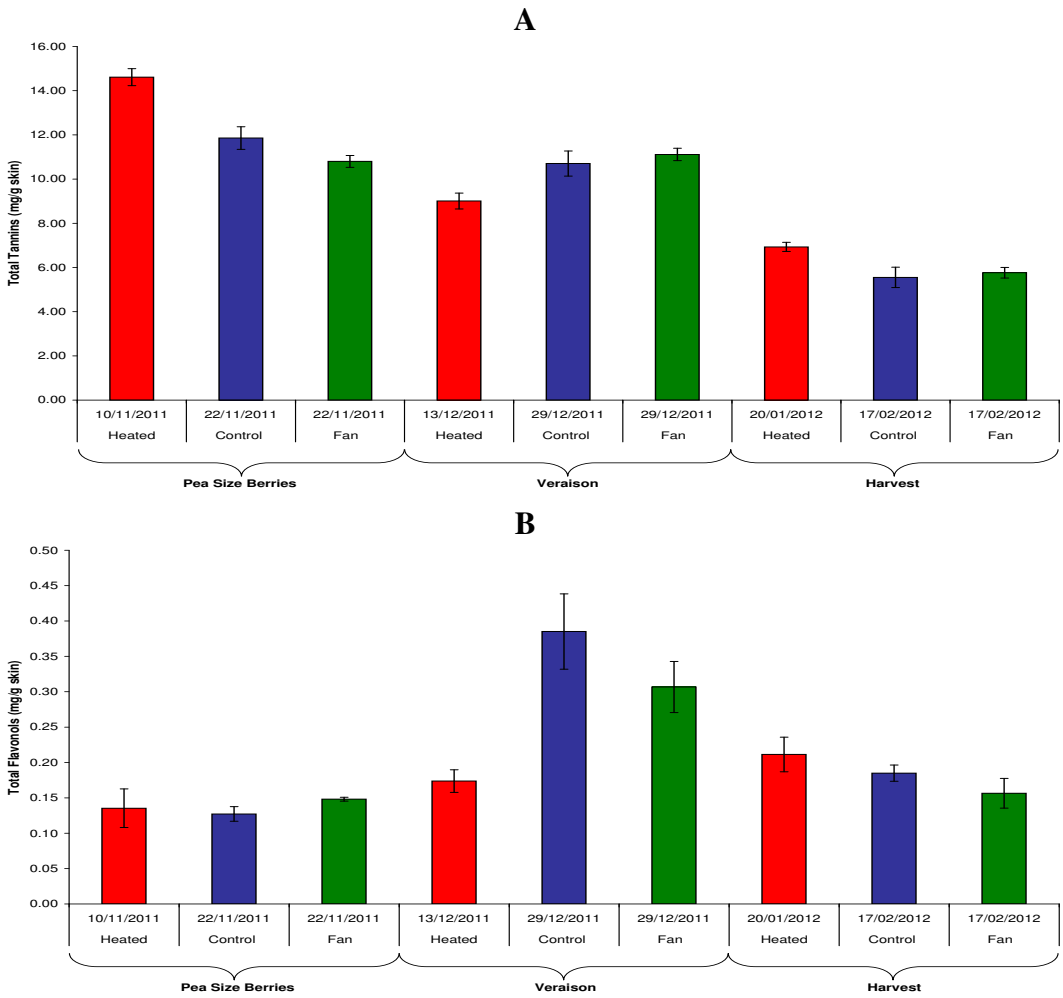


Figure 1.24: Chardonnay fruit collected at 3 developmental periods during the 2011-2012 growing season, from Control, Fan Only and Heated treatment (Fan + Heater, +3 °C). A. Total Tannin mg/g of skin expressed as catechin equivalents,and B. Total Flavonols mg/g of skin expressed as quercetin-3-glucoside equivalents).

effect of increased temperature was not consistently apparent across both seasons and additional data would be required to be able to draw a general conclusion. However based on the data presented here (Figures 1.25 on page 38 and 1.26 on page 39) tannin concentration appears to be lower in the skin of fruit from the heated treatment.

Flavonols Total flavonols were highest at harvest in both seasons. In 2010-11, the fan only treatment had a higher flavonol concentration at veraison and harvest than either the control or the heated treatment. In 2011-12, the fan-only treatment also had the highest flavonol concentration at harvest. For the heated and control treatments there was not a consistent pattern making it difficult to draw a general conclusion on the effect of temperature on flavonol synthesis in Shiraz grapes skins. This reflects a number of parameters including the small data set (two seasons), that light rather than temperature is likely the greatest driver of flavonol biosynthesis and that other indirect effect, for example temperature and/or water status effects on phenology and canopy development altering the light environment.

There is also the possibility of a chamber effect on flavonol accumulation in Shiraz grape skin independent of heating. However, this was not observed in the Chardonnay fruit.

Anthocyanins Anthocyanin accumulation begins at veraison and generally increases towards harvest. A number of factors have been identified that influence anthocyanin accumulation including light and temperature (Weaver & McCune, 1960; Dokoozlian & Kliewer, 1996; Spayd et al., 2002; Downey et al., 2004). Previous research indicates that the effect of light on anthocyanin biosynthesis variety dependent with some varieties more sensitive to low light (or shading) than others. The light-independent temperature effect increased biosynthesis at higher temperature as a result of increased rates of biochemical processes (em eg biosynthetic enzymes). At high (or extreme) temperatures anthocyanin degradation occurs (Downey et al., 2006).

In Shiraz grape skin in 2010-11, anthocyanin concentration at veraison was higher in the fan only and heated treatments than in the control (Figure 1.25 on page 38). In the heated treatment this is likely due to the increased temperature accelerating biochemical processes, although in the fan only treatment this is probably not the case as the difference in temperature between the control and the fan only treatment was only around 0.1 °C (Section 1.3.1 on page 10). At harvest in 2010-11 anthocyanin concentration was highest in the control and fan only treated fruit. Total anthocyanin concentration in the heated treatment was around 37% lower than the control. This observation was consistent with previous research and industry experience suggesting higher temperature reduces colour.

In 2011-12, the pattern of anthocyanin accumulation differed somewhat. At veraison the highest concentration of anthocyanins was observed in the skins of the control fruit and lowest level in fruit from the fan only treatment (Figure 1.26). At harvest, the highest anthocyanin concentration was measured in fruit from the fan only treatment and the lowest concentration was observed in the heated treatment.

Thus, in both seasons the anthocyanin concentration at harvest was lowest in the skins of Shiraz fruit from the heated treatment. These observations are consistent with much of the previous literature and experience that suggests fruit colour is reduced at high temperature.

Cabernet Sauvignon

Total Skin Tannins Tannin accumulation in Cabernet Sauvignon grapes skins followed a similar pattern to previously published data (Hanlin & Downey, 2009), with the highest concentration

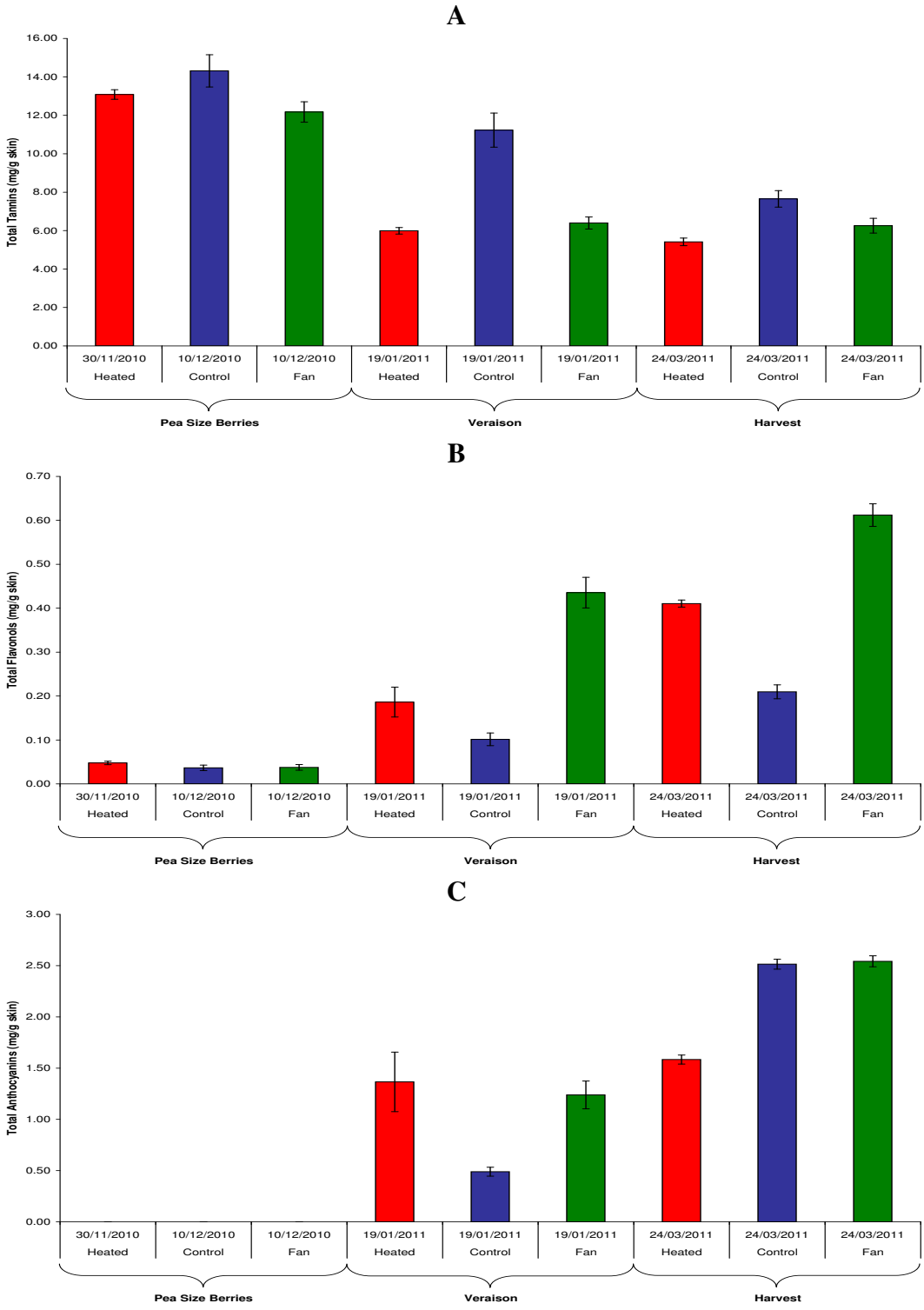


Figure 1.25: Shiraz fruit collected at 3 developmental periods during the 2010-2011 growing season, from Control, Fan Only and Heated treatment (Fan + Heater, +3 °C). A. Total Tannin mg/g of skin expressed as catechin equivalents, and B. Total Flavonols mg/g of skin expressed as quercetin-3-glucoside equivalents, and C. Total Anthocyanins mg/g of skin expressed as malvidin-3-glucoside equivalents.

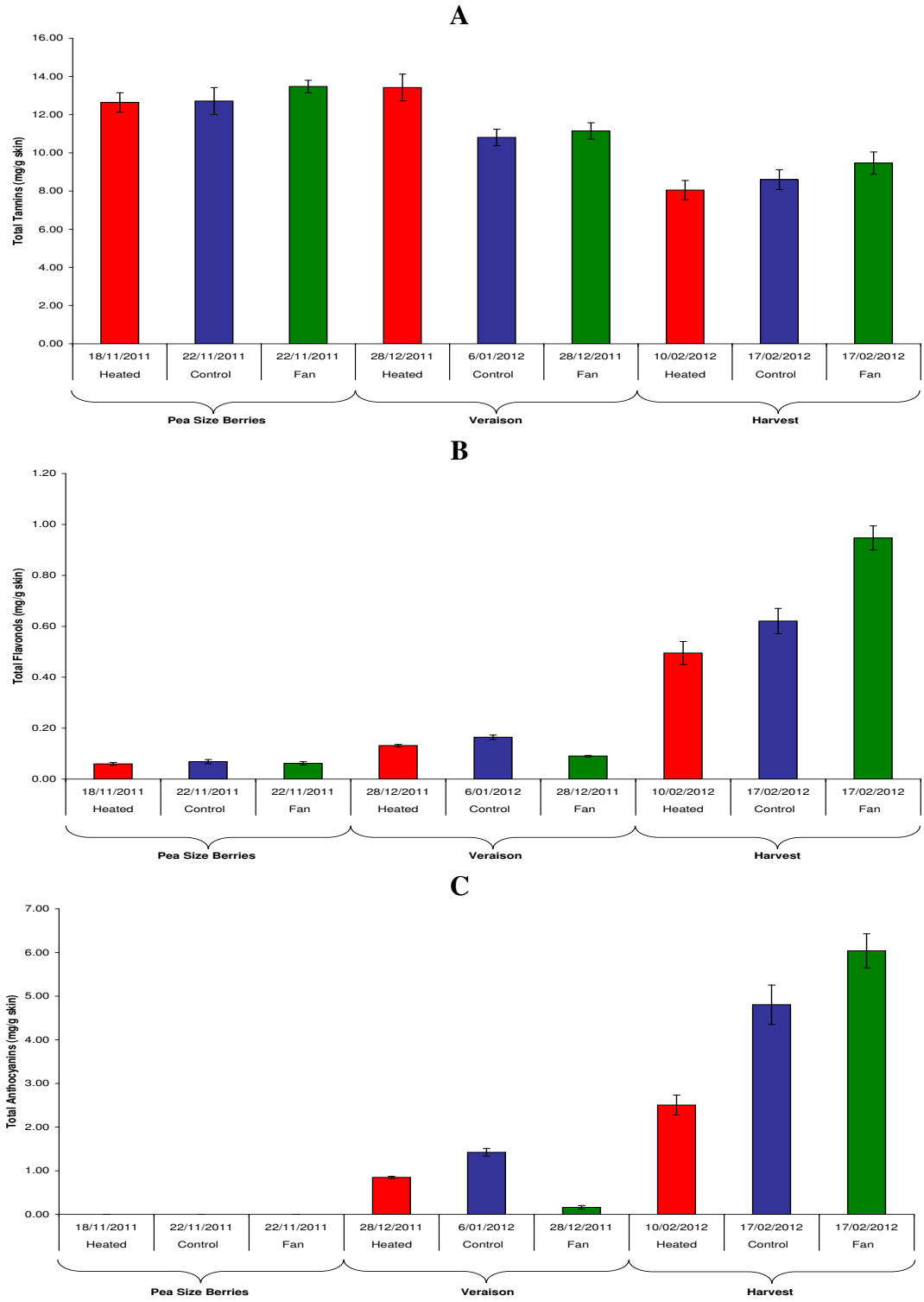


Figure 1.26: Shiraz fruit collected at 3 developmental periods during the 2011-2012 growing season, from Control, Fan Only and Heated treatment (Fan + Heater, +3 °C). A. Total Tannin mg/g of skin expressed as catechin equivalents, and B. Total Flavonols mg/g of skin expressed as quercetin-3-glucoside equivalents, and C. Total Anthocyanins mg/g of skin expressed as malvidin-3-glucoside equivalents.

of tannins being recorded early in berry development (pea-sized berries) and then decreasing through veraison then harvest (Figure 1.27 on page 41 and 1.28 on page 42).

In 2010-11, the tannin concentration in Cabernet Sauvignon skin was around 20% lower in fruit from the heated treatment compared to the control and the fan only treatments at harvest. However, in 2011-12 there was no difference in tannin concentration at harvest between treatments.

This suggests that while there may be a broad regional difference that affects the overall pattern of tannin accumulation, i.e. with a peak occurring early in berry development rather than around veraison as reported in cooler regions (Downey et al., 2003a) there does not appear to be a consistent temperature effect on grape skin tannin concentration at harvest. Generally speaking, a warmer climate may shift the timing of tannin biosynthesis, but temperature does not appear to be driving seasonal differences in tannin biosynthesis.

Flavonols In both seasons (2010-11 and 2011-12), the pattern of flavonol accumulation was broadly similar to that observed for both Chardonnay and Shiraz with the highest concentrations recorded at harvest (Figure 1.27 and 1.28).

In 2010-11, the highest flavonol concentration at harvest was observed in the fan only treatment and the lowest in the heated treatment (Figure 1.27). The fan only treatment also had the highest flavonol concentration at veraison in 2010-11. In 2011-12, the flavonol concentration at harvest was lower in fruit from the heated treatment, although this was not statistically significant. There does not appear to be a direct heating impact on flavonol accumulation in grapes skin.

The observations reported here for flavonol accumulation were similar for Chardonnay, Shiraz and Cabernet Sauvignon; a higher concentration of flavonols was often observed in fruit from the fan only treatment compared with the control and the heated treatments. This could indicate a chamber effect, where the Laser light™ material used for the open-topped chamber altered the light environment resulting in a change in fruit flavonol concentrations. However, light and canopy measurements do not support this.

It is also possible that the fan effect without the additional heating was having an effect on flavonol biosynthesis. Such a phenomenon has not been previously reported and it is uncertain what effect this might be or the mechanism by which this occurs. Given that the response is fairly consistent across varieties and seasons, it may warrant further investigation.

Anthocyanins Anthocyanin accumulation in Cabernet Sauvignon grapes was consistent with established patterns, commencing at veraison and increasing towards harvest in both seasons (Figure 1.27 and 1.28). At harvest in both seasons (2010-11 and 2011-12) the concentration of anthocyanins in Cabernet Sauvignon skin was lowest in the heated treatment, being around 35% lower than the control in 2010-11. The anthocyanin concentration in the control and fan only treatments was similar at veraison and harvest in both seasons with fan only slightly higher at harvest in 2010-11 (Figure 1.27). This was similar to observations for Shiraz, at harvest total anthocyanin concentration was significantly reduced in the heated treatment compared to the control.

1.3.10 Wine quality indicators 2010-2011

Ultimately the measure of climate change impacts on wine grape quality is going to be determined in the wine by consumers. If these impacts are generally negative the impact will be on wine value. Therefore, it is important to understand the effects that changes in fruit composition have on wine composition and wine quality as perceived by the consumer and their wine prefer-

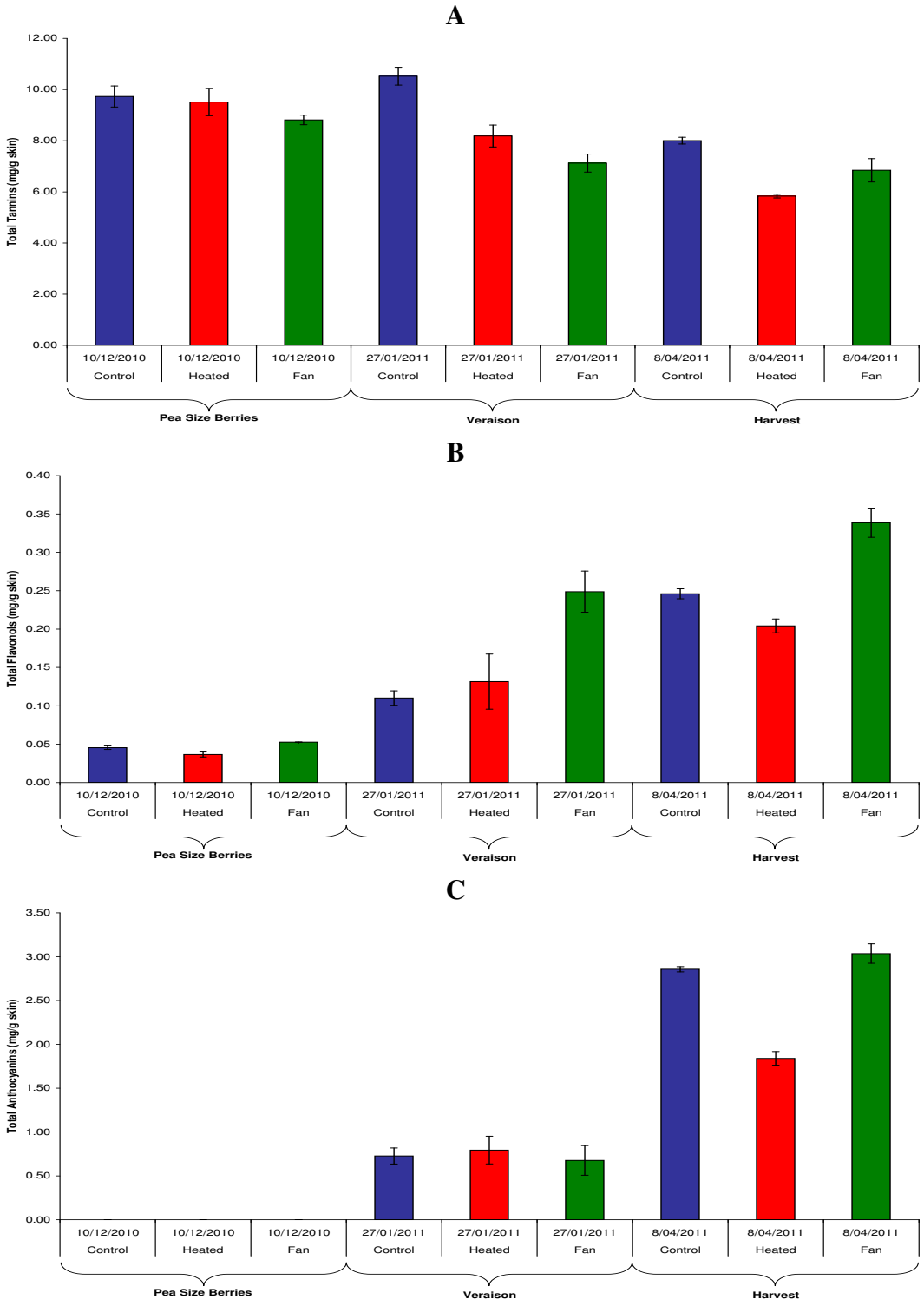


Figure 1.27: Cabernet S. fruit collected at 3 developmental periods during the 2010-2011 growing season, from Control, Fan (Fan Only) and Heated treatment (Fan + Heater, +3 °C). A. Total Tannin mg/g of skin expressed as catechin equivalents, B. Total Flavonols mg/g of skin expressed as quercetin-3-glucoside equivalents and C. Total Anthocyanins mg/g of skin expressed as malvidin-3-glucoside equivalents.

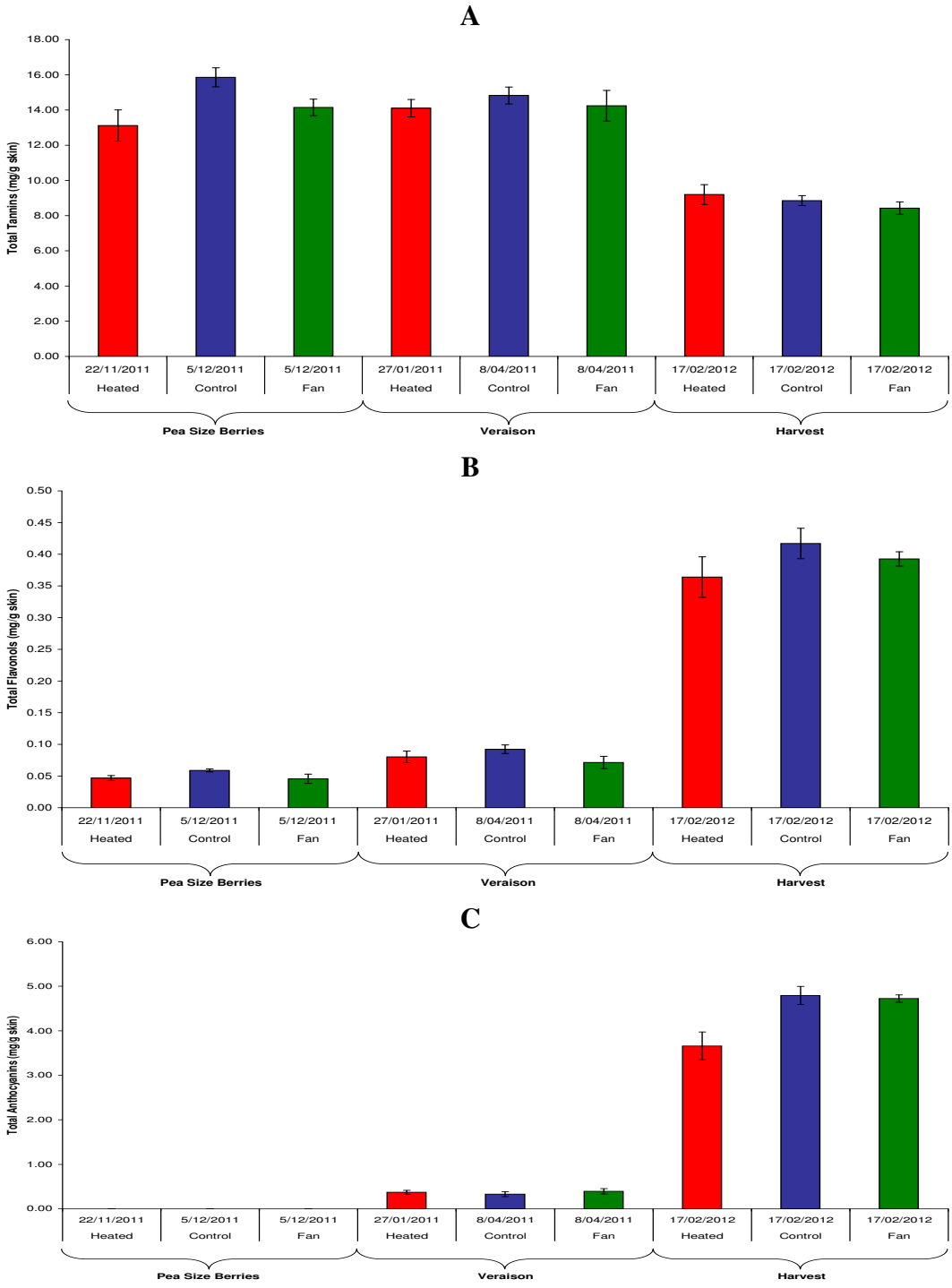


Figure 1.28: Cabernet S. fruit collected at 3 developmental periods during the 2011-2012 growing season, from Control, Fan (Fan Only) and Heated treatment (Fan + Heater, +3 °C). A. Total Tannin mg/g of skin expressed as catechin equivalents, B. Total Flavonols mg/g of skin expressed as quercetin-3-glucoside equivalents and C. Total Anthocyanins mg/g of skin expressed as malvidin-3-glucoside equivalents.

ences. Armed with this information it will be possible to develop strategies to manage changes in composition and quality through alternate varieties, different production and winemaking practices, or blending and new products. However, we currently have very little data that indicates the likely impacts of climate changes on fruit composition and virtually no data on how those changes translate into the final wine. In this project we made small-scale wines from Shiraz, Cabernet Sauvignon and Chardonnay grapes from the control and heated treatments and analysed the composition of those wines. Wines from the 2010-11 season were sampled repeatedly from fermentation until the end of the project. Wines from the second season (2011-12) were only sampled once prior to the end of the current project.

Wine tannin, anthocyanin and flavonol

Total tannins and phenolics Tannins contribute to the mouthfeel of wines and are the main class of phenolics in grapes and wine. Here we report the tannin concentration of the wines as well as the total phenolic concentration, which also captures non-tannin phenolics in the wine

Tannins in grapes are located in the seeds as well as the skins and are extracted during winemaking. Grape skin tannin has been shown to vary with a number of viticultural, seasonal and environmental factors, while seed tannin accumulation is generally much more stable (Kennedy et al., 2000; Ristic et al., 2001; Downey et al., 2003a). Furthermore, skin tannin is more readily extracted into the wine than seed tannin. For these reasons, only skin tannin was analysed in the fruit.

During red winemaking the wine is in contact with both the seeds and skins. The period of skin contact, or maceration, varies from a few days to weeks or months and this affects the amount of tannin and other phenolics that are extracted into the wine (Boulton et al., 1998). Because white wines, such as Chardonnay, are made without skin contact, they generally do not have tannin and only very low levels of phenolics in the wine (Boulton et al., 1998).

While there was little or no difference in total skin tannin concentration in fruit from the control and heated treatments of both Shiraz and Cabernet Sauvignon, this was not reflected in the wine (Figure 1.29).

Generally wines made from the heated treatment had a higher tannin concentration than wines made from the control fruit. In the Shiraz wines made from the 2010-11 fruit, tannin was higher in the heated treatment (138.3 mg/L) than the control (106.2 mg/L) at first racking. The concentrations were similar at bottling and six months post bottling, however at 12 months post bottling the concentration of tannin was significantly greater in the wine made from the heated fruit. This was not observed in the wines made from 2011-12 fruit where the control wine had around 30% more tannin than wines made from the heated fruit (Table 1.7 on page 46) despite similar levels in both control and heated fruit at harvest (Figure 1.26).

In the Cabernet Sauvignon wines from 2010-11, the tannin concentration was higher in the wine made from heated fruit at all sampling dates from first racking to 12 months post-bottling. From bottling onward the concentration of tannins in the wines made from heated fruit was more than 50% greater than the tannin concentration in the control wines. Interestingly, tannin concentration declined from first racking to bottling then began to increase to six months post-bottling and was highest at 12 months post-bottling in wines made from both the control and heated fruit.

Generally tannin and phenolic concentration was high at first racking or after pressing, which is likely a result of pressing, when the phenolics are freshly extracted and largely unmodified. During the latter stages of vinification and during wine aging, phenolics continue to react and interact with other wine components and each other (Haslam, 1998; Fulcrand et al., 2006). Early in the vinification process many of the phenolic compounds are low molecular weight oligomers

and these may not be captured by some analytical techniques. For example, the method utilised here to measure tannins employs protein precipitation, which does not precipitate oligomers below tetramer (Harbertson et al., 2003). Over time reactions, interactions and rearrangement can form larger material that is measured by protein precipitation.

The data for total phenolics showed this to some extent. For the Shiraz wines the total phenolic concentration, which includes tannins, did not change, even though the tannin concentration did change over time (Figure 1.29). In the Cabernet Sauvignon wines, total phenolics concentration declined over time, which tends to happen as phenolics gradually form insoluble complexes. This was apparent in the Cabernet Sauvignon wines and not the Shiraz wines because the overall concentration of tannins and phenolics in the Cabernet Sauvignon wines was much higher than in the Shiraz wines.

That for both Shiraz and Cabernet Sauvignon, total tannin and phenolic concentration was higher in wines made from fruit from the heated treatment when there was little difference in the fruit tannin concentration highlights the main challenge in using fruit tannin content (or composition) as a predictor of wine tannin. Tannin extraction into wine is a complex process influenced by a number of factors (Hanlin et al., 2010). These compounds then undergo significant changes and modifications in the wine during winemaking and throughout aging (Fulcrand et al., 2006). Much of this area of grape and wine quality is poorly understood.

Total anthocyanins and polymeric pigments The colour of young red wines is due primarily to the anthocyanins in the wine (Somers, 1971). As red wine ages, there is a shift towards more stable pigments and polymeric pigments become predominantly responsible for red wine colour.

Here we report total anthocyanins, which capture all of the pigmented material in the wine including the free, or monomeric, anthocyanins as well as any polymeric or other modified material. We also report total polymeric pigments, which is any pigmented material that is resistant to bisulphite bleaching. Because of the nature of this measure and the absence of any relevant standards, pigmented polymers is reported as the spectrophotometer absorbance (after accounting for dilutions).

In 2010-11 for both wines the general pattern was high total anthocyanins in the wines made from the control fruit (Figure 1.30). For the Shiraz wine at first racking this was not the case and total anthocyanins were higher in the wine made from heated fruit. However, by bottling this had reversed and at six months post-bottling anthocyanins were significantly higher in the wines made from control fruit (134.6 mg/L) compared to the wine made from heated fruit (103.0 mg/L). A similar difference was observed at 12 months post-bottling.

Total anthocyanins were also higher in the 2011-12 Shiraz (Table 1.7), where total anthocyanins in the wine made from control fruit was around 20% higher than in the wines made from the heated fruit.

In the Cabernet Sauvignon wines from 2010-11, total anthocyanins were consistently higher in the control wine that in wines made from heated fruit (Figure 1.30). The difference was greatest early in vinification and was less apparent by 12 months post bottling. Similarly, in 2011-12, the Cabernet Sauvignon wines made from control fruit had around 35% more colour that the wines made from the heated vines (Table 1.7), which was similar to the difference in anthocyanin concentration between the control and heated fruit at harvest (Figure 1.27).

To some extent this reflects the grape anthocyanin concentration, which was higher in the control fruit than it was in the heated fruit (Section 1.3.9).

Polymeric pigments in the Shiraz wines from 2010-11 showed the opposite pattern to total anthocyanins (Figure 1.30). Generally, polymeric pigments were higher in the wines made from the heated fruit than the control. No difference was observed in the polymeric pigment at bottling.

This is due to addition of SO_2, which bleaches monomeric anthocyanins (Boulton et al., 1998).

At six and 12 months post-bottling there was a two-fold difference in the amount of polymeric pigments in the wines made from the heated fruit compared to the control. While total anthocyanins were lower in the wines made from the heated fruit, more of that material was in polymeric form in the wines made from heated fruit. After the first racking of 2011-12 wines, total anthocyanins and polymeric pigments were both higher in the control wine.

The pattern for the Cabernet Sauvignon wines was different to that observed for Shiraz. While the total anthocyanin pattern was similar with the control wines having higher total anthocyanins, there was very little difference in the levels of polymeric pigments throughout vinification of the Cabernet Sauvignon wines. In the 2011-12 wines, total anthocyanins in the control wines were higher than the wines made from heated fruit, which was consistent with the difference observed in the fruit (Figure 1.28 on page 42). Polymeric pigments were also higher in the control wines from 2011-12 (Table 1.7 on page 46).

From the limited data presented here it is difficult to see a clear relationship between heating and wine colour. This is partly because wine colour, while being correlated with grape anthocyanin concentration in young wines, forms complex associations with tannins and other wine components to form a diverse array of compounds that are responsible for long term colour stability. While many of these reactions are understood, we do not yet have sufficient understanding of polymeric pigment formation in wine to develop an adequate algorithm for predicting wine colour.

Wine hue and wine colour density Wine hue is an indicator of the brownness of wine as opposed wine colour density which is an indication of the colour intensity or redness. Young red wines tend to have high colour density and low hue values and as the wine ages, oxidation and other modifications of the anthocyanins result in a gradual loss of the red colour (A_{520}) and increase in browning (A_{420}) (Iland et al., 2000).

For both Shiraz and Cabernet Sauvignon wines in 2010-11, wine colour density and wine hue were highest at first racking and decreased post-bottling (Figure 1.31 on page 49). For Shiraz, at bottling and six and 12 months post-bottling, wines made from heated fruit had higher wine colour density than wines made from control fruit. This is interesting given that these wines had lower total anthocyanins, but indicates that there were already greater brown pigments present as well as significantly higher levels of polymeric pigments.

This was not the case for the Cabernet Sauvignon wines from 2010-11, which had similar or slightly higher colour density in the control wines (Figure 1.31). The Cabernet Sauvignon wines from both the heated and control fruit had similar levels of polymeric pigments throughout vinification.

In the 2011-12 wines after first racking there was no difference wine colour density between any of the wines (Table 1.7 on page 46). Wine hue was slightly higher in the wine made from heated fruit, but this could not be attributed to greater polymeric pigments. There was no difference in hue for the Cabernet Sauvignon wines.

Brown pigments and hydroxycinnamates in white wine Hydroxycinnamates are one of the major non-flavonoid components grapes and wine. They are present in the skin and flesh of the grape berry and a major constituent of grape juice. As a result hydroxycinnamates are a major component of the phenolic composition of white wines, which is made from the free run juice (Boulton et al., 1998). Phenolic compounds are readily oxidised to form brown pigments. This occurs in red and white wines and is generally considered undesirable in white wines. Hydroxycinnamates as well as other low molecular weight phenols can undergo oxidation during white winemaking

and thus measures of hydroxycinnamates are an indication of browning potential, subsequently measured as brown pigments.

Following winemaking of the 2010-11 wines, hydroxycinnamate were observed to be greatest in Chardonnay wines made from heated fruit. Although the differences observed between the heated and control wines varied at different sampling time points, the heated wines had consistently higher hydroxycinnamates.

In contrast, there was no pattern to the measures of the brown pigments in these wines. Thus, while there was increased potential for the formation of brow pigments due to the higher hydroxycinnamate concentration in the wines made from heated fruit, this did not translate into increased brown pigments.

This may not always be the case as oxidation of phenolics is a process that can be affected as well as managed by winemaking practice.

In the 2011-12 wines, hydroxycinnamates were higher in the control wines than in the wines made from heated fruit, which was in contrast to the observations from 2010-11. Contradictory data such as these indicate that the increased temperature in the heated treatment was not the main driver of hydroxycinnamate concentration in the wine.

Table 1.7: Phenolic analysis of wines made from fruit harvested in 2012. Analysis was conducted after bottling for Chardonnay wines and at cold settling (pre bottling) for Shiraz and Cabernet Sauvignon (n=3 ±SE).

Variety	Treatment	Total Tannins mg/L	Total Antho-cyanins mg/L	Total Phenolics a.u.	Total Polymeric Pigments a.u.	Wine Colour Density a.u.	Wine Hue a.u	Total Hydroxy-cinnamates a.u.	Estimate of Brow Pigments a.u.
Chardonnay	Control	n.d.[1]	–	44±6	–	–	–	2.8±0.1	0.17±0.01
	Heated	n.d.	–	28±5	–	–	–	1.9±0.1	0.09±0.01
Shiraz	Control	204±21	550±11	965±29	2.6±0.1	12.1±0.1	0.56±0.01	–	–
	Heated	156±12	468±17	867±27	2.1±0.1	12.1±0.1	0.62±0.03	–	–
Cabernet Sauvignon	Control	519±21	598±28	1329±39	3.6±0.1	12.1±0.1	0.62±0.03	–	–
	Heated	402±14	444± 5	1389±28	3.4±0.4	12.1±0.1	0.61±0.01	–	–

1.3.11 General discussion on fruit and wine quality

Fruit quality

There was little observable difference in °Brix, pH and TA at harvest between the control, fan only and heated treatments across all three varieties and both seasons (2010-11 and 2011-12). While this suggests that these parameters are not affected by temperature, there were marked differences in the timing and rate of accumulation of °Brix, TA, and pH due to temperature. Sugar accumulation is a particularly strong indicator of the effect that increased temperature has had on berry development. Previous research and extensive industry experience also indicates that pH and TA changes during berry development are temperature sensitive with generally higher and TA lower in warmer grape growing regions (Winkler et al., 1974).

A decline in total tannins from early in berry development to harvest is consistent with previous research by Hanlin & Downey (2009) in Cabernet Sauvignon and Shiraz. The research presented here shows that this may also be the case for Chardonnay grape skin tannin. These results are consistent with the conclusions of Hanlin & Downey (2009) that the difference in the pattern

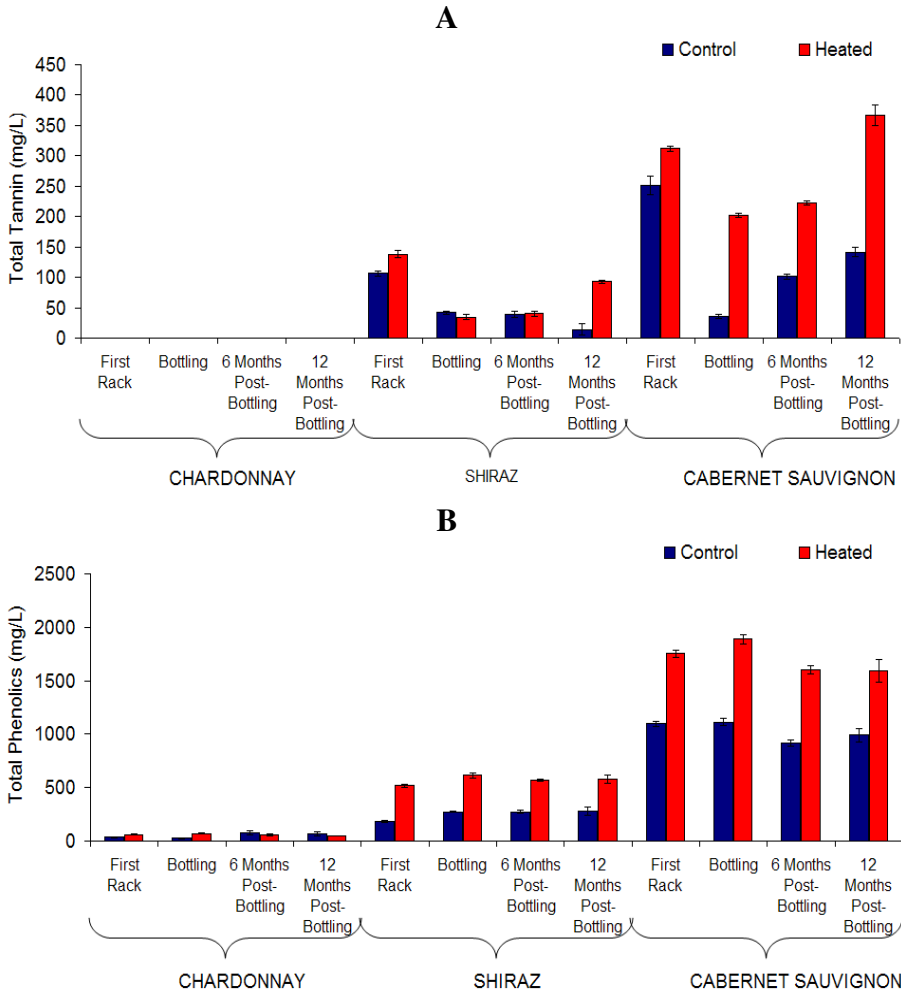


Figure 1.29: Wine tannin and total phenolics concentrations at first racking, bottling, 6 and 12 months post bottling from fruit of the 2010-2011 season of Chardonnay, Shiraz and Cabernet Sauvignon wines from Control and Heated treatment fruit. A. Total Tannin mg/L expressed as catechin equivalents. B. Total Phenolics mg/L expressed as catechin equivalents.

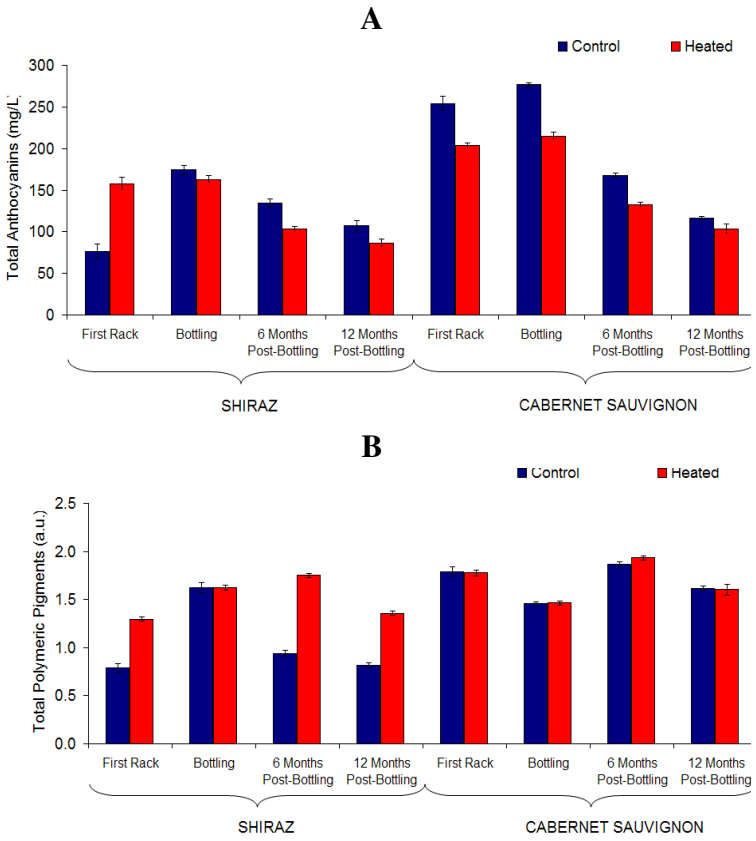


Figure 1.30: Wine anthocyanin and polymeric pigment concentrations at first racking, bottling, 6 and 12 months post bottling from fruit of the 2010-2011 season of Shiraz and Cabernet Sauvignon wines from Control and Heated treatment fruit. A. Total Anthocyanin mg/L expressed as malvidin-3-glucoside equivalents. B. Total Polymeric Pigment measures (a.u.)

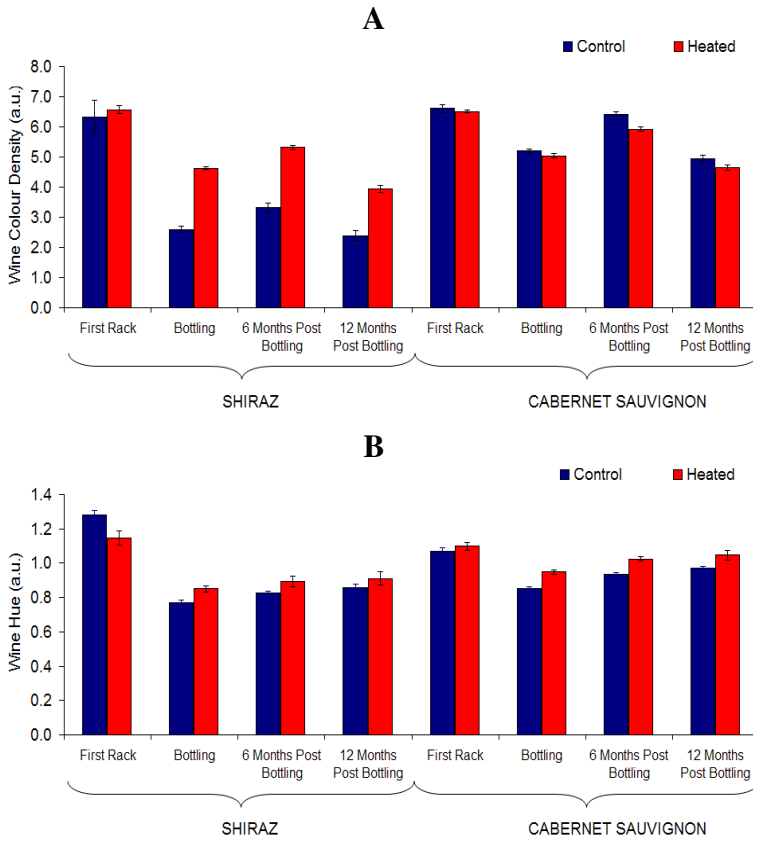


Figure 1.31: Wine colour measures at first racking, bottling, 6 and 12 months post bottling from fruit of the 2010-2011 season of Shiraz and Cabernet Sauvignon wines from Control and Heated treatment fruit. A. Wine Colour Density (a.u.) B. Wine Hue (a.u.).

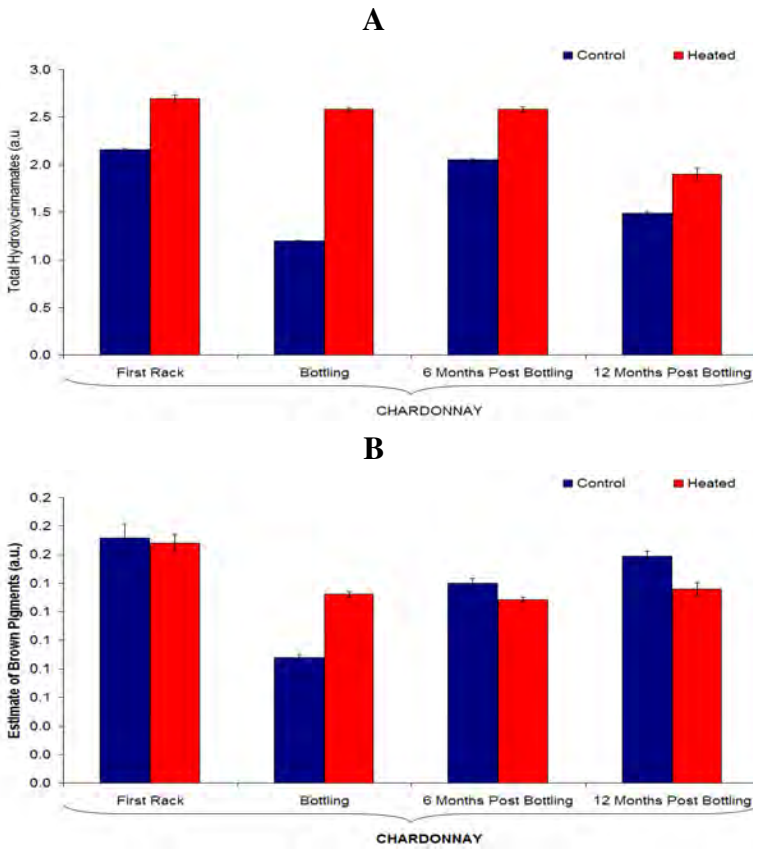


Figure 1.32: White wine spectral measures at first racking, bottling, 6 and 12 months post bottling from fruit of the 2010-2011 season of Chardonnay wines from Control and Heated treatment fruit. A. Total Hydroxycinnamates (a.u.) B. Estimate of Brown Pigments (a.u.)

of condensed tannin accumulation between McLaren Vale (SA) and Sunraysia (Vic.) are due to regional climatic (temperature) differences.

The implication of this observation is that as warming occurs, the pattern of tannin accumulation in grape berries in currently cooler regions, such as McLaren Vale and the Barossa Valley, may shift to a pattern similar to Sunraysia. The extent to which this will impact wine quality has not been adequately explored.

While this is only a limited data set with just two seasons, there does not appear to be any evidence that temperature is a major driver of flavonol biosynthesis in grape skin.

Over the two seasons studied here (2010-11 and 2011-12) anthocyanin concentration in the skin of both Shiraz and Cabernet Sauvignon grapes was lower in the heated treatment than in the control. This is consistent with previous research, which indicates that at high or extreme temperature anthocyanin accumulation is reduced (Kliewer, 1977; Bergqvist et al., 2001; Spayd et al., 2002; Downey et al., 2004). Research also indicates that higher night temperatures may be the main factor affecting anthocyanin biosynthesis (Kliewer & Torres, 1972; Mori et al., 2005), which suggests a connection between anthocyanin biosynthesis and respiration metabolism.

With the caveat that this is only a limited data-set, the conclusion based on this data and previous research is that an increase in average temperature over the next 20-40 years is likely to impact on anthocyanin accumulation in Shiraz and Cabernet Sauvignon wine grapes, which could have potential impacts on wine colour and quality.

Wine quality

From a climate change perspective, the implications for grape and wine tannin are difficult to distil from a couple of seasons of field data and only one real set of winemaking data. Interpretation is further limited by relatively little comparable research in the literature that this work can build on. Thus, the real value of this part of the work is yet to be realised.

We have observed in the limited data collected so far that there appear to be some trends across seasons and wines, for example, total anthocyanins in grapes tends to be lower in warmer fruit or that total tannin concentration at harvest was largely unchanged by any of the treatments.

These were not as obvious as the inconsistencies, for example similar tannin concentrations in the fruit across treatments, but much higher tannin concentrations in the wine from the heated treatment in 2010-11, and not in 2011-12.

What this indicates is that while there may have been an effect on grape quality and sometimes on wine quality, this was not consistent or predictable and that there are drivers of grape composition other than temperature; such as light, vine balance, water status, etc. These may often be greater than the temperature effect. All of these factors may act synergistically or antagonistically and these relationships are largely undocumented and poorly understood. This is a major limitation of research into understanding the drivers of grape quality and grape composition and requires a coordinated effort to address.

As with many of the past studies that have sought to link grape composition or grape quality parameters to wine quality or wine composition, the great limitation is a lack of fundamental understanding of the winemaking process in terms of the chemistry of the compounds involved. Wine chemistry is a complex multi-factorial system that has historically been explored using a traditional reductionist approach examining the effect of a single parameter on another parameter, hampered by the absence of methods to adequately extract, purify and measure any of those parameters.

Objective 3. Investigate the "tipping points" at which extreme heat events permanently impact on vine physiology and fruit composition to define damage thresholds

1.3.12 Assessment of heatwave chamber performance

The same chamber was used for all the heatwave events, but the actual performance was dependant on the weather conditions. In the 2010/11 season nine events were run and the season as a whole was unusually wet (see above), so it was difficult to target periods of clear weather and, therefore, the weather conditions varied considerably between runs. The heatwave chamber was intended to produce an increase in air temperature of 6 °C or greater, representing the typical difference between a commonly occurring air temperature within a given time of year and an unusually high air temperature; a 'heatwave'. The warming actually achieved varied between 2 °C and 9 °C, with the average being 4 °C (Table 1.8). This was not dependant on ambient temperature, but other weather aspects.

Table 1.8: Mean difference in air temperature, relative humidity and vapour pressure deficit (VPD) ± standard deviation between the 'heatwave' treatments and control plot during the 2010/11 growing season and mean air temperature of the control plot. Data were not collected for the veraison heatwave events in Cabernet Sauvignon or Chardonnay.

Variety	Phenological Event/ Data Period	Air Temperature °C	Relative Humidity Humidity %	VPD kPa	Ambient Air Temperature °C
Cabernet	Anthesis	5.4±2.3	-22.9±8.8	0.88±0.40	14.6±4.1
	Harvest	2.0±1.1	-4.9±4.5	0.28±0.42	21.7±5.9
Shiraz	Anthesis	2.3±1.3	-12.4±5.0	0.49±0.23	19.5±6.3
	Veraison	3.9±1.7	-11.5±6.8	0.89±0.38	25.8±5.4
	Harvest	9.0±1.8	-26.9±7.3	1.87±0.84	19.2±6.1
Cabernet	Anthesis	2.5±1.1	-13.5±4.9	0.51±0.23	18.5±6.7
	Harvest	4.4±1.6	-19.8±11.7	1.06±0.63	24.1±3.3

In the 2011/12 season the heatwave events were only run on the Cabernet Sauvignon plots and, together with the less extreme weather conditions generally, resulted in all three runs occurring during periods of clear bright weather. The warming achieved in each case was over 5 °C, daily maximum temperatures in the heatwave chamber were above the long-term average for the given time of the year and over 40 °C in the veraison and harvest runs (Table 1.9).

As with the long-term warming chambers large diurnal effects were not seen (Figure 1.33), so both day and night time maximums were increased relative the ambient conditions, as would be expected during a natural heatwave.

1.3.13 Impacts on leaf canopy and bunch temperature

Leaf temperature during a heatwave is likely to be critical in determining the impact on photosynthetic rates (Liu & Huang, 2000) and on leaf damage (Berry & Björkman, 1980). Leaf temperature was not able to be assessed during the 2010/11 season but was assessed during the 2011/12 season heatwave events using both spot measurements of leaves and whole canopy infrared imaging. Both sides of the vine row were measured as the row orientation resulted in the NE

Table 1.9: Mean difference in air temperature, relative humidity and vapour pressure deficit (VPD) ± standard deviation between the 'heatwave' treatments and control plot in Cabernet Sauvignon vines during the 2011/12 growing season and mean air temperature of the control plot.

Stage	Air temperature difference (°C)			Relative humidity difference (%)			VPD difference (kPa)			Control plot air temperature (°C)	Heat wave air temperature (°C)
	Daily values										
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Fruit set	6.8	8.7	3.9	-14.8	-25.8	-3.1	1.25	1.81	0.56	23.2	37.1
Veraison	5.3	7.8	2.4	-9.4	-15.3	-1.5	1.41	2.72	0.48	28.6	43.4
Harvest	5.6	7.1	3.8	-12.6	-20.3	-3.7	1.21	2.32	0.53	24.6	40.2

Table 1.10: . Mean temperature, standard deviation, number of pixels per measurement and temperature difference between treatments extracted from infra-red images of Cabernet Sauvignon vines and bunches exposed to ambient or 'heatwave' conditions during the 2011/12 growing season.

		Fruit Set	Veraison		Harvest		
		NE Canopy	NE Canopy	SW Canopy	NE Canopy	SW Canopy	Bunch
		(°C)					
Control	Mean	35.3	36.0	34.7	36.1	36.4	38.6
	SD	1.0	1.5	1.5	1.9	2.2	0.3
	No. Pixel	48,332	24,543	20,160	25,296	27,993	8,993
Heatwave	Mean	35.4	39.2	39.9	40.8	41.1	42.7
	SD	1.4	2.0	1.1	2.0	1.5	0.4
	No. Pixel	48,332	24,543	20,160	25,296	27,993	8,993
Treatment Differences		0.1	3.2	5.2	4.7	4.7	4.2

side of the canopy receiving direct solar irradiance for longer than the SW side. The infra-red imaging was taken during the afternoon and suggested little difference in actual leaf temperature between the sides of the row, despite the NE side having received direct sun for several more hours at the time (Table 1.10). Canopy temperatures were fairly uniform in both control and heatwave treatments, with the standard deviations of the 20,000+ pixels assessed in each image being approximately 5% of the average. The results suggested that there was no difference in leaf temperature during the fruits set event, but 3-5 °C difference during the veraison event and almost 5 °C during the harvest event. Typical images, with areas of assessment marked are provided in Figure 1.34.

The imaging results were corroborated by the spot measurements of leaf temperature, with again no difference being found during the fruit set event, but significant differences during both morning and afternoon measurements during the veraison and harvest events (Figure 1.35).

Infra-red imaging also allowed bunch temperature's to be easily assessed at the harvest heatwave event. Differences in bunch temperature were similar to those in leaves, with little variation between berries (Table 1.10). This was surprising as leaf temperature is, at least partially, regulated by transpirational cooling (Gates, 1968) to be inserted) and transpiration rates of the berries

would probably be significantly less than the leaves (Boselli & Di Vaio, 1996). However, despite being shaded, bunches of both ambient and heatwave vines were hotter than the canopy surface.

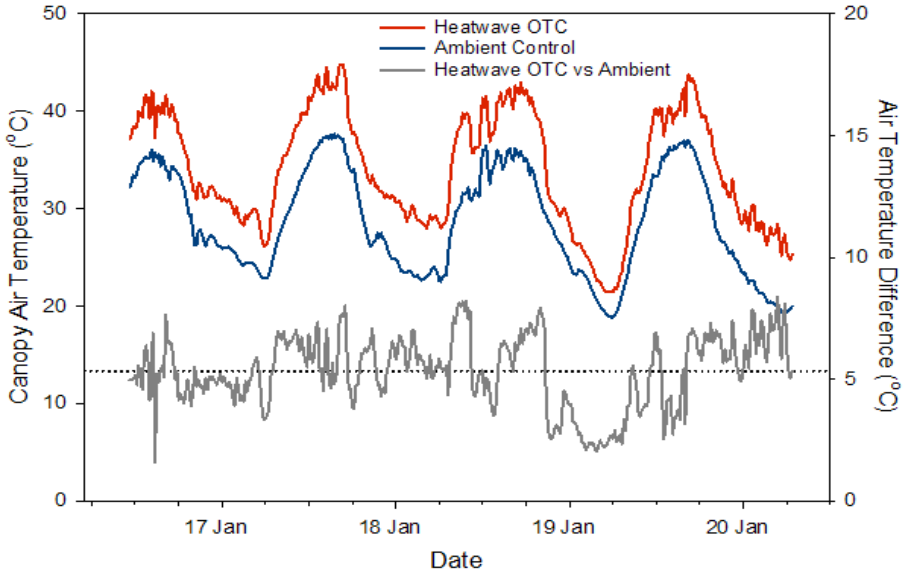


Figure 1.33: Air temperature within the canopy of the 'heatwave' treatment and ambient control at veraison 2012 in Cabernet Sauvignon (left axis) and the difference between the two values (right axis).

1.3.14 Leaf physiology

Differences in stomatal conductance did explain the similar leaf temperatures in both ambient and heatwave treatments at fruit set in 2011/12. Stomatal conductance during this event was consistently higher in the heatwave vines than those under ambient conditions in both morning and afternoon measurements (Figure 1.36). At veraison, afternoon measurements of conductance were similar in the two treatments, but the heatwave vines had a lower conductance in the morning and at harvest the heatwave vines had a lower conductance at all times (Figure 1.36). This suggests that, either the vines were unable to supply water enough water to their canopies later in the season, or the impact of a heatwave on stomatal conductance, and therefore leaf temperature, varied with phenological period. Although soil moisture was not measured in the heatwave treatments, soil moisture of the various replicates in the main warming experiment suggested little difference in soil water content between the dates, with soil moisture to 1 m depth being 183 mm during fruit set, 169 mm during veraison and 172 mm during the harvest heatwave event. Any difference in stomatal response to a high temperature event during the season has the potential to influence the risk of that event to leaf function.

The ability to measure stomatal conductance during the 2010/11 season was severely curtailed by the weather conditions as clear bright weather is required. However, effective measurements were able to be made for all three varieties at flowering. Conductance in all three varieties was higher in the heatwave treated vines than the control vines in both morning and afternoon measurements, although not every comparison was significant (Figure 1.37). The data supports that from the 2011/12 season and doesn't indicate any qualitative differences between the three varieties.

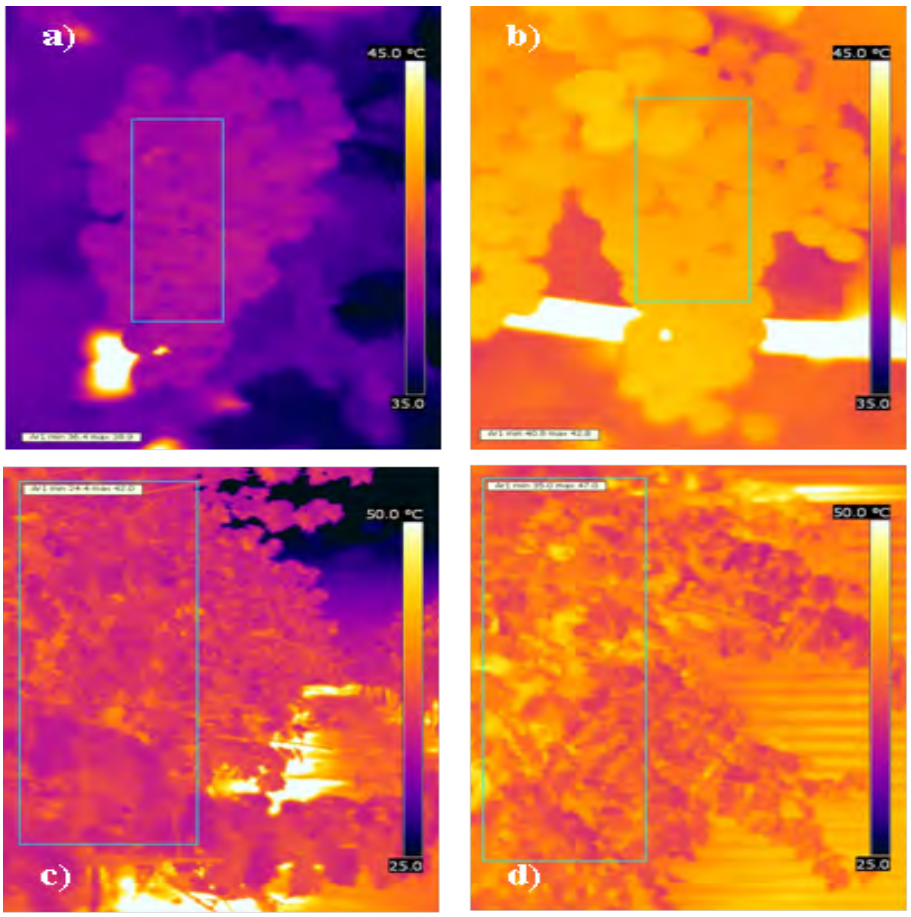


Figure 1.34: Infra-red images of bunches (a and b) and vine canopies (c and d) under ambient (a and c) or heatwave (b and d) conditions. Examples of the areas used to extract temperature data are indicated on each image.

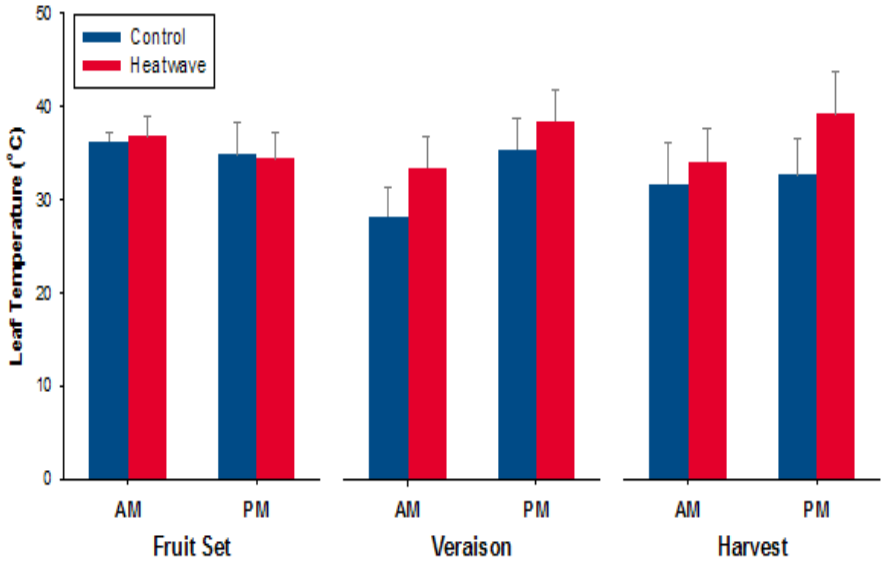


Figure 1.35: Leaf temperature of Cabernet Sauvignon vines exposed to 'heatwave' or ambient atmospheric conditions at fruit set, veraison and harvest during the 2011/12 season. Each bar is a mean of at least 130 readings + SD.

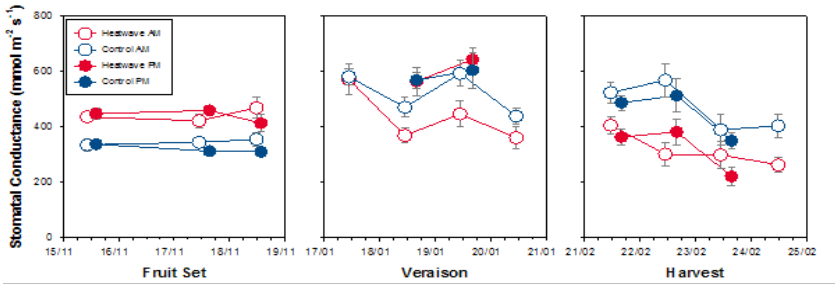


Figure 1.36: Stomatal conductance of Cabernet Sauvignon vines exposed to 'heatwave' or ambient atmospheric conditions at fruit set, veraison and harvest during the 2011/12 season. Each point is a mean of at least eight measurements ± SE.

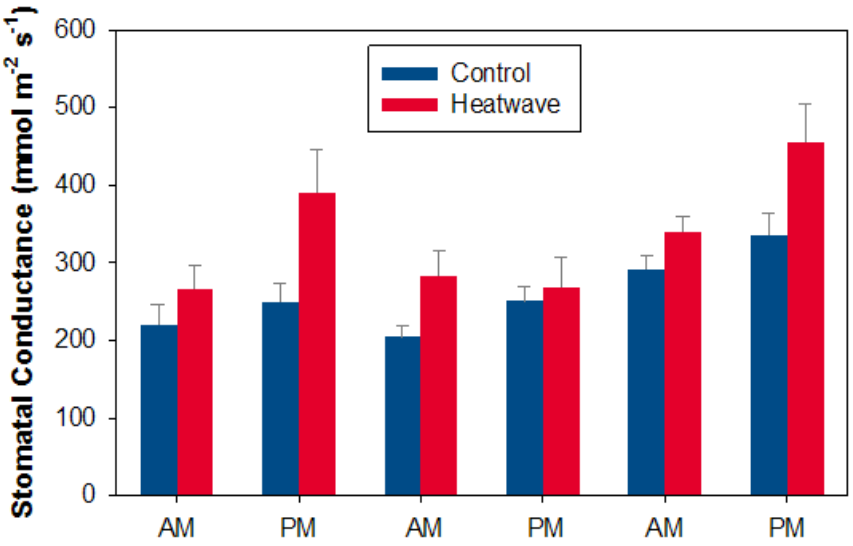


Figure 1.37: Stomatal conductance of Cabernet Sauvignon vines exposed to 'heatwave' or ambient atmospheric conditions at fruit set, veraison and harvest during the 2011/12 season. Each point is a mean of at least eight measurements ± SE.

However, the increase in stomatal conductance due to the heatwave conditions was higher in the afternoon, when atmospheric evaporative demand was highest, for both Chardonnay and Shiraz vines.Stomatal conductance has been shown to respond directly to transpiration rate, with stomata closing when rates are high (Mott & Parkhurst, 1991). 1991). However, this response is not seen at very low carbon dioxide concentrations (Bunce, 2008) and in grapevines, stomatal responses to VPD are inconsistent (Rogiers et al., 2012). Although the number of measurements was limited, this suggests that the stomata were responding to increased evaporative demand/transpiration by opening further, rather than closing to minimise water loss as might be expected.

Leaf water potential was not measured during the heatwave events in the 2010/11 season, but was during the 2011/12 season events, although no measurements were made during the fruit set event. Pre-dawn leaf water potential at veraison suggested that there was indeed no difference in soil water status between the treatments as there was no difference in leaf water potential at that time (Figure 1.38). This also suggested that the severity of the heatwave impact on the vine was limited as impacts of heat events on pre-dawn water potential in the absence of differences in soil moisture have previously been observed (Edwards et al., 2011). Midday leaf water potential was slightly lower in the heatwave treated vines at both veraison and harvest (Figure 1.38), but all vines were at the limits typically observed in Cabernet Sauvignon vines under local conditions (Edwards & Clingeleffer, 2011). The difference was significant at harvest, but not at veraison.

Stem water was also only slightly different between the treatments and also only significantly different at the harvest measurements (Figure 1.38). However, stem water potential was significantly lower at harvest than at veraison in both treatments despite there being no difference in soil water availability (see above). This suggests a change in the ability of the plant to take up and transport water, potentially through changes in hydraulic conductance and the lower stomatal conductance at harvest may be a consequence of this.

Gas exchange measurements, made separately to the conductance measurements reported above, also supported these conclusions, with stomatal conductance higher during the heatwave events

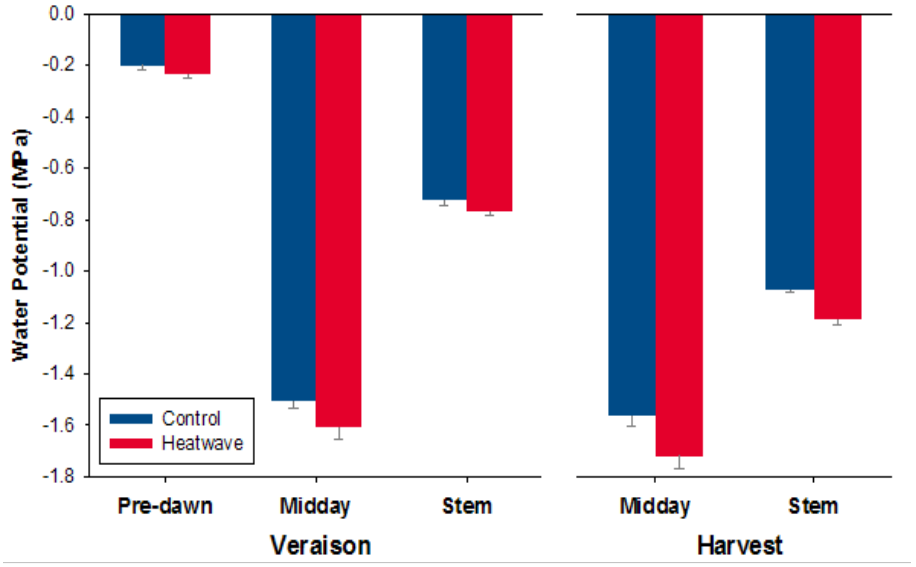


Figure 1.38: Leaf and stem water potentials of Cabernet Sauvignon vines exposed to heatwave or ambient atmospheric conditions at veraison and harvest during the 2011/12 season and pre-dawn leaf water potential at veraison. Each bar is a mean of at least eight measurements - SE.

at fruitset, but lower at veraison and harvest and lower in both treatments at harvest than veraison (Figure 1.39a). The impact of these differences in conductance were evident in the direct transpiration measurements made, with much higher transpiration rates under the heatwave treatment at fruit set, but no significant difference at veraison or harvest (Figure 1.39b). This was consistent with the leaf temperature measurements reported above and with those obtained during the gas exchange measurements (data not shown).

Assimilation rates were unaffected by the heatwave at fruit set, but lower in the heatwave vines at veraison and harvest (Figure 1.39c). As stomatal conductance was higher in the heatwave vines at fruit set, resulting in higher inter-cellular CO_2 concentrations (data not shown), this suggests that some degree of inhibition was occurring in those vines. It was possible to determine directly if the lower rates of assimilation in the heatwave vines during the subsequent measurements were due entirely to lower stomatal conductance, or if inhibition was also occurring at these times. The gas exchange data was used to estimate the maximum carboxylation rate ($V_{c\,max}$), which was then adjusted to a common temperature. Assuming that there was no prior difference between the vines, differences in $V_{c\,max}$ are indicative of inhibition of assimilation as a result of the heatwave treatment. Differences in $V_{c\,max}$ between the treatments occurred during all three events, despite no difference in assimilation being observed at fruit set (Figure 1.39d). This supports the conclusion that inhibition of assimilation in the heatwave vines was occurring over and above the impact of effects on stomatal conductance. There are various mechanisms by which this could have occurred, such as photo-inhibition (Tan & Whitlow, 2001) or down regulation of Rubisco activation (Salvucci & Crafts-Brandner, 2004), and basic chlorophyll fluorescence measurements were made in an attempt to further examine this. None of the slight difference in PSII yield observed were significant (Figure 1.40), but F_o' from those measurements was significantly higher in the heated vines (data not shown), suggesting that some heat stress may have been occurring. Dark adapted F_v/F_m was lower in the heatwave vines (Figure 1.40) and again F_o' was invariably higher (data not shown), both results being indicative of photo-inhibition as

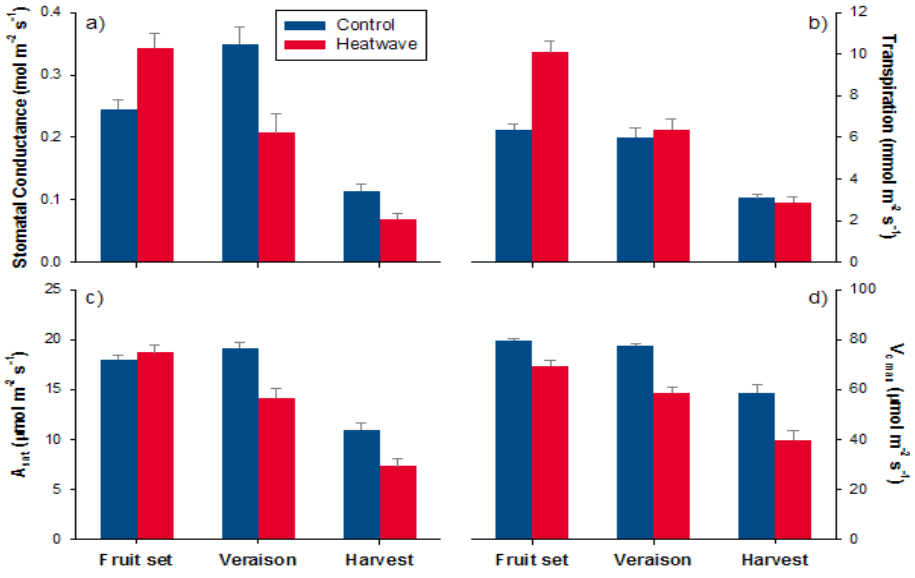


Figure 1.39: . Stomatal conductance (a), transpiration (b), assimilation (c) and maximum carboxylation rate at 25 °C (d) of Cabernet Sauvignon vines exposed to 'heatwave' or ambient atmospheric conditions at fruit set, veraison and harvest during the 2011/12 season. Each bar is a mean of at least eight measurements +SE.

a result of heat stress (Gamon & Pearcy, 1989). A pre-dawn measurement of F_v/F_m at veraison found no significant difference between the treatments, with the heated vines at 0.849±0.003 and the control vines at 0.855±0.002. The lack of any difference in these data and the almost ideal level of 0.85 (Björkmann & Demming, 1987) suggests that no lasting impact on the PSII system was occurring from any increase in photo-inhibition with heating during the day.

In addition to the gas exchange measurements night-time respiration was measured at veraison, the heatwave that achieved the highest air temperature. Along with leaf temperature data recorded at the same time, these data were also used to calculate Q_{10}, the relative increase in respiration for a 10 °C increase in temperature. At 11:30 PM the heatwave vines had almost a 50% higher respiratory rate than the ambient vines (Figure 1.41), equivalent to a Q_{10} of 3.0 and higher than 'typical' short-term values for leaves of approximately 2 (Larigauderie & Korner, 1995). In contrast, by 1 AM the difference was not significant and equivalent to a Q_{10} of only 1.6. There was only a slight decrease in leaf temperature between the two sets of measurements in either treatment, resulting in extremely high apparent Q_{10} values. The difference between the temperature response as a result of the heatwave treatment seen at 11:30 PM and that at 1 AM was probably due to down regulation as a result of reduced respiratory demand, rather than a direct effect of temperature (Bruhn et al., 2008). However, given that photosynthetic rates were lower in the heatwave vines at veraison and dark respiration rates higher, it is clear that over the course of a day much less assimilate would be available for transport to other parts of the vine (e.g. for fruit filling or the accumulation of storage reserves) during a heatwave than at more moderate temperatures.

1.3.15 Grape compositional analysis following heatwave treatments

Samples were collected at veraison and commercial harvest (~24 °Brix) and analysed for sugar (total soluble solids measured as °Brix), titratable acidity (TA) and pH.

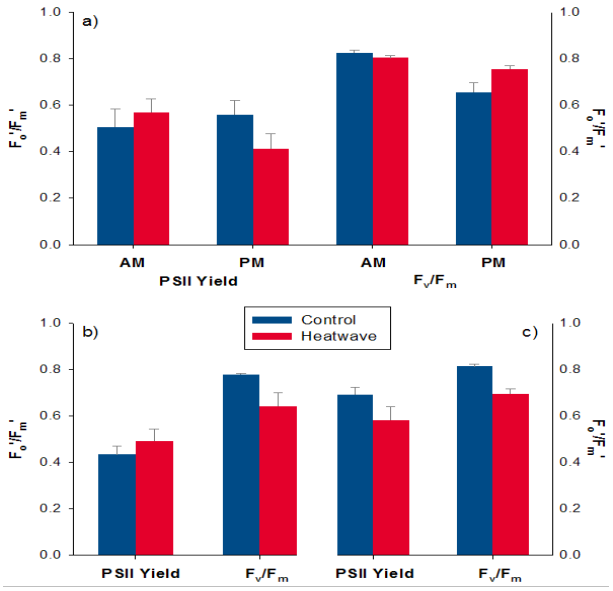


Figure 1.40: PSII yield and Fv/Fm of Cabernet Sauvignon vines exposed to 'heatwave' or ambient atmospheric conditions at fruit set (a), veraison (b) and harvest (c) during the 2011/12 season. Each bar is a mean of nine measurements + SE.

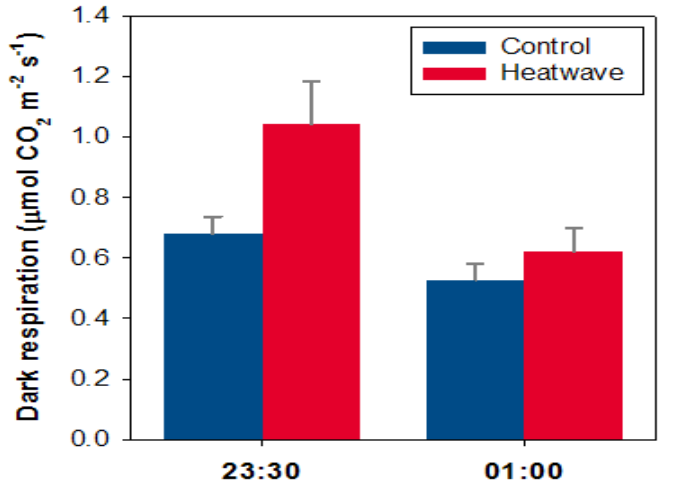


Figure 1.41: Leaf respiration rates at two times during the night of Cabernet Sauvigon vines exposed to 'heatwave' or ambient atmospheric conditions at veraison in the 2011/12 season.

Samples were also collected at pea-sized berry stage, veraison and harvest and analysed for skin tannins and flavonols for all three varieties as well as and anthocyanins for Shiraz and Cabernet Sauvignon.

In 2011-12, the heatwave treatment was only applied to Cabernet Sauvignon with more intensive monitoring of the plant physiology. The heatwaves were applied at the same developmental stages, pre-flowering, pre-veraison and pre-harvest. Total soluble solids (°Brix), TA and pH were analysed at veraison and harvest and tannins, flavonols and anthocyanins analysed in pea-sized berries, and fruit collected at veraison and harvest.

It should be noted that the control data presented here is the same as for the previous section and represented the average three field replicates ±SEM (standard error of the mean). The data for the heatwave treatments represents a single field replicate analysed in triplicate, the average of those analytical replicates is presented.

Total soluble solids, titratable acidity and pH

In 2010-11 similar results were observed for all three grape varieties, Chardonnay, Shiraz and Cabernet Sauvignon. Consistent with previous research and other aspect of this research sugar (°Brix) and pH increased towards harvest and TA decreased.

For Chardonnay in 2010-11, there was no effect of heatwave applied at either pre-flowering or pre-veraison on the veraison pH, TA or °Brix (Figure 1.42). While pH increased from veraison to harvest and TA decreased, there was no difference in either of these parameters in the harvest sample from any of the applied heatwave treatments including the control. Total soluble solids (°Brix) at harvest was the same for the control, pre-flowering and pre-veraison heatwave treatments, but slightly lower in the pre-harvest heatwave treatment. This may have been due to decreased photosynthesis during the heatwave (see Section 1.3.12).

For Shiraz in 2010-11, there was no effect of heatwave applied at either pre-flowering or pre-veraison on the pH, TA or total soluble solids °Brix of samples collected at veraison (Figure 1.43). Total soluble solids (°Brix) and pH increased from veraison to harvest and TA decreased, there was no difference in any of these parameters in the harvest sample between any of the applied treatments including the control.

Similar results were observed for the Cabernet Sauvignon grapes in 2010-11. There was no effect of the heatwaves applied at pre-flowering and pre-veraison on the pH, TA or °Brix of samples collected at veraison (Figure 1.44) °Brix and pH increased and TA decreased from veraison to harvest, there was no difference in these parameters between any of the applied treatments including the control at commercial harvest.

In 2011-12, only Cabernet Sauvignon was studied. The results were similar to those reported for 2010-11 with no effect of treatment on either °Brix, TA or pH at veraison or harvest.

Tannins, flavonols and anthocyanins

Tannin concentration in the heatwave treated Chardonnay vines in 2010-11 exhibited a similar pattern of accumulation as reported in Section 1.4.9. At harvest there was no difference between any of the heatwave treatments or between the heatwave treatments and the control (Figure 1.46).

The same pattern was observed in Shiraz (Figure 1.47) and Cabernet Sauvignon (Figure 1.38) skin tannins in 2010-11 and Cabernet Sauvignon skins in 2011-12 (Figure 1.49). The accumulation pattern followed previous reports (Hanlin & Downey, 2009) and there were no differences between any of the treatments including the control.

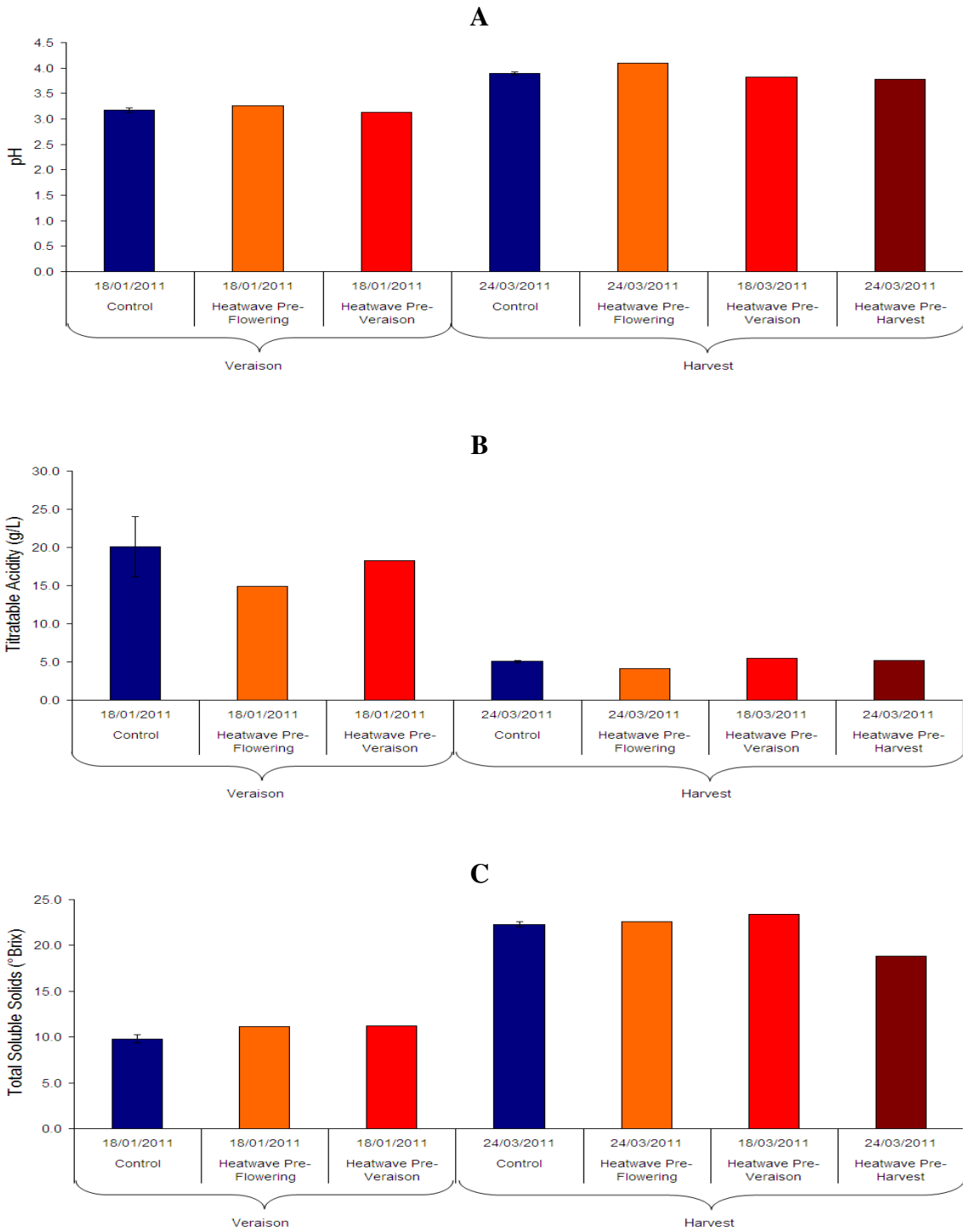


Figure 1.42: Chardonnay fruit collected at 2 developmental periods during the 2010-2011 growing season, from Control, Heatwave Pre-Flowering, Heatwave Pre-Veraison and Heatwave Pre-Harvest. A. pH, B. Titratable Acidity (g/L) and C. Total Soluble solids (°Brix).

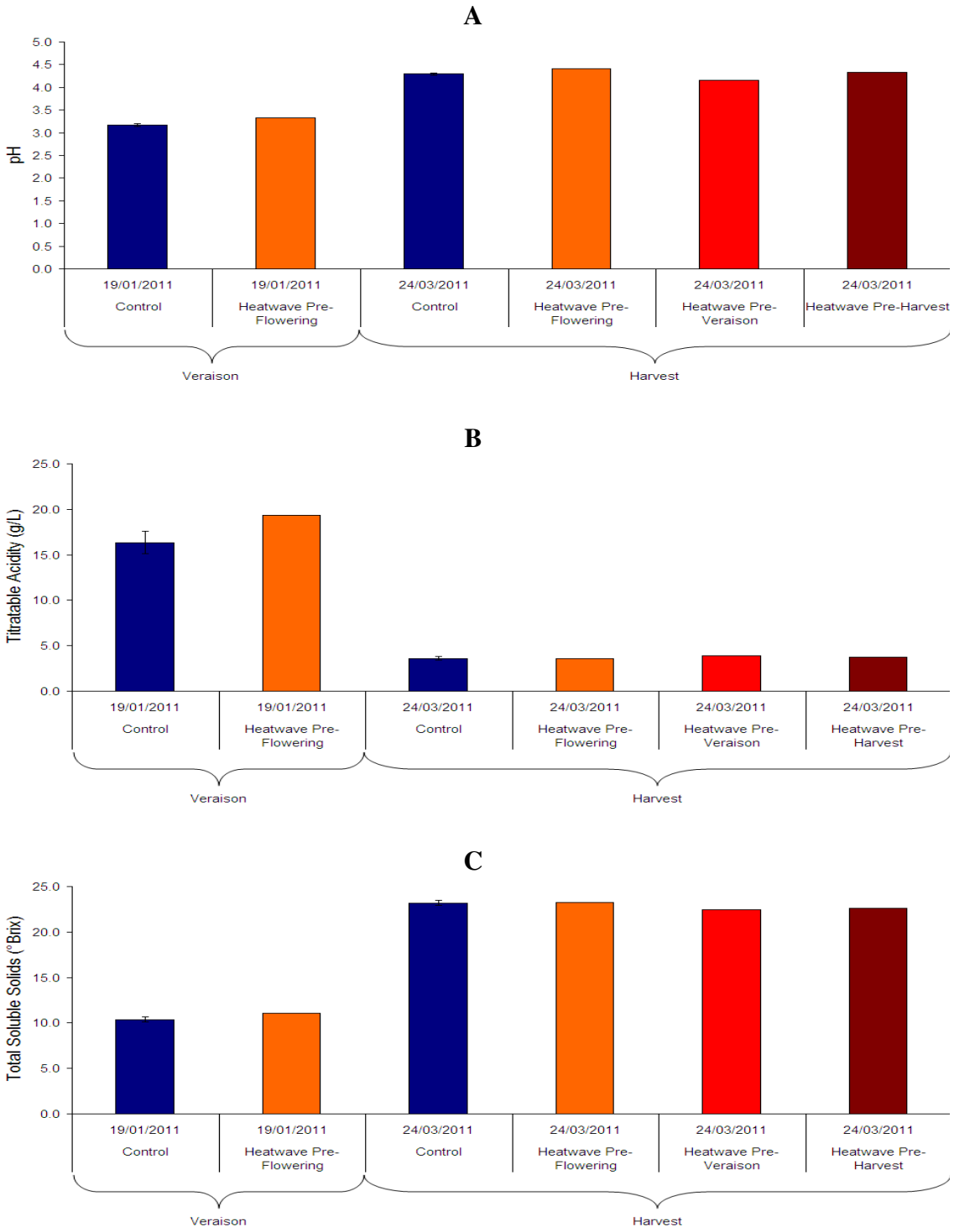


Figure 1.43: Shiraz fruit collected at 2 developmental periods during the 2010-2011 growing season, from Control, Heatwave Pre-Flowering, Heatwave Pre-Veraison and Heatwave Pre-Harvest. A. pH, B. Titratable Acidity (g/L) and C. Total Soluble solids (°Brix).

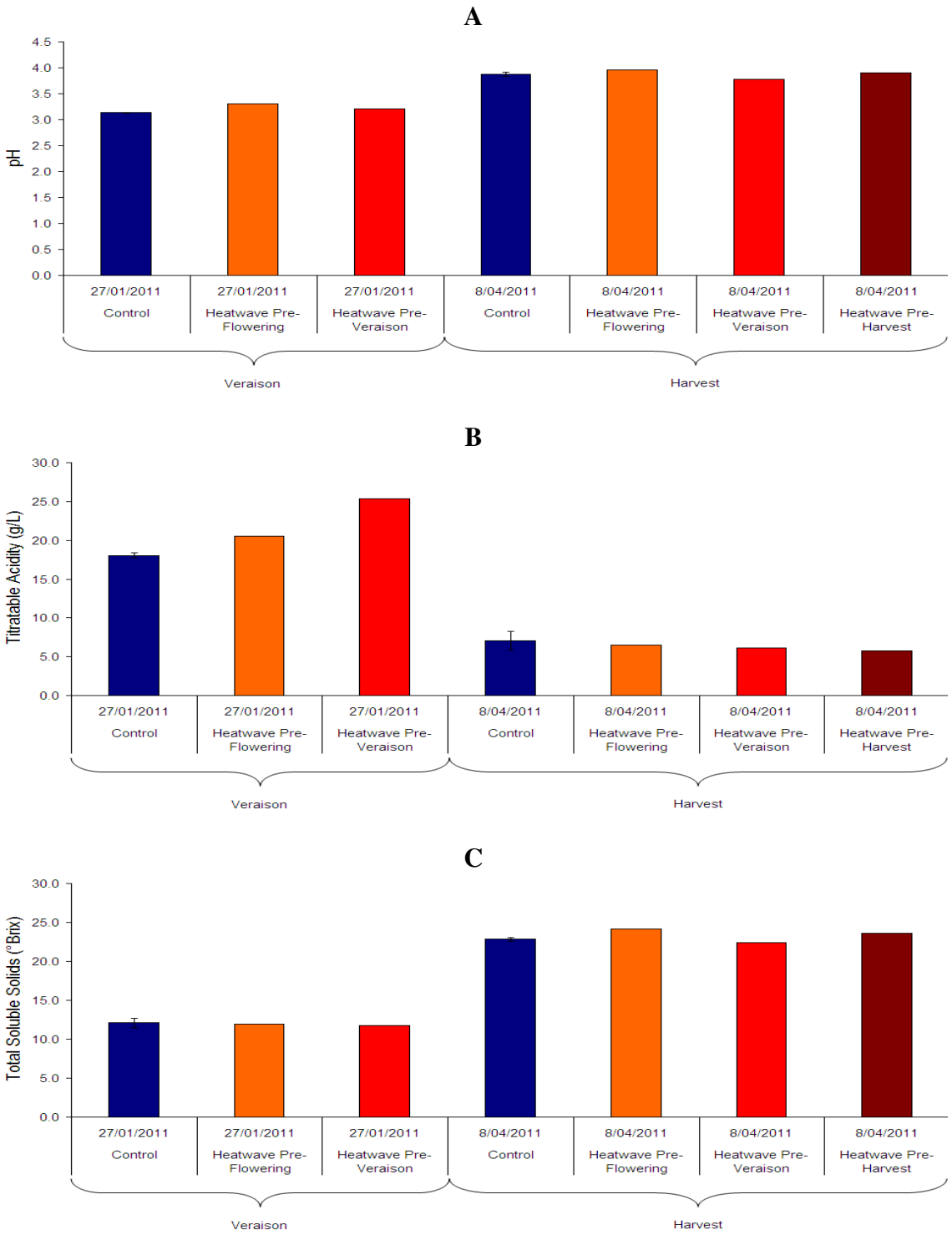


Figure 1.44: Cabernet S. fruit collected at 3 developmental periods during the 2010-2011 growing season, from Control, Heatwave Pre-Flowering, Heatwave Pre-Veraison and Heatwave Pre-Harvest. A. pH, B. Titratable Acidity (g/L) and C. Total Soluble solids (°Brix).

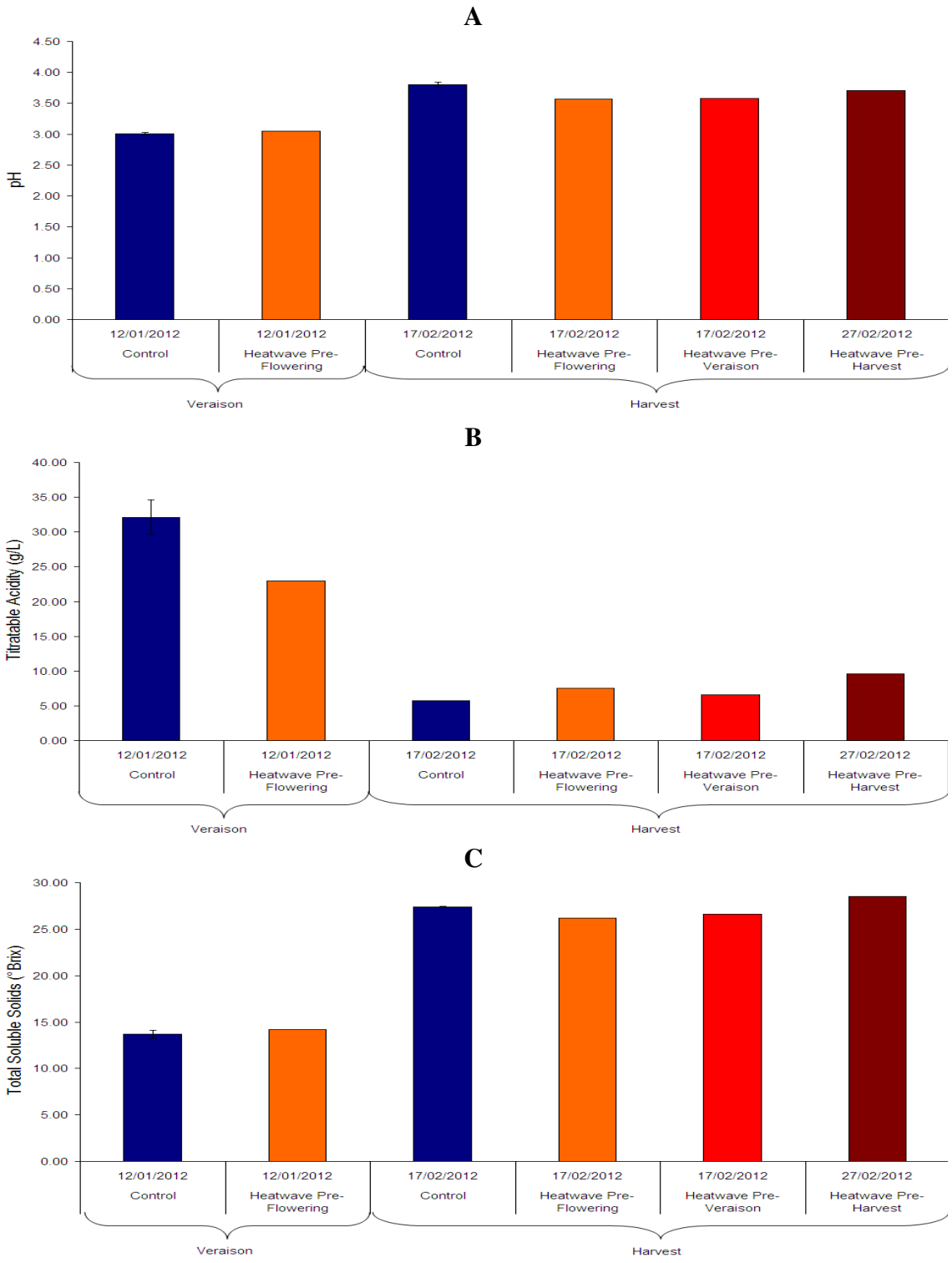


Figure 1.45: Cabernet S. fruit collected at 3 developmental periods during the 2011-2012 growing season, from Control, Heatwave Pre-Flowering, Heatwave Pre-Veraison and Heatwave Pre-Harvest. A. pH, B. Titratable Acidity (g/L) and C. Total Soluble solids (°Brix).

These observations for condensed tannin in grape skin were consistent with the conclusion of the previous section (Section 1.3.9 on page 34), that tannin biosynthesis is largely independent of direct temperature effects.

Grape skin flavonols were more variable than grape skin tannins in both the sustained heating trials (Section 1.3.9 on page 34) and the heatwave trials reported here. In the 2010-11 Chardonnay, the pre-flowering and pre-veraison heatwave fruit had similar concentrations of flavonols (Figure 1.46). However, there were noticeable differences between the control and the pre-flowering and pre-veraison heatwaves, which had higher flavonol concentrations than the control and the pre-harvest heatwave treatments at commercial harvest. The pre-harvest heatwave fruit and the control had similar flavonol concentrations.

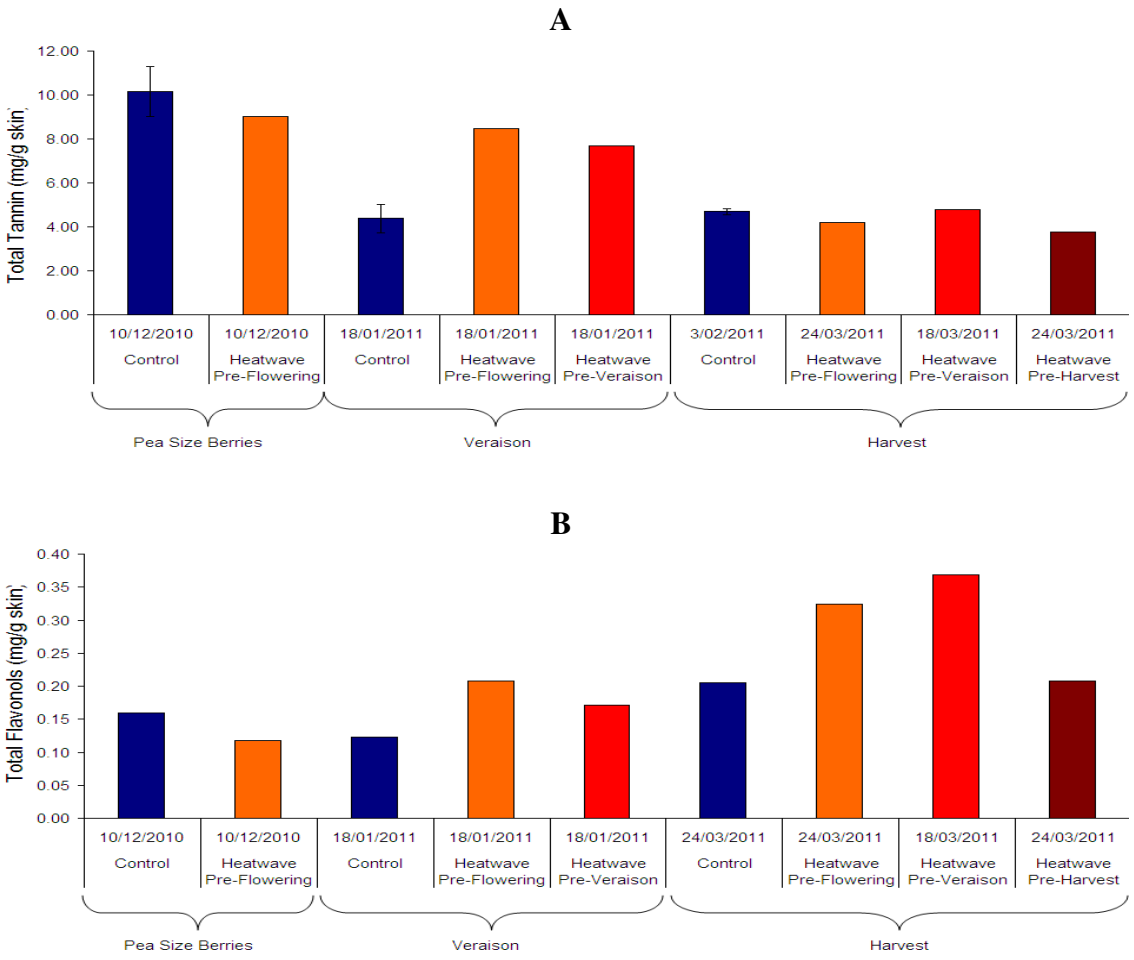


Figure 1.46: Chardonnay fruit collected at 3 developmental periods during the 2010-2011 growing season, from Control, Heatwave Pre-Flowering, Heatwave Pre-Veraison and Heatwave Pre-Harvest. A. Total Tannin mg/g of skin, expressed as catechin equivalents and B. Total Flavonols mg/g of skin expressed as quercetin-3-glucoside equivalents.

In the 2010-11 Shiraz fruit there was only a small difference in flavonols between the treatments at harvest (Figure 1.47). The pre-harvest heatwave treatment had slightly lower flavonols than the other treatments, which were all similar.

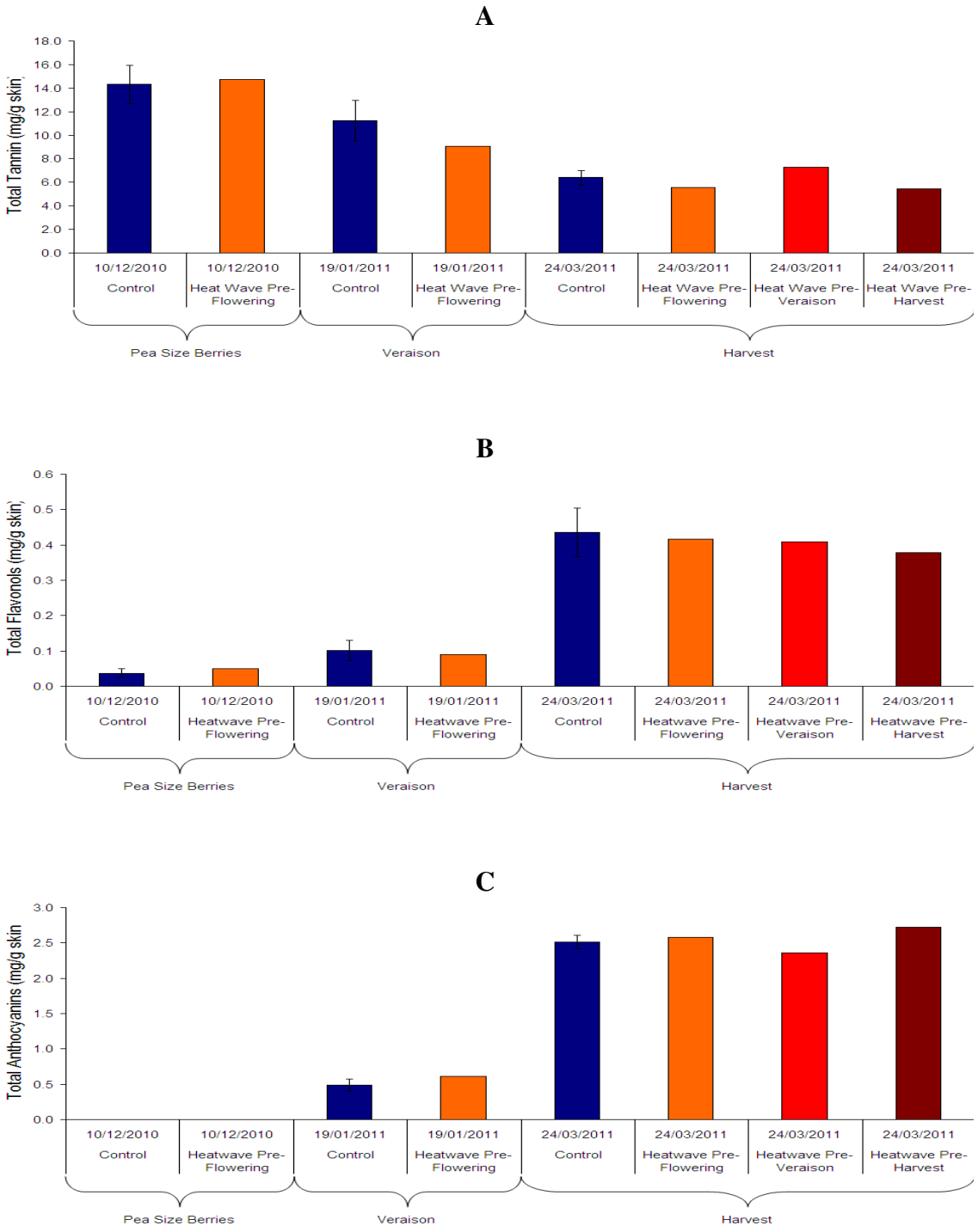


Figure 1.47: Shiraz fruit collected at 3 developmental periods during the 2010-2011 growing season, from Control, Heatwave Pre-Flowering, Heatwave Pre-Veraison and Heatwave Pre-Harvest. A. Total Tannin mg/g skin expressed as catechin equivalents, and B. Total Flavonols mg/g expressed as quercetin-3-glucoside equivalents C. Total Anthocyanins mg/g skin expressed as malvidin-3-glucoside equivalents.

In 2010-11 Cabernet Sauvignon grapes, there was no difference in flavonol concentration at harvest between any of the treatments including the control (Figure 1.48). The same pattern was observed for flavonols in Cabernet Sauvignon grape skin in 2011-12 (Figure 1.49).

This confirms the conclusion from the previous section (Section 1.3.9 on page 34) that flavonol biosynthesis is also largely independent of direct temperature effects. As was also reported earlier, this result was reasonably constant for Shiraz and Cabernet Sauvignon, but more variable for Chardonnay. That variability suggests that flavonol biosynthesis in Chardonnay grape skins may be more sensitive to temperature, or that other grapevine physiological parameters are more sensitive to temperature and were causing and indirect effect, for example altering canopy size or structure resulting in increased direct sun exposure of the fruit. A relationship between light exposure and flavonol accumulation in grape being well established (Price et al., 1995; Haselgrove et al., 2000; Downey et al., 2004).

Anthocyanins only occur in the skins of red grape varieties and accumulate from veraison onwards. In both Shiraz and Cabernet Sauvignon this general pattern was observed. In 2010-11 in Shiraz, there was very little difference in the anthocyanin concentration between the control and any of the heatwave treatments (Figure 1.47).

In the 2010-11 Cabernet Sauvignon harvest samples there were differences in the anthocyanin concentration between the control and the pre-harvest heatwave with grapes from the pre-harvest heatwave treatment having a lower concentration of total anthocyanins (Figure 1.48). There was no difference between the control and the other heatwave treatments.

In the 2011-12 heatwave treatments applied to Cabernet Sauvignon grapes there were also differences in the final anthocyanin concentration at harvest (Figure 1.49). Fruit from the pre-veraison heatwave had a higher anthocyanin concentration than the control or the pre-flowering and the pre-harvest heatwaves. There was no difference between the control, pre-flowering and pre-harvest treatments.

Decreases in anthocyanins in Cabernet Sauvignon skin from the pre-harvest heatwave in 2010-11 was consistent with some previous reports that high temperatures during ripening impact on anthocyanin biosynthesis (Bergqvist et al., 2001; Downey et al., 2004). The higher anthocyanin concentration at harvest from the pre-veraison heatwave in 201-12 is also consistent with the thinking that heating at this time increases metabolic rate and advances ripening, although tis wasn't apparent in other data such as sugar accumulation (Figure 1.45 on page 65).

Neither of these effects was consistent, which indicates that there are factors that offset or ameliorate the temperature effects or that the temperature effects on anthocyanin synthesis, and possibly anthocyanin degradation, are indirect.

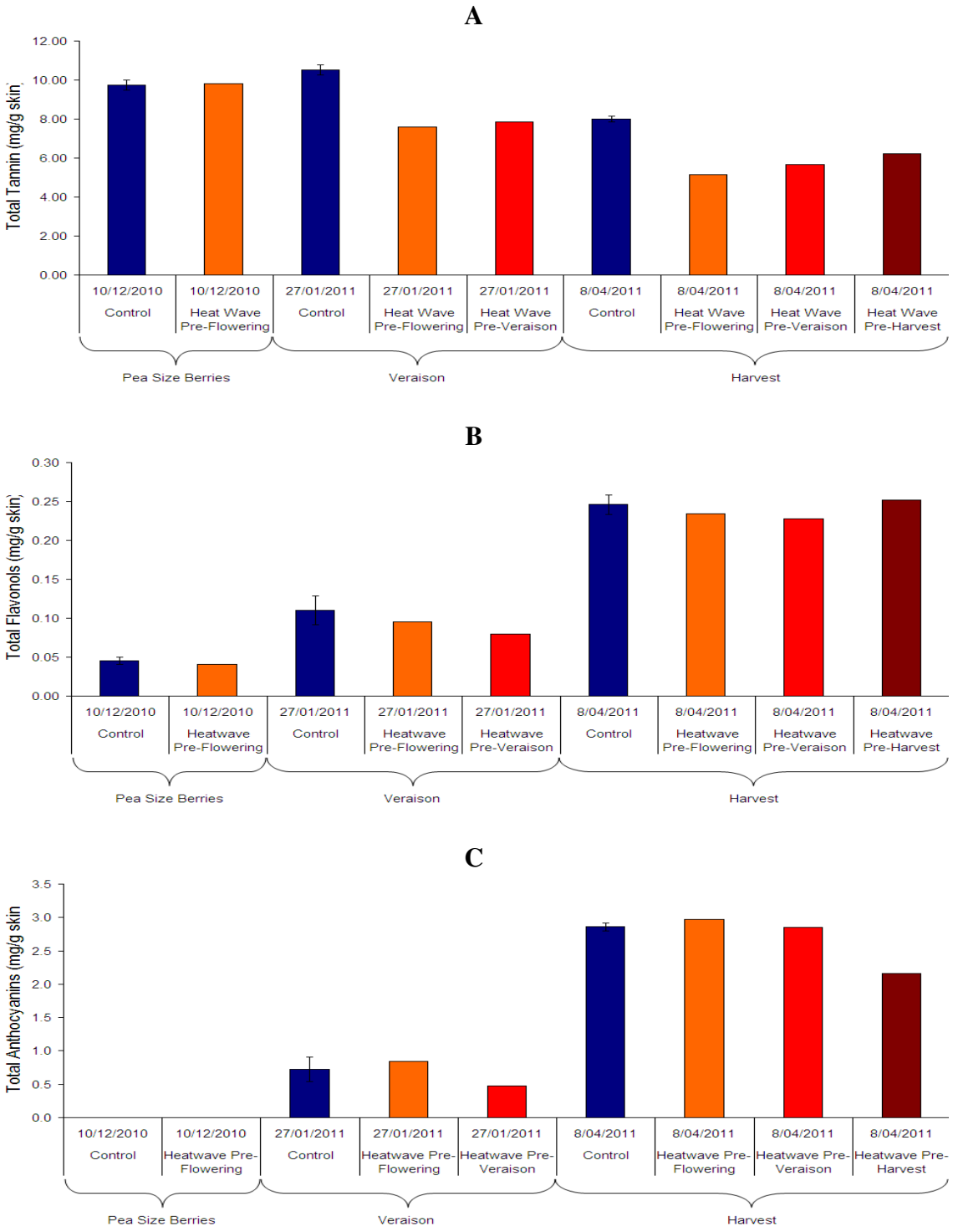


Figure 1.48: Cabernet Sauvignon fruit collected at 3 developmental periods during the 2010-2011 growing season, from Control, Heatwave Pre-Flowering, Heatwave Pre-Veraison and Heatwave Pre-Harvest. A. Total Tannin mg/g skin expressed as catechin equivalents, and B. Total Flavonols mg/g expressed as quercetin-3-glucoside equivalents C. Total Anthocyanins mg/g skin expressed as malvidin-3-glucoside equivalents.

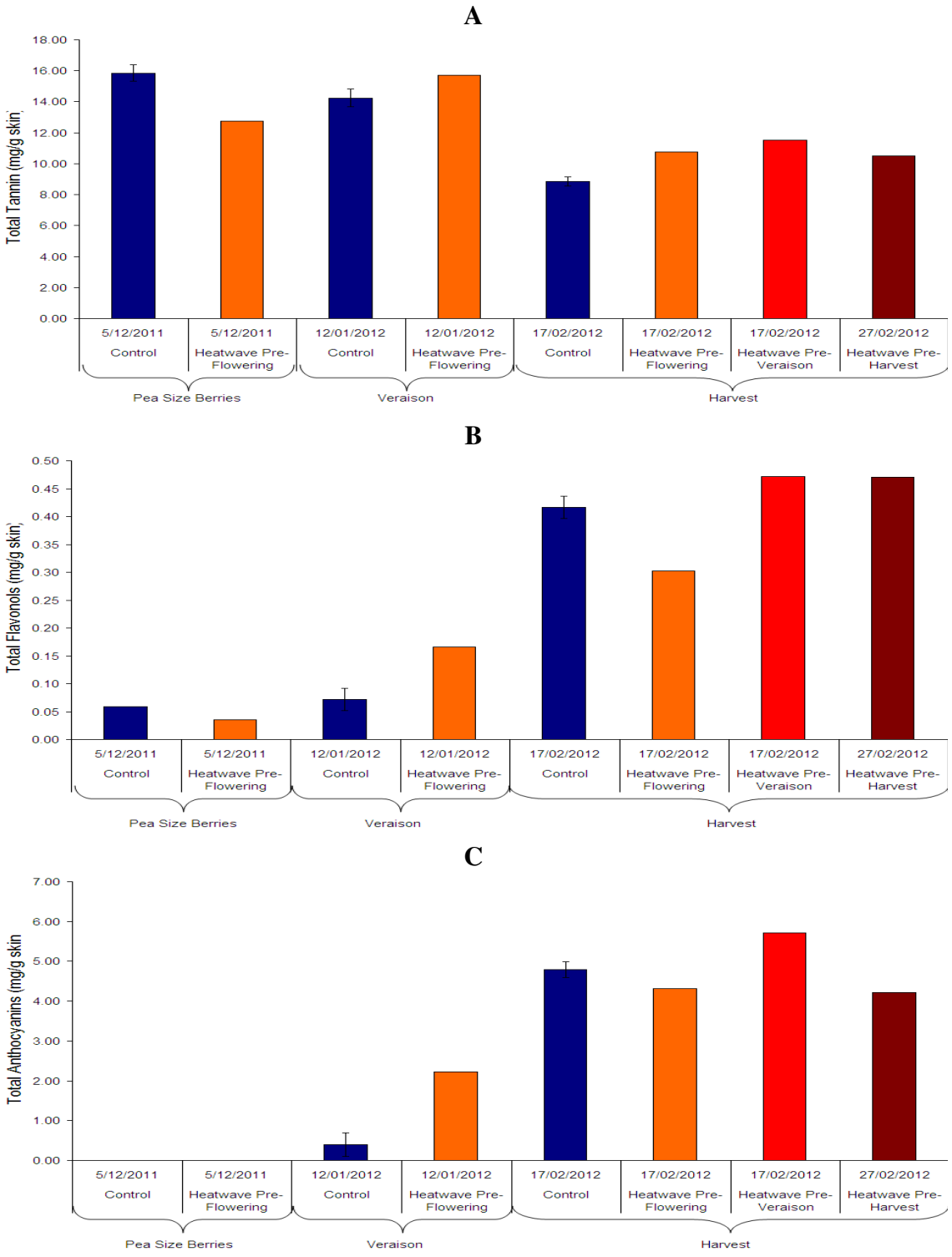


Figure 1.49: Cabernet Sauvignon fruit collected at 3 developmental periods during the 2011-2012 growing season, from Control, Heatwave Pre-Flowering, Heatwave Pre-Veraison and Heatwave Pre-Harvest. A. Total Tannin mg/g skin expressed as catechin equivalents, and B. Total Flavonols mg/g expressed as quercetin-3-glucoside equivalents C. Total Anthocyanins mg/g skin expressed as malvidin-3-glucoside equivalents.

1.3.16 Conclusions, objective 2 and 3

The heatwave treatments, and this part of the project, were aimed at potentially identifying "tipping points" for various physiological processes including metabolism of grape quality parameters. This was not designed as a replicated trial, being more of a preliminary investigation to inform future research directions.

Although the unusual weather conditions of 2010/11 impacted performance of the heatwave chamber, this was not the case in 2011/12 when the heatwave chamber effectively replicated the temperatures experienced during a naturally occurring heatwave in this region. However, the extensive physiological measurements indicated only moderate heat stress. As a result "tipping points" were not identified.

The stomatal conductance and gas exchange measurements also demonstrated a difference in the canopy response to heat, depending on the phenological period. Increased transpiration occurred at fruit set, preventing additional heat stress to the leaf, but not later in the season.

As with the sustained heating treatment from Section 1.3.9, on page 26 there was little impact of the increase in temperature on the composition of the grape, despite the demonstrated increase in bunch temperature. This suggests that the grapes generally and synthesis of sugar and acid particularly are relatively adaptable and resilient to short-term extremes of temperature changes.

Where changes were observed, these were inconsistent between seasons and varieties and are likely the result of indirect temperature effects or the limited replication available.

From the work presented here, it is clear that the increased temperature generated by the heatwave chamber was insufficient to highly stress the vines or have a significant impact on the grapes. With this in mind it is recommended that the heatwave component of this work be discontinued as a routine part of the research program, but capability be retained to apply a heatwave during a naturally occurring heatwave event in the future, where it is anticipated that a 40-45 °C event could be utilised to generate a 45-50 °C event.

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Chapter 2

Management strategies

Objective 4. Explore management strategies for wine grape producers to respond to increased temperature and increased frequency of extreme heat events

2.1 Introduction

A series of review and desktop studies addressed this objective. This approach was adopted because undertaking field trials to explore possible management practices to adapt viticultural production to a warmer climate was beyond the scope of the project. The information required to develop such trials would be generated by the current project with the possibility of including such trials in a future project. However, the project management team felt that it was important to provide as much information as possible for industry to assist adaptation decision making in the absence of experimental data. To achieve this, the following reviews and desktop studies were undertaken:

- A review of the likely impacts of a warming climate on winegrape production in the SE Australia including discussion of options and management strategies for adaptation to a warmer climate.
- Overseas study tours of warm production regions in the USA (California), southern Italy, North Africa and Spain.
- An analysis of the forecast changes in temperature, rainfall, evaporative demand and irrigation and examination of the land use suitability for viticultural production in the Sunraysia and Goulburn-Broken regions in response to a warming climate.
- A study considering the economic case for relocation of the industry in warm production regions, eg Riverland and Sunraysia to cooler regions as the climate warms.

2.2 Summary

Development of adaptation strategies for the Australian wine industry in response to a warming climate requires a fundamental understanding of the environmental change as well as the plant

response to that change. The current project (DPI 09/01) sought to generate some of this information as a preliminary step towards developing such strategies. This was partly achieved by the field-based experimental work and partly through a series of desktop analyses of existing and modelled data. These studies comprised a review of the likely impacts of a warmer climate, a number of overseas study tours, an analysis of changing land suitability in the Sunraysia and Goulburn Valley regions and an economic analysis of relocating enterprises from warm to cool climatic regions as an adaptive strategy. Several of these analyses were commissioned by the project team or were produced by other DPI funded research projects following input from the DPI 09/01 project team. These studies are summarised below and the full reports are included as attachments in Appendix 2 on page 90.

2.3 Review of impacts of climate on viticulture and possible adaptation strategies

During project development a body of previous research was collated to inform research objectives and direction. This material was subsequently collected into a review and expanded upon to provide an up-to-date summary of the likely impacts of a warmer climate on grape and wine production and to review possible adaptation strategies. The manuscript has been reviewed internally and submitted to the journal Climate Change, reviewer comments have been received and corrections completed.

Adaptation strategies for the South-Eastern Australian wine grape industry in response to global warming

THOMSON, G.E. and DOWNEY, M.O

Abstract
Temperature has a key influence on plant growth and development and rising temperatures associated with the enhanced greenhouse effect are likely to have important impacts on the plants that humans grow for food. This review examines some of the implications of elevated temperature on South-Eastern Australia¡¦s grapevines which generate important value-added wine exports. Increased warming could cause inconsistent cropping, decreased yields and deleterious changes in berry biochemistry of currently grown varieties. Many of South-Eastern Australia¡¦s premium, fine-wine growing areas may become too hot to produce the high quality wines for which they are renowned. Nonetheless, it is anticipated that this threat to wine quality can be at least partly alleviated by deploying adaptive strategies such as shifts to cooler growing locations, a change to varieties that are more heat tolerant and adoption of on-farm practices that help cool and protect the grape crop. Adopting new, heat-tolerant varieties is a practical option that should enable growers to maintain production in current locations. South-Eastern Australian wine producers have already begun investigating varieties from the southern Mediterranean region.

2.4 Overseas study tours

Australia's warm Winegrape producing regions are largely based in the Riverland (SA) and Sunraysia (Vic.) regions. While these are considered warm or even hot production regions, with

mean January temperatures of around 24 °C, there are other warmer wine grape producing regions around the world. As part of assessing potential adaptation strategies for the Australian wine industry, the project leader, Dr. Mark Downey, visited some of these regions to investigate adaptation strategies currently employed in those regions and assess those for adoption in Australia.

The first of these tours was to California (USA), specifically the Coachella, Temecula, Central and Napa Valley regions. The Temecula and Coachella Valleys are located in southern California (south of Los Angeles), while the Central Valley, as the name suggests, encompasses most of the central part of the State, extending from north of Los Angeles almost to the Oregon border. The climate is hottest to the south, on average 3 °C warmer than Mildura around Bakersfield and cooling further north, similar to Mildura around Fresno-Modesto and cooler nearer to Lodi, Sacramento and the Napa Valley. Most of the same varieties are grown in California as Australia and production systems are similar. During the tour of California in July-August 2009, the main adaptive response of the industry was to increase irrigation (Downey, 2010). While this is relatively effective in managing heat stress, there is a tendency towards high cropping levels as a result of the additional irrigation. In the bulk wine producing regions this is less of an issue, but has potential implications for wine quality in other regions. Furthermore, in a water limited environment access to and use of additional irrigation water could pose environmental and economic problems. The full details of this travel were published in Australian Viticulture (Downey, 2010) (see also Appendix 2 on page 90).

The second tour was undertaken in July-August 2010 and included Sicily and southern Italy, Tunisia and Morocco in North Africa and the Ribiera del Duero, Rioja and Priorat regions of Spain. Sicily and southern Italy have similar temperature ranges to many of Australia's wine producing regions and while there are some differences in soils, particularly compared to the Sunraysia and Riverland regions of SE Australia, growers face many of the same challenges in terms of temperature and water availability. The two major differences between this region and Australia that reflect efforts to adapt to this climate are a tendency to carry lower crop loads and a wide selection of local varieties in addition to the classic or international varieties such as Cabernet Sauvignon, Merlot, Pinot Noir and Chardonnay, etc. Many of the Italian varieties appear to be well suited to Australian conditions and most of these can already be found in cultivation in various parts of Australia. The outcomes of this part of the travel have been reported in an article submitted to the "Wine and Viticulture Journal" (Downey & Scafidi, 2012),(submitted). In North Africa, production often focuses around cooperative wineries where wine quality can be quite variable and generally low by international standards, although there are a number of outstanding wines produced from these regions. While these tend to be produced by wineries owned and managed by overseas wineries, eg. Italy, rather than made by cooperative wineries. One of the most notable wines was a Carignan from Tunisia, an area where summer temperatures can exceed 50 °C as the Sirocco winds blow off the Sahara Desert. These winds can blow for several days at a time in a region where scheduled irrigation is largely absent and even where present, not well understood or managed. The adaptation strategy in this region is primarily the production system, which is based around bush vines, perhaps a meter in height with very low crop loads, often less than a tonne per hectare, sometimes as few as 1-2 bunches per vine. While this production system doesn't lend itself well to mechanisation, the take home message is that lower crop loads may be one of the best adaptation strategies. This was observed generally throughout southern Italy, North Africa and Spain. While often crop load is mandated by DOC (Denominazione di Origine Controllata) regulations, and traditions of viticultural agronomy that have evolved in a DOC culture, it also reflects a response to the environment where higher crop loads are not possible; generally because of water limitations.

2.5 Land Use Suitability Analysis for the Sunraysia and Goulburn-Broken Regions

Within DPI there is a group of climate and landscape modellers who have developed a novel methodology that has Land Suitability Analysis at its core. The approach combines current research knowledge with the knowledge and experience of subject matter experts and leading growers to generate theoretical relationships where empirical evidence is lacking to model natural systems. The DPI 09/01 project team leader, Dr. Mark Downey, had an opportunity to provide input into the development of capability in this area during the life of the GWRDC-funded project (DPI 09/01) with a view to generating outcomes that could be used to inform wine industry decision making in response to climate change. The initial part of these studies was to establish the factors driving grape production, to provide weightings to these factors and to use the weighted factors to inform development of the model. Obviously climate, soil and water were major drivers and in order to model future production scenarios it would be necessary to have suitable datasets for each of these parameters. Climate and water parameters, eg. temperature, rainfall, evaporative demand and irrigation requirements could be derived from climate change forecasting and existing plant water requirement algorithms and these data are reported for both the Sunraysia and Goulburn Valley regions. In order to run the land suitability models the underlying soils need to be classified to a fairly high resolution. DPI Victoria holds this data for the Goulburn-Broken catchment and the project team was able to utilize this to model changing land suitability for that region. However, DPI does not have a complete soils dataset for the Sunraysia region, nor is there such a dataset in the public domain. However, much of the necessary data is likely held by individual wineries and growers - where this may have been collected prior to planting. At the end of the current project the land suitability analysis for Sunraysia will not be completed, although the climatic analysis is complete, along with a report of the extent of the soil data resource. The executive summaries for both of these reports are included below and the full reports are included in Appendix 2.

2.5.1 Climate challenges for horticulture in the Goulburn Broken region

Executive Summary

A copy of the full report (Sposito et al., 2012) is attached as part of Appendix 2 on page 90. The report is part of the project *Climate Change Impact Modelling in Horticulture*. It covers the assessment of the likely climate change impacts on viticulture (wine grapes) in the Goulburn Broken Region through a DPI methodology based on Biophysical Land Suitability Analysis.

Regional Climate Change Projections for the Goulburn Broken Region Climate change projections for Goulburn Broken, under the IPCC A1FI (high global warming) scenario, indicate: (i) an increase in mean temperature of 1 °C (by 2030) to 1.5 °C (by 2050) from the baseline (average climate in 1996-2005) with a maximum of 2.5 °C between the baseline and 2050; (ii) a decrease in total rainfall of 5 mm to 500 mm between succeeding time periods, with a maximum decrease of around 50 mm in the irrigation districts and over 300 mm in the southern areas between the baseline and 2050.

Two important indicators of wine production are heat degree days (HDD) and spring frost index (SFI). The HDD classifies the climate of a wine growing region, with the resultant mapping output divided into five production regions. Application of HDD to Victoria places Region V in the North West, around Mildura. Under climate change projections, Region V moved progressively south, alternating with Region I and II across the central part of the state. Projected HDD for

2050 showed a substantial reduction in the size of Regions I and II with a concomitant increase in the size of Regions IV and V.

The SFI is a measure of an area's tendency to produce large variations in temperatures in a short period of time. Temperature variability affects grapevine phenology and production. In particular, frost damage to berries is a major problem during spring growth and ripening periods. Currently, areas of northern Victoria have a high SFI, whilst areas south of the Great Dividing Range have a low SFI. SFI projections for 2050 indicate a reduction in areas with high frost risk. This reflected projected increases in both mean and minimum temperatures across Victoria.

Evapotranspiration and irrigation requirements in Goulburn Broken for the baseline, 2030 and 2050 were compared. The results showed: (i) an increase of between 30 mm to 150 mm in evapotranspiration, with a maximum of 210 mm difference between the baseline and 2050; (ii) an increase of between 5 mm/ha to 70 mm/ha in irrigation to 2030 and 50 mm/ha to 110 mm/ha to 2050.

Viticultural Biophysical Land Suitability Analysis (LSA) in Goulburn Broken Biophysical LSA modelling assumed that: (a) the whole region is potentially available for wine grape production (minus protected areas under native vegetation), and (b) no introduction of adaptive production strategies. The analysis showed that land suitability for wine grape production is likely to decline with a shift from a high (i.e. greater than 80% suitable) to a moderate (i.e. 50-70% suitable) suitability by 2050, particularly in southern parts of the region. The higher suitability-ranked land in the north is also likely to reduce in size, but by 2050, about two thirds of the land in northern areas would still remain within the higher suitability categories for wine grape production. Areas to the east of Seymour would potentially retain a high suitability ranking by 2050, even as the surrounding areas decline. The largest changes in land suitability would occur in the southern districts, in particular around Kilmore, Yea, Alexandra and Mansfield.

These results were compared with the HDD Regions. The comparison depicted how HDD Regions may change by 2050 and how they influence resulting LSA model outputs. Grape Production Regions I to IV were identified in the baseline. Regions I and II, in the south of the study region, correlated well with high ratings of suitability at 90%, particularly Region I. Regions III and IV occurred in the north; these regions are associated with lower suitability ratings. By 2050, there was a projected southward shift of all the identified regions, with the northern half of Goulburn Broken projected to be within Region V. This southerly retraction and the inclusion of Region V reflect reductions in land suitability across Goulburn Broken.

While the combination of shifting land suitability, as indicated by LSA, and modifications in the HDD Regions that indicate changes in the potential for wine grape production in the Goulburn Broken Region, much of the production area within this region will remain suitable for wine grape production into the foreseeable future; notwithstanding competition for other land uses.

2.5.2 Climate challenges for horticulture in the Sunraysia region

Executive Summary

A copy of the full report (Romeijn et al., 2012) is attached as part of Appendix 2 on page 90. The report is a component of the project Climate Change Impact Modelling in Horticulture that investigated the likely impacts of climate change on Victorian perennial horticulture. It covers two objectives: (i) assessment of the likely impacts on water availability for wine grape production in the Sunraysia Region, and (ii) assessment of key gaps in the soil information in the Sunraysia Region. Water Availability ,mean temperature, total annual rainfall and solar radiation, both in a current and future climate, are considered for the Sunraysia Region.

- Mean baseline temperature (1996-2005) ranged from 15.5 to 17.5 °C, with projected increases of 1 to 1.5°C to 2030 (17 to 18.5 °C) and up to a 2.5°C through to 2050 (18 to 20 °C).
- Baseline total annual rainfall ranged from 215 to 360 mm, with projections indicating likely decreases of 15 to 25 mm to 2030 (200 to 335 mm) and a 80 mm decrease into 2050 (170 to 280 mm).
- Baseline solar radiation ranged from 17.5 to 18.5 MJ/ m^2/day with a possible increase of up to 1 MJ/m^2/day through to 2030 and a 0.5 to 1.5 MJ/m^2/day increase to 2050.

Projected changes in these primary factors would have concomitant influences on other climatic indicators such as heat degree days, evapotranspiration and irrigation.

- Baseline heat degree days ranged from 1,975 to 2,390 day°C, with projections indicating likely increases of 210 to 285 day°C to 2030 and a 270 day°C increase into 2050.
- Baseline evapotranspiration ranged from 1,310 to 1,450 mm, with possible increases of 40 to 130 mm to 2030 and a 70 mm increase through to 2050.
- Baseline irrigation ranged from 485 to 640 mm/ha, with a likely increase of 35 to 60 mm/ha to 2030 and a 55 mm/ha increases into 2050.

Projected climatic shifts will have a significant impact on water availability for wine grape production. With increasing temperature, there will be a greater need for irrigation to replace water loss in the plant through evaporation and transpiration. Further, as temperatures increase, there is also a potential lowering of rainfall amounts, which will reduce water availability for irrigation allotments.

Soil Information Gaps Analysis - For Land Suitability Analysis (LSA) modelling, a relevant soil data layer has to be generated in a GIS domain. The layer must contain the attributes of differing soil units over the entire study region at a consistent spatial resolution. However, the readily available sources of soil information for Sunraysia include data at multiple levels of spatial resolution. Collectively, they do not cover the entire irrigation zone of the study region and all attributes are not reported.

Two options exist for achieving data consistency between the point, broad and fine scale information in Sunraysia:

1. Focus the soil data layer upon the irrigation zones that have detailed soil surveys. This requires an extrapolation of soil units to join individual soil surveys, whilst the previously unmapped irrigation areas need to be defined by incorporating the fine scale soil surveys within the broader scale maps.
2. Disaggregate and restructure the current data from all sources (soil surveys, land systems, geomorphological and point source data) to achieve a uniform resolution, which contains all relevant attributes over the larger study region.

There is a greater benefit in considering a larger study region (Option 2), since this will permit identification of suitable agricultural areas outside the current irrigation zones. However, a smaller area (Option 1), will be quicker to complete and will encompass a majority of the irrigated agriculture within the defined study boundary. Work requiring LSA as a basis will need to take into account the incorporation of one of these options into approaches considering future agricultural development of the Sunraysia Region of Victoria.

2.6 Economic analysis of adaptation options

During development of the GRWDC-funded project DPI 09/01, a number of discussions were held with industry representatives and subsequently with the GWRDC program manager. One of the outcomes of these conversations was a response from a number of industry representatives that should winegrape production become untenable in the hot production areas such as Sunraysia or the Riverland, the industry would relocate. To test this assumption, the DPI 09/01 project leader, Dr Mark Downey commissioned Dr Alexandria Sinnet, an Agricultural Economist with DPI, to undertake an economic assessment of the option of relocating in response to a changing climate. The executive summary of this study (Sinnet, 2012) presented below and the report is included in Appendix 2 on page 90.

2.6.1 Climate adaptation options for viticulture in Sunraysia

Executive Summary

One of the major factors impacting on grapevines is temperature. Temperature drives the timing of key events in the grapevine lifecycle and reproduction and impacts on fruit and therefore final wine quality.

According to Webb (2006), in Australia annual average temperature will rise in the order of 0.3 to 1.7 °C by 2030 in the main viticulture areas. By 2070 mean annual temperatures are expected to increase in the main viticulture areas by 0.8 to 5.2 °C. It is expected that an increase in temperature will be detrimental to productivity and fruit quality. Webb et al. (2007) found that without adaptive measures, wine grape quality in Australia would decrease by 7% to 39% by 2030.

It is also expected that there will be an increase in the frequency of extreme heat events. White et al. (2006) found that an increase in the frequency of heatwaves is expected to have a much greater impact on the wine grape sector compared with an increase in mean annual temperatures. Researchers such as Webb and White and others have found that a change in temperature (whether it is through an increase in the mean annual average or an increase in the frequency of extreme heat events) will decrease income. Webb et al. (2007) argued that income from wine grapes in Sunraysia could fall by as little as 8% or as much as 30% by 2030.

Such findings have prompted the researchers to ask:

- What is the potential impact of this change in temperature on the wealth of a grower who earns from investing in a wine grape business in Sunraysia, without making any changes to their business?
- What are the different adaptation options available and what is the net benefit (or cost) of these different options for this grower?

This research has used a case study wine grape farm to explore these two questions. For this wine grape farm it was found that:

- A change in temperature, which causes income to fall, is expected to decrease the wealth earned from investing in this farm business. Further, decreasing income and not making changes on-farm is expected to cause a decline in land values.
- A productivity improvement (input costs decreasing at a compounded rate each year) would help to offset the expected fall in income. It is expected that there would need

to be a productivity gain that lowers costs by at least 2 per cent per annum compounded in order for this grower to still earn their desired rate of return in the current location.

- One of the existing adaptation options to mitigate against an increase in temperature is building shade cloth over the grapes. However, it was found that this was expected to be too costly to implement on-farm at current wine grape prices.
- The option of relocating to a more suitable micro climate might be possible, but growers will make this decision based on a complex combination of production, financial, human and market considerations.

The overall conclusion from this project was that for this case study farmer, and it could be inferred that for other winegrape growers, the best solution to manage a change in temperature would be an advancement in management practices that increased productivity at a rate commensurate with forecast decreases in income.

2.7 Conclusions, objective 4

Increase in temperature is likely to cause a fall in income and a decrease in land value. Installing shade to mitigate against temperature is expected to be too costly at current grape prices. Relocating to a cooler climate may be an option for some growers but decision will have to be based on a combination of production, financial and market factors

Anticipation of hot weather and the accurate provision of irrigation may overcome the detrimental effect of excessive heat on vineyard productivity and grape quality. Application of best irrigation management practice therefore has the potential to mitigate the most detrimental effects of warming.

Comprehensive evaluation of grape varieties and rootstocks that are well adapted to hot and dry environments should be pursued locally and through international collaboration.

References

Downey, M. (2010). How hot is hot? A Californian perspective. *Australian Viticulture*, *14*(6), 59–62.

Downey, M. & Scafidi, P. (2012). Hot Winegrape Production: Italian lessons. *Wine and Viticulture Journal*, *submitted*.

Romeijn, H., Sposito, V., Faggian, R., & Rees, D. (2012). Climate challenges for horticulture in the Sunraysia region. Technical report, Future Farming Systems Research Division, DPI Victoria, Parkville.

Sinnet, A. (2012). Climate adaptation options for viticulture in Sunraysia. Technical report, Future Farming Systems Research Division, DPI Victoria, Parkville. A report and presentatioin for GWRDC project DPI 09/01.

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Objective 5. Communicate the outcomes of objectives 1-4 to the warm inland regions of Australia

2.8 Collaborations

During the course of this project a number of new collaborations were developed to facilitate access to information and expertise from key warm climate production areas that would assist to deliver project outcomes. A number of existing collaborations were also utilised.

1. E & J Gallo Winery, California (USA). The E & J Gallo Winery in California is located in the Central Valley, an area with a similar climate to Mildura in Australia. the winery sources fruit from throughout the Central Valley, with southern regions having on average higher temperatures than the warm production regions in Australia. Employing the existing long-standing relationship between DPI Vic. and E & J Gallo Winery enabled the project leader, Dr.Mark Downey, to identify key research and extension staff and industry representatives in the Central Valley and southern California (Temecula Valley and Coachella Valley) during late summer (northern hemisphere) in 2010.

2. Constellation Wines US. Constellation Wines, US are also a long-standing collaborative partner of the DPI Victoria team based in Mildura and contacts within Constellation Wines US were instrumental I gaining an overall view of Central Valley and Napa Valley production and response to climate variability.

3. University of Palermo, Sicily. Southern Italy and Sicily are warm production areas with similar growing conditions to many places in Australia. To access knowledge of these production areas and production techniques and varieties that might be of use to the Australian industry, the DPI Vic. research team have a developed a collaboration with Dr. Pietro Scafidi and other members of the faculty at the University of Palermo, Department of Arboriculture. The team leader, Dr. Mark Downey visited southern Italy in mid-summer (northern hemisphere) 2011. The University hosted this visit and facilitated Dr. Downey's visit to Tunisia, Morocco and Spain during that trip and organised industry, research and extension staff to meet with Dr. Downey. The University of Palermo has considerable expertise in the agronomy of regional varieties that may be suitable for Australian conditions and may form part of a long term adaptation strategy for the industry. A Memorandum of Understanding has been developed and signed between the University of Palermo and DPI Victoria.

4. CSIRO Plant Industries, Adelaide. DPI Victoria (Mildura) have had a long-standing collaborative relationship with CSIRO Plant Industry in Adelaide around grape and wine tannin analysis and biochemistry. As part of the current project (DPI 09/01), the relationship has expanded and Dr. Everard Edwards has been sub-contracted to DPI with CSIRO in-kind

support to contribute depth to our understanding of the plant physiological response to increased temperature.

5. DPI Victoria. This project sought to access expertise and capability across DPI that was not captured in the original project development team. The project team had primary expertise in grapevine physiology and grape and wine quality. In order to undertake land suitability and economic modelling the project team developed collaborations with other groups internally. Key DPI collaborators include Dr Victor Sposito, Spatial Information Sciences (Parkville), Dr Alexandria Sinnet, Policy and Strategy Group (Spring St) and Mr Graeme Thomson, Plant Production Sciences, (Knoxfield).

2.9 Communication Activities

Communication activities undertaken as part of the current project included oral and poster presentations at industry meetings and conferences, displays at field days and workshops and publication of articles in industry journals and newsletters.

2.9.1 Field days

1. Stand at the 59th *Mildura Horticultural Field Days* (25 and 26-May-2010) showcasing climate change research.

2. Stand at the 60th *Mildura Horticultural Field Days* (25 and 25-May-2011) showcasing climate change research.

3. Stand and attendance at the 61st *Mildura Field Days* (29 and 30-May-2012) showcasing climate change research.

2.9.2 Workshops, Seminars, Conferences and other Media

1. Facebook: The project team established a Facebook page as part of the communication strategy for this project. This was the first DPI Facebook page and a pilot for the Department. The page was initially set-up as Climate Change Research for Victorian Horticulture, but was revised to Research at Mildura, which encompasses more than the current project. The page currently has 91 friends, 42 likes and 5 current discussions on recent postings.

2. Newsletter: Downey, M., Brady, S, Unwin, D., and Baker, N. (2011) Understanding the effects of climate change on wine grapes. Murray Valley Winegrowers Association Newsletter. October 2010-January 2011: 6-7. 3.

2.9.3 Posters presentations and abstracts

1. Unwin, D.J., Thomson, G.E. & Downey, M.O. (2010) Impacts of global warming on grape and wine production: Viticulture in a changing climate (Proceedings of the 14th Australian Wine Industry Technical Conference, Adelaide, Australia pp. 287. see Appendix 2.9.7

2.9.4 Industry Articles

1. Downey, MO. (2010) How hot is hot? A Californian perspective. *Australian Viticulture*. 14(6):59-62.

2. Edwards, E.J., Unwin, D.J., Mazza M. & Downey M.O. (in press) Hot and getting hotter – how will a warming climate impact affect warm climate viticulture? *Wine and Viticulture Journal*.

3. Downey, MO & Scafidi, P (submitted) HOT Winegrape Production: Italian lessons, *Wine and Viticulture Journal*.

2.9.5 Peer Reviewed Papers

1. Thompson, G.E. and Downey M.O. (submitted) Adaptation strategies for the South-Eastern Australian wine grape industry in response to global warming, submitted to *Climate Change*.

2. Mollah, M, Unwin, DJ, Edwards, EJ, Mazza, M, Sommer, KJ, Downey, MO & Fitzgerald, G. (in prep) Injection of carbon dioxide inside open-top chambers as a prototype Grapevine Free Air CO_2 Enrichment (GrapeFACE) facility. *Agricultural Forest Meteorology*.

2.9.6 Conference Proceedings

1. Unwin, D.J., Thomson, G.E., and Downey, M.O. (2010) Impacts of global warming on grape and wine production: Viticulture in a changing climate. In: Proceedings of the 14th Australian Wine Industry Technical Conference. 287-288.

2.9.7 Site Visits and media interviews

- *2009-2010*
  - **National Wine and Grape Industry Centre (NWGIC)**
    - Mr. Jason Capello – DPI NSW
    - Mr. Duncan Farquhar – Charles Sturt University
    - Dr. Denis Greer – Charles Sturt University
  - **Wine Innovation Cluster**
    - Dr. Victor Sadras & 2 technical staff – SARDI
    - 15 students – University of Adelaide
  - **GWRDC**
    - Dr. John Harvey
  - **CSIRO**
    - Dr. Everard Edwards
    - Dr. Simon Robinson
    - Dr. Many Walker
    - Mr. Peter Clingeleffer
  - **International**

        * Dr. Hui Chong – E & J Gallo Winery, California, USA
        * Associate Prof. Jim Harbertson – Washington State University, USA
        * Dr. Pietro Scafidi – University of Palermo, Sicily

- *2010-2011*
    - **Victorian Government**
        * Hon. Peter Walsh – Member for Swan Hill, Minister for Agriculture and Food Security, Minister for Water
        * Dr Ron Prestige – Executive Director, Future Farming Systems Research Division, DPI Victoria
    - **Primary Industries Climate Challenge (PICCC)**
        * Prof. Snow Barlow – Melbourne University
        * Dr. Richard Eckard – Melbourne University/DPI Victoria
    - **Industry Groups**
        * Mr. Mike Stone & Mr. Mike de Palma – Murray Valley Winegrape Growers Assoc.
        * Mr. Ross Skinner & Mr Ben Brown – Almond Board of Australia
    - **GWRDC**
        * Dr. Mark Krstic
        * Mr Troy Fischer
    - **International**
        * Dr. Mark Kelm & Dr John Thorngate – Constellation Wines, USA
        * Dr. Mike Cleary, Dr. Robert Sui & Ms Cyd Yonker – E & J Gallo Winery, California, USA
        * Assoc. Prof. Jim Harbertson – Washington State University, USA
        * Dr. Pietro Scafidi – University of Palermo, Sicily

- *2011-2012*
    - **Wine Innovation Cluster**
        * Dr. Sigfredo Fuentes – University of Adelaide
    - **Industry Groups**
        * Barossa Valley Technical Group
        * Mr. Mark Mackenzie – Murray Valley Winegrape Growers Assoc.
    - **International**
        * Dr. Mark Krasnow – Eastern Institute of Technology, Hawkes Bay, NZ
        * Prof. Allan Lakso – Cornell University, New York, USA
        * Assoc. Prof. Jim Harbertson – Washington State University, USA
        * Dr. Pietro Scafidi – University of Palermo, Sicily
        * Dr. Pietro Scaffidi – University of Palermo, Sicily

see attached media portal report in Appendix 2, Att. 10 on page 183 for further details.

Table 2.1: Media Interviews

Year	Type	Organisation and Interviewee
2009–10	**Radio Interview**	ABC Regional Radio – Mark Downey ABC Southwest Radio – Mark Downey ABC Radio Bendigo – Mark Downey
	Newspaper Article	Sunraysia Daily, Mildura – Mark Downey

Appendix 1: Staff

Table 2.2: Research staff working on the proejct

Name	Positon/Role	Dates
Dr Mark Downey	Project supervisor	July 2009 – June 2012
Key Research Staff		
Dr Everard Edwards	Senior Research Scientist	July 2011 – June 2012
Dr Karl Sommer	Senior Research Scientist	July 2011 – June 2012
Nardia Baker	Research Scientist	September 2011 – January 2011
Marica Mazza	Research Scientist	July 2010 – March 2012
Graeme Thomson	Research Scientist	July 2009 – December 2011
Dale Unwin	Research Scientist	July 2009 – June 2012
Scott Brady	Graduate Student	September 2010 – March 2011
Jo Behncke	Casual Technical Assistant	July 2010 – August 2011
Michael Cowling	Casual Technical Assistantt	October 2011 – June 2012

Appendix 2: Attachments

List of attachements

Anonymous (2012). Media Portal Report. Webpage. http://mediaportal.com/. See Att. 10 on page 183

Downey, M. (2010). How hot is hot? A Californian perspective. *Australian Viticulture*, *14*(6), 59–62. See Att. 2 on page 104

Downey, M. & Scafidi, P. (submitted). Hot Winegrape Production: Italian lessons. *Wine and Viticulture Journal*, *submitted*. See Att. 3 on page 106

Edwards, E., Unwin, D., Mazza, M., & Downey, M. (2012). Hot and getting hotter – how will a warming climate affect warm climate viticulture? *Wine and Viticulture Journal*, *in press*. See Att. 9 on page 178

Romeijn, H., Sposito, V., Faggian, R., & Rees, D. (2012). Climate challenges for horticulture in the Sunraysia region. Technical report, Future Farming Systems Research Division, DPI Victoria, Parkville. See Att. 4 on page 111

Sinnet, A. (2012). Climate adaptation options for viticulture in Sunraysia. Technical report, Future Farming Systems Research Division, DPI Victoria, Parkville. A report and presentatioin for GWRDC project DPI 09/01. See Att. 6 on page 161

Sposito, V., Faggian, R., Romeijn, H., & Rees, D. (2012). Climate challenges for horticulture in the Goulburn Broken region. Technical report, Future Farming Systems Research Division, DPI Victoria, Parkville. *submitted*. See Att. 5 on page 130

Thomson, G. & Downey, M. (in preparation). Adaptation strategies for the South-Eastern Australian wine grape industry to global warming. *Climate Change*. in preparation. See Att. 1 on page 91

Unwin, D., Thomson, G., & Downey, M. (2010). Impacts of global warming on grape and wine production: viticulture in a changing climate. In *Proceedings of the 14th Australian Wine Industry Technical Conference, Adelaide, Australia*, (pp. 287). See Att. 7 on page 177

Adaptation strategies for the South-Eastern Australian wine grape industry in response to global warming

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Abstract

Temperature has a key influence on plant growth and development and rising temperatures associated with the enhanced greenhouse effect are likely to have important impacts on the plants that humans grow for food. This review examines some of the implications of elevated temperature on South-Eastern Australia's grapevines which generate important value-added wine exports. Increased warming could cause inconsistent cropping, decreased yields and deleterious changes in berry biochemistry of currently grown varieties. Many of South-Eastern Australia's premium, fine-wine growing areas may become too hot to produce the high quality wines for which they are renowned. Nonetheless, it is anticipated that this threat to wine quality can be at least partly alleviated by deploying adaptive strategies such as shifts to cooler growing locations, a change to varieties that are more heat tolerant and adoption of on-farm practices that help cool and protect the grape crop. Adopting new, heat-tolerant varieties is a practical option that should enable growers to maintain production in current locations. South-Eastern Australian wine producers have already begun investigating varieties from the southern Mediterranean region.

Keywords: *climate change*; *global warming*; *grape*; *temperature*; Vitis vinifera *L.*; *wine*

Introduction

Transitory or constantly high temperatures cause an array of morpho-anatomical, physiological and biochemical changes in plants which affect plant growth and development, and may lead to drastic reductions in economic yield (Wahid *et al.*, 2007). Continued global warming will subject deciduous, perennial wine grapevines to increasing temperatures in existing growing environments. In South-Eastern Australia a hotter climate will impact on the biology of vines and is expected to be detrimental to productivity and wine quality. Excessive heat and lack of winter chill could cause inconsistent cropping, decreased yields and heat injuries to berries.

Climate change has already exerted a profound influence on vine phenology and grape composition and is affecting vinifications, wine microbiology and chemistry (Mira de Orduña 2010). Production of perennial crops in horticulture is a long-term investment and sound decision-making for the future should be based on accurate information that has been scientifically evaluated. Given the long time-scales for growth and production of vineyards, climate change should be an important factor in deciding where and when new vines are planted (Lobell et al. 2006).

By 2030, Victorian annual average temperatures are expected to increase by approximately 0.8℃ (the result of various models indicates a range from 0.6 to 1.2℃) (DSE 2008). By 2070, the average annual temperature could increase by 1.4℃ under a lower emissions growth scenario (0.9 to 2.0℃) or by as much as 2.7℃ under a higher emissions growth scenario (1.8 to 3.8℃) (DSE 2008). At the low end, the impact to Victorian viticulture could be manageable given appropriate adaptation but a 3°C increase would have deleterious implications. This report explores how the viability of wine grape production could be maintained in the future by continuous adaptation through use of new vineyard management strategies, alternative production sites and new heat tolerant varieties.

Vine performance in a changing climate

Premium wine production is limited to regions climatically conducive to growing grapes with balanced composition and varietal typicity (White et al. 2006). Climate exerts the most profound effect on the ability of a region to produce quality grapes and temperature is the most

important climate parameter affecting wine style and quality (Smart 2008). Three temperature related conditions are required: (i) adequate heat accumulation; (ii) low risk of severe frost damage; and (iii) the absence of extreme heat (White et al. 2006). Production of the highest-quality wines requires a delicate balance between these three conditions. Vine phenology is predominantly temperature driven and sensitivity occurs through the interrelated effects of temperature on vegetative and reproductive growth. Timing of key events in the annual cycle of growth and reproduction; photosynthesis, respiration and transport of assimilated carbon; and biochemistry and transport of flavour molecules, all affect wine quality (Jones & Davis 2000, Pearce & Coombe 2004, Anderson et al. 2008). Only recently has improved specificity of the links between weather and red wine quality been quantitatively determined for regions across Australia (Soar et al. 2008).

Grape vine phenology and berry quality and yield are very dependent on climate at a regional, local (mesoclimate: altitude, slope aspect and proximity to water and wind) and microclimate scale (influenced by vine spacing, reflectance of radiation from soil and canopy management) (Gladestones 2004). The wine industry is dependent on unique terroirs that are strongly climate related (Jones et al. 2005, Seguin & de Cortazar 2005). History has shown that the narrow climatic zones suitable for growing wine grapes are especially prone to variations in climate and therefore, long-term climate change (Jones 2009).

The broader physiological responses of vines are likely to be influenced in ways that are reasonably predictable. In future warmer climates, some Australian wine grape growing regions may be adversely affected because the chilling requirement for initiation of certain growth phases may not be met (Webb 2006). With sufficient chilling, budburst will be brought forward into an earlier part of the season but when chilling is inadequate, budburst may be delayed (Webb et al. 2007b). In general, grape growers can expect rising temperatures to shorten the time from budburst to harvest and bring harvest forward. This is problematic because earlier harvests would occur in a warmer part of the season (Mira de Orduña 2010) and this might reduce berry quality through greater loss of volatiles and greater water loss (Anderson et al. 2008).

Wine biochemistry

There is general consensus that additional heat will be detrimental to the quality of wine produced from the cooler-climate, French-origin varieties that make up most production from South-Eastern Australia [i.e. Shiraz (Rhône, South-East France); Cabernet Sauvignon (Bordeaux, South-West France); Chardonnay (Burgundy, Central-East France)]. High temperatures during wine grape production increase the rate of acid degradation resulting in lower natural acidity and higher pH (Swinburn 2003, Smart 2008). Grapes lose malic acid at greater rates as ripening mean temperatures increase. Above about 21°C in the ripening period, grapes tend to develop too low an acid level at ripeness for making naturally balanced wines (Gladstones 1997). Precise ripeness monitoring will become paramount to prevent sugar levels from spiralling upwards to the detriment of acid/phenol balance.

Heat and sunlight increase the sugar levels in grapes through photosynthesis and this can boost alcohol content beyond what is palatable (Smart 2008; Mira de Orduña 2010). When the climate is too hot for a given variety, sugar-ripe, low acid, cooked flavoured fruit are produced. When fermented, these result in a stronger wine which is overly alcoholic. Use of tartaric acid to address the imbalance of acidity caused by hot climates is likely to increase (Anderson et al. 2008).

With hotter weather, grapes mature earlier, do not have time to develop biochemical complexity and are less likely to impart subtle complexities of flavour to wine. Earlier sugar ripeness, coupled to increased acid loss through respiration, may contribute to increasingly unbalanced wines (Webb et al. 2007b). Many wines will lose varietal flavours and typicity (Smart 2008) with modification of varietal aroma compounds (Mira de Orduña 2010).

Some red wines may lose colour (Smart 2008) because high temperatures during grape production affect the metabolism of anthocyanins (Downey et al. 2006). Temperature is more important than light for anthocyanin development (Downey et al. 2006). Trials with Merlot have elucidated the direct effect of temperature on rate of fruit development and phenolic metabolism (Cohen et al. 2008). Spayd et al. (2002) demonstrated that excessive absolute temperatures (number of hours above 35°C) reduced Merlot berry colour. Cabernet Sauvignon

berry colour levels were higher at 20°C than 30°C (Buttrose et al. 1971) and Haselgrove et al. (2000) also established that high temperatures are not conducive to anthocyanin production in Shiraz grapes.

Economic and production impacts

Climate warming is likely to reduce overall productivity and lower wine quality from vineyards in South-Eastern Australia, with excessive heat in existing growing locations creating sub-optimal conditions for existing, popular French-origin varieties. Projections for the future suggest that the area for cool variety grape growing in Australia could be severely reduced if the overall quality of grapes is to remain equivalent to that of the present day (Webb et al. 2007a). In a high-warming scenario, land suitable for grape growing might be cut by 10% by 2030. However, by 2050, Australia's suitable area for cool variety viticulture is likely to be reduced by 27% (mid greenhouse warming) to 44% (high greenhouse warming) (Webb 2006, Webb et al. 2008).

Modelling the effect of temperature increase shows that grape quality (grape price paid at the weighbridge) could be reduced in some Australian regions by 7 to 23% by 2030 and 12 to 57% by 2050 (Webb 2006). Gross returns at a national level are estimated to decrease between 4.5% and 16% by 2030 and by up to 52% by 2050 if no adaptive strategies are implemented (Webb 2006).

Modelling shows a likely reduction in suitable Australian growing areas for Shiraz of between 15 and 25% by 2050 (Webb et al. 2008). Production of Chardonnay might be maintained in most regions with higher projected temperatures but quality will be heavily impacted. Projections suggest a reduction in suitable growing areas for Chardonnay of between 40 and 60% by 2050 (Webb et al. 2008). Cabernet Sauvignon has become established in Australia's medium-to-cool regions but can grow in regions with hot climates (Jones 2007).

Impact will be variable through the region. With climate warming, some areas presently considered too cool for grape growing could potentially become available for viticulture if reliable water supplies can be secured (Webb et al. 2007c). Ripening of one or two current varieties may be enhanced in the coolest growing parts of South-Eastern Australia (e.g. Tasmania).

So that the timing of adaptive changes can be planned, vineyard managers are keen to know at what point in the future significant quality loss might occur from French-origin varieties. The South Australian Research and Development Institute and Victorian Department of Primary Industries have research trials underway to evaluate possible future impacts on existing varieties in current Australian wine production regions. The work investigates air temperature increase under open-field conditions using mature vines in chambers. In the South Australian study, field heating was used to increase maximum temperature by 2-4°C during 2 to 3 week phenological windows from budburst to a few days before harvest. None of the treatments affected yield or yield components of irrigated Shiraz. Irrigated Shiraz under typical Barossa conditions also maintained berry anthocyanins at harvest in response to discrete episodes of high temperature during ripening (Sadras et al. 2009). Determining the exact temperature limits that our popular varieties can endure while still maintaining productivity and quality will take many years. Such long-term studies, ideally conducted in conjunction with elevated carbon dioxide, are critical to enable development of future mitigation strategies and to test varietal suitability in a changing climate (Keller 2010).

Adaptation strategies

The capacity of South-Eastern Australia's wine industry to adapt to climate change will depend on the magnitude of temperature increase over time. Historically, Australia's agricultural sector has adjusted and adapted continuously to changes in the natural resource base, including climate variability. The adaptive capacity of Australian producers is generally high, as they have historically had to cope with a highly variable climate (Steffen et al. 2010). Such adaptation has been achieved predominantly through productivity improvements brought about by technological changes (Gunasekera et al. 2007). Farming in Australia is highly decentralised, technologically well-supported, market-responsive and routinely deals with variability on a variety of time-scales arising from climatic, biological and market factors (IPCC 1997). Adjusting production systems to a changing climate will not be without cost and will

require systematic awareness raising and information dissemination. However, climate change may be a slower influence than continuous changes arising from markets, prices and technology (Stafford Smith et al. 1994).

It is likely that the wine industry will have to adapt to climate change to maintain productivity and quality. Many potential adaptation options already exist but their widespread adoption will require further research under local conditions. An understanding of how and why certain practices work where they do is needed to facilitate site-appropriate adaptation and adoption of response strategies (Cahill 2009).

As a minimum response, perseverance with existing French-origin varieties in our hotter climate will require changes in vineyard practices to assist in cooling the fruit. However, beyond a critical temperature increase these varieties might only remain viable in South-Eastern Australia with relocation to cooler production areas. High temperature increases could also drive the need to change to new heat-tolerant varieties if production in existing geographic zones remains an economic and logistical necessity. Nonetheless, even heat-tolerant varieties are likely to benefit from on-farm management changes that help to cool grapes.

Vineyard design and management

Within Australia's established wine-producing regions, vineyard management options to ameliorate the impact of hot conditions will help reduce negative impacts on wine quality and may enable the ongoing successful practice of viticulture (Webb et al. 2007a). Changes in vineyard practices will be essential to maintain production and quality from French-origin varieties.

Root zone watering

Heat-wave conditions in Victoria during summer 2008–09 demonstrated that adequate water application was critical in reducing heat stress to grapevines (Webb et al. 2009). In late January 2009, maximum temperatures reached their highest levels since at least 1939 and in early February, record high temperatures were set for over 87% of the state (Webb et al. 2009). Watering root zones to full capacity prior to heat-wave events and then maintaining high moisture status through the hot weather period, were the main strategies employed to minimise damage. Compared to own-rooted vines, plants grafted to drought-tolerant rootstocks tended to perform better as these typically had more extensive root systems and could potentially transport the large volumes of water required to hydrate and cool the canopy (Webb et al. 2009).

Floor management

Vineyard floor management should utilise mulches or cover crops to reduce soil temperatures. Under-vine mulch reduces soil heating, reflection from the soil and limits some heat build up in the canopy. During the heat-wave conditions over summer 2009 in South-Eastern Australia, there was evidence of radiation from heated soil affecting berries positioned lower in canopies when inter-rows were bare (Webb et al. 2009). Under-vine mulch and inter-row swards or cover crops reduce this impact. However, maintaining a green cover crop throughout the growing season in dry regions could require installation of additional irrigation hardware and cover crops can compete with grapevines for water and nutrients (Keller 2010).

Row orientation

No vineyard decision is more permanent and costly to modify than row direction. In the heat-wave conditions over South-Eastern Australia in January - February 2009, one obvious trend in the amount of damage reported was variation with different row orientation and aspect of the canopy. Rows orientated North-South were more adversely affected than rows planted East-West (Webb et al. 2009). Local surveys showed that in East-West oriented rows there was either no difference between sides or the North side had more damage; the western aspect of North-South rows was more affected than the eastern (Webb et al. 2009). Spayd et al. (2002) found that Merlot berry temperatures on exposed West-facing fruit were higher than on the East due to heat accumulation, and colour in West-side bunches was lower due to degradation of anthocyanin and inhibition of anthocyanin synthesis. Webb et al. (2009) suggest that in vineyards with East-West oriented rows, berries typically receive little direct radiant energy because the sun passes over the top of the canopy and does not shine directly on the canopy sides. In contrast, where rows are North-South oriented the West aspect

receives direct radiant energy during the hot afternoon period. The combination of additional radiant energy on already heated berries results in higher heat-loads, greater susceptibility to damage and higher potential losses (Webb et al. 2009).

Canopies

For years, winemakers all over the world have encouraged exposure of red grape clusters to sunlight which encourages the fruit to develop protective polyphenols that contribute to colour and flavour (Price et al. 1995, Haselgrove et al. 2000, Downey et al. 2004). In South-Eastern Australia, vineyard management practices are also typically geared to exposing fruit in order to minimise disease pressure, i.e. the opposite strategy to managing for extreme heat. Encouraging good canopy growth and creating shade for potentially exposed berries is important in reducing heat damage (Bergqvist et al. 2001; Webb et al. 2009). Vineyards with good irrigation throughout the season grow vines with large canopy structures that minimise losses due to summer heat. In contrast, with extended tight watering regimes, vines develop smaller canopies with more exposed grapes that are susceptible in extreme conditions.

Vineyards in Europe have been amongst the first to respond to climate change and shading to avoid the detrimental effects of excessive sunlight exposure is now considered necessary for many varieties. In some vineyards in hotter areas near the Mediterranean, adaptation has included changing to canopies and trellis systems that provide grapes with better shade. Some growers are returning to old style, over-head pergolas that keep bunches in the shade, although they can be more difficult to harvest and are not suited to current mechanisation technologies. To help screen berries from intense heat in southern Europe growers are also experimenting with ending the practice of basal leaf removal. Even in cooler regions such as Germany, protection of grapes by foliage is of importance in guarding against sun damage (During 2005).

Working with Cabernet Sauvignon and Grenache in California, Bergqvist et al. (2001) observed that the temperature of fully exposed berries was 9 to 10^{o}C higher than shaded fruit. High temperature exposure over the ripening period caused a marked difference in berry composition. Fruit colour on the shaded side of the canopy had a linear increase with

exposure whereas colour of exposed bunches decreased due to effects of high temperature accumulation. Phenolics were also lower in exposed fruit (Bergqvist et al. 2001). The mechanism for promotion of red colour development relies on a heating effect from light exposure but at some critical point over-heating decreases fruit colour (Downey et al. 2006). Downey et al. (2005) used temperature data from loggers in canopies to calculate heat summation units (Gladstones 1997) from flowering to harvest (120 days). Consideration of the heat summation data and anthocyanin levels in Shiraz fruit suggested that there is a critical temperature level between 1,300-1,400 heat units above which anthocyanin accumulation ceases or degradation of anthocyanins occurs (Downey et al. 2005).

During the summer 2009 heat-wave, some Victorian growers modified their pruning, trellising and/or training to increase shading of fruit. Foliage wires were used to modify the canopy and provide shade on the West side of North-South rows. Measures were taken to ensure that the canopy did not roll on the cordon wire and the canopy was encouraged to splay and provide more shade by not using some foliage wires (Whiting, J., pers. comm., 2009). A 'lazy-lift' fruiting wire on the West side of North-South oriented rows ensured that the leaf-canopy protected the fruit-zone from direct radiation. Similarly, preventing downward rolling of the canopy, by appropriate positioning of foliage wires, assisted in reducing fruit exposure with some trellis designs (Webb et al. 2009). Vertical shoot positioned vines and the bi-lateral single cordon were associated with higher levels of damage and loss during heat-wave conditions (Webb et al. 2009). 'Sprawl' systems without shoot positioning can offer better shading to avoid sun-exposed fruit (Keller 2010). They are cheaper to construct and often only one wire is required to support the permanent cordon, sometimes with the addition of one pair of 'foliage' wires to prevent excessive wind damage (Keller 2010).

Water cooling

Evaporative cooling with overhead water sprinklers has been used for decades to cool horticultural plants (Andrews & Johnson 1996), however, for perennial fruit crops its widespread use is a relatively recent practice (Evans & Van der Gulik 2011). Overhead watering for canopy and fruit cooling is rarely practiced for wine grapevines grown in South-Eastern Australia. The table grape industry in North-West Victoria used overhead sprinklers for cooling during the 2009 summer heat-wave and grower reports suggest that cooled plants

experienced fewer deleterious effects of the heat. A few years earlier, Smart (2005) reported that wine grape growers in the same area were using sprinkler irrigation intermittently during the hottest part of the afternoon and into the early evening, with early adopters claiming encouraging results.

Any cooling technique must counteract the effects of direct solar radiation which is the principal source of heat load raising the temperature of exposed grapes. Water-based cooling systems make use of one or more of either convective cooling, hydro-cooling or evaporative cooling, however, evaporation of water from the surface of crops is the most effective (Evans 1999, Evans & Van der Gulik 2011). Evaporative cooling directly extracts heat by sensible-to-latent heat transfer and uses less water, but rates of evaporation depend on radiation, wind, temperature and humidity. Low humidity and windy conditions tend to facilitate evaporative cooling (Evans 1999). Once fruit or leaf surfaces are dry, evaporation is no longer a source of cooling and surface temperatures can rapidly increase and result in heat damage. Also, overhead irrigation is effective only at the actual time of risk during critically high temperatures; it confers no advantage before or after the event. And, while overhead evaporative cooling is the most effective means of decreasing fruit surface temperature, evaporative cooling does not filter out damaging ultra-violet rays.

Unfortunately, evaporative cooling activities can potentially impact negatively on several areas of crop management (Evans 2004). Evaporative cooling of vineyards uses a lot of water (Smart 2008) and water availability and price could be major barriers to adoption. Smart (2005) suggests that over-vine sprinkler use nearly doubles irrigation costs and water requirements (since it is in addition to drip irrigation). Given that most Australian vineyards currently use either drip irrigation or under canopy sprinklers, the capital expense of installing an additional overhead system for cooling could be prohibitive. The cooling process can also wash off beneficial foliar sprays and herbicides on weed cover. Disease risk, especially botrytis and downy mildew, can be elevated due to higher humidity surrounding leaves and fruit (Gilbert et al. 1971, Swinburn 2003, Magarey 2010). Water suitable for sprinkler cooling must be low in salt otherwise accumulated mineral deposits cause leaf and fruit burn (Evans 1999, Evans & Van der Gulik 2011). Kliewer and Schultz (1973) found that water suitable for sprinkler cooling

of wine grapevines must be less than 750 EC. Gilbert et al. (1971) also noted possible delays in sugar accumulation in sprinkler cooled canopies.

Most literature outlining water-cooling of grapevines tends to focus on temperature reduction of the canopy rather than direct impacts on berries. Kliewer and Schultz (1973) found that when air temperatures were 38°C or more, moist grapevine leaves were cooler than unsprinkled leaves by 17 to 22°C. When air temperatures were 32 to 38°C, moist leaves were 11 to 17°C lower. If air temperatures were 30 to 32°C, moist leaves were less than 11°C lower (Kliewer & Schultz 1973). In related work, Gilbert et al. (1971) examined the effect of sprinkler cooling on Tokay vines. Sprinklers were activated when air temperatures exceeded 32°C and operated for three minutes on and fifteen minutes off. They found that plant temperatures were reduced by 8.3 to 14°C (down from around 40°C). Positive benefits included an increase in yield through lack of fruit dehydration and fruit acid was higher (Gilbert et al. 1971).

Netting

Netting is deployed over perennial horticultural crops for protection from hail, wind, frost, pests and/or high intensity sunlight. Few Australian wine grape producers currently use netting for the purpose of shading berries. Where there is a requirement for shading in other perennial crops (e.g. pome fruit), hail netting is typically favored. Netting is used successfully in apple orchards worldwide to prevent sunburn and heat damage (Dussi et al. 2005, Iglesias & Alegre 2006, Amarante et al. 2009). Over-tree netting reduces fruit warming by direct screening from infra-red radiation exposure and also protects from the damaging effects of high ultra-violet B light levels.

Overhead netting changes the microclimate around plants by decreasing light, restricting airflow, reducing wind speed and increasing humidity. The extent of microclimate modification depends on type and colour of the net as well as design of the structural framework, e.g. presence or absence of sidewalls. Changes to microclimate are greater when nets with small mesh size are deployed (e.g. 12 mm hail net) as compared to large size (e.g. 37 mm mesh flying fox exclusion net) (Rigden 2008). More light is intercepted by heavier, stronger nets (i.e. heavier stitch density, thicker fibres) and they have a greater impact on the under-net

microclimate (Rigden 2008). Solomakhin & Blanke (2010) found that hail-nets reduced photosynthetically active radiation by 12 to 23% and ultra-violet by 20 to 28%. While netting reduces the sunburn effects of high ultra-violet periods, ultra-violet variances essentially remain independent of broader climate change issues. Since the mid-1990's, clear-sky ultra-violet light levels in unpolluted environments have been approximately constant, which is consistent with ozone column observations over this period (WMO 2011).

There is conflicting information as to whether air temperatures under netting are increased (Ebert & Casierra 2000, Rigden 2008, Lloyd et al. 2005) or decreased (Iglesias & Alegre 2006, Solomakhin & Blanke 2010) around perennial crops. Effects on air temperature tend to be in the range of a degree or two and less important than the primary role of blocking incoming infra-red radiation and reducing fruit surface temperatures. Gindaba & Wand (2005) observed that netted apples were up to 10°C cooler, while Solomakhin & Blanke (2010) noted a potential 6°C decrease.

Higher humidity and less airflow under netting could increase the risk of fungal infections but in dryer regions like North-West Victoria this will probably not be a problem. Changing the amount and quality of light that reaches grapes can potentially influence biochemistry, colour, wine quality and yield. Reduced light levels under netting could impact negatively on berry colour development and rates of photosynthesis, and therefore potential productivity. The effects are likely to vary regionally and in North-West Victoria, where light is not a limiting factor, a reduction in light through net use may not be a problem. Other drawbacks with shade netting include the need to rapidly attain and maintain high yields to recoup the cost of the netting and support structures.

Sunscreen sprays

Spray-on sunscreen products applied to leaves and fruit act as a physical barrier to reduce temperatures and water stress. The calcined kaolin product Surround®WP is used for apples, citrus and other crops and is perhaps the best known horticultural sunscreen. Kaolins are near-white clay minerals. Specially engineered kaolin particles in the Surround®WP formulation link together into a loose particle film network. In the Australian wine grape

industry there are concerns about Surround®WP remaining on grape berries after harvest and in the crush (Swinburn 2003). Most other types of harvested fruits (e.g. apples) are washed in packing-sheds to remove kaolin. Nonetheless, Clingeleffer et al. (2006) applied Surround®WP to reduce leaf temperature and minimise stresses associated with hot weather and water deficits on own-rooted Cabernet Sauvignon vines grown in South-Eastern Australia. Kaolin lowered leaf temperature and reduced the impact of soil moisture deficits on leaf physiology but did not impact on yield, berry weight or pH of berry juice at harvest (Cooley et al. 2008). However, kaolin did increase berry juice organic acid concentrations (tartaric, malic and citric acid) and elevated sucrose and glucose concentrations. Cahill (2009) reports that wine grape growers in California (USA) do spray a kaolin clay compound to act as a sunscreen.

Chemical dormancy breakers

Most deciduous plants have a low temperature or chilling requirement for initiation of different growth phases. Use of chemical sprays to overcome dormancy is widespread in warm-climate countries, and glasshouse cropping systems, that grow temperate fruit. Global warming has brought about increased use of dormancy breakers in temperate countries (Erez et al. 2008). Use of chemical dormancy breakers with wine grapes may be needed in Australian regions where chilling accumulation will no longer be met (Webb et al. 2007b). Dormex® [Hydrogen cyanamide (H_2CN_2)] is registered in all Australian states as a plant growth regulator suitable for wine grapes. In the Northern Territory, Dormex® (5% v/v) has been successfully used with table grapevines to reduce low chill effects. One of the factors determining the vines' response in terms of early, even budburst is how effectively the chemical is applied (Kenna et al. 2000). Duomax HC520® and Cyan™ are also registered in Australian states for grapevine bud break. To date, deployment of chemical dormancy breakers in the wine industry has been limited.

Relocation

Warmer conditions globally could lead to poleward locations becoming increasingly conducive to grape growing and wine production (Jones et al. 2005). Models suggest a need for overall southward and altitudinal shifting of viticulture to maintain production and quality in South-Eastern Australia. A southward shift of 40 km by 2030 and 65 to 115 km by 2050 could maintain gross returns (Webb 2006). Within Victoria, potential shifts for current varieties are

likely to be to coastal areas of the South-West and South-East or to higher altitudes in the Great Dividing Range highlands (Anderson et al. 2008, Webb et al. 2007c). Future warming could see Tasmania's South-East become better suited to existing varieties (Webb et al. 2007c).

Although an adaptation option, moving production to cooler regions would require substantial investment and could be limited by non-climatic constraints (Lobell et al. 2006). Apart from the direct expense associated with re-building vineyards and wineries, other drawbacks include possible restrictions on new land availability, competition from alternative land uses, restrictions on water/irrigation availability, lack of transport infrastructure, difficulties in attracting labour, and the unknown long-term performance of new sites.

Geographic moves to cooler regions could allow growers to continue using the vine varieties they currently grow and alleviate the need to find and evaluate alternative heat tolerant varieties, but moving location might also be necessary if impacts of climate change exceed all achievable adaptive capacities at existing, traditional grape-growing locations.

Heat tolerant varieties

The south-eastern Australian wine industry may choose to remain at current locations and change to varieties better adapted to hotter climates. To alleviate climate impact, Smart (2008) suggests that a change of varieties is an easier option than moving to new growing regions. Shifts in the variety profile of different regions and the possible emergence of hitherto unsuitable, lesser known, or even novel, varieties can be expected over coming decades (Keller 2010). Currently, Australia's principal wine grape varieties have their origins in France and at best can only be considered suitable for warm rather than hot climates (Jones 2006, Anderson et al. 2008). New varieties will be needed for existing hot Australian regions (Smart 2008). Smart (2005) has nominated 22 red and white varieties worth considering for hotter climates. Grapevines have been successfully grown in hot climates of the southern Mediterranean and North Africa for centuries and these heat-adapted varieties which are not widely grown in Australia may be suitable for our increasingly hot production areas. Varieties sourced from Crete, Sicily, Spain, Portugal, Cyprus and North Africa are adapted to hot, dry

conditions. There is potentially an abundance of material to evaluate.

Adoption of varieties better suited to hotter (and possibly dryer) conditions will help assure the industry's future but new grape varieties must still ripen with both good flavour and acidity. Alternative varieties are likely to offer flavour options similar to those that currently meet consumer demand. In the vineyard, varieties can be changed in a time-span of five years. However, the time required for building expertise in viticultural management and wine-making, and in developing markets for new varieties, is likely to be between 20 and 30 years (Anderson et al. 2008).

Current varietal evaluation in Australia

A small number of south-eastern Australian nurseries have been importing and propagating alternative wine grape varieties for the past decade and they are now in a position to evaluate performance. Focus has been on plants that can produce high quality fruit in warmer, dryer climates and a number of varieties have met expectations (Chalmers 2009). Standout white varieties are Vermentino and Fiano, natives of Sardinia and Avellino (Italy). Vermentino is grown without irrigation in Sardinia. In the nine years that Fiano has been evaluated in New South Wales (South-Eastern Australia), heat stress to the fruit and foliage has not been evident (Chalmers 2009). Fiano and Vermentino are also later ripening varieties which should be better able to tolerate the problems of advanced vintage date and higher temperatures in the last month of ripening.

The red Italian varieties Negro Amaro and Sagrantino also performed well in the hot and dry conditions of south-eastern Australian trials (Chalmers 2009). Sagrantino fruit survived heat-waves that caused damage to many other varieties. Additional red varieties that were deemed potentially tolerant of harsh growing conditions were Aglianico and Lambrusco Maestri.

South Australian Vine Improvements Inc. has invested in around 100 selections of alternative grapes and these are currently being established. Included are an extensive number of Spanish and Portugese varieties with new clones of Albariño, Tempranillo and

Graciano, as well as lesser known Arinto, Macabeo and Verdejo, all selected for their suitability to hot climate viticulture (Chalmers 2009).

It could be necessary to start afresh and breed new varieties suited to the hotter conditions brought about by global warming (Louime et al. 2007, Smart 2008). Keller (2010) suggests it may be time to develop genetically modified varieties that will cope with warmer temperature, higher carbon dioxide concentrations and less water of higher salinity, and still be capable of producing high quality fruit.

Recent years have seen increased use of currently available drought-tolerant rootstocks but breeding new, improved rootstocks that are able to provide good fruit with lower water requirements may be necessary. In South-Eastern Australia's summer heatwave of 2009, vines grafted to drought-tolerant rootstocks tended to perform better than drought-sensitive rootstocks or own-rooted vines. Webb et al. (2009) report that 1103 Paulsen, 110 Richter, 140 Ruggeri and Ramsey performed well while Schwarzmann and 101-14 suffered badly. Sommer et al. (2010) also found that Sultana vines grafted to 101-14 and Schwarzmann rootstocks performed poorly during drought conditions and sometimes did not recover after re-watering. Conversely, Sultana on rootstocks Lider 116-60 and Lider 187-24 performed well with potential for high resilience during drought and good recovery following a return to normal watering.

Future projections and research recommendations for South-Eastern Australia

Future projections for adaptation to climate change will depend on the success of mitigation strategies in reducing greenhouse gas emissions. Assuming the A1FI emissions scenario (IPCC 2007), the following strategies for future time-frames are recommended.

2010 to 2015

- Gather empirical data on effect of high temperatures and water shortages on current varieties under field conditions.
- Assess yield and quality responses to future climate to assist in prioritisation of adaptation strategies.
- Evaluate canopy management practices including pruning systems, netting, sunscreens and hydro-cooling to mitigate impact of increased temperature.

- Continue identification of potential cooler growing areas on local scales for current varieties and determine the cost-benefit of relocation options.
- Evaluate heat (and drought) tolerant varieties.
- Assess fertilizing effect of higher atmospheric carbon dioxide levels.

2016 to 2030

- Adopt short-term pragmatic management strategies to reduce the impact of heat on production and quality, especially in the hottest regions.
- On-going evaluation of irrigation strategies to reduce impact of heat and maximise water use efficiency.
- No new plantings of existing French-origin varieties in hottest production regions.
- New plantings of existing varieties largely restricted to cooler climate regions or sites with higher altitude.
- Evaluate performance of new heat and drought tolerant varieties for new plantings in hottest regions.

2031 to 2080

- Adaptation strategies developed and implemented for more frequent extended drought periods.
- New plantings restricted to varieties adapted to hotter conditions for all production regions.

2080 onwards

- Viticulture industry may contract substantially in the face of competition from food crops.
- Probable food shortages and starvation more important then global warming impact on wine production (Smart 2008).

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In the spirit of leaving no stone unturned, Mark Downey has been looking at production techniques in hot grape and wine-producing regions around the world. In this issue, Mark reports on a study tour of California he undertook in 2009. In future issues, he will report on his upcoming visit to the western Mediterranean, with a visit to the Middle East planned for 2011.

How hot is hot? A Californian perspective

By Mark Downey[1]

The challenges of growing winegrapes in hot production areas are well recognised in regions both within Australia and internationally. A joint project between the Grape and Wine Research and Development Corporation (GWRDC) and the Victorian Department of Primary Industries (DPI Vic) is looking to see what the Australian wine industry might learn from those areas.

In California, in the US, there are a number of growing regions warmer than the major production areas in Australia. The project team asked Californian growers the following questions: How were regions defined as being hot?; What regions were considered hot?; What strategies were employed to mitigate temperature or manage vines under high temperature?; What grape varieties were grown in these hot regions?

Californian grape production extends from the Coachella Valley in the south of the state towards the Mexican border, in the Temecula Valley south of Los Angeles, throughout the Central Valley of California, and along the northern coastal hills, through Napa Valley to Mendocino County (Figure 1). The hot regions in California are mainly considered to be the Coachella Valley (e.g., Palm Springs) and Central Valley, from Bakersfield to Stockton.

As can be seen in the temperature graphs of Figure 2 (see page 60), the average daily maximum at the height of summer in all of the production areas is quite a bit higher than it is in the hot production areas in Australia, such as Mildura (Figure 2a). Bakersfield and Palm Springs also have higher daily minimum temperatures (Figure 2b), so it would be reasonable to expect that if there were readily adaptable strategies for managing high temperature in vineyards, these regions might be the best place to start looking.



Figure 1. Map of California showing the Sacramento-San-Joaquin River delta and major cities, Central Valley, Temecula Valley, Coachella Valley, Napa Valley and other wine-producing region.

Temecula Valley

The Temecula Valley is about two hours drive south of Los Angeles and is a region that thrives on wine tourism. The region has experienced rapid growth since 2005, expanding from eight to 35 wineries. While warm, the Temecula Valley is not generally considered to be hot, as it frequently experiences cooling maritime breezes in the afternoon. However, it also experiences hot Santa Anna winds, which can take temperatures well above 100°F (37.8°C). The region is an ancient drainage basin of heavily dissected ridges of coarse granitic sand and fine gravel, which have been widely landscaped (by bulldozer) to ease vineyard management and for aesthetic reasons. This has resulted in a range of fertility issues with the removal of top-soil from hillocks and considerable effort has been devoted to increasing soil organic matter using green waste. In conversation with producers such as Michael Rennie, from Leonesse Cellars, and Carmen Gispert, University of California Cooperative Extension (UCCE) specialist (Figure 3, see page 68), heat is not the major concern in the region. The biggest issue for Temecula Valley producers, apart from decreased fertility in landscaped vineyards, is Pierce's disease.

Pierce's disease is caused by a pathogenic bacteria transmitted by an insect vector, the glassy-winged sharpshooter. The bacteria affects vines, citrus and oleander and considerable effort is expended on eradicating the insect and potential host plants, such as native (Muscadine) vines that are resistant to the pathogen. Native vines are widely dispersed from historical plantings or have been planted as ornamentals.

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State Government Victoria Department of Primary Industries

Grape Phylloxera Workshops January 2011

The Department of Primary Industries (DPI) works in partnership with the community to manage Victoria's land, water and living resources.
Grape phylloxera is described as the world's worse grapevine pest. Grape Phylloxera Identification and Management Workshops are designed to minimise the impact of this insect on the Australian grape growing industry.
Grape phylloxera awareness, quarantine procedures, early identification and management options are essential skills for vineyard managers and staff, winemakers, contractors, consultants, viticulture students quarantine officers and researchers.

The one-day accredited workshop provides the opportunity to gain grape phylloxera identification and management skills during information and practical based sessions, covering:

Biology and distribution of phylloxera in Australia
Identifying phylloxera symptoms in vineyards
Phylloxera detection techniques
Rootstock selection
Quarantine protocols
Risk management
Guest speaker/viticulturist with phylloxera management experience
Current, leading edge phylloxera research in Australia.

Location & Dates: Northeast Victoria January 2011
Cost: $100 (incl. GST) Student discounts apply.
Lunch and refreshments included.
Numbers will be restricted to 30 people, so book early to ensure your place.

For further information and bookings contact:
Ginger Korosi, Department of Primary Industries, RMB 1145 Chiltern Valley Rd, Rutherglen, VIC 3685, Telephone: (02) 6030 4500, Facsimile: (02) 6030 4600, or via email at ginger.korosi@dpi.vic.gov.au

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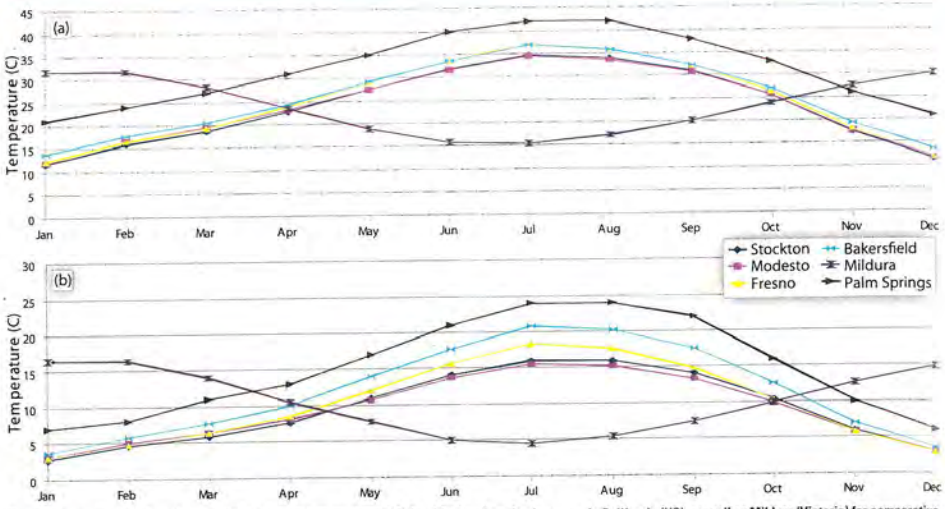


Figure 2. Average daily (a) maximum and (b) minimum temperatures (°C) for viticultural production areas in California (US), as well as Mildura (Victoria) for comparative purposes.



Figure 3. Michael Rennie (left), of Leonesse Cellars, in the Temecula Valley, California, Carmen Gispert (right), of the University of California Cooperative Extension (UCCE) service, in the Leonesse Cellars vineyards, and her sister.

Coachella Valley

The Coachella Valley lies to the east of the Temecula region, beyond the Santa Rosa Mountains and extends from Palm Springs to the Salton Sea. There is considerable horticultural production in the region, including citrus, dates and viticulture (Figure 4). While a major feature of the Coachella Valley is the Salton Sea, its position below sea level makes it highly saline and irrigation is sourced by open channel (All-American Canal) from Lake Mead on the Colorado River (Hoover Dam).

Viticultural production in the Coachella Valley is almost exclusively tablegrape production, with some dried grapes and a couple of minor lifestyle winemaking efforts. When questioned why there wasn't more winegrape production in the Coachella Valley, large producers in the Central Valley initially responded that it was because of high temperature, although further discussion revealed that the distance from the major winemaking infrastructure was the greatest obstacle.

Central Valley

The Central Valley of California extends from just above Los Angeles in the south, almost to the Oregon border in the north, with viticultural production scattered throughout the valley. The largest production areas are in the southern part of the valley, between Stockton and Bakersfield. Throughout the area, plantings are primarily Syrah (Shiraz), Cabernet Sauvignon, Cabernet Franc, Merlot, Zinfandel, Chardonnay, Sultana, French Colombard, Rubired and Ruby Cabernet, with Pinot Noir, Pinot Gris, Petite Sirah (Durif), Chenin Blanc, and Muscat of Alexandria (Gordo) planted less widely. Pinot Noir and Pinot Gris tend not to be planted as far south as Bakersfield, as growers perceive that these varieties don't handle the heat well. However, it was generally conceded that this really meant that Oregon Pinot Noir could not be made from Central Valley-grown grapes. Riesling and Sauvignon Blanc tended to be grown towards the north, from Stockton onwards and around Napa, Sonoma and Russian River, but not so much in the Central Valley.

Producers and extension specialists across the Central Valley generally considered hot production areas to be anywhere south of Modesto, for example, Fresno and Bakersfield.

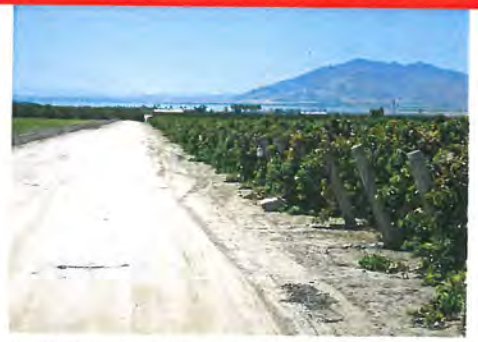


Figure 4. Viticulture in the Coachella Valley of California, looking towards the Salton Sea.



Figure 5. Recharging an irrigation reservoir in the Bakersfield region of the Central Valley of California.

The criteria was regular daily temperatures of more than 105°F (40.5°C) with limited night time cooling i.e., night time temperatures more than 70°F (21.1°C). Around Stockton and Lodi, there is a strong cooling effect as afternoon sea breezes flow through the San Francisco bay area and Sacramento-San Joaquin River delta (Figure 1).

Irrigation and pest management

Growers and vineyard managers generally thought that vine damage occurred at more than 100°F (37.8°C). Some said damage did not occur until 110°F (43.3°C), while others thought it was only when there had been temperatures of more than 100°F (37.8°C) for two or more weeks straight. This reflects different experiences, and probably different irrigation strategies, in response to heat. What was clear, however, was that no real data exists on what the threshold temperature is for vine damage. The current DPI Victoria project seeks to explore this question in more detail.

The main response to high temperature is to increase irrigation (Figure 5). During the height of summer in hot regions, especially around Fresno and Bakersfield, it would be uncommon to enter a vineyard during the day and find the drip system not operating. Almost all plantings (85-90%) are on drip irrigation, although there remain some producers using flood or furrow irrigation and a few on micro-jets and overheads. Drip lines were commonly about 30cm above the soil and, in many cases, a second drip line had been added to increase overall water output or to manage low vigour parts of the vineyard.

While some growers talked of using tensiometers, gypsum blocks and pressure bombs to monitor water status and watering to 100% of ET_o (evapotranspiration), in practise, most simply turned on the tap when it was hot and turned it off when it cooled down or when they thought they had watered enough. There were few restrictions on water allocations. The price of additional water ranged from US$30 per acre-foot (approximately 1.23 megalitres) in the Coachella Valley, to US$400/acre-foot in Temecula Valley. In the Central Valley, the price was US$200-300/acre-foot.





Figure 6. Paul Verdegall, of the University of California Cooperative (UCCE), beside a recently planted variety trial in the Lodi-Stockton region of California.

In the southern part of the Central Valley, there was little regard for deficit irrigation amongst growers. While wineries recognised the advantages of lower yields and the impacts of decreased vine vigour on colour, growers were generally not being paid bonuses. As a result, most growers were looking to produce from 10-12t/ac, or up to 20-25t/ac for some varieties, while the wineries were setting targets of 6-8t/ac. The majority of the production in these hotter regions sold for less than US$10/bottle, with a lot of production directed towards jug wine (flagons) or cask wine.

Against a background of very large growers and wineries, there was a scattering of small producers, some lifestyle-based and some older family wineries that were focussing on producing higher quality, low volume wines. While these tended to be concentrated around Lodi and Stockton, there were examples throughout the Central Valley.

Other concessions to temperature were not to spray sulfur when temperatures exceeded 100°F (37.8°C) because of the risk of tip burn, and not to disc weeds when temperatures were more than 100°F as growers recognised that this increased evaporative water loss from the soil.

Changes in trellis design

There has also been a shift in trellis design. Much of the Central Valley is planted on a single wire, known locally as the California Sprawl, or on a two-wire vertical trellis. However, many vineyards have been planted to VSP trellis or variations of the Scott-Henry trellis. Recognising the deleterious heat effects, particularly on the western side of north-south oriented rows, there has been a trend away from trellises that increase bunch exposure.

Choices in plantings of varieties

In managing rising temperatures, alternate varieties are often suggested. In California, while there are considerable plantings of new varieties, these are not generally driven by temperature considerations.

The biggest increase in plantings in recent years has been in Pinot Gris, driven by consumer demand for a light wine style as an alternative to Chardonnay. For the same reason, there are also plantings of Marsanne, Roussanne and Viognier. Nero d'Avela has been discussed as an alternative variety, but there are no large plantings. Other varieties planted across the Central Valley include Petit Verdot, Dornfelder, Limberger, Verdhello, Tannat, Mataro, Grenache, Cinsault and Barbera.

While the impression is that there are few efforts being made to identify alternate varieties in California, there are quite large variety collections and new and ongoing variety trials (Figure 6). The University of California (UC Davis) and the US Department of Agriculture (USDA) have an extensive variety collection at Davis and some of these are planted on a larger scale at the Kearney Agricultural Center, at Parlier, near Fresno. In collaboration with a local winery, commercial-scale wines made from Refosco, Aglianico, Carmenère, Petit Verdot, Durif (Petite Sirah) and Tannat grapes are being evaluated for their potential as alternatives to current varieties but, again, this is largely driven by consumer demand for alternatives rather than by climatic conditions.

The Californian perspective

From the California perspective, the term 'hot' is applied to any region that exceeds 40°C during the day and doesn't cool down below 20°C at night, which covers the Riverland and Sunraysia regions of Australia. In terms of management strategies, the Californians tend to have one drawcard: water. This obviously is not an option consistent with either Australian conditions or our trend away from high tonnages in order to produce a higher quality product. While there have been some efforts to evaluate alternate varieties and manage quality in California, there are currently no widespread plantings of alternate varieties better suited to hot climates.

HOT Winegrape Production: Italian lessons

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Hot winegrowing regions around the world potentially hold examples of where management practices have been adapted to adverse climates. As part of a joint project between the Victorian Department of Primary Industries (DPI) and the Grape and Wine Research and Development Corporation (GWRDC) those lessons are being captured through a series of study tours of hot viticultural production areas.

The hot production areas in Australia, in the Riverland and Sunraysia, are comparable to many other wine producing regions in terms of climate. As we face a hotter, drier climate, it is worth looking at hot production areas that have similar or hotter climates to see what ideas and innovations we could use to adapt to a hotter climate and to gain a new perspective on our current conditions.

Previously, a tour of California reported (*Australian Viticulture* Vol. 14, No. 6, pp59-62) that the primary strategy for managing high temperatures in California, particularly in the Central Valley, has been to apply irrigation. While this strategy can be adapted in Australia and already has been adapted to some extent, water availability and impacts on fruit quality of excess irrigation make such an approach less than ideal for most of the industry.

To explore other strategies in regions with limited water availability and temperatures similar to current temperatures in Australia or conditions that might reflect climate change forecasts for Australia, we examined some of the production systems in southern Italy.

Southern Italy and Sicily are wine producing regions where daily average temperatures range from 10°C in winter to 24°C in summer. The average maximum temperature in summer is around 29°C (Figure 1), but extreme heat events are also frequently reported as a result of hot winds blowing from the desert regions of North Africa. At these times, temperatures can reach 38-40°C for 2-3 days at a time and 40-44°C in the south of Sicily (www.scia.sinanet.apat.it/sciaweb/scia_kriging_mappe.html).

Generally in winter, temperatures in Sicily (Palermo and Trapani) are warmer than in Mildura. Notably, the average minimum temperatures are higher as a result of the maritime effect from the Mediterranean Sea (Figure 1). Other areas such as Manduria, Catsrovillari and Ragusa have a similar winter temperature range to Mildura.

The climate of the region is relatively dry, with most of the rainfall occurring in the autumn and winter (Figure 2). While there are quite high winter rainfalls recorded in some areas, such as Palermo and Castrovillari, the summer rainfall is generally very low, with little or no summer rainfall in Sicily (Palermo, Ragusa and Trapani). Annual rainfall in Palermo is around 800 mm, while in Trapani the average is 450 mm and around 592 mm in Ragusa. In Manduria, the average is around

625 mm, while in Castrovillari about 750 mm of rain falls annually. By comparison, Mildura receives approximately 300 mm per year.

Given these conditions and their similarity to some wine producing regions in Australia, the 2010 study tour visited Sicily, Calabria and Puglia. Sicily is an island of around 25,700 square kilometres with approximately 115,686 hectares planted to winegrapes producing around 6.2 million hectolitres of wine and must of which 1.5 million hectolitres is bottled (200 million bottles)[1].

The main winegrape varieties in production in Sicily are Catarratto Bianco (40,000 Ha), Nero d'Avola (18,830 Ha) Inzolia (7,084 Ha) Trebbiano Toscano (6,239 Ha) and Grillo (5,629 Ha)[1]. Of these, a few have previously been suggested as possibly suitable to production in Australia.

The tour started with the regions of Palermo, Trapani and Marsala, visiting Calastrasi, Feudo Arancio and Rapitalà vineyards and wineries, as well as Florio and Donnafugata wineries guided by Prof. Gabriella Barbagallo and Dr Pietro Scafidi from the University of Palermo (Figure 3.). The white varieties in production were mainly Cataratto and Grillo and the red varieties were mainly Nero d'Avola, Nerello Mascalese and the usual international varieties, Shiraz, Merlot, Cabernet Sauvignon (13,885 Ha in Sicily). Grillo, which makes a light white table wine, is drought hardy and not overly susceptible to Powdery Mildew and seemed well suited to Australia. Nero d'Avola, while arousing interest in Australia as a major variety in Sicily, is susceptible to Powdery Mildew, Downy Mildew and Botrytis, is not drought tolerant and is also susceptible to sunburn and therefore probably not well suited to hot wine producing regions in Australian, although very high quality wines can be made from this variety. One of the features of Sicilian viticulture that was observed was the widespread virus loads in vines and many vineyards were infested with a sap-sucking pest, *Jacobiasca libica*.

In Sicily, the soils are generally young clays overlaying limestone or sandstone, but can be variable in depth from 0.5 to 2+m. The Sicily are clayey limestone, sandstone and gypsum surrounded by extensive coastal plains. The hills are gently to steeper sloping (mean slope 12%) ant an average height of 247 m above sea level. Soils in the western part of Sicily show an accumulation of carbonates, soluble salts and clays as well as alluvial soils with a lot of variation in thickness, rockiness and some localised salinity. Figure 4 shows the different pedalogical regions of Sicily and southern Italy.

To the south east around Ragusa, the mountains are a mixture of limestone, dolomite and igneous (volcanic) rock, generally a little higher than in the west at an average of 297 m above sea level and 11% slope. The soils are generally shallower with greater organic matter content, rocky and stony with some heavy clays, acidity and localised steep slopes.

North of Ragusa, production is centred on the volcanic soils of Mt Etna, which are highly fertile once excess rock is removed. As a result the area is characterised by dry-stone walls and numerous other stone constructions. Altitude around 1,000 to 1,300m, bush vines are dry grown with some good but unusual wines. While interesting, these had little relevance to Australian production.

Viticulture in Calabria is only around 13,500 hectares[2], while the most important crop is olives (about 196,000 Ha). However, in this region a number of local varieties were examined, including Magliocco, Trebbiano, Greco de Tufo, Fiano, Falanghina, Aglianico and Montelpuciano with good examples of these in the vineyards around Castrovillari. Of these Fiano, Falanghina, Aglianico and Montelpuciano have potential for production in

[1] Salvia Francesca. 2011. "The Sicilian Viticulture in numbers". REGIONE SICILIANA , ISTITUTO REGIONALE DELLA VITE E DEL VINO.

[2] Source: ISTAT (Italian National Institute of Statistics) http://www.istat.it/it/calabria/dati?q=gettable&dataset=DCSP_COLTIVAZ&dim=113,1,9,0,0&lang=2&tr=0&te=0

Australia being drought hardy and well-suited to hot climates. these varieties also mak excellent wines. There are small plantings of all of the varieties in Australia and some good examples of these wines in commercial production.

The hills of Calabria are mainly tertiary limestone rocks, dolomite and associated sediments with alluvial and coastal plains, a mixture of sloping and level land with escarpments. The hills and mountains are generally higher than elsewhere in southern Italy with the average height of the uplands being around 430 m and an average slope of 24%.

Further to the east, the heel of Italy, is the Puglia region. In Puglia, 101,175 hectares[3] are planted to winegrapes with about half of the production in the Foggia (32,300 Ha) and Taranto (18,135 Ha) area. The main varieties in Puglia are Primitivo, Nero di Troia and Greco di Tufo as well as lesser plantings of Montelpuciano, Negroamaro, and Fiano. Primitivo is considered to be the same variety as Zinfandel in the USA (California) and is well suited to hot production areas and is a versatile grape, although it can be hard to grow, thin-skinned and disease prone. While the variety produces some outstanding wines, the production issues make it hard to recommend, particularly in a highly mechanised industry. Nero di Troia might have greater potential being largely free of the limitations of Primitivo.

In the Puglia region, the soil is characterised by shallow clay soils over limestone, often with excessive limestone on the surface. In the Manduria region of Puglia, where Primitivo is the major wine produced, the soils are easily crumbled limestone clays, on a fairly level coastal plain with adjacent hills less than 200 m above sea level. The soils on the hills are often shallow and eroded carbonates, clay and iron oxide accumulation at depth with a very mild slope (3%).

Further to the east, the region is famous for the dry-stone walls and small, conical-roofed stone cottages known as “trullo” (Figure 5). In some parts of Puglia major earthworks to break and pulverise the limestone to around 1.5m is undertaken at a cost of around 20,000 euro per hectare (Figure 6). Montelpuciano was widely grown in this region and performed well under both water and heat stress.

Generally, viticulture in southern Italy was similar to Australia in terms of the climatic conditions, soils in some areas were notably different as were many of the production practices. Irrigation systems are a relatively new adoption and knowledge of irrigation management or scheduling is low. While there are many new plantings and some highly mechanised operations, much of the viticulture still follows traditional practices. A major difference between southern Italian and Australian winegrape production was the lower yields as low as 4-5 tonnes per hectare or lower in some cases, but other areas had yields of 25 tonnes per hectare or more. However, in many areas DOC (Denominazione di Origine Controllata - controlled designation of origin) regulations limit production to around 12 tonnes or lower.

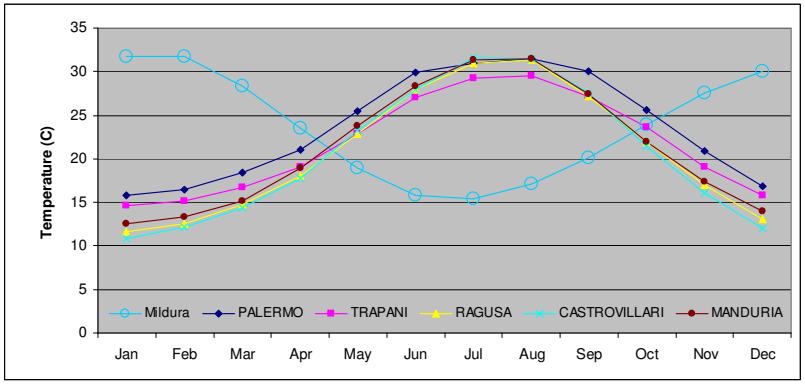
The most noticeable difference in Italian viticulture was the range of cultivars in widespread production and array of wines produced that are not commonly seem in Australia. Of the many varieties observed in southern Italy, some seemed particularly well-suited to warm or hot production conditions in Australia including; Grillo, Fiano, Falanghina, Aglianico, Nero de Troia and Monteulciano. Despite all of these varieties being grown in Australia, only a few of these great wines appear in our bottleshops.

[3] Source: ISTAT (Italian National Institute of Statistics)
http://www.istat.it/it/puglia/dati?q=gettable&dataset=DCSP_COLTIVAZ&dim=104,2,9,0,0&lang=2&tr=0&te=0

Figure 1.

Average daily A) maximum and B) minimum temperatures for viticultural production areas in southern Italy and Sicily as well as Mildura (Vic.) for comparison.

A. Average Daily Maximum
B. Average Daily Minimum



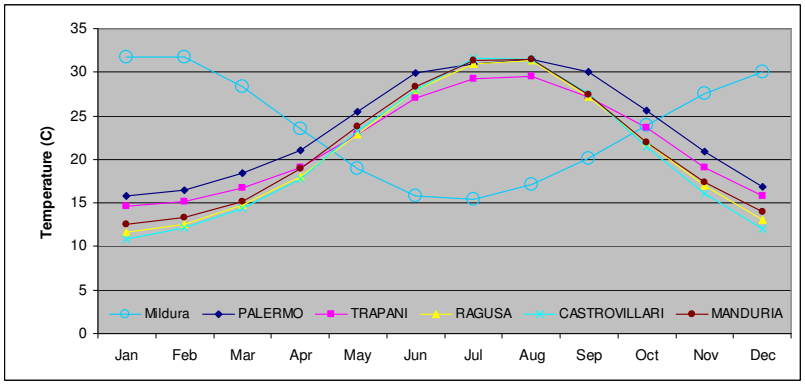


Figure 2. Average rainfall (mm) for southern Italy and Sicily, as well as for Mildura (Vic.) for comparison.

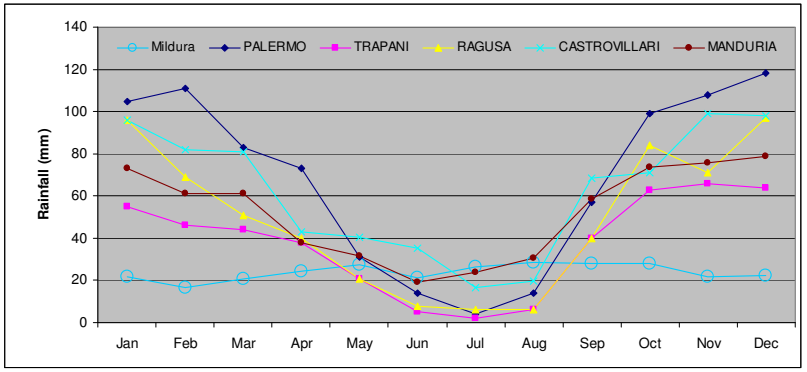


Figure 3.

Dr. Pietro Scafidi (left) and Professor Gabriella Barbagallo from the University of Palermo (Sicily) visiting vineyards in the Etna region of Sicily.



Figure 4. Pedological (soil) map of southern Italy and Sicily. *Source: SOIL REGIONS OF ITALY. Edoardo A. C. Costantini, Ferdinando Urbano, Giovanni L'Abate (modified). www.soilmaps.it*

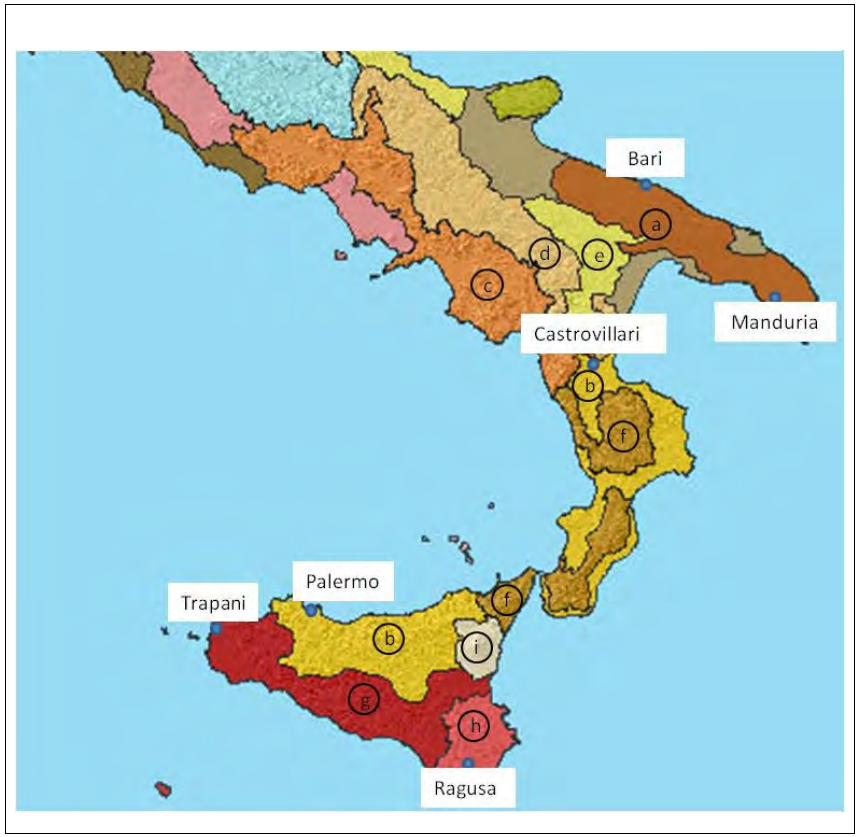
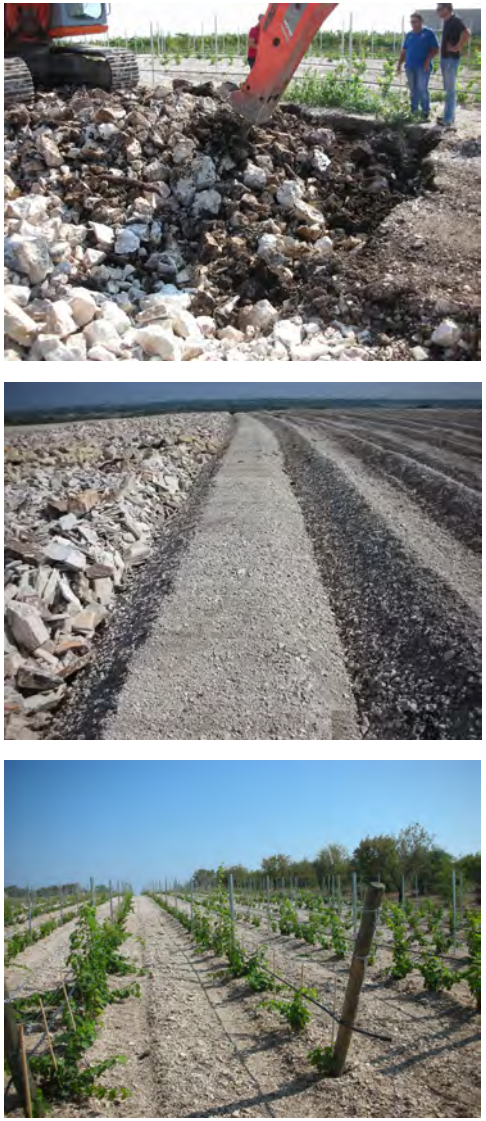


Figure 5. Dr Mark Downey and Luigi Tarricone (Institute for Experimental Viticulture, Puglia) examining a traditional limestone "trullo" (plural trulli) in Puglia, Italy.



Figure 6. Land preparation for vineyard planting in Puglia (southern Italy). Where the soil is shallow and underlain by limestone, the limestone is broken up, then crushed before planting of new vineyards. a) Dr Nino Pisciotta (left) and Dr Pietro Scafidi watch an excavator breaking the limestone, B) before and after crushing, C) a recently planted vineyard on the crushed limestone - where's the soil?





CLIMATE CHALLENGES FOR HORTICULTURE IN THE SUNRAYSIA REGION

MILESTONE REPORT – GAPS IN SOIL INFORMATION AND IMPACT ON WATER AVAILABILITY FOR WINE GRAPE PRODUCTION IN THE SUNRAYSIA REGION,

State Government Victoria

DEPARTMENT OF PRIMARY INDUSTRIES | future farming systems research

111

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EXECUTIVE SUMMARY

This Milestone Report is a component of the project *Climate Change Impact Modelling in Horticulture* that investigates the likely impacts of climate change on Victorian perennial horticulture. It covers two objectives: (i) assessment of the likely impacts on water availability for wine grape production in the Sunraysia Region, and (ii) assessment of key gaps in the soil information in the Sunraysia Region.

Water Availability – Mean temperature, total annual rainfall and solar radiation, both in a current and future climate, are considered for the Sunraysia Region.

- Mean baseline temperature (1996-2005) ranged from 15.5 to 17.5ºC, with projected increases of 1 to 1.5ºC to 2030 (17 to 18.5ºC) and up to a 2.5ºC through to 2050 (18 to 20ºC).
- Baseline total annual rainfall ranged from 215 to 360 mm, with projections indicating likely decreases of 15 to 25 mm to 2030 (200 to 335 mm) and a 80 mm decrease into 2050 (170 to 280 mm).
- Baseline solar radiation ranged from 17.5 to 18.5 MJ m^2/day, with a possible increase of up to 1 MJ m^2/day through to 2030 and a 0.5 to 1.5 MJ m^2/day increase to 2050.

Projected changes in these primary factors would have concomitant influences on other climatic indicators such as heat degree days, evapotranspiration and irrigation.

- Baseline heat degree days ranged from 1,975 to 2,390 dayºC, with projections indicating likely increases of 210 to 285 dayºC to 2030 and a 270 dayºC increase into 2050.
- Baseline evapotranspiration ranged from 1,310 to 1,450 mm, with possible increases of 40 to 130 mm to 2030 and a 70 mm increase through to 2050.
- Baseline irrigation ranged from 485 to 640 mm/ha, with a likely increase of 35 to 60 mm/ha to 2030 and a 55 mm/ha increases into 2050.

Projected climatic shifts will have a significant impact on water availability for wine grape production. With increasing temperature, there will be a greater need for irrigation to replace water loss in the plant through evaporation and transpiration. Further, as temperatures increase, there is also a potential lowering of rainfall amounts, which will reduce water availability for irrigation allotments.

Soil Information Gaps Analysis - For Land Suitability Analysis (LSA) modelling, a relevant soil data layer has to be generated in a GIS domain. The layer must contain the attributes of differing soil units over the entire study region at a consistent spatial resolution. However, the readily available sources of soil information for Sunraysia include data at multiple levels of spatial resolution. Collectively, they do not cover the entire irrigation zone of the study region and all attributes are not reported.

Two options exist for achieving data consistency between the point, broad and fine scale information in Sunraysia:

1. Focus the soil data layer upon the irrigation zones that have detailed soil surveys. This requires an extrapolation of soil units to join individual soil surveys, whilst the previously unmapped irrigation areas need to be defined by incorporating the fine scale soil surveys within the broader scale maps.
2. Disaggregate and restructure the current data from all sources (soil surveys, land systems, geomorphological and point source data) to achieve a uniform resolution, which contains all relevant attributes over the larger study region.

There is a greater benefit in considering a larger study region (Option 2), since this will permit identification of suitable agricultural areas outside the current irrigation zones. However, a smaller area (Option 1), will be quicker to complete and will encompass a majority of the irrigated agriculture within the defined study boundary. Work requiring LSA as a basis will need to take into account the incorporation of one of these options into approaches considering future agricultural development of the Sunraysia Region of Victoria.

ACKNOWLEDGMENTS

This project is a component of the DPI *Future Farming Strategy*; in particular it implements "Action 3: Understanding and managing climate change". Its development has been possible through a special allocation of funds from both the State Government and DPI. Bruce Tomkins was the Project Manager during the initial development of the project and David Marland is the current Key Project Manager

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An *Experimental Pre-schedule* meeting to discuss various aspects of the overall project methodology was conducted under the chairmanship of Kim Lowell (formerly Principal Scientist in the FFSR Division). This focused, in particular, on the initial application of the methodology on land suitability modelling for pears, but the flow-on effects from the pre-scheduling are also reflected in this report. The Project Team are indebted to the participants and Lowell for their valuable contributions. They were: Pam Strange, Horticulture Climate Adaptation Manager (representing Graeme Anderson – DPI Farm Services Victoria); and Mohammad Abuzar, Kurt Benke, Michael Hurley, Mark Imhof, Esther Liu, Christopher Pettit (formerly Research Manager), Subhash Sharma, Kathryn Sheffield and Falak Sheth all from the FFSR Division.

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1. INTRODUCTION

This Milestone Report is a component of the project *Climate Change Impact Modelling in Horticulture* (CMI 102313; MIS 08444) developed by the Future Farming Systems Research (FFSR) Division of DPI over a 4-year period (2008/09 - 2012/13). The project investigates the likely impacts of climate change on Victorian perennial horticulture, and possible adaptation options to respond to the potential impacts. This report covers two specific objectives of the project: (i) assessment of key gaps in the soil information in the Sunraysia Region for use in Land Suitability Analysis (LSA) and other relevant modelling, and (ii) assessment of the likely impacts on water availability for wine grape production in the Sunraysia Region. The years examined are 2030 and 2050 and, for comparison purposes, a baseline, year 2000 (defined as the average climate in the period 1996-2005).

1.1 PROJECT OUTCOME

Researchers and policy makers in industry and government enabled to develop strategic and tactical (i.e. operational) options that maximise opportunities for perennial horticulture to adapt to climate change in Goulburn Valley and Sunraysia Regions of Victoria.

1.2 PROJECT BACKGROUND

Agriculture and its key industries, particularly horticulture, are being exposed to rapid and intensive transformations associated with the impacts of various drivers of change. The main driving forces include: globalisation, modifications in markets and trade, climate change, competition for natural resources (land and water), socio-cultural and organisational change. Climate change is of particular importance - aside from biodiversity, agriculture is the most vulnerable sector to the impacts of climate change (Stokes & Howden, 2010). Therefore, the future development of agriculture will be dependent on its ability to respond to these complex challenges. The Victorian Government, through DPI, has a key role to play in assisting agriculture and its horticultural industries to analyse, plan and respond to those challenges, but also to ensure that the valuable natural resource base of the state is conserved for the future. The success of the planning, adaptation and mitigation activities could determine the well-being of Victorian regions and their rural communities in an uncertain and risky future.

Guiding systemic change within the agricultural sector will require sound research, evidence-based policy development and targeted action. Understanding how the rapid and intense transformations will impact on farming systems and their long-term viability is thus a key factor in formulating successful adaptation strategies and measures for agriculture and its horticultural industries.

Developing an understanding of the complex changes and potential impacts on agriculture (within a regional context) requires the design and application of innovative modelling approaches. They must be formulated to support existing policy development and decision-making processes and be flexible to respond to a multiplicity of possible futures. Therefore, any new modelling approach must have a strong route to market and be capable of managing new information as well as connecting biophysical data with modelled data, visualisation and communication tools.

1.3 PROJECT OBJECTIVES

The initial, specific objectives, formulated within the context mentioned above, changed during the life of the project. Detailed examination of the soil information available in the Sunraysia Region showed the existence of gaps in both the geographic (spatial) coverage and in a number of key soils attributes required for the study. These gaps in information were not apparent in the planning phase of the project. This meant that Land Suitability Analysis (LSA) modelling for Sunraysia was not possible within the resources and time available to develop the project. A Project Variation was requested, and

approved on 19/07/2011. One initial objective was modified (Objective 1) and two more objectives (Objectives 5 and 6) were added. The final list of specific objectives is therefore as follows.

1. Assess the climate change impacts on: (i) pome fruits (pears), (ii) pome fruit (apples – three varieties), (iii) viticulture - wine grapes (iv) stone fruit (peaches and nectarines) in the Goulburn Broken Region.

2. Develop climate change projections for the Goulburn Broken and Sunraysia Regions for three marker IPCC SRES scenarios – B1 (low global warming), A2 (medium global warming) and A1FI (high global warming).

3. Analyse the potential land suitability changes in the study regions, up-to the year 2050, for the horticulture industries mentioned in Objective 1.

4. Examine the likely climate impacts on surface and ground water (hydrological) resources, including the impacts on and opportunities for the use of water recycling schemes, in the study regions.

5. Assess the key gaps in the soil information for the Sunraysia Region for use in LSA and other relevant modelling (see the complete text in Section 1.4, below).

6. Assess the likely impacts on water availability for wine grape production in the Sunraysia Region (see the complete text in Section 1.4, below).

The achievement of Objectives 1-4 was reported in four previous volumes of the study. This Milestone Report covers Objectives 5 and 6.

1.4 MILESTONE OBJECTIVES

1. Assessment of the gaps in soil information in the Sunraysia Region with an indication of the resources, timing and funding required to producing such information for use in LSA and other relevant modelling.
2. Assessment of likely impacts on water availability for wine grape production in the Sunraysia Region by 2030 and 2050, in a worst case global warming – focus on mean temperature, total rainfall, solar radiation and evapotranspiration.

2. MILESTONE ACHIEVEMENT

2.1 IMPACTS OF CLIMATE CHANGE ON WATER AVAILABILITY FOR WINE GRAPE PRODUCTION IN SUNRAYSIA

2.1.1 Climate and Wine Grape Production

Of the agricultural industries, the cultivation of wine grapes is considered by some to be one of the most sensitive to climate. In a changing climate, it is therefore important to examine the possible climate change impacts on wine grape production. As with other perennial crops, the establishment and costs and period of production reflect an investment cycle of several decades and limit the responsiveness of the industry. Australia is fortunate to be among the Southern Hemisphere wine-producing countries where the projected climate change effects would be less than for the Northern Hemisphere. Already, some wine producing companies in Spain are buying land at a higher altitude and in cooler regions, so that they might be well prepared to shift production in the future (Smart, 2006).

Temperature is one of the major determinates of wine grape phenology and maturity (Pearce & Coombe, 2004). Winegrapes are particularly sensitive to impacts of climatic changes due to the fundamental link between climate, temperature and end-quality of the grape. In Australia, without adaptation, winegrape quality may be reduced from 7% to 39% (low to high warming, respectively) by the year 2030 and 9% to 76% by the year 2050 (all uncertainties considered) (Webb *et al.*, 2008). The impact of projected climate change on the phenology of wine grapes was also modelled (Webb *et al*., 2007). This study showed that budburst of winegrapes may occur earlier in some areas by up to 8 days into 2030 and up to 11 days into 2050. Overall, a compression of the growing season was indicated in all regions studied, with some areas showing harvest occurring 45 days early by 2050 (high warming scenario). This compression and alteration of phenological stages could ultimately impact on maturity and ripening dates in winegrapes, with projections indicating earlier dates for both these stages (Webb *et al.,* 2011; Webb *et al.,* 2012).

Furthermore, investigations on winegrape production in the Goulburn Broken Region confirmed that climate is a major factor affecting its future development (Sposito *et al.*, 2011a). Temperature over other factors had a large influence on production. A reduction in the land suitability for winegrape production was noted in the existing viticultural regions from a baseline (average climate in the period 1996-2005) through three future years (2030, 2050 and 2070) under a high warming scenario.

There is a broad association between average mean temperature and the styles of wine produced (Gladstones, 1992). Mean temperature is a key influence on the heat degree day summation, which is a method used for classifying the climate of a wine growing region. The method was created by Amerine and Winkler (1944) for wine production in California, but has been successfully applied in a number of regions worldwide. Temperature summation system is based on a system developed in France by de Candolle, which relied on the observation that vines start active growth in the spring when mean air temperature reaches about 10ºC (Gladstones, 1992). The method is a summation of degree days over a seven month growing period. Degree days for this method are calculated by subtracting 10ºC from the daily mean air temperature, this value is then summed for each day of the growing period. The resultant output can then be broadly divided up into five regions for grape production based on the degree day values. According to Amerine and Winkler, the grape production regions are defined as:

- Region I – less than 1370 dayºC
- Region II – 1370 – 1650 dayºC
- Region III – 1650 – 1930 dayºC
- Region IV – 1930 – 2200 dayºC
- Region V – greater than 2200 dayºC.

This can give indication of the wines types that can be best produced in these regions. Thus, Region IV is considered to be best for sweet dessert wines, whilst Region III produces full-bodied dry wines and some of the port-type wines. Region I & II are regarded as the best for table wines. Region V is considered to be suitable mainly for fresh and drying grapes, and for bulk table wines of lower quality. Limitations of this system lie in that it was primarily produced for California where temperature is a good predictor of rainfall and sunshine. Elsewhere, the method has been less successful, particularly in warm summer-rainfall areas, such as sub-tropical NSW and Queensland, where summer rain and frequent cloud cover can counteract or negate temperature effects on fruit qualities (Gladstones in Dry and Coombe, 2005). The method is nevertheless useful as a primary approximation to viticultural climate regions. This approach has therefore been utilised in the current study to inform changes in land suitability.

Figure 1 shows the resultant output for Victoria (with corresponding regional divisions) over the baseline period (years 1996 – 2005)[1]. In the North West Mallee Region, two distinctive Viticulture Climate Regions can be identified. The majority of the northern area is within Region V, with Region IV seen in the south towards Swan Hill. This changes progressively down into the south of Victoria, with an alternating Region I and II across the central region from East to West.

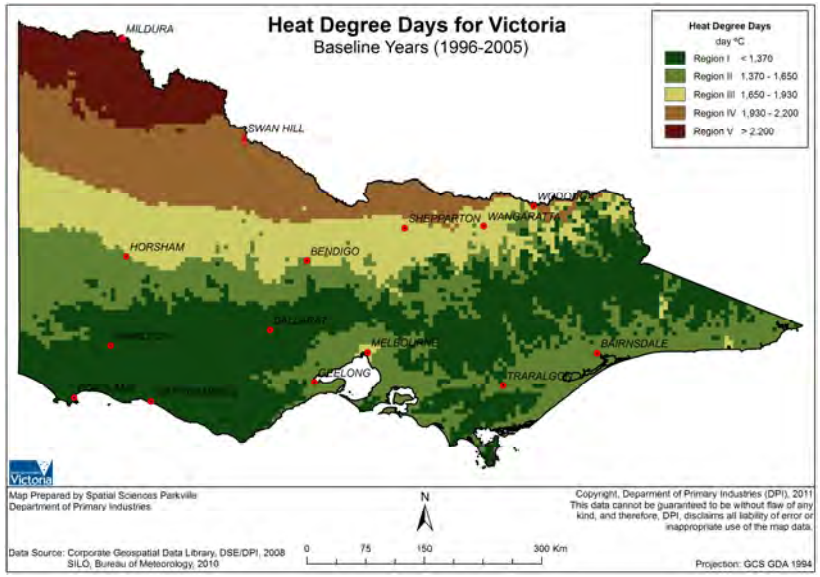


Figure 1 **Heat Degree Days for Victoria – Baseline Years (1996 – 2005)**

Figure 2 depicts the projected output for the year 2050[2]. The comparison of **Figure 1** and **Figure 2** shows that a substantial reduction in the size of Regions I and II would occur with a concomitant increase in the size of Regions IV and V clearly reflecting projected increases in temperature across Victoria.

[1] Climate data for historical observations were sourced by the Department of Natural Resources and Mines, Queensland, in conjunction with the Bureau of Meteorology (BOM) weather recordings, through their SILO program (Department of Natural Resources and Mines, 2010). These data are produced as text files which then can be presented in a map grid at a resolution of approximately 5 square km (grid) (0.05^0).

[2] The future climate scenarios for the years 2030 and 2050 were generated using the CSIRO's Atmosphere-Ocean Global Circulation Model (AOGCM) *CSIRO-Mk3.5* model and the IPCC SRES A1FI (extreme change) scenario. This climate scenario provided the spatial spread of the needed climatic factors at a resolution of approximately 5 square km (grid) (0.05^0).

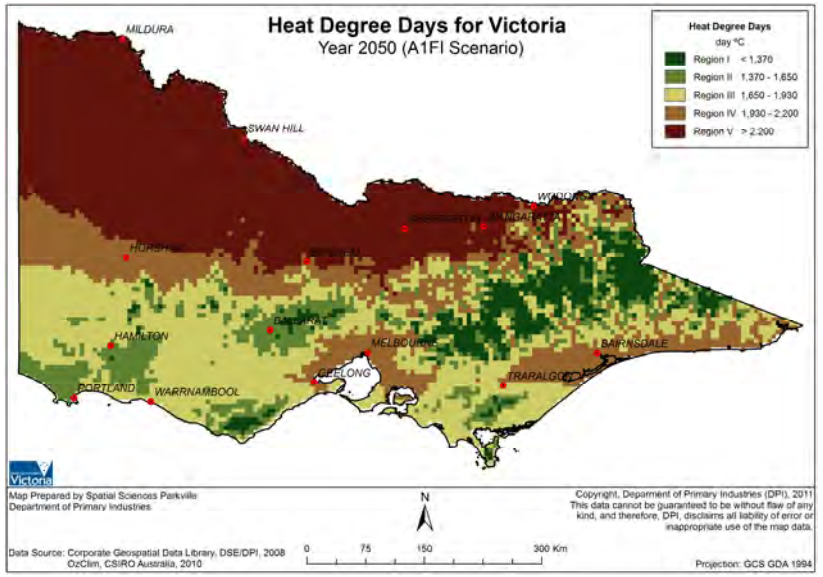


Figure 2 **Heat Degree Days for Victoria – Year 2050 (A1FI Scenario)**

Of importance also within the suitability model(s) for winegrapes is water availability, both in terms of rainfall and irrigation. Water requirements for grapevine growth are dependent on factors such as climate, cultivar (including rootstock) and soils. As a general rule, the requirement for water can be divided up into five main stages; (i) budburst to flowering, (ii) flowering to fruit set, (iii) fruit set to ripening, (iv) ripening to harvest and (v) harvest to leaf fall. Some grapevines varieties are easily water stressed, particularly during the fruiting stages, and low amounts of water can delay the onset of ripening and lower production yields. It is thus important to maintain the right balance between rainfall and irrigation. Irrigation requirements and the amount of water applied are dependent on local climatic factors, such as temperature and rainfall, as well as evapotranspiration (refer to **Appendix A** for a discussion on irrigation and evapotranspiration). The process of evapotranspiration is primarily determined by the amount of energy available to vaporise water. In the calculation of evapotranspiration, factors such as temperature, rainfall and humidity are taken into account. Solar radiation is also considered, as it is the largest energy source able to change large quantities of liquid water into water vapour (Allen *et al.*, 1998).

Based on the above discussion, average temperature, total annual rainfall and solar radiation must be considered in the analysis of water availability for wine grape production in the Sunraysia Region, both in a current and likely future climate. The influence these factors may have on the heat degree days, evapotranspiration and irrigation requirements in an area can then be assessed to determine impacts on current and future water availability.

2.1.2 Average Temperature

Mean temperatures for the study region are shown in **Figure 3**, where the annual average temperature for the baseline (period 1996-2005), 2030 and 2050 are detailed. In the baseline, mean temperature ranges from 15.5ºC to 17.5ºC, into 2030 this temperature range is from 17ºC to 18.5ºC and into 2050 the range is from 18ºC to 20ºC. Overall, there is a 1ºC to 1.5ºC projected increase between each period with a 2.5ºC difference between the baseline and 2050. Projected changes are more pronounced in the south east areas where into 2030 projections indicate an increase of 1.25ºC against the baseline and a 2.5ºC increase into 2050. Compared against the Mildura area where into 2030 there is a likely 0.75ºC increase and a 2ºC increase by 2050.

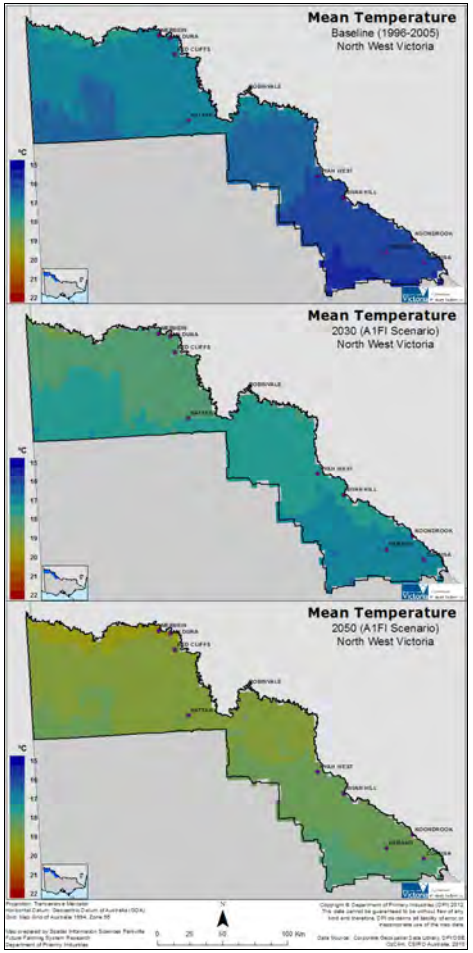


Figure 3 Mean temperatures for the study region in the baseline (1996-2005), 2030 and 2050

2.1.3 Total Rainfall

Total rainfall for the region is shown in **Figure 4**, where the total annual rainfall for the baseline (period 1996-2005), 2030 and 2050 are detailed. In the baseline, rainfalls range from 215 mm to 360 mm, into 2030 this rainfall range is from 200 mm to 335 mm and into 2050 the range is from 170 mm to 280 mm. Overall there is a projected decline in rainfall amounts from 5 mm to 55 mm between each period with a 30 mm to 105 mm difference between the baseline and 2050. Projected declines in total annual rainfall are more pronounced in the Nyah area where into 2030 projections indicate a decrease of 55 mm against the baseline and a 100 mm decline into 2050. Compared against the Mildura area where into 2030 there is a likely decrease of 5 mm and a 50 mm decline by 2050.

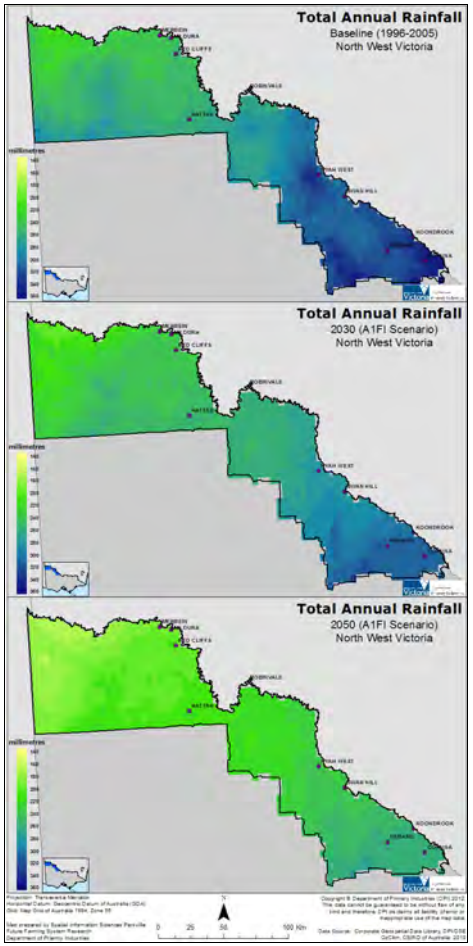


Figure 4 Total annual rainfall for the study region in the baseline (1996-2005), 2030 and 2050

2.1.4 Solar Radiation

Solar radiation for the study region is shown in **Figure 5**, where the annual average solar radiation for the baseline, 2030 and 2050 are detailed. In the baseline, solar radiation range from 17.5 MJ m^2/day to 18.5 MJ m^2/day, into 2030 the projected range is from 17.5 MJ m^2/day to 19.5 MJ m^2/day and into 2050 the range is from 18 MJ m^2/day to 20 MJ m^2/day. Overall, there is a 0 to 1 MJ m^2/day projected increase in solar radiation amounts between each period with a 0.5 to 1.5 MJ m^2/day difference between the baseline and 2050. Solar radiation amounts are more pronounced in the Mildura area where into 2030 projections indicate an increase of 1 MJ m^2/day against the baseline and a 1.25 MJ m^2/day increase into 2050. Compared against the Swan Hill area where into 2030 there is a likely increase of 0.1 MJ m^2/day and a 0.25 MJ m^2/day by 2050.

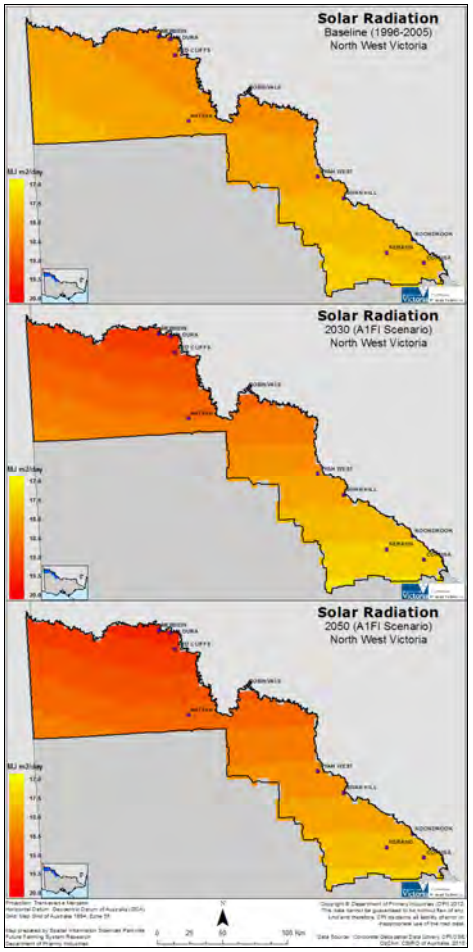


Figure 5 Solar radiation for the study region in the baseline (1996-2005), 2030 and 2050

2.1.5 Heat Degree Days

Heat degree days for the study region are shown in **Figure 6**, where the heat degree day summation for the baseline (period 1996-2005), 2030 and 2050 are detailed. In the baseline, heat degree days range from 1,975 day°C to 2,390 day°C. Into 2030 the projected range is from 2,260 day°C to 2,610 day°C and into 2050 the range is from 2,530 day°C to 2,880 day°C. Overall there is a 160 day°C to 285 day°C projected increase in heat degree days between each period, with a 440 day°C to 575 day°C difference between the baseline and 2050. Changes in the heat degree day summation amounts are more pronounced in the Swan Hill area where projections indicate an increase of 295 day°C into 2030 against the baseline with a 570 day°C increase into 2050. Compared against the Mildura region where into 2030 there is a likely increase of 225 day°C and a 500 day°C increase by 2050.

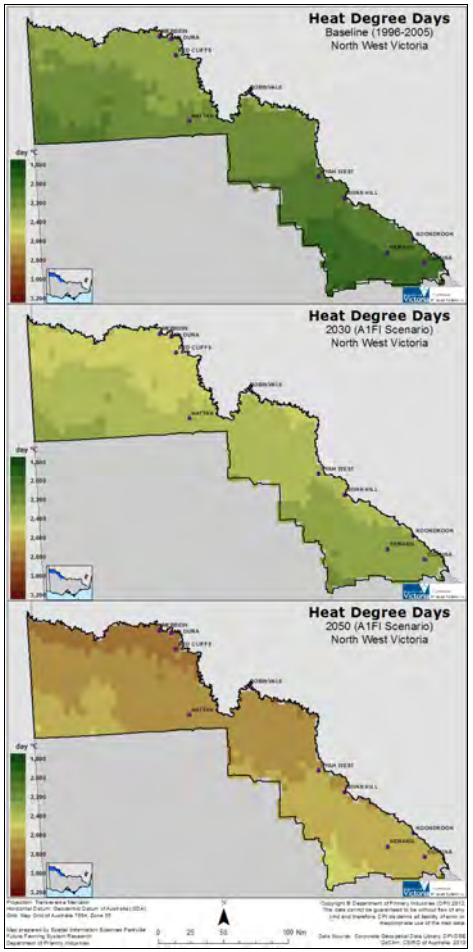


Figure 6 Heat degree days for the study region in the baseline (1996-2005), 2030 and 2050

2.1.6 Evapotranspiration

Evapotranspiration for the region is shown in **Figure 7**, where the annual evapotranspiration for the baseline, 2030 and 2050 are detailed. In the baseline, evapotranspiration ranges from 1,310 mm to 1,450 mm, through to 2030 the projected range is from 1,350 mm to 1,570 mm and into 2050 this is from 1,410 mm to 1,640 mm. Overall, there is a 40 mm to 130 mm projected increase in evapotranspiration between each period, with a 100 mm to 190 mm difference between the baseline and 2050. Projected increases in evapotranspiration are larger around Mildura where increases of over 115 mm from the baseline into 2030 are possible, with a likely increase of 185 mm into 2050. Compared against the southern areas of the region where into 2030 there is a likely increase of 45 mm and a 60 mm increase by 2050.

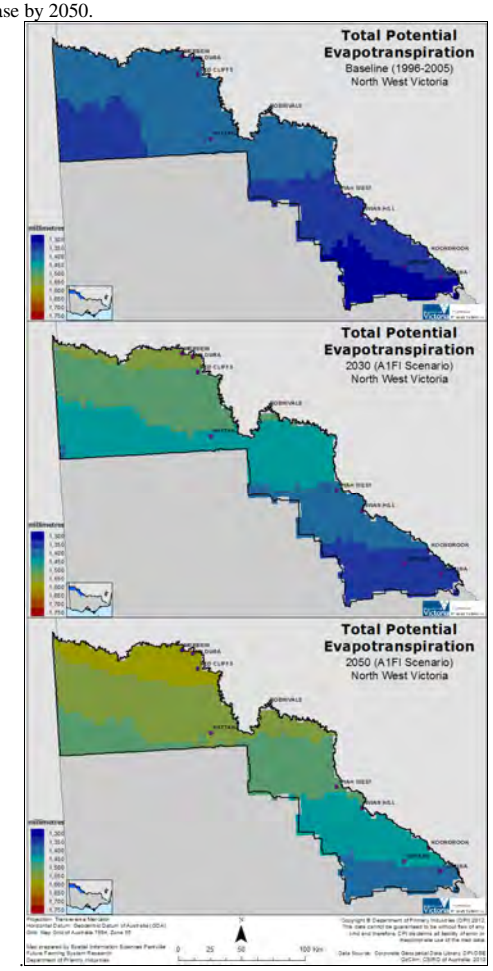


Figure 7 Evapotranspiration for the study region in the baseline (1996-2005), 2030 and 2050

2.1.7 Irrigation

Irrigation amounts for the region are shown in **Figure 8**, where the annual irrigation amounts for the baseline, 2030 and 2050 are detailed. In the baseline, irrigation ranges from 485 mm/ha to 640 mm/ha, through to 2030 the projected range is from 520 mm/ha to 700 mm/ha and into 2050 the range is from 575 mm/ha to 745 mm/ha. Overall, there is approximately a 15 mm/ha to 80 mm/ha projected increase in irrigation between each period, with a 60 mm/ha to 130 mm/ha difference between the baseline and 2050. Projected increases in irrigation amounts are more pronounced towards Mildura, where projections indicate a required increase of 75 mm/ha into 2030 against the baseline, with a 125 mm/ha increase into 2050. Compared against the southern areas where into 2030 there is a likely increase of 15 mm/ha and a 65 mm/ha increase by 2050.

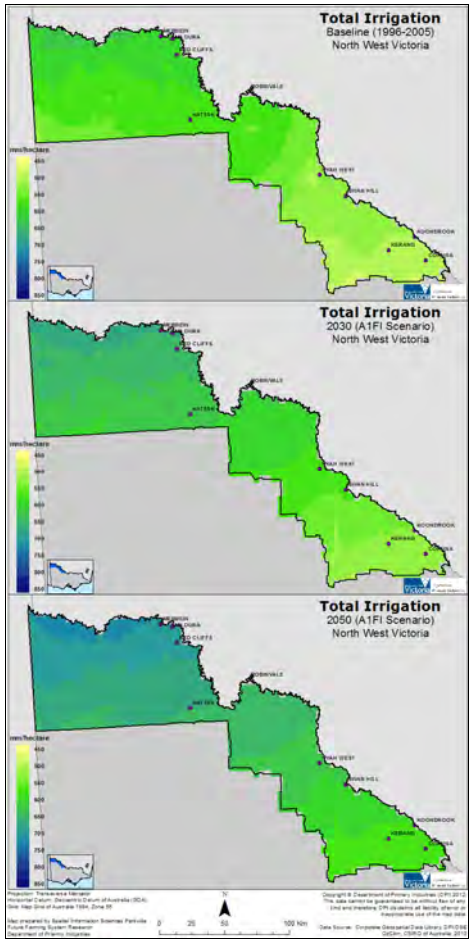


Figure 8 Total irrigation amounts for the study region in the baseline (1996-2005), 2030 and 2050

2.1.8 Discussion on Water Availability for Wine Grape Production

Heat Degrees – As mentioned, heat degree days provide an indication on the climate within a wine growing region and the type of wine that can potentially benefit from that climate. Under the current climatic conditions, Sunraysia is rated across Region IV (1930-2200 dayºC) and Region V (over 2200 dayºC). In general, these regions are better suited for warm climate grape production. The increases likely to occur in the mean temperatures from the baseline through to 2030 and 2050 have a direct effect on the heat degree day summations as shown in **Figure 6**. By 2050, the whole region will be rated as Region V. The calculation of heat degree days is reliant upon mean temperatures and, as such, any increase in temperature will increase the heat degree day summation.

Irrigation - The calculation of irrigation amounts is dependent on plant evapotranspiration, which in turn is reliant on solar radiation, total rainfall, mean temperature and minimum and maximum temperatures (not covered in this report). The increases into future year scenarios seen in mean temperature and solar radiation and the declines in total rainfall have impacts upon plant evapotranspiration, which is projected to increase into future scenarios, as shown in **Figure 7**. Thus, the irrigation requirements, calculated for the study region, increase between the three time periods analysed. With these increases, there are concomitants increases in irrigation amounts as displayed in **Figure 8**.

In the Mallee Region, which encompasses the defined Sunraysia Region, an association between irrigation amounts and total rainfall can be established. By comparing irrigation application rates for grapevines in this region (as reported by the Australian Bureau of Statistics - ABS) against average rainfall amounts (**Table 1**)[3], an increase in irrigation as rainfall amounts decrease can be noted.

Table 1 Grapevine irrigation application rates and average rainfalls in the Mallee Region, Victoria, 2005-2009

Year *	Area Irrigated (ha)	Volume Applied (ML)	Application Rate (ML/ha)	(mm)	Average Rainfall (mm)
2005-06	25,000	168,377	6.74	673.51	298.82
2006-07	32,000	190,528	5.95	595.40	253.67
2007-08	27,090	131,267	4.85	484.61	177.96
2008-09	24,830	138,811	5.59	559.00	254.45

Source: ABS 2006; ABS 2007; ABS 2008; ABS 2009
Year refers to ABS statistical reporting period which extends from the 1st July to 31st June of any given year.

In the 2005-06 period, which had the highest average rainfall of the four periods included in the table, the application rate is just over double that of the average rainfall. However, in the 2007-08 period, which has the lowest average rainfall, the application rate is over two-and-a-half times that of the rainfall amount, even though the application rate is the lowest reported. If this correlation is attributed to the declining rainfall figures into 2030 and 2050 in the Sunraysia Region, as seen in **Figure 4**, then, in future scenarios, the application rates for irrigation may potentially be lower, but the proportion of application rates to rainfall may increase.

[3] The irrigation data included in Table 1 is supplied by ABS. As such, the reported amounts are only provided by registered businesses. Businesses that do not meet the reporting guidelines of the ABS are not detailed and included in the statistics. Further, the data supplied is for the entire Mallee Region. This could include grapevines that may fall outside the defined study region used in this report. It is however considered that this is a small number of grapevines that rely on bore-well irrigation or other irrigation supplies outside the Murray River Irrigation Districts.

There is an inverse relationship between rainfall and temperatures; i.e. as mean temperatures increase, decreases in the total annual rainfall amounts are experienced. In the Sunraysia Region, as temperatures are projected to increase, rainfall amounts will decline. This will in turn provoke an increase in the demand for irrigation for wine grape production. This situation can be ascribed to the relationship between temperature increases and heat related stresses placed on vines. As a vine moves outside its optimal temperature range, particularly due to higher temperatures, more external stresses are placed upon it which may increase the water loss. A greater need for irrigation to replace this water loss in the plant will then ensue. As temperatures increase, there is also a concomitant potential lowering of rainfall amounts. Consequently, there is less available water overall that is recharging the water system, which can reduce water availability for irrigation allotments and irrigation application rates.

2.2 SOIL GAPS ANALYSIS

Determining the suitable land for the growth of a specific agricultural commodity is a complex process. Each agricultural commodity has specific growth requirements that can be detailed through a combination of soil, climate, and landscape (i.e. biophysical) characteristics/factors. Each of the three biophysical criterion used in this method has particular benefits or limitations for plant development. Climatic conditions are key metrics, either by promoting or restricting ecological process (e.g. plant establishment and growth rate), or by limiting management activities such as the timing of specific farm practices (e.g. ploughing, sowing or harvesting). Landscape characteristics relate to factors within the structure of the land that may influence plant growth conditions. The soil information required for Land Suitability Analysis (LSA) [4] modelling refers to the inherent factors within the soil that can either promote or constrain the growth of an agricultural commodity.

2.2.1 Soil-related Attributes

There are six main soil-related attributes that are primarily utilised for LSA modelling: soil texture, useable depth, drainage, pH, electrical conductivity and sodicity. A number of other attributes can also be used in the formulation of LSA for certain agricultural commodities, and these can be ascertained through a soil profile. The full list of soil attributes is in **Table 2**.

Table 2 Soil attributes within a soil profile

Soil attributes data (physical, chemical, morphological and biological)	
	Physical Attributes
Texture	Used to express moisture holding and porosity. Based on field observations and physical analyses from soil pits. Ranges have been averaged.
Internal Drainage	Based on factors such as soil structure, texture, organic carbon, porosity, and landscape position from field observation.
Useable soil depth	Expert knowledge of depth to rock, hardpans, aluminium toxicity, sodicity. A proxy for water holding capacity.
Depth to bedrock	Depth of soil profile to the fresh bedrock determined from field observation.
Depth of surface soil	Determined from field observation.
Depth to subsoil	Determined from field observation.
Impedance of B Horizon	Based on nature of the B Horizon (subsoil) with the overlying horizon (including texture contrast) and structure of the B horizon.
Field Capacity	The percentage of moisture remaining in a soil horizon 2-3 days after being saturated (by rainfall or irrigation) and after free drainage has ceased.
Wilting Point	The percentage water content of the soil where the plant is no longer able to extract it and therefore the plant wilts.
Water Holding Capacity	The amount of soil water that can be extracted by plant. Defined as the difference in soil moisture content between the field capacity and the wilting point. It is expressed as millimetres of plant-available water within the root zone.
Coarse Fragments	Determined from field observation.
	Chemical Attributes
pH	Chemical analysis for soil pits, existing data from soil pits, additional pH done by the State Chemistry laboratory. Ranges of values have been averaged.
EC	Field observations and chemical analyses completed for soil pits: • EC<0.15 dS/m—low and harmless • EC 0.15–0.30 dS/m—slightly higher than normal • EC 0.3–0.55 dS/m—higher than normal • EC>0.55 dS/m—unfavourable to harmful
Sodicity	From field observations and chemical analyses completed for soil pits. Measured as sum exchangeable sodium cations. Na+ can cause soil dispersion proneness. • Not sodic = <5 Na% / ECEC • Slightly sodic = 5 – 15 Na% / ECEC • Sodic => 15Na% / ECEC
	Morphological Attributes
ASC Order ASC Suborder	Australian Soil Classification Order classifies the soil according to the concentration of organic material and other chemical components (e.g. silicate clay, iron, aluminium) in the B horizon.
	Biological Attributes
Organic Carbon	Plant derived organic accumulations.

[4] The background and initial explanations of the Land Suitability Analysis (LSA) methodology can be seen in Volume 1, Chapter 4, of Sposito *et al.,* (2010a). Further adaptations of the LSA can be seen in Volumes 2 to 4 of this study (Sposito *et al*., 2010b; Sposito *et al*., 2011a; Sposito *et al*., 2011b). A more comprehensive explanation of the methodology is in the publications of *Geography Compass* (Sposito *et al*., 2010c), *Applied Spatial Analysis* (Pelizaro *et al*., 2010) and *Applied GIS* (Sposito *et al*., 2009) to which the reader is referred.

2.2.2 Available Soil Information

As an input into LSA, and other, modelling for the Sunraysia Region, the required soil layer dataset must be consistent across the region. This consistency relates primarily to the spatial (i.e. geographic) resolution that is used for mapping the data. Moreover, the information underpinning the soil data used in the construction of the layer ought to be consistent as well as valid for the defined region.

The Sunraysia Region (though it has not fully defined boundaries) describes an area in the north west of Victoria and south west of New South Wales (see **Figure 9**). The Victorian (sub-)region encompasses areas around Mildura, Merbein, Red Cliffs and Robinvale, which are all located along the Murray River. For the purposes of this study, the *defined Sunraysia Region* covers areas further to the south east in the Swan Hill and Kerang (sub-)regions (minus areas delineated as 'parks and reserves'). This delimitation is done so as to cover the wine grape production areas of the northwest which includes the Victorian areas of the 'North West Wine Zone'.

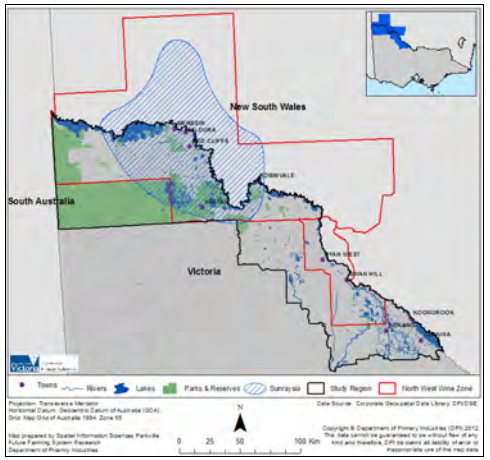


Figure 9 Overview map detailing the Sunraysia Region, the report study region and the North West Wine Zone

Several sources of soil information were identified for the defined Sunraysia Region of Victoria. The information has been primarily obtained from the Victorian Resources Online (VRO) website (DPI, 2012a) and the Victorian Soils Information System (VSIS) (DPI, 2012b). This included data at multiple levels of spatial resolution, from detailed location-specific soils survey mapping, to region-wide and/or state-wide land-system and geomorphology mapping, and point source data. Soil information for the regions into NSW is not considered within the scope of this report. The diverse information available is documented below.

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Soils Survey Mapping

The soil survey mapping available covers seven different locales along the Murray River Irrigation District. Refer to **Appendix B** for reference to location maps for each individual study. This information is at a fine scale of resolution, on average at about 1:20,000. The seven studies are listed in **Table 3**.

Table 3 Soil surveys across the study region

Soil Survey District	Year	Authors	Area (ha)
Merbein Irrigation District	1939	F. Penman, T. Marshall, P. D. Hooper, J. K. Taylor	3,500
Mildura Irrigation Settlement	1940	F. Penman, G. Hubble, J. K. Taylor, P. D. Hooper	7,000
Red Cliffs Irrigation Settlement	1941	G. D. Hubble, R. L. Crocker	5,000
Nangiloc-Colignan Irrigation Area	1986	T. Mikhail, J. Martin	11,000
Robinvale Irrigation Area	1951	J. K. M. Skene	6,000
Swan Hill Irrigation Area	1966	J. K. M. Skene, I. J. Sargeant	28,000
Torrumbarry Irrigation District	1979	I. J. Sargeant, J. W. Newell, W. I. Walbran	51,500

Land System Mapping

A *land-system* is a complex mapping unit that contains a pattern of components (e.g. soils, geology, topography) each of which has little variation in climate, lithology (rock type), landform, soil and indigenous vegetation (DPI, 2012a). Land-system mapping available for the north west of Victoria is a region-wide analysis of land-systems initially carried out in 1963. The map coverage and associated report has since been updated and revised several times for incorporation into a state-wide coverage and into more detailed mapping for the region (**Table 4**).

Table 4 Land system mapping in the study region

Map & Report Title	Year	Authors	Resolution
A Study of the Land in North-Western Australia	1963	J. N. Rowan, R. G. Downes	1:250,000
Land Systems: Mallee Area Review	1987	J. N. Rowan	1:250,000
Land Systems of Victoria	1990	J. N. Rowan	1:250,000
Land Systems of Victoria, 2nd Edition	1994	J. N. Rowan, L. D. Russell, S. W. Ransom	1:250,000
Land Systems of Victoria, 3rd Edition	2000	D. B. Rees, J. N. Rowan, L. D. Russell, S. W. Ransom	1:250,000
Disaggregation of the Victorian Mallee land systems into landform components: Final Project Report for the Mallee CMA	2010	J. Hopley, R. Clark	1:100,000

Geomorphology Mapping

Victoria's Geomorphology Framework Mapping can also inform a soil information layer for the Sunraysia Region. Refer to **Appendix B** for the map of this region. This mapping has been continued and updated by the Geomorphology Reference Group and is led by Jim Rowan in the Mallee Region. It has been carried out at a resolution of 1:250,000. The geomorphology framework is spatially-orientated and incorporates a hierarchical structure of land-unit descriptions over Victoria. This system integrates information from geomorphological, pedological and ecological fields to derive land-unit descriptions that can assist in understanding soils and other factors and their distribution state-wide.

Point Source Data

A soil information layer can also be informed by point source data, which is often supplied by soil pit and soil profile analysis. A primary source of this point source data is the Victorian Soils Information System (VSIS) (DPI, 2012b). The VSIS is a database repository for Victorian soil information, which is supplied through various soil surveys carried out state-wide. This database repository can be queried to retrieve relevant information such as chemical or physical attributes of a particular point locale. **Figure 10** shows the VSIS Map Viewer main page. There are over a hundred soil pit sites for the

Sunraysia Region in the VSIS, and if the area towards Swan Hill is added there is information on over two hundred points for the defined region.

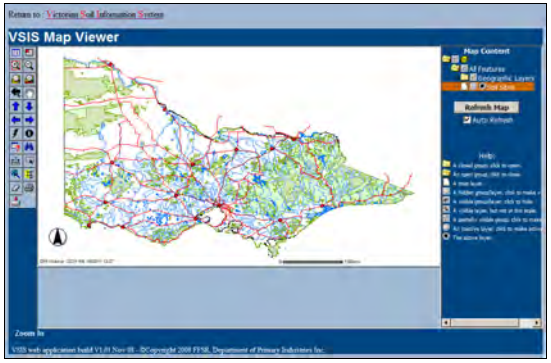


Figure 10 Victorian Soil Information System (VSIS) Map Viewer main page

Other point source data sources that can be made available could potentially come from private land owners within the irrigation districts along the Murray River, for example wineries and vineyard managers. For these districts there is a requirement for land owners to perform soil analyses on their properties, which is usually done through private consultants and contractors. In these instances data may be made available directly through the owners or from the consultancy groups. Depending on the detail that has been used in the surveys and analyses, data that may be available could include simple attribute and profile information.

2.2.3 Soil Information Gaps Analysis

Several problems and gaps can be identified in the principal sources of soil information mentioned above that prevent the generation of a useful, sound soil data layer. These will be discussed under four headings: (i) spatial resolution, (ii) location, (iii) description, and (iv) other.

(i) Spatial resolution – There are substantial differences spatial resolution of the available information. The land systems and geomorphology mapping describe a complex mapping unit which comprises several components across a broad scale, whilst the soil surveys generate information at a finer level of detail and can describe multiple soil units in a given area. In many cases, the broad scale mapping identifies a land unit that describes a large portion of a region, whereas the specific soil survey mapping identifies individual soil units that comprise the larger land unit. In the Sunraysia Region, the larger state-wide and region-wide mapping have been undertaken at a scale of 1:250,000 down to 1:100,000 in some cases. The soil surveys, by contrast, have been carried out mainly at the higher resolution of 1:20,000. Consequently, there are major variations in the detail of information available with no consistency between the resolutions of mapping.

(ii) Location - The soil surveys have been undertaken for specific areas in the study region. Predominantly, these have been done within the irrigation districts along the Murray River. Areas outside these districts have not been mapped at all or to the same level of detail.

(iii) Description - When moving from the soil survey mapping to the land systems and geomorphology mapping, a variation exists from detailed soil unit descriptions to broad land unit descriptions. In some instances, the soil units can be extrapolated into previously undescribed areas, but this is largely dependent on the land unit descriptions and consistencies (or otherwise) between the soil and land units used.

Other gaps exist in the data that has been recorded in the individual soil surveys. In the above mentioned reports, each soil unit is often described by one or more soil pits and is accompanied by a detailed soil profile description, including chemical and physical attribute data. Generally, there is consistency in the way the information is recorded in the various reports and also with current soil survey methodologies and reporting. Nevertheless, inconsistencies can arise among reports through descriptions of each individual soil unit, or soil type, which can potentially change between surveyors and/or methodologies. Overall, surveys within the same general area share soil unit names and descriptions. When the areas lose connectivity (i.e. they are not contiguous), different descriptors can arise for essentially the same soil type.

In some soil surveys there is the lack of relevant soil pit data from the published profile analyses (i.e. not all relevant attributes are described in a soil pit analysis). Likewise, some soil units are not described by a soil profile analysis; hence, in these areas there is no data to describe a soil type. This problem raises the question of soil data substitution. For example, if Survey A and Survey B describe the same soil unit but Survey B lacks adequate data, a question arises that if there can be substitution of data to describe the unit sufficiently. Similarly, if Survey A and Survey B are different in soil unit names but not in descriptions, can there be a correlation between the two. The solution of this problem is largely dependent on multiple factors, such as land unit descriptions and geomorphology, and in some instances this cannot be resolved by simply substituting pre-existing data.

(iv) Other - The inconsistencies of soil profile data detected in the individual surveys can also be seen within the application and use of VSIS soil information. Information contained in the VSIS repository is all for single point locales across the state and the database can be queried to display particular records. Problems arise when trying to relate the VSIS point data to previously described mapping units.

Point data not generated as part of a survey may or may not be representative of that part of the survey area. While individual point data is valuable information for that site, it still needs to be correlated with survey (polygonal) units in order to estimate representativeness of the point data. In some instances, this data can contradict the description that has been defined for that unit and any existing soil profile data. When applying the point source data to the broad scale units, problems can occur when several conflicting VSIS points appear within one land unit. In this situation, there is a question as to what soil pit point is more representative (or both- deciding on internal unit variability), or how can the land unit be further defined to account for these variances. For example there may be pattern of soil types within a unit, such as linear dunefields where the dominant soils are calcareous sands (ASC: Calcarosols) but an individual site on a dune may be non-calcareous (ASC: Tenosol) but still part of the dune complex.

2.2.4 Options and Resources

There are two main options that could be considered to take into account the irregularities mentioned above. The first option is to narrow the study region for undertaking LSA and other modelling to only the irrigation zones that have been adequately surveyed. The second option relates to a restructuring of the current mapping information to achieve a uniform resolution and consistency across the entire, defined (as per **Figure 9**) Sunraysia Region. [5]

[5] A relevant, current project involving soils mapping is the Digital Soil Mapping (DSM). DSM, as a field of research, is a predictive soil mapping science where computer models are used to create digital maps of soil types and soil properties. This project aims to create a digital soil map of Victoria using a raster grid format (as compared to the vector polygonal methodology, as suggested in this report). The raster grids can be as small as 30 m^2 and contain over a half dozen attributes, elevation and climate information as well as other relevant data. The project is however in its initial phases of research and trial sites/areas and a product is to be expected by approximately 2014.

Option 1: If the focus of the study region is narrowed down to only the irrigation zones, there would be a significant loss in the scope and value of the LSA modelling. Nevertheless, as discussed in **Section 2.2.2** the soil surveys do not cover the entire irrigation zones within the study region and the current information in the soil surveys is incomplete for some areas.

Therefore, some resources would need to be allocated to generate a complete soil data layer. As the majority of the soil data exists in one form or another in the smaller region, most of the work will centre upon validation of this data and creating the GIS layer. An extrapolation of soil units to join each of the individual soil surveys will then be required. Lastly, the previously unmapped irrigation regions will need to be defined. This last step will incorporate the fine scale soil surveys within the broader scale land systems and geomorphology units.

A portion of the required data may reside with private landholders, including wineries and vineyards, or with agricultural and land systems analysts and consultants. This data may be accessible through a direct approach to these landholders and consultants. Consequently, it is recommended that this approach be investigated as an initial step towards generating an adequate soli data layer.

Option 2: This option centres on the creation of a uniform soil data layer across the larger study region (see **Figure 9**). This will permit the analysis of areas previously not considered for certain types of agriculture (areas that could be used in the future) as well as exploring possible changes to agricultural land suitability (as impacted, for instance, by climate change) over time in a large geographical area. As discussed in **Section 2.2.3**, the necessary soil information lies across several differing spatial resolutions and the merging of the information into one source would require substantial more resources than those for Option 1. Ultimately, this would produce a higher scale resolution as well as LSA modelling more valuable. As mentioned above, some of this data for the broader region may also reside with private landholders or consultants.

A uniform soil data layer can be generated at a broad scale resolution of **1:100,000**, or at a finer scale of **1:50,000**. Either of these two resolution alternatives requires the disaggregation of the existing soil data from all sources - soil surveys, land systems, geomorphological, site (point) – and assembling them into small scale components that adequately describe one particular soil type or unit. This work will ensure that there is consistency in the resolution and detail of the data across all the irrigation zones as well as correlation of the existing (and new) soil data to topographic features, land forms and other landscape features.

The implementation of either Option 1 or Option 2 is mainly based on desk-top analysis, using computers and maps. A major consideration for both options is however the possibility of carrying out on-ground works within the study region. There may be a requirement to gather more soil information in the field and/or validate existing data in the soil surveys. This would require the digging of (a number of) soil pits for physical and chemical analysis

Overall, there is a greater benefit in considering a larger study region, as considered in Option 2, since this will permit the identification of suitable agricultural areas outside the current irrigation zones around Mildura. However, it is foreseen that a smaller area, as considered in Option 1, will be quicker to complete and will encompass a majority of irrigated agriculture within the defined study boundary. Knowledge of the agricultural potential of either a smaller or larger region will undoubtedly be an important consideration in any strategy for the future development of the North West of Victoria.

3. APPENDICES

APPENDIX A EVAPOTRANSPIRATION AND IRRIGATION – METHODOLOGY FOR CALCULATION AND COMPARISON WITH OTHER METHODS

One of the complexities of modelling land suitability in horticulture is dealing with irrigation. To estimate the irrigation requirements of a given crop one of the most important factors is the crop evapotranspiration.

Penman-Monteith

The well-known Penman-Monteith (PM) equation is the best method of estimating reference evapotranspiration (Khoob, 2008; Wang *et al*., 2008). The Food and Agricultural Organisation of the United Nations (FAO) adopted the original PM equation in combination with equations for the aerodynamic resistance and surface resistance to produce a standardised FAO PM equation. The method overcomes shortcomings of the previous FAO method and provides values that are more consistent with actual crop water use data worldwide (Allen *et al.,* 1998).

Hargreaves

However, problems can arise in the use of the FAO PM equation when meteorological data, such as relative humidity data, wind speed data and vapour pressure data are missing. The absence of data can prevent the application of the FAO PM equation since not all variables can be input into it.

Alternate equations do exist for the estimation of evapotranspiration that only utilise a minimal set of variables. One key equation, which like the PM equation has been standardised by the FAO, is the *Hargreaves equation* (Hargreaves and Samani, 1985). The only variables that are required for input are maximum, minimum and mean temperatures, and solar radiation. This equation allows for the calculation of evapotranspiration for both present situations using SILO data and for future scenarios using OzClim data[6, 7].

Analytical Neural Networks

Another alternate method, other than the FAO PM and FAO Hargreaves equation for the estimation of evapotranspiration that was explored was the use of *Artificial Neural Networks* (ANN). ANN techniques have previously been demonstrated useful in situations where data is limited (Sudheer *et al*., 2003; Kisi, 2007; Chauhan and Shrivastava, 2008; Wang *et al*., 2008). Landeras *et al*. (2008) highlighted the necessity of application of an ANN in modelling a non-linear process such as evapotranspiration and, after comparing seven ANN models against various locally calibrated reference evapotranspiration equations, they concluded that ANN-based models were generally more reliable than the locally-calibrated equations. In all of the above-sited studies, ANN models were developed using fewer predictors than required by Penman-Monteith (PM) equations.

[6] SILO data already contain daily observations for evapotranspiration using the FAO PM equation. There are also available relative humidity observations but no wind speed observations. However, OzClim data do not contain the FAO PM observations and the relative humidity observations are measured in a different fashion to the SILO observations. For this reason, the FAO Hargreaves equation provides a consistent measure of evapotranspiration between present and future scenarios as the same equation with the same basic four inputs can be used for both time frames.

[7] OzClim predictions for future scenarios are given in a monthly format, rather than in SILO where observations are given in a daily format. In these instances, where required, values can be converted from monthly to daily or vice-versa.

Comparison of Results

For each technique available, the FAO PM equation, the FAO Hargreaves equation and the ANN, outputs were calculated (**Figure A1**). The outputs were based on the ten year baseline (1996-2005) for the defined Sunraysia Region. All inputs into each of the equations were obtained through SILO as text files which were obtained through the Department of Natural Resources and Mines, Queensland, in conjunction with the BoM weather recordings.

When compared against the FAO PM observations, the ANN results did produce a comparable output, though this was also comparable with the FAO Hargreaves outputs. Major differences were seen in the south eastern areas of the study region. The differences for each output were minimal, the FAO PM ranged from 1,306 to 1,465 mm, the FAO Hargreaves ranged from 1,313 to 1,446 mm whilst the ANN ranged from 1,370 to 1,463 mm. When comparing these ranges against one another it can be seen that there are only slight differences between the minimum and maximum values – about 70 mm in the minimum and 20 mm in the maximum.

From this it was concluded that the ANN was a comparable estimator of evapotranspiration to the established FAO PM equation. However, the overall complexity and time it took in setting up the ANN network and the fact that predicted values would change every time the network was run outweighed its usefulness compared to that of the simplicity of the FAO Hargreaves equation. Therefore for application in the Sunraysia Region, the FAO Hargreaves equation was utilised and this is reported in the body of the text.

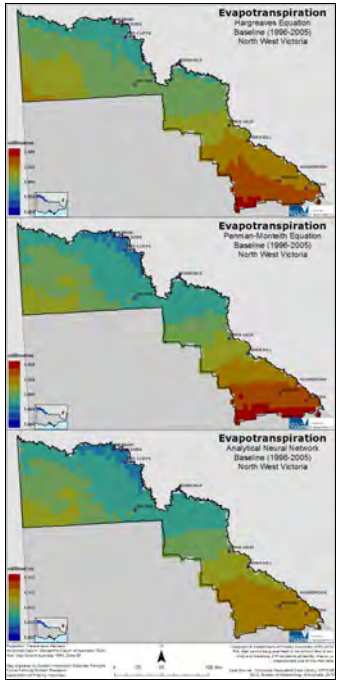


Figure A1 **Evapotranspiration outputs for 3 different methods – FAO Hargreaves equation (top), FAO PM equation (centre), Analytical Neural Network (bottom)**

APPENDIX B SOIL SURVEY, LAND SYSTEMS AND GEOMORPHOLOGY MAPS

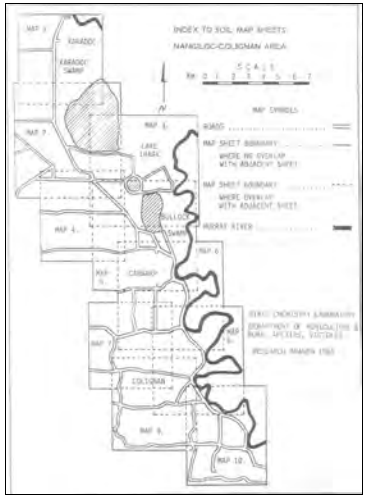


Figure B1 **Index mapsheet to soil survey mapsheets for the Nangiloc-Colignan Area**
Source: Mikhail & Martin, 1986; DPI, 2012a

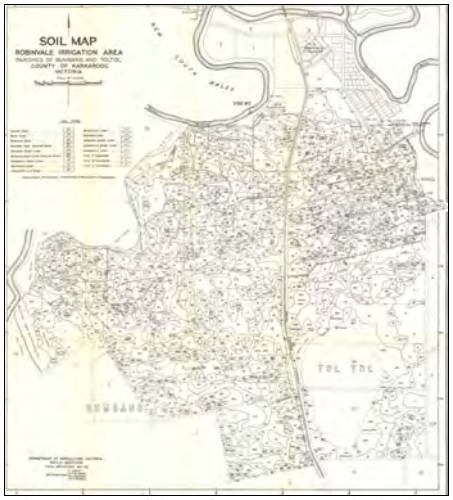


Figure B2 **Soil map for the Robinvale Irrigation Area**
Source: Skene, 1951; DPI, 2012a



Figure B3 **Soil survey map for the Mildura Irrigation District**
Source: Penman *et. al.*, 1940; DPI, 2012a

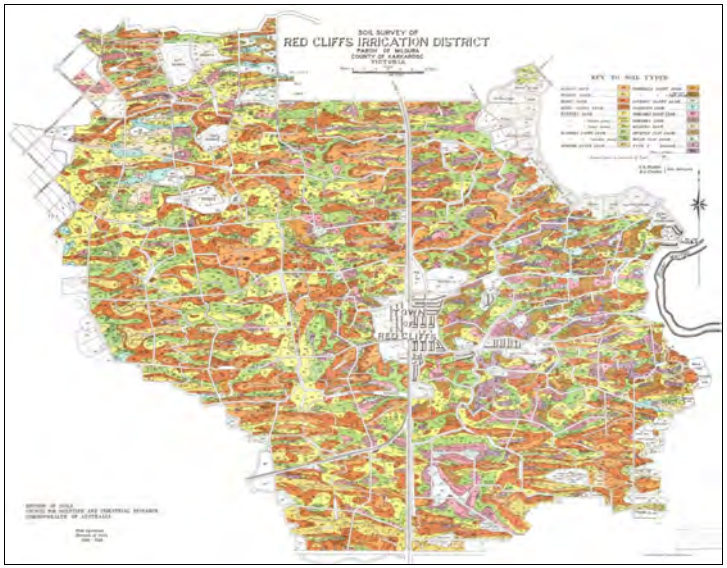


Figure B4 **Soil survey map for the Red Cliffs Irrigation District**
Source: Hubble & Crocker, 1941; DPI, 2012a

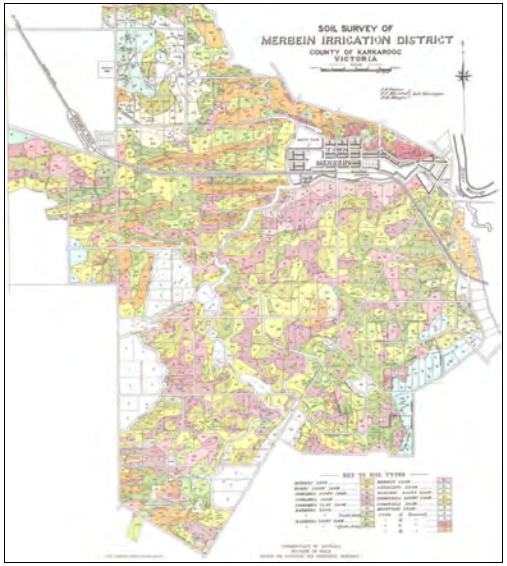


Figure B5 **Soil survey map for the Merbein Irrigation District**
Source: Penman *et. al.*, 1939; DPI, 2012a

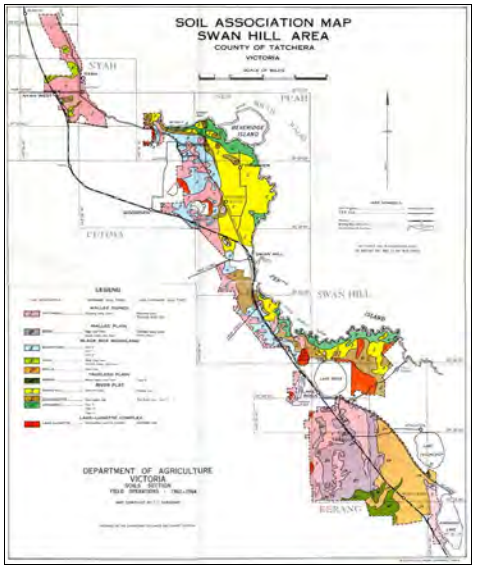


Figure B6 **Soil association map for the Swan Hill Area**
Source: Skene & Sargeant, 1966; DPI, 2012a

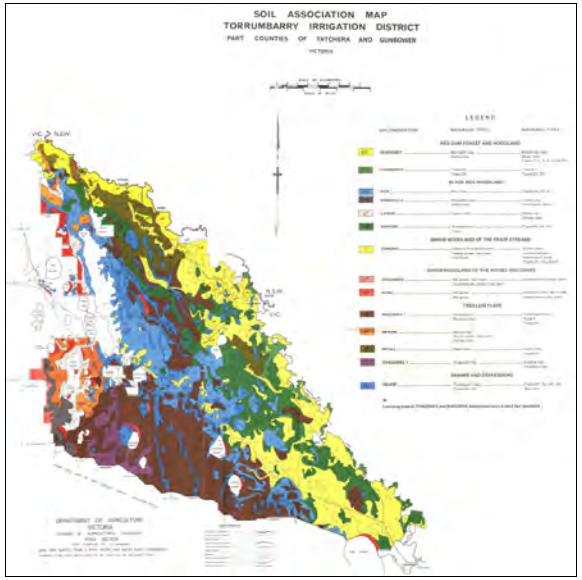


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Source: Sargeant *et. al.*, 1978, 1986; DPI, 2012a

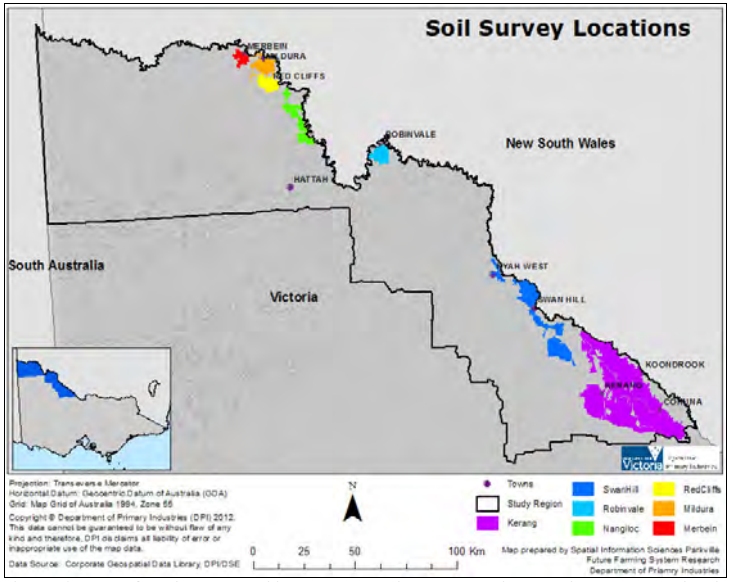


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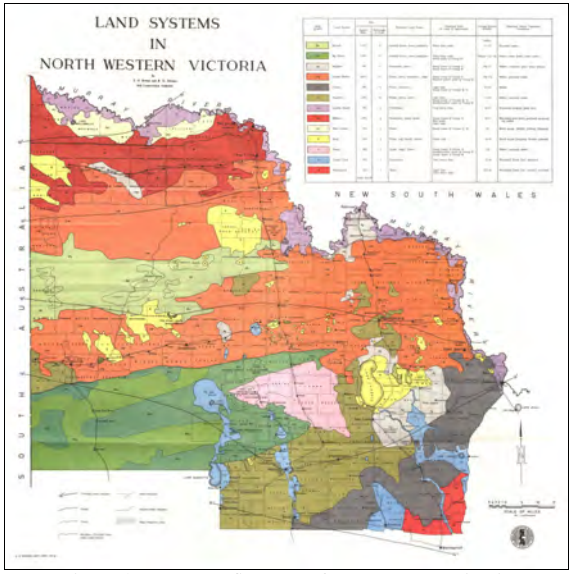


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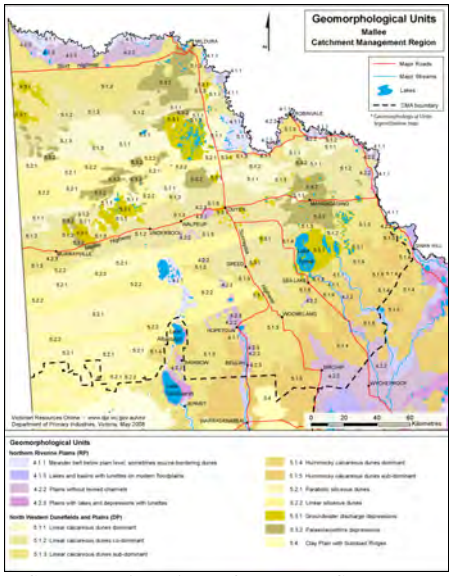


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Source: DPI, 2012a

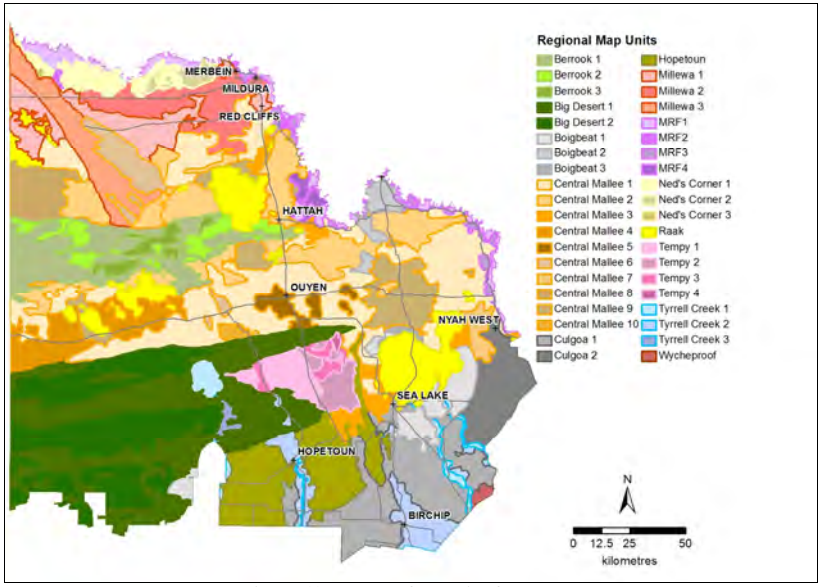


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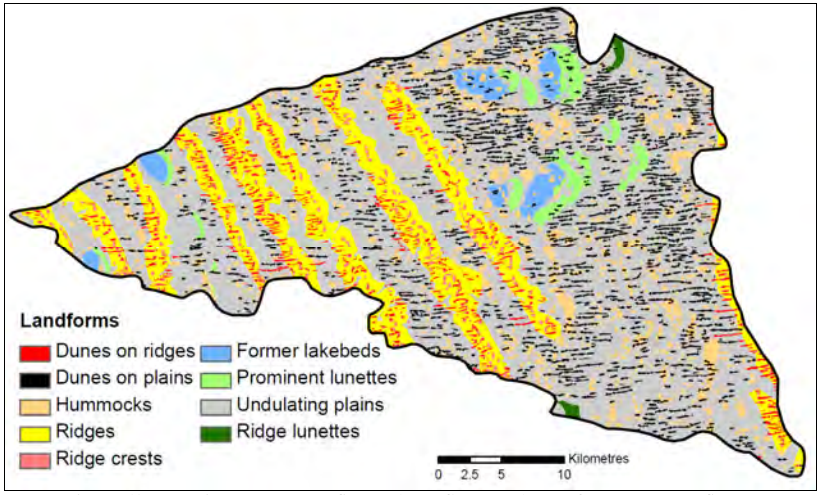


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Source: Hopley & Clark, 2010

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WINE GRAPE PRODUCTION IN THE GOULBURN BROKEN REGION, VICTORIA, AUSTRALIA

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DEPARTMENT OF PRIMARY INDUSTRIES

CLIMATE CHALLENGES FOR HORTICUTURE IN THE GOULBURN BROKEN REGION

WINE GRAPE PRODUCTION IN THE GOULBURN BROKEN REGION, VICTORIA, AUSTRALIA

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FUTURE FARMING SYSTEMS RESEARCH DIVISION
VICTORIA, AUSTRALIA

2012

EXECUTIVE SUMMARY

This report is part of the project *Climate Change Impact Modelling in Horticulture*. It covers the assessment of the likely climate change impacts on viticulture (wine grapes) in the Goulburn Broken Region through a DPI methodology based on Biophysical Land Suitability Analysis.

Regional Climate Change Projections for the Goulburn Broken Region
Climate change projections for Goulburn Broken, under the IPCC A1FI (high global warming) scenario, indicate: (i) an increase in mean temperature of 1ºC (by 2030) to 1.5ºC (by 2050) from the baseline (average climate in 1996-2005) with a maximum of 2.5ºC between the baseline and 2050; (ii) a decrease in total rainfall of 5 mm to 500 mm between succeeding time periods, with a maximum decrease of around 50 mm in the irrigation districts and over 300 mm in the southern areas between the baseline and 2050.

Two important indicators of wine production are heat degree days (HDD) and spring frost index (SFI). The HDD classifies the climate of a wine growing region, with the resultant mapping output divided into five production regions. Application of HDD to Victoria places Region V in the North West, around Mildura. Under climate change projections, Region V moved progressively south, alternating with Region I and II across the central part of the state. Projected HDD for 2050 showed a substantial reduction in the size of Regions I and II with a concomitant increase in the size of Regions IV and V.

The SFI is a measure of an area's tendency to produce large variations in temperatures in a short period of time. Temperature variability affects grapevine phenology and production. In particular, frost damage to berries is a major problem during spring growth and ripening periods. Currently, areas of northern Victoria have a high SFI, whilst areas south of the Great Dividing Range have a low SFI. SFI projections for 2050 indicate a reduction in areas with high frost risk. This reflected projected increases in both mean and minimum temperatures across Victoria.

Evapotranspiration and irrigation requirements in Goulburn Broken for the baseline, 2030 and 2050 were compared. The results showed: (i) an increase of between 30 mm to 150 mm in evapotranspiration, with a maximum of 210 mm difference between the baseline and 2050; (ii) an increase of between 5 mm/ha to 70 mm/ha in irrigation to 2030 and 50 mm/ha to 110 mm/ha to 2050.

Viticultural Biophysical Land Suitability Analysis (LSA) in Goulburn Broken
Biophysical LSA modelling assumed that: (a) the whole region is potentially available for wine grape production (minus protected areas under native vegetation), and (b) no introduction of adaptive production strategies. The analysis showed that land suitability for wine grape production is likely to decline with a shift from a high (i.e. greater than 80% suitable) to a moderate (i.e. 50-70% suitable) suitability by 2050, particularly in southern parts of the region. The higher suitability-ranked land in the north is also likely to reduce in size, but by 2050, about two thirds of the land in northern areas would still remain within the higher suitability categories for wine grape production. Areas to the east of Seymour would potentially retain a high suitability ranking by 2050, even as the surrounding areas decline. The largest changes in land suitability would occur in the southern districts, in particular around Kilmore, Yea, Alexandra and Mansfield.

These results were compared with the HDD Regions. The comparison depicted how HDD Regions may change by 2050 and how they influence resulting LSA model outputs. Grape Production Regions I to IV were identified in the baseline. Regions I and II, in the south of the study region, correlated well with high ratings of suitability at 90%, particularly Region I. Regions III and IV occurred in the north; these regions are associated with lower suitability ratings. By 2050, there was a projected southward shift of all the identified regions, with the northern half of Goulburn Broken projected to be within Region V. This southerly retraction and the inclusion of Region V reflect reductions in land suitability across Goulburn Broken.

While the combination of shifting land suitability, as indicated by LSA, and modifications in the HDD Regions that indicate changes in the potential for wine grape production in the Goulburn Broken Region, much of the production area within this region will remain suitable for wine grape production into the foreseeable future; notwithstanding competition for other land uses.

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An *Experimental Pre-schedule* meeting to discuss various aspects of the overall project methodology was conducted under the chairmanship of Kim Lowell. This focused, in particular, on the initial application of the methodology on land suitability modelling for pears, but the flow-on effects from the pre-scheduling are also reflected in this report. The Project Team are indebted to the participants and Lowell for their valuable contributions. They were: Pam Strange, Horticulture Climate Adaptation Manager (representing Graeme Anderson – DPI Farm Services Victoria); and Mohammad Abuzar, Kurt Benke, Michael Hurley, Mark Imhof, Esther Liu, Christopher Pettit, Subhash Sharma, Kathryn Sheffield and Falak Sheth all from the FFSR Division.

1. INTRODUCTION

This report is a component of the project *Climate Change Impact Modelling in Horticulture* (CMI 102313; MIS 08444) developed by the Future Farming Systems Research (FFSR) Division of DPI over a 4-year period (2008/09 - 2011/12). The project investigates the likely impacts of climate change on Victorian perennial horticulture, and possible adaptation options to respond to the potential impacts. This report covers the assessment of the impacts on viticulture (wine grapes) in the Goulburn Broken Region through a novel DPI methodology that has Land Suitability Analysis (LSA) at its core. The years examined are 2030 and 2050 and, for comparison purposes, a baseline, year 2000 (defined as the average climate in the period 1996-2005).

1.1 PROJECT OUTCOME

Researchers and policy makers in industry and government enabled to develop strategic and tactical (i.e. operational) options that maximise opportunities for perennial horticulture to adapt to climate change in Goulburn Valley and Sunraysia regions of Victoria.

1.2 PROJECT BACKGROUND

Agriculture and its key industries, particularly horticulture, are being exposed to rapid and intensive transformations associated with the impacts of various drivers of change. The main driving forces include: globalisation, modifications in markets and trade, climate change, competition for natural resources (land and water), socio-cultural and organisational change. Climate change is of particular importance - aside from biodiversity, agriculture is the most vulnerable sector to the impacts of climate change (Stokes & Howden, 2010). Therefore, the future development of agriculture will be dependent on its ability to respond to these complex challenges. The Victorian Government, through DPI, has a key role to play in assisting agriculture and its horticultural industries to analyse, plan and respond to those challenges, but also to ensure that the valuable natural resource base of the state is conserved for the future. The success of the planning, adaptation and mitigation activities could determine the well-being of Victorian regions and their rural communities in an uncertain and risky future.

Guiding systemic change within the agricultural sector will require sound research, evidence-based policy development and targeted action. Understanding how the rapid and intense transformations will impact on farming systems and their long-term viability is thus a key factor in formulating successful adaptation strategies and measures for agriculture and its horticultural industries.

Developing an understanding of the complex changes and potential impacts on agriculture (within a regional context) requires the design and application of innovative modelling approaches. They must be formulated to support existing policy development and decision-making processes and be flexible to respond to a multiplicity of possible futures. Therefore, any new modelling approach must have a strong route to market and be capable of managing new information as well as connecting biophysical data with modelled data, visualisation and communication tools.

1.3 PROJECT OBJECTIVES

Within the context of the project, specific objectives were:

1. Assess the climate change impacts on: (i) pome fruits - pears, (ii) pome fruit - apples (three varieties), (iii) viticulture - wine grapes, and (iv) stone fruit (peaches and nectarines) in the Goulburn Broken Region.
2. Develop climate change projections for the Goulburn Broken and Sunraysia Regions for three marker IPCC SRES scenarios – B1 (low global warming), A2 (medium global warming) and A1FI (high global warming).
3. Analyse the potential land suitability changes in the study regions, up-to the year 2050, for the horticulture industries mentioned in Objective 1.
4. Examine the likely climate impacts on surface and ground water (hydrological) resources, including the impacts on and opportunities for the use of water recycling schemes, in the study regions.
5. Assess the key gaps in the soil information for the Sunraysia Region for use in LSA and other relevant modelling (see the complete text in Section 1.4, below).
6. Assess the likely impacts on water availability for wine grape production in the Sunraysia Region (see the complete text in Section 1.4, below).

The assessment of climate change impacts, and the analysis of potential land suitability changes, on pome fruits - pears and apples (parts of Objectives 1 and 3) and Objectives 2, 5 and 6 were reported previously. This report addresses the assessment of climate change impacts, and the analysis of potential land suitability changes, on viticulture – wine grapes (part of Objectives 1 and 3).

1.4 THE GOULBURN BROKEN REGION

The Goulburn Broken Region (defined as the geographic area under the jurisdiction of the Goulburn Broken Catchment Management Authority – CMA), in northern Victoria, Australia, covers an area of approximately 24,800 square kilometres, or about 10.5 % of the state's total area; the region is part of the Murray Darling Basin (MDB). It is home to approximately 181,000 people, with around 40% of the population living in rural areas. The major cities and towns in the region include Shepparton, Benalla, Cobram, Kyabram, Mangalore, Mansfield, Mooroopna, Nathalia, Numurkah, Seymour, Tatura, Yarrawonga, and Yea.

The region is considered by many as the food bowl of the MDB. The main primary industries are horticulture, dairy, cropping, viticulture, wool, forestry and grazing of both sheep and cattle. Goulburn Broken also supports a large fruit and vegetable food processing industry centred on Shepparton. The production of timber is also an important regional employer. Tourism is increasingly significant to the region. In the southern regional areas, easy access to Melbourne provides numerous options for tourism and recreational activities. In the northern regional areas, the Murray River is a strong tourist attraction.

Major land uses in the Goulburn Broken include dryland agriculture (about 58 %). irrigated agriculture (about 8%). Native forests (26%) plantations forests (1%), urban uses (4%) and water bodies (2%).

The majority of wine grape production in Victoria is in the North West of the state, comprising the Murray Darling and Swan Hill Wine Regions (**Figure 1**). In these regions, production accounts for over 70% of Victorias total with Chardonnay, Cabernet Sauvignon and Shiraz being the majority of grapes that are grown. The Central Victorian Zone, which is mainly centred on the Goulburn Broken Wine Region, is the second largest producer of wine grapes at 9% of the Victorian total production.

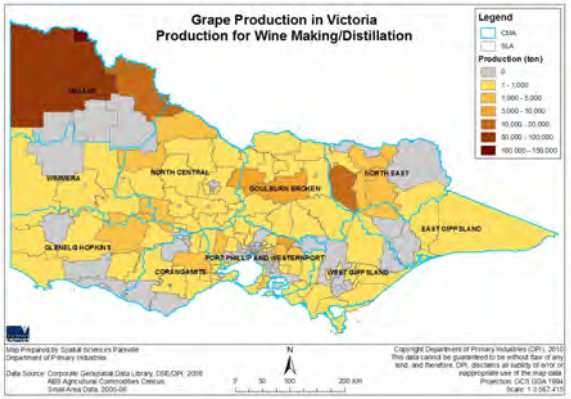


Figure 1 **Total grape production for winemaking purposes in Victoria**
Source: Australian Bureau of Statistics (2009)

In 2008 Australia produced 1,956,794 tonnes of grapes of which 1,837,034 tonnes of grapes were for winemaking purposes. Of this, the three major varieties of wine grapes were Shiraz (about 26%), Chardonnay (about 19%) and Cabernet Sauvignon (about 14%). Other important wine grape varieties in the Australian market are Merlot and Semillon, which account for 7% and 5% of production. In the Goulburn Broken Region, some of the major varieties, such as Shiraz, Cabernet Sauvignon and Chardonnay, have increased in production from 2002 to 2005 (**Table 1**). This rise is also mirrored in overall production across Victoria for these, and other, wine grape cultivars.

Table 1 **Grape production for winemaking (tonnes), by selected varieties. Goulburn Broken Region compared with Victoria, 2002-2005**

Year	2002		2003		2004		2005	
	GB	Vic	GB	Vic	GB	Vic	GB	Vic
Shiraz	3,317	49,897	3,097	45,894	5,571	63,750	6,406	64,789
Cabernet Sauvignon	2,259	50,916	2,033	40,344	3,488	50,912	2,965	51,025
Merlot	828	28,292	923	24,405	1,284	30,423	1,266	34,329
Pinot Noir	686	5,487	956	8,553	1,468	14,263	1,167	11,724
Verdelho	132	1,045	139	1,000	222	1,192	186	1,332
Chardonnay	2,851	67,371	2,607	62,455	3,560	81,612	4,008	98,211
Sauvignon Blanc	980	5,644	636	4,111	1,596	7,813	1,367	7,899
Riesling	406	3,976	434	3,295	581	4,178	822	4,452
Semillon	244	11,647	186	7,778	316	9,802	218	11,164
Cabernet Franc	199	653	131	822	130	594	121	518
Marsanne	469	627	408	547	528	757	445	627

Source: Australian Bureau of Statistics (2011)

2. Climate Change Projections

2.1 The Earth's Climate System

Recent and future human-induced (or anthropogenic) changes to the Earth's climate system have to be considered in the context of natural climate alterations. The climate results from the systemic interaction of many components: the ocean, atmosphere, cryosphere and biosphere (Flannery, 2005). Although the climate system is ultimately driven by the external solar energy, changes to any of the internal components, and how they interact with each other as well as the variability in the solar radiation received from the Sun, can lead to changes in climatic conditions. These influences are often considered as 'forcing' changes to the energy inputs and outputs that result in modifications in the climate. On the longest time scales are mechanisms such as geological processes and the changes in the Earth's orbit relative to the Sun. The latter is believed to be the mechanisms underlying the cycle of ice ages and inter-glacial periods. Geological processes can also work on a much shorter time scale through volcanism (IPCC, 2007a).

Human activity has modified and continues to modify the Earth's surface on a very large scale through urbanisation, deforestation, forestation, cultivation, irrigation, mineral extraction, drainage and flooding. These modifications in land cover change the surface short-wave reflectivity and hydrological thermal properties of the land surface. Therefore, the crux of the *enhanced greenhouse effect* is that human modification of the atmospheric concentration of the key radiation-absorbing gases and various halocarbons since the Industrial Revolution (around 1750, which is widely regarded as the threshold of dangerous change) has resulted in a 'radiative' forcing of the climate system. Those increases are unprecedented in the Earth's history. As a result of higher green house gas (GHG) concentrations, global average surface temperature has increased by about 0.7ºC during the 20th century with the 1990s as the warmest decade on record. These averages mask, however, larger regional variations. For instance, higher latitudes have warmed more than the equatorial regions (IPCC, 2007a).

World renowned climate scientists have explored various scenarios of future GHG and aerosols emissions (called SRES scenarios – Special Report Emissions Scenarios) based on assumptions about future demographic, economic, land use, and science and technological changes (Nakicenovic and Swart, 2000). Advanced computer models of the climate system, driven by these emissions scenarios, are deployed to formulate climate change projections. All models simulate further global warming, but the magnitude depends on the emission scenario examined and the response of each climate change model. The best, and latest, estimates and *likely* ranges for globally average surface air warming at the end of the 21st century in the SRES low 'marker' scenario is 1.8ºC (*likely* range 1.1ºC to 2.9ºC) and the best estimate for the high marker scenario is 4.0ºC (*likely* range is 2.4ºC to 6.4ºC) (IPCC, 2007a) [1].

[1] The standard terms used in IPCC reports to define the likelihood of an outcome, or result, where this can be estimated probabilistically are: (i) *virtually certain* > 99% probability of occurrence; *extreme likely* > 95% probability; *very likely* > 90% probability; *likely* > 66% probability; *unlikely* < 33% probability; *extreme unlikely* < 5% probability. Most of the values given in IPCC report are assessed best estimates and their uncertainty ranges are 90% confidence intervals (i.e.; there is an estimated 5% likelihood of the value below the lower end of the range of above the upper end of the range (Solomon et al., 2007, p. 23).

2.2 CLIMATE PROJECTIONS FOR VICTORIA

CSIRO and the Bureau of Meteorology (BoM) published new climate change projections for Australia and its States in October 2007 (CSIRO and BoM, 2007). The report, *Climate Change in Australia*, provides the information on observed climate change in the country and its likely causes, as well as updated projections of change in the key climatic variables and other aspects of climate that can be expected over the coming decades. Projections are formulated for the years 2030, 2050 and 2070[2]. Climate change projections for Victoria indicate the following.

- Average temperatures will increase by around 0.9°C by 2030, with a range of 0.6-1.2°C. By 2070 this increase is projected to be around 1.5°C (range of 1.0-2.0°C) under a low emissions scenario (B1) or around 3°C (range of 2.0-4.0°C) under a high emissions scenario (A1FI).
- The chance of at least a 1°C warming in 2030 is around 20-30%. This rises to 80-90% for the 2070 low emission scenario and over 90% for the 2070 high emission scenario. There is a 1-10% chance of a 2°C warming for the 2070 low emission case and 80-90% for the 2070 high emission case.
- As per previous projections (CSIRO, 2004), annual, winter and spring rainfall is likely to decrease, whereas changes in summer and autumn rainfall are less certain. By 2030 annual rainfall is projected to decrease by around 5% (range of 0-10%) relative to the climate of the past century. By 2070 the change is projected to be a decrease of 5-10% (with a range of 0-20%) under a low emission scenario, or 10-20% (with a range of +5 to -30%) under a high emission scenario. Extreme daily rainfall is less affected by the drying tendency and may increase.

The chance of an annual average decrease of at least 10% increases over time. There is a 1 to 10% chance by 2030, 20-30% by 2070 for the low emission case, and 50-60% by 2070 for the high emission case.

2.3 CLIMATE PROJECTIONS FOR THE GOULBURN BROKEN REGION

Average Temperature [3,4]

Mean temperatures for the Goulburn Broken Region are shown in **Figures 2**, **3** and **4**, where the annual average temperature for the baseline (period 1996-2005), 2030 and 2050 are detailed. Baseline mean temperature ranged from 6.5ºC to 16ºC, with a projected range between 7ºC to 17ºC by 2030, whilst the range is between 8ºC to 18.5ºC by 2050. Overall, there is a 1ºC to 1.5ºC projected increase between each time period with a 1.5ºC to 2.5ºC difference between the baseline and 2050. Projected changes are more pronounced in the northern areas where by 2030 projections indicate an increase of 1.15ºC against the baseline

[2] Due to the scope of this report, only a succinct overview of the key projections for Victoria is presented in this section. The interested reader is therefore referred to the original publication of CSIRO and BoM (2007).

[3] Climate data for historical observations were sourced by the Department of Natural Resources and Mines, Queensland, in conjunction with the Bureau of Meteorology (BOM) weather recordings, through their SILO program (Department of Natural Resources and Mines, 2010). These data are produced as text files which then can be presented in a map grid at a resolution of approximately 5 square km (grid) (0.05^0).

[4] The future climate scenarios for the years 2030 and 2050 were generated using the CSIRO's Atmosphere-Ocean Global Circulation Model (AOGCM) *CSIRO-Mk3.5* model and the IPCC SRES A1FI (extreme change) scenario. This climate scenario provided the spatial spread of the needed climatic factors at a resolution of approximately 5 square km (grid) (0.05^0).

and a 2.5ºC increase into 2050. Compared against the southern areas through to 2030 there is a likely 1ºC increase and a 2ºC by 2050.

Total Rainfall

Total rainfall for the region is shown in **Figure 5** to **Figure 7**, where the total annual rainfall for the baseline (period 1996-2005), 2030 and 2050 are detailed. In the baseline, rainfalls ranged from 345 mm to 1,740 mm, by 2030 this rainfall range is from 340 mm to 1,255 mm and by 2050 the range is from 290 mm to 1,095 mm. Overall, there is a projected decline in rainfall amounts form 5 mm to 485 mm between each period with a 55 mm to 645 mm difference between the baseline and 2050. Projected declines in total annual rainfall are more pronounced in the southern regional areas where into 2030 projections indicate a decrease of over 150 mm against the baseline and over a 300 mm decrease into 2050. Compared against the northern areas where into 2030 there is a likely decrease of 5 mm and a 55 mm decline by 2050.

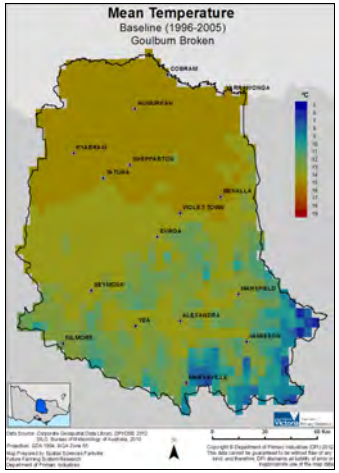


Figure 2 **Mean Temperature for the Goulburn Broken in the baseline (1996-2005)**

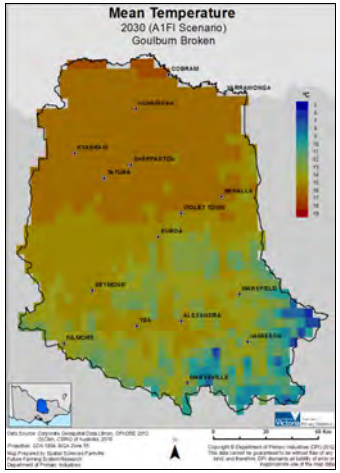


Figure 3 **Mean Temperature for the Goulburn Broken in 2030 (A1FI Scenario)**

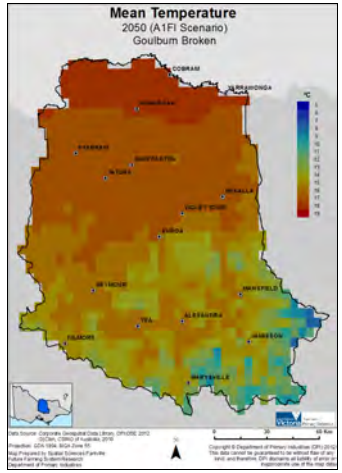


Figure 4 **Mean Temperature for the Goulburn Broken in 2050 (A1FI Scenario)**

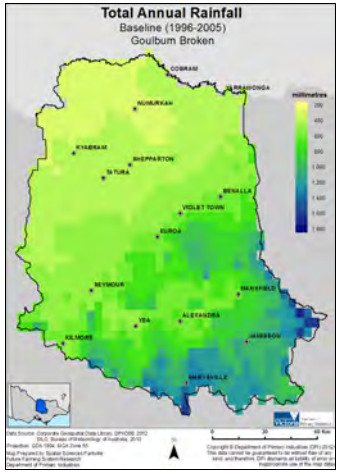


Figure 5 Total Annual Rainfall for the Goulburn Broken in the baseline (1996-2005)

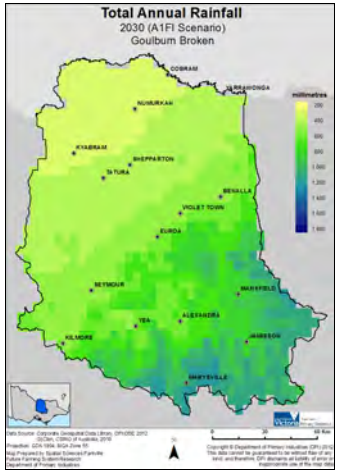


Figure 6 Total Annual Rainfall for the Goulburn Broken in 2030 (A1FI Scenario)

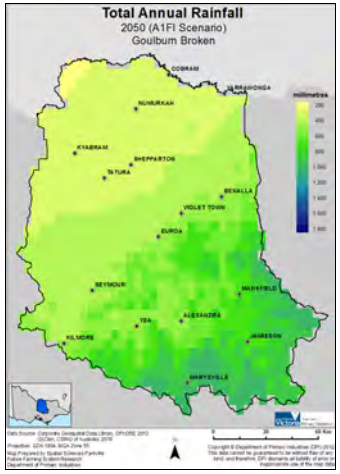


Figure 7 Total Annual Rainfall for the Goulburn Broken in 2050 (A1FI Scenario)

2.4 Climate Implications for Plant Growth

The geographic (spatial) distribution of plant species, vegetation types and agricultural cropping patterns demonstrate the strong influence that climate has on plant growth. Solar radiation, temperature and precipitation (in turn impacting on water availability), and seasonal patterns are key determinants of plant growth through a variety of direct and indirect effects. Other climatic characteristics are also major influences, such as wind speed and storm intensity and frequency. Plant function is inextricably linked to climate and atmospheric carbon dioxide (CO2) concentrations. On the shortest and smallest temporal and spatial scales, the climate affects the plant immediate environment and thus directly affects physiological processes. On longer and larger time and space scales, climate influences species distribution and community composition as well as determines what crops can be viably produced in managed agricultural and forestry ecosystems. Plant growth also influences the local, regional and global climate through the exchanges of energy and gases between the plants and the air around them (Morison and Morecroft, 2006).

There are a rapidly growing number of well-documented instances of change in ecosystems due to recent (and most likely human-induced) climate change (Callaghan *et. al.*, 2004; Steffen *et. al.*, 2004; Millennium Ecosystem Assessment, 2005; Stephen, 2009). Overall, the Intergovernmental Panel on Climate Change (IPCC, 2007b) concluded that "from collective evidence, there is high confidence that recent regional changes in temperature have had discernible impacts on many physical and biological systems". These recent climate changes are likely to accelerate as human activities continue to perturb the climate system and many reviews have made predictions of serious consequences for ecosystems.

Climate change poses major scientific and practical challenges. Our comprehension of plant responses to future climate has to be built on a better understanding of the climate system itself, especially at the regional scale. Plant production has to be maximised to overcome the new, or altered, climatic conditions on food and fibre production in the face of continuing population growth, but this ought to occur in a sustainable way. The sustainability of agricultural and forestry production systems needs to be improved by reducing GHG emissions from land use and the use of fossil fuels and by reducing water and nutrient consumption. The management of natural resources have to be adjusted to conserve biodiversity in changing environmental conditions.

3. Climate Change and the Viticultural Industry

Of the agricultural industries, the cultivation of wine grapes is one of the most sensitive to climate. It is therefore important to examine the possible climate change impacts, especially because wine grape production takes decades to pay-off the extensive capital investment needed in vineyards and wineries. Australia is fortunate to be among the Southern Hemisphere wine-producing countries where the projected climate change effects would be less than for the Northern Hemisphere. Already, some wine producing companies in Spain are buying land at a higher altitude and in cooler regions, so that they might be well prepared to shift production in the future (Smart, 2006).

Climate is seen a major driver of both end-quality and maturation of wine grapes. A study on the likely climate change impact on the phenology of wine grapes in Australia by Webb *et al*. (2008a) found that a warming climate will have a negative impact on wine grape quality if no adaptive production strategies are implemented. These results agreed with an earlier study by Jones *et al*. (2005). Webb *et al*. (2008a) also found that without adaptation, wine grape quality may be reduced at the national level in Australia by 7% to 39% by the year 2030 and by 9% to 76% by the year 2050 (all uncertainties considered).

3.1 Temperature

Temperature, as a climatic factor, is one of the major determinates of winegrape phenology and maturity (Pearce & Coombe, 2004). Although wine grape phenology is also influenced by soils, landscape and water availability, grapes are particularly sensitive to impacts of climatic changes due to the fundamental link between climate, temperature and end-quality of the grape. In a broad sense, the grape vine is a temperate-climate species. It cannot tolerate extreme winter cold and it requires a warm to hot summer for the maturation of its fruits. Vine phenological processes respond more or less linearly from a mean temperature of about 10ºC (below which no growth occurs) to around 16-17ºC, after which the response slows (Gladstones, in Dry and Coombe, 2005).

3.2 Heat Degree Days

As reported by Gladstones (1992), there is a broad association between average mean temperature and the styles of wine produced. The mean temperature is a key influence on the heat degree day summation, which is a method used for classifying the climate of a wine growing region. The method was created by Amerine and Winkler (1944) for wine production in California, but has been successfully applied in a number of regions worldwide. Amerine and Winkler based their temperature summation system on that developed in France by de Candolle, which relied on the observation that vines start active growth in the spring when mean air temperature reaches about 10ºC (Gladstones, 1992). The method is a summation of degree days over a seven month growing period. Degree days for this method are calculated by taking away 10ºC from the mean air temperature, this value is then summed over each day of the growing period. The resultant output can then be broadly divided up into five regions for grape production based on the degree day values. According to Amerine and Winkler, the grape production regions are defined as:

- Region I – less than 1370 dayºC
- Region II – 1370 – 1650 dayºC
- Region III – 1650 – 1930 dayºC
- Region IV – 1930 – 2200 dayºC
- Region V – greater than 2200 dayºC.

This can give indication of the wines types that can be best produced in these regions. Thus, Region IV is considered to be best for sweet dessert wines, whilst Region III produces full-bodied dry wines and some of the port-type wines. Region I & II are regarded as the best for table wines. Region V is considered to be suitable mainly for fresh and drying grapes, and for bulk table wines of lower quality.

Figure 8 is the resultant mapping output for Victoria (with corresponding regional divisions) over the baseline period. The majority of the northern regional areas are within Region V, with Region IV seen in the south towards Swan Hill. In the north of Goulburn Broken, around Shepparton, there are two distinct Regions that are identified; Region III and IV. As we move towards the southern highlands of Goulburn Broken, this changes into Regions I and II. This changes progressively down into the south of Victoria, with an alternating Region I and II across the central region from East to West.

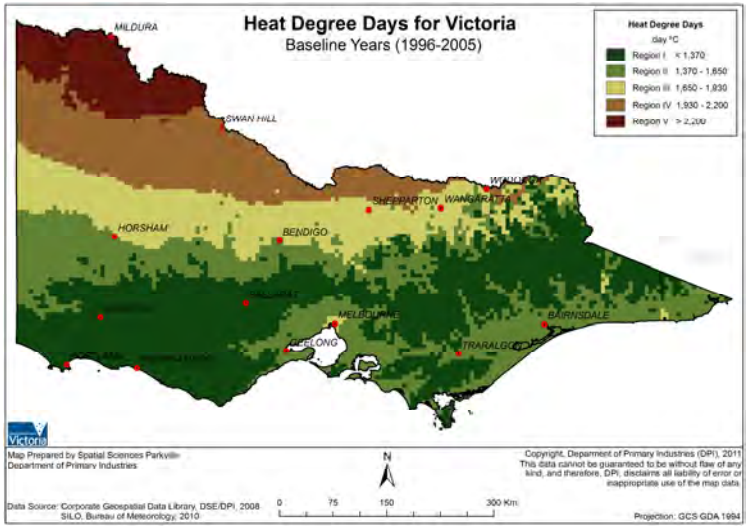


Figure 8 **Heat Degree Days for Victoria – Baseline Years (1996 – 2005)**

Figure 9 is the projected output for the year 2050. The comparison of **Figure 8** and **Figure 9** shows that a substantial reduction in the size of Regions I and II would occur with a concomitant increase in the size of Regions IV and V clearly reflecting projected increases in temperature across Victoria.

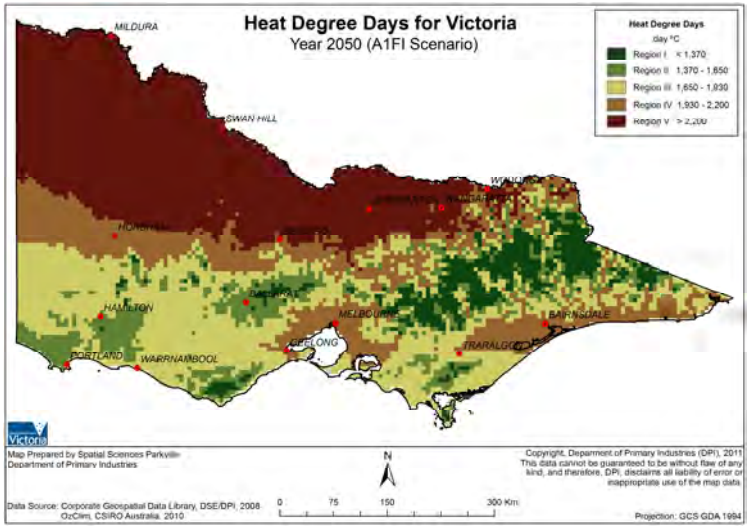


Figure 9 **Heat Degree Days for Victoria – Year 2050 (A1FI Scenario)**

3.3 Spring Frost Index

Extremes in temperature variability, more than any other climatic factor, can have a detrimental effect on the phenological stages of grapevine growth and resultant production. There are a number of ways of looking at temperature variation such as measuring the difference between local mean and maxima temperature values, or between local mean and minima temperature values. There is a correlation between higher values in the latter measure and large negative impacts upon grapevine development and production. Frost after budburst is a common hazard for which variability of the minimum temperature forms the strongest predictor (Gladstones in Dry and Coombe, 2005). Frost damage to berries is a major problem during spring growth and ripening periods, and excessive low minimum temperatures following high day temperatures can cause injury to the grapes. Apart from freezing injury to the grapes, these low minimums coupled with significant temperature variation can inhibit grape metabolism, slow down development and effect grape quality.

Spring frosts are associated with variation of (i) the minimum temperature between the diurnal temperature and nightly temperatures, and (ii) minimum temperatures between days. The *Spring Frost Index (SFI),* developed by Gladstones (2000), is a measure of an area's tendency to produce large variations in temperatures over a short period of time. It details the magnitude of variation, in a given spring month, between the average mean temperature and lowest minimum temperature for that month. The SFI measures primarily the risks of advective frosts which result from the migration of extensive cold air masses and are the main cause of widespread frost damage in southeast Australia from which local site selection and defence measures (e.g. wind machines) provide least protection (Gladstones, 2005, p. 113). The result is an indexed range value that depicts areas that are at highest risk of frosts through to those that have low risk. Values below 11 indicate a low risk, 11 to 13 denote a moderate risk and values above 13 indicate a high risk of frost. The SFI, hence, provides a good indication of areas that may be prone to frosts and the associated damage of frosts. However, the climate in some sites may be warm enough to mitigate the damage of frosts.

Figure 10 shows the SFI for Victoria, calculated for the baseline for October and November with the output separated into 1ºC divisions. According to this result, areas to the north of Victoria are in the high frost risk category whilst those to the south of the Great Dividing Range are in low frost risk category. It should be noted that the figure and associated values depict a broad regional indicator of frost prone areas; site specific details are not taken into account in the calculation of the SFI and this may affect frost risk in any given area.

Figure 11 is the projected SFI for 2050. Comparison of **Figure 10** and **Figure 11** shows that there is a projected reduction in the higher values indicating a frost risk, with concomitant increases in areas with a lower frost risk. This reflects the projected increases, both in mean and minimum temperatures, across Victoria. Also, the increase in areas with lower frost risk values reflect the projected decrease in the range of temperature between the average temperature and the lowest minimum temperature in the two spring months analysed.

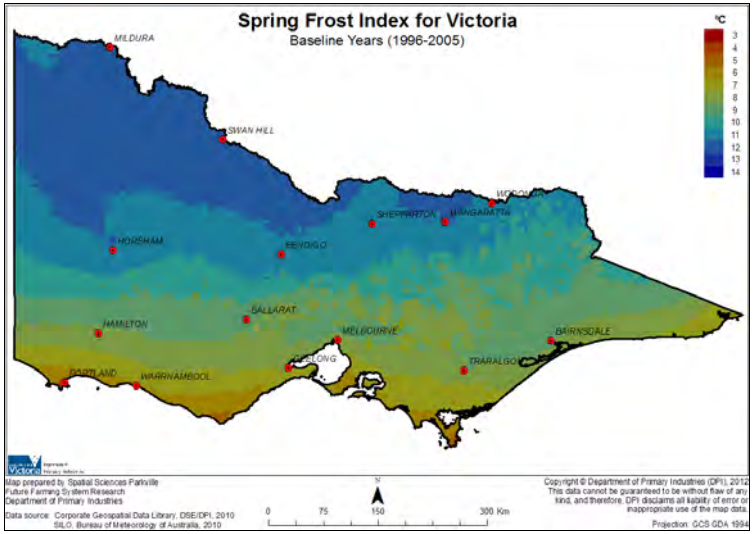


Figure 10 **Spring Frost Index for Victoria – Baseline Years (1996 – 2005)**

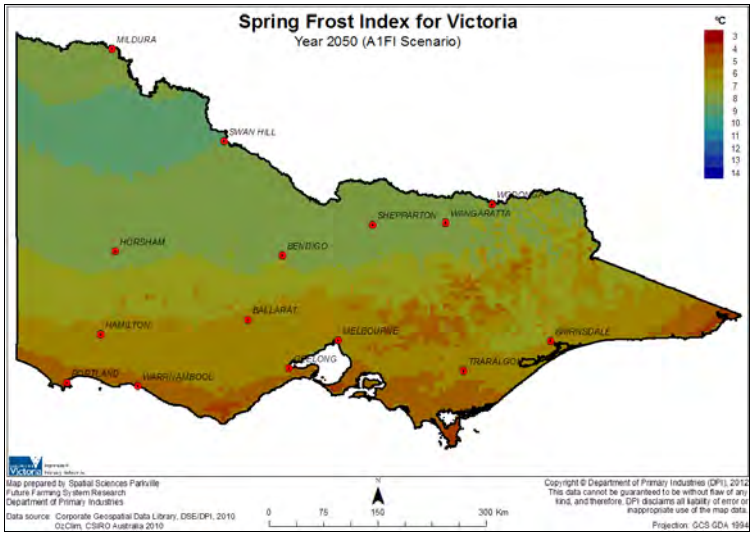


Figure 11 **Spring Frost Index for Victoria – Year 2050 (A1FI Scenario)**

3.4 Water Availability – Irrigation and Evapotranspiration

A study by Webb *et al.* (2012) concluded that wine grapes were reaching maturity and ripening earlier in recent years. Using a time series up to 64 years in duration, this earlier ripening was attributed to two main climatic factors – temperature increases and decreases in soil water content. It is noted, though, that climate is not the only factor that affects wine grape quality. Soil type, water availability (irrigation regimes), canopy management, fertilizer and pest management can also affect winegrape quality.

Of importance for winegrapes is water availability, both in terms of rainfall and irrigation. Water requirements for grapevine growth are dependent on factors such as climate, cultivar and soils. Grapevines can become water stressed and low water availability can delay the onset of ripening and lower production yields. It is therefore important to manage the balance between rainfall and irrigation to maintain the desired plant water status. Irrigation requirements and the amount of water applied are dependent on local climatic factors, such as temperature and rainfall, as well as evapotranspiration.

As discussed previously, rainfall amounts across Goulburn Broken are projected to decrease in future years. This decline is the inverse of projected increases to temperature, i.e. as temperatures increase rainfalls are projected to decline. This will in turn impact on water availability for wine grape production since there will be increases in evapotranspiration and, hence, on total irrigation requirements.

Evapotranspiration

Evapotranspiration[5] for the Goulburn Broken Region is shown in **Figure 12** to **Figure 14**, where the annual evapotranspiration for the baseline, 2030 and 2050 are detailed. Baseline, evapotranspiration ranged from 825 mm to 1,360 mm, through to 2030 the projected range is from 970 mm to 1,390 mm and by 2050 the range is from 1,030 mm to 1,460 mm. Overall, there is a 30 mm to 145 mm projected increase between each time period, with a 100 - 205 mm difference between the baseline and 2050. Projected increases in evapotranspiration are larger in the southern regional areas where increases over 100 mm from the baseline through to 2030 are likely, with a projected increase of over 190 mm into 2050. Compared against the northern areas where increases in evapotranspiration are also projected, but not as high as seen in the south.

Irrigation

Irrigation amounts in Goulburn Broken for the baseline, 2030 and 2050 are shown in **Figure 15** to **Figure 17**. Baseline irrigation ranged from 0 mm/ha to 515 mm/ha, through to 2030 the projected ranges is from 65 mm/ha to 520 mm/ha and by 2050 this is from 110 mm/ha to 570 mm/ha reflecting increased evapotranspiration. Overall, there is a 5 mm/ha to 65 mm/ha increase between each period, with a 55 mm/ha to 110 mm/ha difference between the baseline and 2050. Projected increases in irrigation are larger into the southern regional areas, whilst there is a shift in irrigation requirements rather than a decline in the northern areas. Some areas are projected to remain stable. By 2050, projected increases in irrigation are higher in the south, of the region with some regional areas increasing over 150 mm/ha compared to the baseline.

[5] Refer to **Appendix A** for a discussion on irrigation and evapotranspiration and the methods used in this report to determine these amounts.

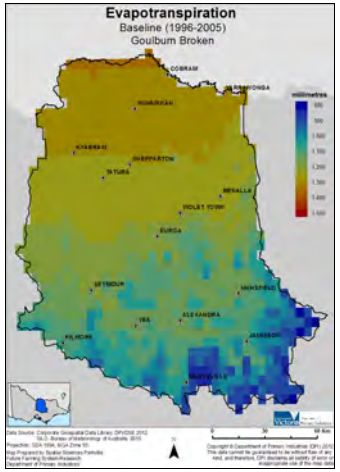


Figure 12 Evapotranspiration for the Goulburn Broken in the baseline (1996-2005)

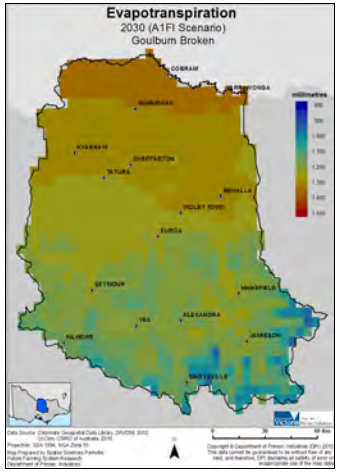


Figure 13 Evapotranspiration for the Goulburn Broken in 2030 (A1FI Scenario)

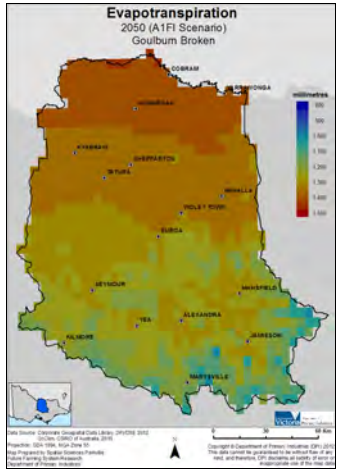


Figure 14 Evapotranspiration for the Goulburn Broken in 2050 (A1FI Scenario)

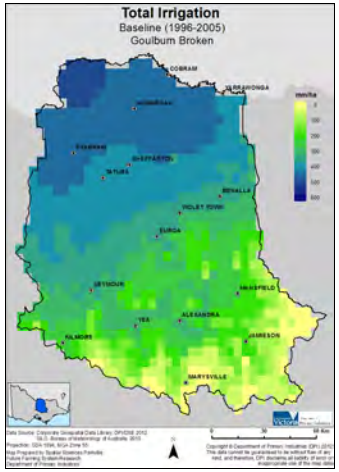


Figure 15 Total Irrigation for the Goulburn Broken in the baseline (1996-2005)

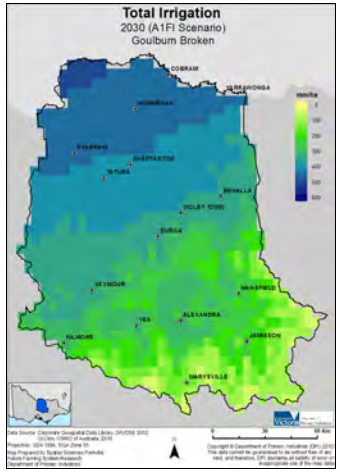


Figure 16 Total Irrigation for the Goulburn Broken in 2030 (A1FI Scenario)

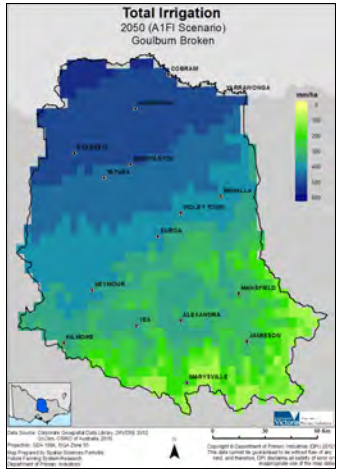


Figure 17 Total Irrigation for the Goulburn Broken in 2050 (A1FI Scenario)

3.5 Soils and Landscape

The growth and production of grapes is influenced by both the physical structure and chemistry of the soils. For viticulturists, a good balance between all the soil properties, allowing for a full fruit set with high quality grapes, is desirable. A highly fertile soil can cause problems through the promotion of over-abundant vegetative growth and a reduction in fruit set. Grapes prefer soils that are well drained, but with the capacity to retain moisture. Loamy soil types are preferred as they have significant nutrient holding capacity and good soil water retention, but drain freely to minimise water-logging the plant root zone. Grape vines have a deep root set and, as such, prefer a deep soil for greater root penetration - this permits a deep and dispersive root system. Shallow soils may limit vine growth by restricting root growth and reducing water availability. Grapes prefer slightly acidic soils, but can be tolerant of soils that are neutral and/or slightly alkaline. Soils that are too acidic or too alkaline can cause root stress and effect vegetative growth and fruit set. Grapes are also intolerant of soils that have high soil salinity levels.

Aspect, or orientation, and steepness of the land also play an important role in the establishment and growth of grape vines. In Australia, a north, east or west-facing site is preferred due to the amount on sunlight a vine may receive. A site with these features may also result in higher soil temperatures and re-radiation of soil warmth in the early evening, at night and during cloudy days. This can be important for strong growth during budburst and flowering. During other times of the year, aspect plays a minor role due to a more vertical sun angle with respect to grape vine location. Southerly facing sites are usually avoided due to the lower amount of sun received, and the fact that they are more prone to frosts which are potentially damaging to grape plants and fruit. Steepness of the land can impact on plant growth, particularly where it provides a gradient for the movement of cold air away from vines. Generally, steeper lad is avoided in Australia for practical considerations of operating machinery.

4. Modelling Potential Impacts of Climate Change on Viticultural Land Suitability

Smart (2006) put forward that as regions warm with a changing climate, the suitability of the existing viticulture regions to produce certain varieties and styles of wine may diminish. Regions that are already at the upper range of climatic suitability may become in the future too hot for production of certain wine grape varieties. A similar study by Webb *et al.* (2008b) showed that across the southern coast of Australia, by 2030, there may be a reduction of more that 10% in the land with temperatures suitable for grape production, and by 2050 this could be in excess of 27% (mid warming scenario) to 44% (high warming scenario). Some inland areas, such as the Murray Valley and the Riverina, may potentially have significant reductions in the land with suitable temperatures for wine grape production. However, it was shown that as some areas, in particular cooler climate regions, with likely augments in temperatures there would be increases in land with suitable temperatures for 'warmer' climate grapevines.

4.1 Biophysical Land Suitability Analysis

The core methodology [6] used for assessment of land suitability for viticultural production in the Goulburn Broken Region utilises the Biophysical Land Suitability Analysis (LSA) modelling approach. Biophysical suitability analysis is defined as the process of determining the fitness, or the appropriateness, of a given area of land for a specified use (adapted from FAO, 1977; see also McHarg, 1969/1992 and 1997; Hopkins, 1977; and Steiner, 2008). Biophysical LSA can provide a rational basis for the most favourable utilisation of land resources and land use planning (FAO, 1993). It examines the degree of land suitability (LS) for the growth (cropping or cultivation) of the agricultural commodity of interest – grapes in this study. Modifications in the agriculture land suitability caused by climate change can be assessed by comparing future suitability maps (years 2030, 2050 and 2070) with the baseline maps (average of the 1996-2005 decade – 5 years either side of the year 2000). The LSA requires several data inputs that are derived from the plant growth characteristics; these include historical observed weather (for the decade 1996-2005), soils and landscape.

The LSA focuses upon the *biophysical* factors that affect the suitability of a unit of land. Economic and crop management information is also important, but it does not inform the LSA modelling approach used in this report. We developed a semi-quantitative approach to map and assess regional agricultural land suitability through the deployment of a Multiple-Criteria Analysis (MCA) method - the Analytic Hierarchy Process – AHP (Saaty, 2000) - in a GIS domain.

The grape land suitability model (**Appendix B**) targets the identification of land capable of producing between 5 to 15 tonnes of grapes per hectare per year (t/ha/ye). Scientific research and experts in their respective fields helped determine and prioritise the decision making factors and criteria included in the LSA/AHP model. It was assumed that the available land was utilised to its maximum through Best Management Practices (BMP). Current yields, as reported by the Australian Bureau of Statistics (ABS), show that the average production of all current Victorian vineyards is between 5-10 t/ha/yr. Weights assigned within the model indicate the relative importance of each criterion in terms of their contribution to the overall evaluation index.

[6] The overarching methodology used in the project can be seen in Sposito *et. al.,* (2010a) – Assessment of Climate Change Impacts on Horticulture: Volume 1 – Pear Production in the Goulburn Broken Region, Victoria, Australia.

A GIS model-based on the AHP tree was developed using ArcGIS (ArcGIS 9.3, 2008) and PyScripter for Python 2.5 (PyScripter 1.9.9.7, 2008). The model was then linked with the data required for the analysis. For comparative purposes, current climate data was created by taking the average historical values of the key climatic variables for a 10-year period from 1996 to 2005 (for simplification we will refer in what follows only to year 2000 as the 'baseline' year). The use of a decade as the current climate 'smoothes out' any ('unusual') climate events, such as extreme weather, generating an even spread of climate data.

Model Application

The execution of the model produces a composite map that ranks areas in terms of suitability for the growth of grapes; it has an index range of 0 to 1, where 0 means a site which is deemed to have zero potential for growing grapes and 1 represents a site deemed ideal for growing grapes (i.e. 100% suitability). As the estimated suitability is positively correlated to productivity (see next section), it is likely that a linear relationship will provide a reasonable approximation for interpreting suitability ratings in terms of production. To achieve this, suitability ratings are scaled to the highest yield (suitability = 1.0) through to zero yield (suitability = 0). For example, if a yield of 10 tonnes per hectare (t/ha/y) is achieved in an area with 1.0 (or 100%) suitability; then, in another area with a suitability of 0.8 (or 80%) we can expect a yield of (0.8 x 10 t/ha/y =) 8t/ha/y.

While suitability ratings can be related to productivity in this fashion, the relationships between the ratings and fruit quality (another important factor) are more complex and dependant on the occurrence and interplay between those factors that have contributed to the rating. Consequently, areas with similar ratings may have comparative production but differ more widely in the quality of the grapes produced.

It should be noted, however, that existing land uses are the result of many factors including tradition, and past and current market conditions, whilst the land suitability maps primarily reflect biophysical conditions.

Model Sensitivity and Validation

Two methods have been applied for examining the sensitivity of, and validating, the AHP hierarchy and resultant LSA model outputs. In the *climate sensitivity analysis* method, LSA outputs were derived for several seasons. The impact of each season on the land suitability was then assessed. Due to the strong influence that climate has in the AHP hierarchy (a weight of 60%), there should be a response within the suitability ratings produced by the models to seasonal variability. Analysis of the sensitivity of the model to climatic variables is important because if the model does not respond as expected, its predictive capacity is low and it is not fit for purpose. The sensitivity analysis focused on examining the impacts of maximum and minimum temperature and total annual rainfall, as these variables have a heavy weighting in the LSA model.

The second method applied for the validation of the LSA outputs was the *Pearson's product-moment correlation coefficient*. This is a measure of the correlation, or linear dependence, between two variables; it is used as a measure of the strength of the relationship between two variables and gives a value in the range of -1 to 1. A strong negative or positive correlation would typically have a value near to the upper (+1) or lower maximums (-1) of the range, whereas no correlation would have a value close to, or at, 0. For validation purposes, the two variables analysed were change in (i) land suitability due to climate, landscape and soils and (ii) grape production in terms of yield. The key premise being tested is that as land suitability increases so should production. It would then be expected that there would be a positive correlation between land suitability and production.

The result[7] for the climate sensitivity analysis method indicates that the biophysical land suitability model for wine grapes is behaving in a responsive fashion and is sensitive to the climatic changes. Shifts in the climate patterns provoked concomitant shifts in the suitability of the land resource for grape production. The result for the Pearson's product moment correlation coefficient showed that there was a strong positive relationship between land suitability and grape production[8] in a given year; as land suitability in a particular area increases or decreases, grape production will increase or decrease in response. This result confirmed that the LSA model is correlated to productivity as expected and is not producing anomalous results; hence we can conclude that the LSA model produces acceptable outputs.

Results

The LSA model was executed to produce land suitability maps. Red, orange, yellow and green colours in the maps and legends represent, respectively, very low (0 to 10%), low (20 to 40%), moderate (50 to 70%) and high (80 to 100% suitability) ranges.

The resulting land suitability map for grapes in the baseline for grapes (**Figure 18**) shows that most areas in Goulburn Broken are potentially high in suitability; only modest scattering of areas show a moderate suitability. Most areas across the region depict a high suitability ranking at 80%. The output indicates that the highest land suitability (90%) occurs in the southern areas south of Euroa and to the east of Mansfield. Moderate land suitability ratings (50% to 70%) are primarily located in the northern half of Goulburn Broken around Euroa, Violet Town, Shepparton and Numurkah. There are also patches of land rated moderate around Alexandra and Kilmore in the south. A large area in the south (shown in grey colour in the maps) and portions of the northwest and east of the region are restricted to protect native vegetation and other natural landscapes.

The map for 2050 (**Figure 19**) portrays a potential larger change of land suitability from the high to the moderate categories. The outputs for grapes show that more of the northern region, north of Euroa, would shift from a high to a moderate land suitability category. Approximately a third of the map now indicates a moderate land suitability rating. A further decrease in high land suitability at 90% to 80% may take place to the east of Seymour. Also, these land suitability rating changes would occur to the east of Mansfield. An expansion of moderate land suitability around Kilmore and Alexandra and to the northwest of Seymour is likely to occur.

Heat degree days (HDD) in the Goulburn Broken for the baseline and 2050 are shown in **Figures 20** and **Figure 21**, respectively. These show how the defined Wine Growing Regions may change in future years and how HDD may affect the resultant LSA. In the baseline, there are four regions: Regions I to IV. Regions I and II occur in the south of the study region, with Region I found predominantly in the northern areas; there are also two patches of Region I to the south of Euroa. These areas, as well as most of Region I in the south, correlate well with high ratings of suitability at 90%. Regions III and IV are linked with lower suitability ratings. In the 2050 HDD map, all five defined regions are found in the Goulburn Broken Region. There is a projected retraction of Regions I and II in the south, with a southerly shift of Regions III and IV. Moreover, the northern half of the study region is projected to be within Region V. This southerly retraction of the Wine Growing Regions and the inclusion of Region V in the north can be clearly linked to reductions in land suitability ratings seen across the Goulburn Broken Region from high to moderate classes.

[7] For a full outline on the use of these two validation methods on the LSA model, readers are referred to **Appendix C**.

[8] Actual production figures for use in the Pearson's correlation coefficient were supplied though the Australian Bureau of Statistics (2011).

The land suitability class change is further highlighted in **Figure 22**, wherein the baseline and 2050 output maps are compared. In this comparison, a decrease indicates that there has been a 10% change from a higher suitability class to a lower suitability class (e.g. 90% to 80%); similarly an increase indicates that there has been a 10% change from a lower class to a higher class (e.g., 80% to 90%). A high increase denotes a 20% change from a low suitability class to a higher suitability class and a high decrease indicates that there has been a 20% reduction from a higher suitability class. No change means that there has not been any variation between the baseline and the respective year. Clearly seen in the land suitability class change map is that across the majority of the Goulburn Broken Region would be a decrease in land suitability. The main areas of change are likely to occur east of Mansfield, south of Yea, around Kilmore and around Euroa. These class decreases are also seen scattered throughout the northern districts.

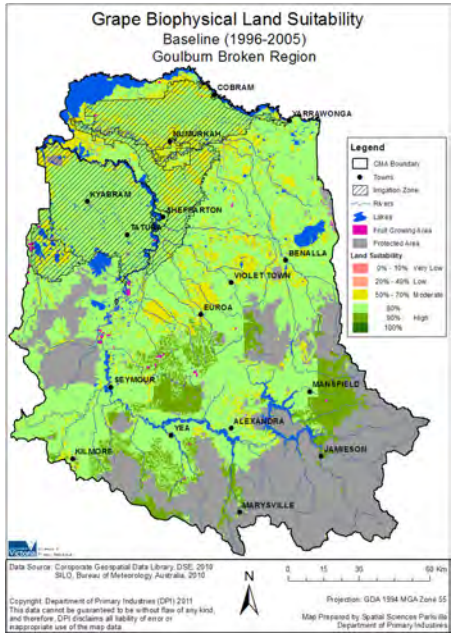


Figure 18 **Grape biophysical land suitability for the Goulburn Broken Region – 2000 (Baseline)**

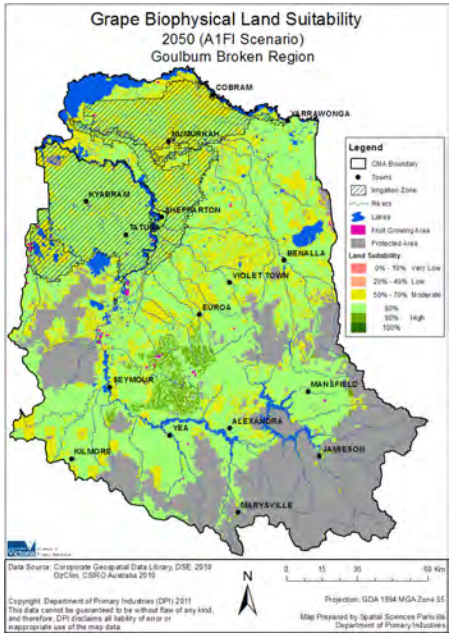


Figure 19 **Grape biophysical land suitability for the Goulburn Broken Region – 2050 (A1FI Scenario)**



Figure 20 **Heat degree days for the Goulburn Broken Region – Baseline (1996-2005)**

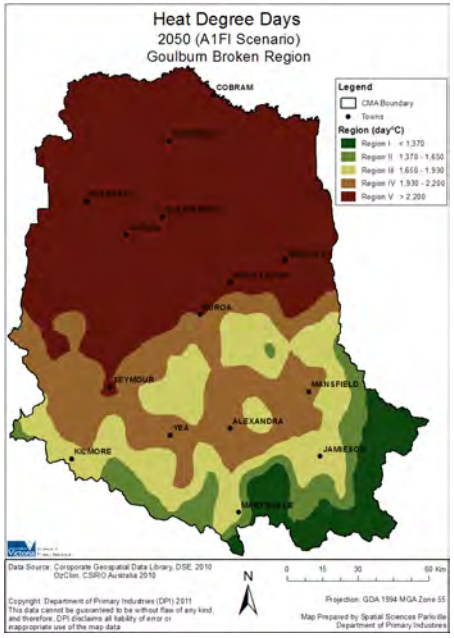


Figure 21 **Heat degree days for the Goulburn Broken Region – 2050 (A1FI Scenario)**

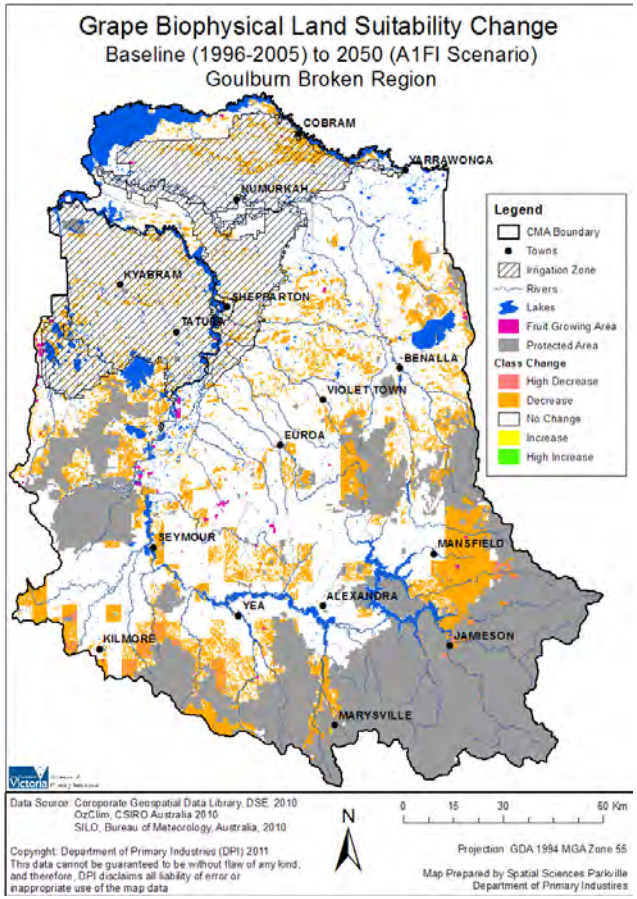


Figure 22 **Grape land suitability change Goulburn Broken Region – 2000 (Baseline) to 2050 (A1FI Scenario)**

The largest shift in suitability would occur in the areas south of Euroa, where a move from a high ranking for land suitability to a lower ranking is likely to occur. While some areas to the east of Seymour would remain highly suitable, the trend depicts a general decline around this area in the suitability of land for growing grapes.

This is further established in **Table 2** which show the land areas under different suitability categories between the baseline and 2050. To provide an estimate of production in these tables, the mid range of the values in the optimal yield range, detailed at the top of the AHP/LSA model (5 – 15 tonne/ha/year) was used (i.e. 10 tonne/ha/year). From this information, possible production amounts can be estimated by multiplying the number of hectares by this yield value and by the respective land suitability index (in decimal form) in all the suitability categories from 10% to 100% and summing up the 10 values thus obtained.

For example, in the column with a suitability index of 70% (or 0.7) in the baseline (year 2000), the number of hectares in this category is 187,216 hence, the possible yield will be 187,216ha x 10t/ha/year x 0.7 = 1,310,512 tonne/year. This analysis provides a broad overview of how each of the land suitability classes is projected to change from the baseline into the future. This method displays the distribution of the suitability categories within a period; and it can also reveal trends in the change of suitability between the baseline and future year projections.

Although in a real sense impractical, a valuable picture of likely trends can then be gained by assuming that the whole region is potentially available for grape production (minus restricted areas to protect native vegetation). **Table 2** shows that areas deemed high in suitability for growing grapes in the baseline would shift into lower categories by 2050. In the high suitability (90%) category both the area (ha) and production (t) would decrease (shown in red). For example, between the baseline and 2050 the hectare change in this category is likely to be a decrease of around 129,227 hectares. What can also be seen in this table is how the land is likely to shift from the higher land suitability rankings into lower rankings. With the decrease of the high suitability categories, there is an increase (shown in black) in nearly all of the lower categories, such as the 80% and 70% columns. The 70% column sees an increase in the 2050 periods, wherein there are gains in land deemed moderately suitable into each time frame.

Table 2 Grape biophysical land suitability and productivity - baseline and 2050

Suitability	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
2000 ha	0	0	0	0	0	7,295	82,800	187,216	1,285,553	170,779	0
2000 tonne	0	0	0	0	0	36,475	496,800	1,310,512	10,284,424	1,537,011	0
2050 ha	0	0	0	0	165	10,601	90,434	369,160	1,221,731	41,552	0
2050 tonne	0	0	0	0	660	53,005	542,604	2,584,120	9,773,848	373,968	0
Ha Change *	0	0	0	0	165	3,306	7,634	181,944	-63,822	-129,227	0
Tonne Change **	0	0	0	0	660	16,530	45,804	1,273,608	-510,576	-1,163,043	0

* and ** - Ha Change and Tonne Change is the difference between the baseline and future year

This reduction in area would equate to a decrease in the production of grapes. With the decrease in land suitability in the 90% category, there is a calculated loss in production of about 1.1 million tonnes (shown in red). Decreases in the higher suitability rankings are mirrored by slight increases in production in the lower rankings, in particular in the 70% and 60% categories.

5. Conclusion

The methodology developed by DPI for assessing climate change impacts, and possible adaptation options, in horticulture has Biophysical Land Suitability Analysis (LSA) at its core. LSA depends, in turn, on climate change projections and the values of several climatic factors including head degree days (HDD) and spring frost index (SFI).

Climate Change Projections - Climate change projections for Goulburn Broken, under the IPCC A1FI (high global warming) scenario, predicted: (i) an increase in mean temperature of 1ºC to 1.5ºC between succeeding time periods - baseline (average climate in 1996-2005), 2030 and 2050 - with a maximum of 2.5ºC between the baseline and 2050; (ii) a decrease in total rainfall of 5 mm to 500 mm between succeeding time periods, with a maximum decrease of around 50 mm in the irrigation districts and over 300 mm in the southern regional areas between the baseline and 2050.

Viticultural Biophysical Land Suitability Analysis (LSA) - Although in a real sense impractical, a valuable picture of likely future trends can be gained by assuming that the whole of the Goulburn Broken Region could be dedicated to agriculture activities. The Biophysical LSA modelling carried out therefore assumed that: (a) the whole region was available for grape production (minus protected areas under native vegetation), and (b) adaptation measures, such as changes in management practices, were not going to be introduced during the study period (baseline to year 2050). The analysis showed that the suitability of the land resource for wine grape production is likely to decline in relation to the baseline experiencing a shift from a high category (i.e. greater than 80% suitable) to a moderate category (50-70% suitable) by 2050, particularly in southern parts of the region. The higher suitability-ranked land in the north of the region is also likely to reduce in size, but, by 2050, about two thirds of the land in northern areas would still remain within the higher suitability categories for the production of grapes. Areas to the east of Seymour would potentially retain a high suitability ranking by 2050, even as the surrounding areas may decline from a high to a moderate suitability. The largest changes in land suitability ranking would occur in the southern districts, in particular around Kilmore, Yea, Alexandra and Mansfield.

These results were compared with the HDD regional divisions, both in the baseline and projections for 2050. This comparison indicated how defined HDD regions may change by 2050 and how they may influence resulting LSA model outputs. Grape Production Regions I to IV were identified in the baseline. Regions I and II, in the south of Goulburn Broken, correlated well with high ratings of suitability at 90%, particularly Region I. Regions III and IV occurred in the north; these regions are associated with lower suitability ratings. By 2050, there was a projected southward shift of all the identified wine growing regions, with the northern half of Goulburn Broken projected to be within Region V. This southerly retraction, as well as the inclusion of Region V, can be linked to reductions in land suitability ratings from high to moderate classes across Goulburn Broken.

Overall, then, the likely shift from highly suitable to a lower suitability in the land resource would contribute to a change in productivity both within each suitability category and also in the projected total tonnages. Furthermore, projected climatic shifts will have a significant impact on water availability for wine grape production. With increasing temperature, there will be a greater need for irrigation to replace water loss in the plant through evaporation and transpiration. Moreover, as temperatures increase, there is also a potential lowering of rainfall amounts, which will reduce water availability for irrigation allotments.

5.2 Suggestions for Further Research

Future research effort could focus upon development and application of other grape-specific climatic growing measurements across a spatial domain. While one of the methods used in this report, HDD, is useful for regionally detailing grape growth, other measurements can be utilised to provide further information. As mentioned by Webb *et al.* (2008c), a number of climatic indicators can be used for regionally-defining climatic zones for wine grapes. These include factors such as: (i) Mean January Temperature (MJT) (Smart & Dry, 1980), (ii) Mean Annual Range (MAR) - the difference between the MJT and the Mean July Temperature (often referred to as 'Continentality') (Smart & Dry 1980; Gladstones, 1992), (iii) Diurnal Range (DR) (Gladstones, 1992), (iv) Relative Humidity (RH) and (v) Sunshine Hours (SH). Some of these indicators are well correlated with those utilised in this report, and can be used to provide a comprehensive picture of the situation in viticulture. However, other indicators have data shortcomings or the inability to (as yet) be projected into the future.

Beeston (1999) has used these indicators to describe climate in established wine zones and regions, whilst Gladstones (1992) used them and also outlined the possible deployment of more detailed climatic indicators. Gladstones, for example, describes: (i) a Heat Stress Index (HSI) where heat stress and maximum temperature variability during summer months is measured, and (ii) a Temperature Variability Index (TVI) which measures the range of fluctuation between day maximum and minimum temperatures (diurnal range) with the variability of maximum and minimum temperature within a given part of the season.

Gladstones (1992) also suggests an improved methodology to calculate the HDD indicator. The HDD method (applied in our study) suffers some shortcomings in that it was developed primarily for the Californian wine growing region. Its application in other regions can become fuzzy if certain considerations, such as regional temperature effects and rainfall patterns, are not taken into account. In this situation, Gladstones suggests measuring the Biological Effective Degree Days (BEDD). The BEDD method is a multi-factorial measurement used to make adjustments to temperature in order to get a good fit between the regional climatic data (matched for periods of records) and observed vine phenology in established viticulture regions. It can thus be useful for both detailing temperature regions and maturity dates for grapevines. BEDD limits the temperature input between a certain ranges, adjusts for the latitude and day length as well as for diurnal temperature ranges. Overall, it seems that the BEDD method could likely produce a more tailored measurement for grapevine growth parameters over that of the HDD method in Australian and Victorian climates and should be tried in future studies.

6. Appendix A – Evapotranspiration and Irrigation – Methodology for Calculation

One of the complexities of modelling land suitability in horticulture is dealing with irrigation. To estimate the irrigation requirements of a given crop one of the most important factors is the crop evapotranspiration.

Penman-Monteith

The well-known Penman-Monteith (PM) equation is the best method of estimating reference evapotranspiration (Khoob, 2008; Wang *et al*., 2008). The Food and Agricultural Organisation of the United Nations (FAO) adopted the original PM equation in combination with equations for the aerodynamic resistance and surface resistance to produce a standardised FAO PM equation. The method overcomes shortcomings of the previous FAO method and provides values that are more consistent with actual crop water use data worldwide (Allen *et al.,* 1998).

Hargreaves

However, problems can arise in the use of the FAO PM equation when meteorological data, such as relative humidity data, wind speed data and vapour pressure data are missing. The absence of data can prevent the application of the FAO PM equation since not all variables can be input into it.

Alternate equations do exist for the estimation of evapotranspiration that only utilise a minimal set of variables. One key equation, which like the PM equation has been standardised by the FAO, is the *Hargreaves equation* (Hargreaves and Samani, 1985). The only variables that are required for input are maximum, minimum and mean temperatures, and solar radiation. This equation allows for the calculation of evapotranspiration for both present situations using SILO data and for future scenarios using OzClim data[9, 10].

Analytical Neural Networks

Another alternate method, other than the FAO PM and FAO Hargreaves equation for the estimation of evapotranspiration that was explored was the use of *Artificial Neural Networks* (ANN). ANN techniques have previously been demonstrated useful in situations where data is limited (Sudheer *et al*., 2003; Kisi, 2007; Chauhan and Shrivastava, 2008; Wang *et al*., 2008). Landeras *et al*. (2008) highlighted the necessity of application of an ANN in modelling a non-linear process such as evapotranspiration and, after comparing seven ANN models against various locally calibrated reference evapotranspiration equations, they concluded that ANN-based models were generally more reliable than the locally-calibrated equations. In all of the above-sited studies, ANN models were developed using fewer predictors than required by Penman-Monteith (PM) equations.

[9] SILO data already contain daily observations for evapotranspiration using the FAO PM equation. There are also available relative humidity observations but no wind speed observations. However, OzClim data do not contain the FAO PM observations and the relative humidity observations are measured in a different fashion to the SILO observations. For this reason, the FAO Hargreaves equation provides a consistent measure of evapotranspiration between present and future scenarios as the same equation with the same basic four inputs can be used for both time frames.

[10] OzClim predictions for future scenarios are given in a monthly format, rather than in SILO where observations are given in a daily format. In these instances, where required, values can be converted from monthly to daily or vice-versa.

Comparison of Results

For each evapotranspiration techniques available, the FAO PM equation, the FAO Hargreaves equation and the ANN, outputs were calculated. The outputs were based on the ten year baseline (1996-2005) for the Goulburn Broken Region. All inputs into each of the equations were obtained through SILO as text files which were obtained through the Department of Natural Resources and Mines, Queensland, in conjunction with the BoM weather recordings.

When compared against the FAO PM observations, the ANN results did produce a comparable evapotranspiration output, though this was also comparable with the FAO Hargreaves outputs for the Goulburn Broken Region (**Figure A1**). The value range differences for each output were minimal, the FAO PM value range was from 736.35 to 1310.68mm, the FAO Hargreaves value range was from 779.99 to 1292.21mm whilst the ANN value range was from 724.55 to 1295.77mm. When comparing these ranges against one another it can be seen that there are only slight differences between the minimum and maximum values – about 50mm in the minimum and 20mm in the maximum.

From this it was concluded that the ANN was a comparable estimator of evapotranspiration to the established FAO PM equation. However, the overall complexity and time it took in setting up the ANN network and training the weights, and also the fact that predicted values would change every time the network was run outweighed its usefulness compared to that of the simplicity of the FAO Hargreaves equation.

Therefore for application in the Goulburn Broken Region, the FAO Hargreaves equation was utilised and this is reported in the body of the text.

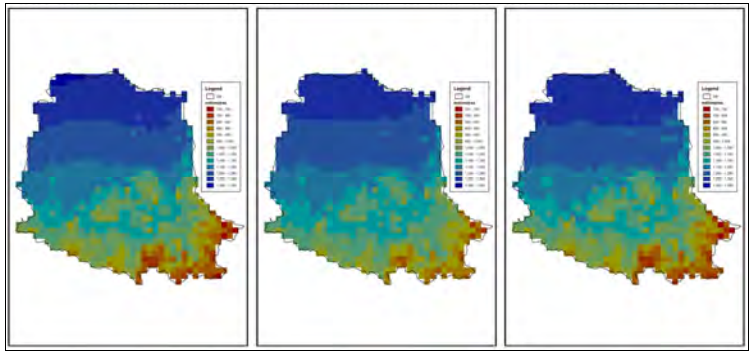


Figure A1 **Evapotranspiration outputs for 3 different methods – FAO PM equation (left), FAO Hargreaves equation (centre), Analytical Neural Network (right)**

Irrigation Requirements

It is then possible to estimate crop irrigation requirements, for the Sunraysia, using evapotranspiration results from the FAO Hargreaves equation and a few other variables. The equation for crop irrigation requirements is given by:

$$IR = \frac{ET_{Ca}}{ET_{Cb} \times (ET_{Cb} - Rain - SoilR)} \quad (6)$$

where $ET_{Ca} = ETo(Kcb + Ke)$ (7)

$$ET_{Cb} = ETo \times Kc \quad (8)$$

$$SoilR = SR + (Rain \times ER) - ET_{Cb} \quad (9)$$

where IR is the irrigation requirement (mm/hectare), ET_0 is potential evapotranspiration (mm d^{-1}), Ke is the soil evaporation coefficient, Kc is the crop coefficient, Kcb is the basal crop coefficient, Rain is the total rainfall (mm), SR is the soil water reserve in the root zone and ER is the effective rainfall.

The top line of equation (6) describes the crop evapotranspiration, or water need (mm d^{-1}). This is where the potential evapotranspiration is multiplied by a dual crop coefficient. The dual crop coefficient is the procedure for estimating the effects of specific wetting events on the value of Kc. It is calculated by adding the soil evaporation coefficient (Ke) with the basal crop coefficient (Kcb).

The denominator of equation (6) describes the difference between crop evapotranspiration and rainfall. By dividing ET_{Ca} by the denominator of equation (6) the crop irrigation requirements can be calculated. This portion has three main sections: crop evapotranspiration based on a single crop coefficient, total rainfall and the total soil reserve (SoilR). The single crop coefficient, Kc, incorporates crop characteristics and average effects of evaporation from the soil (Allen *et al*., 1998). The total soil reserve is based upon the soil water reserve in the plants root zone, the effective rainfall in the region and the crop evapotranspiration based on a single crop coefficient. Effective rainfall is a percentage assigned to how much rain was captured by the root zone; it is calculated by taking the percentage of the total amount of rainfall above a certain level against the overall total amount of rainfall.

This crop irrigation requirement equation is calculated for each month and then summed to produce the yearly irrigation requirement. For each month the soil evaporation coefficient (Ke), crop coefficient (Kc) and basal crop coefficient (Kcb) will change. Using this approach, it is possible to establish a good estimate of the irrigation requirements of a crop, across a geographical area, using readily available climatic data.

Figure A2 shows the results of the irrigation requirement analysis outputs using both the FAO PM equation and the FAO Hargreaves equation for the Goulburn Broken Region. This has been done over the ten year baseline from 1996 to 2005.

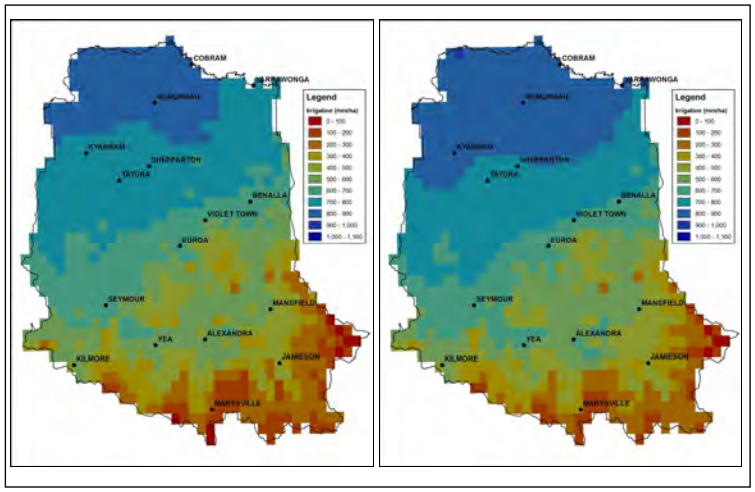


Figure A2 **Irrigation water requirements (in mm per hectare) using the FAO PM equation (left) and the FAO Hargreaves equation (right) as inputs for evapotranspiration, for the Goulburn Broken Region.**

Both outputs show very minor changes between using the FAO PM equation and the FAO Hargreaves equation for evapotranspiration inputs into crop irrigation requirements. The most noticeable changes occur in the northern areas of the study region where the FAO PM output shows irrigation requirements in the range of 700 to 800 mm per hectare, whilst the FAO Hargreaves output shows irrigation requirements in the range of 800 to 900 mm per hectare. The variance between the two outputs is in the range of 15 mm/ha to 55 mm/ha, with the FAO PM indicating lower irrigation requirements than the FAO Hargreaves.

7. Appendix B – Biophysical Land Suitability Analysis Model

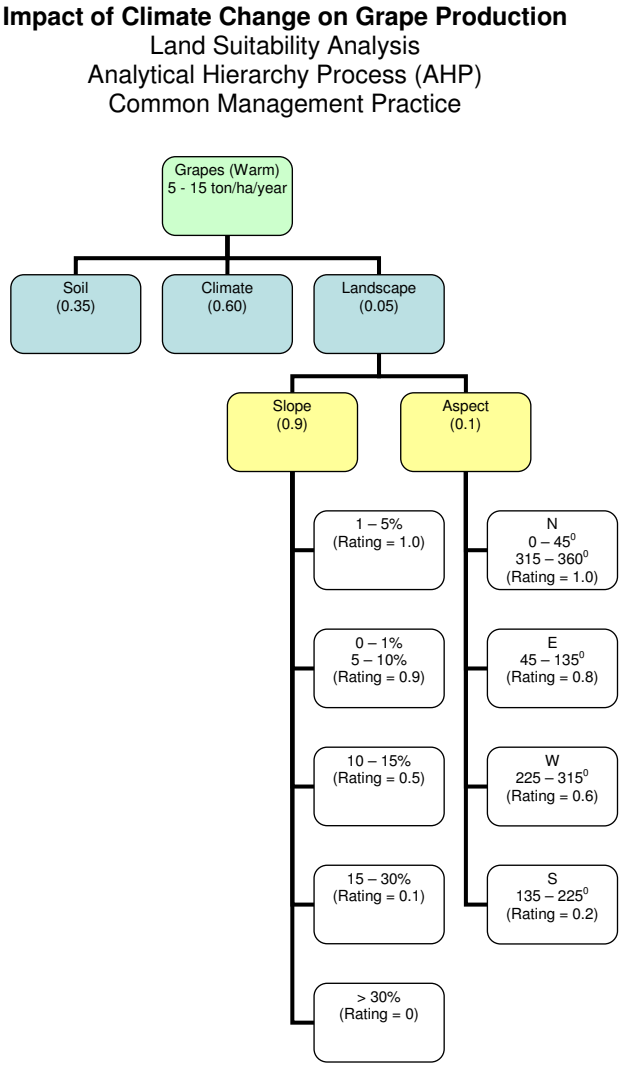


Figure B1 **Grape land suitability model - overall structure and landscape hierarchy**

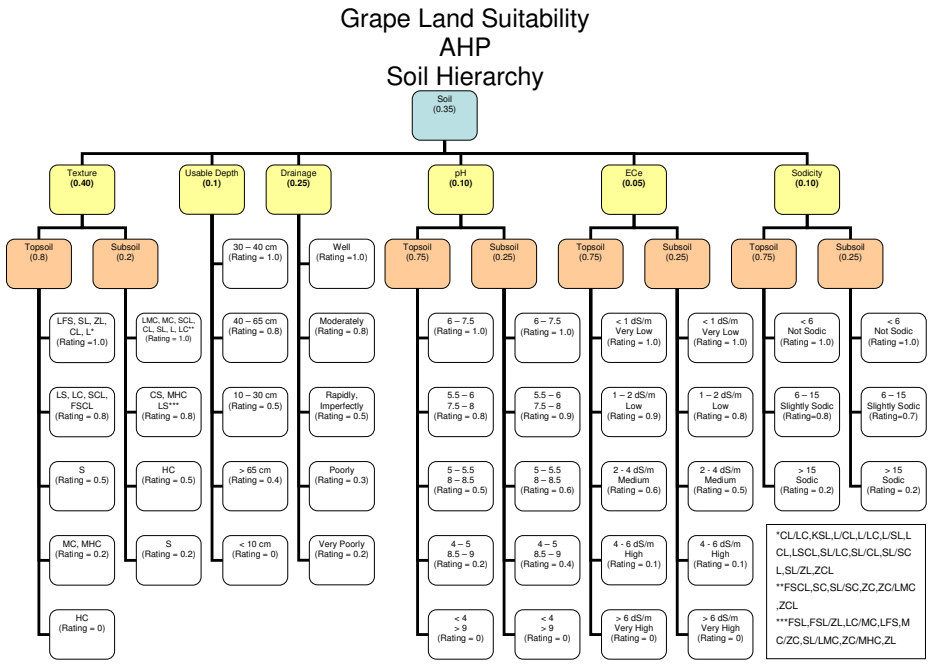


Figure B2 **Grape land suitability model – soil hierarchy**

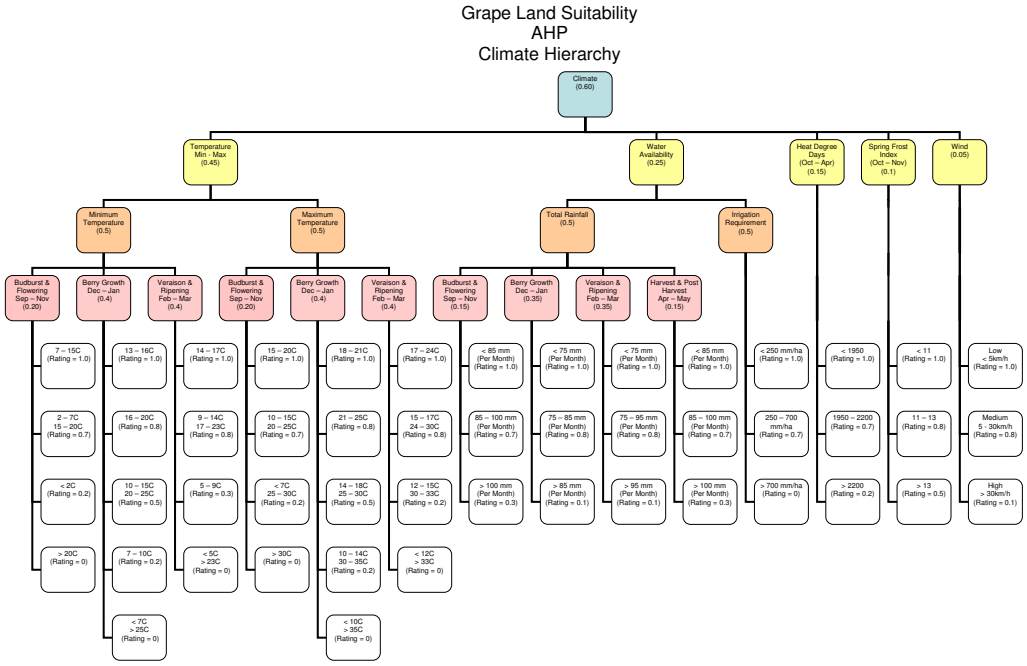


Figure B3 **Grape land suitability model – climate hierarchy**

COMMODITY: GRAPES
VARIETY: WARM CLIMATE VARIETIES
REGION: GOULBURN BROKEN

LAND SUITABILITY AHP

CRITERIA	PREFERRED CONDITIONS (MOST TO LEAST IN DESCENDING ORDER)	RATING	REFERENCE	COMMENT
SOILS - PHYSICAL ATTRIBUTES				
TEXTURE		**0.4**		
TOPSOIL		**0.8**		
	LFS, SL, L, ZL,CL, Gravely Loam	1.0	Wellington Environmental Planning Study	
	LS, LC, SCL, FSCL, Sub Plastic Clay Texture	0.8	"	
	S	0.5	"	
	MC-MHC	0.2	"	
	HC	0	"	
SUBSOIL		**0.2**		
	LC, LMC, MC, SCL, CL, SCL, SL, L	1.0	Wellington Environmental Planning Study	
	LS, CS, SL, MHC	0.8	"	
	HC	0.5	"	
	S	0.2	"	
DRAINAGE		**0.25**		
	Well Drained	1.0	Wellington Environmental Planning Study	
	Moderately Well	0.8	"	
	Rapidly, Imperfectly	0.5	"	
	Poorly	0.1	"	
	Very Poorly	0	"	
USABLE SOIL DEPTH		**0.1**		
	30 – 40cm	1.0	Wellington Environmental Planning Study	
	40 – 60cm	0.8	"	
	10 – 30cm	0.5	"	
	> 65cm	0.4	"	
	< 10cm	0	"	
SOILS - CHEMICAL ATTRIBUTES				
PH		**0.10**		
TOPSOIL		**0.75**		
	6 – 7.5	1.0	Wellington Environmental Planning Study	
	5.5 – 6 or 7.5 – 8	0.8	"	

	5 – 5.5 or 8 – 8.5	0.5	"	
	4 – 5 or 8.5 – 9	0.2	"	
	< 4 or > 9	0	"	
SUBSOIL		**0.25**		
	6 – 7.5	1.0	Wellington Environmental Planning Study	
	5.5 – 6 or 7.5 – 8	0.9	"	
	5 – 5.5 or 8 – 8.5	0.6	"	
	4 – 5 or 8.5 – 9	0.4	"	
	< 4 or > 9	0	"	
ECE		**0.05**		
TOPSOIL		**0.75**		
	< 1 dS/m – Very Low	1.0	Wellington Environmental Planning Study	
	1 – 2 dS/m – Low	0.9	"	
	2 – 4 dS/m – Medium	0.6	"	
	4 – 6 dS/m – High	0.1	"	
	> 6 dS/m – Very High	0	"	
SUBSOIL		**0.25**		
	< 1 dS/m – Very Low	1.0	Wellington Environmental Planning Study	
	1 – 2 dS/m – Low	0.8	"	
	2 – 4 dS/m – Medium	0.5	"	
	4 – 6 dS/m – High	0.1	"	
	> 6 dS/m – Very High	0	"	
SODICITY		**0.10**		
TOPSOIL		**0.75**		
	< 6 – Not Sodic	1.0	Wellington Environmental Planning Study	
	6 – 15 – Slightly Sodic	0.8	"	
	> 15 – Sodic	0.2	"	
SUBSOIL		**0.25**		
	< 6 – Not Sodic	1.0	Wellington Environmental Planning Study	
	6 – 15 – Slightly Sodic	0.7	"	
	> 15 – Sodic	0.2	"	
LANDSCAPE				
SLOPE		**0.85**		
	<5%	1.0	Wellington Environmental Planning Study	
	5 – 10%	0.9	"	
	10 – 15%	0.5	"	

	15 – 30% > 30 %	0.1 0	" "	
ASPECT		**0.15**		
	North; 0 – 45 deg, 315 – 360 deg East; 45 – 135 deg West; 225 – 315 deg South; 135 – 225 deg	1.0 0.8 0.6 0.2	Wellington Environmental Planning Study " " "	

CLIMATE				
SPRING FROST INDEX (OCT – NOV)		**0.10**	Gladstones, J. in; Dry, P.R. Coombe, B.G. 2005. Viticulture: Volume 1 - Resources	Spring Frost Index formulated by Gladstones, J.S in previous work is a measure of spring frost days and temperature variability.
	< 11 11 – 13 > 13	1.0 0.8 0.5		Values produced in this index are given as temperature ranges. Range values used are outlined in Gladstones chapter in the book by Dry and Coombe.
WIND		**0.05**	Gladstones, J. in; Dry, P.R. Coombe, B.G. 2005. Viticulture: Volume 1 - Resources	Strong winds particularly damage young growth in spring when shoots are weak and brittle.
	< 5 km/hr – Low 5 – 30 km/hr – Medium > 30 km/hr – High	1.0 0.8 0.1	Wellington Environmental Planning Study " "	
WATER AVAILABILITY		**0.25**		
IRRIGATION REQUIREMENTS		**0.50**		Goulburn Broken receives about half of annual water requirement from rain-fed sources. The North West only receives, at maximum, one quarter from rain. The rest will need to be accounted for from irrigation
	< 250 mm/ha 250 – 700 mm/ha > 700 mm/ha	1.0 0.7 0	Based on ABS data Based on ABS data Based on ABS data	6ML/Ha is a good level for all grape vines. 2ML/Ha, or 34% reduction in application results in a 25% reduction in yield. Too much or too little water can cause stress on plants. Upper limits are placed due to allotments.
TOTAL RAINFALL		**0.50**	Gladstones, J. 1997. Viticulture & Environment.	In Mediterranean type environments: high autumn to spring rainfall with sunny mostly rain free summer.
BUDBURST – FLOWERING (SEP – NOV)		**0.15**	Chalmers, Y. DPI, Mildura	Weights reflect average water use of

				grape vine during phonological stage.
	< 85mm 85 – 100mm > 100mm	1.0 0.7 0.3		
GROWING – FRUIT SET (DEC – JAN)		**0.35**	Chalmers, Y. DPI, Mildura	Weights reflect average water use of grape vine during phonological stage.
	< 75mm 75 – 85mm > 85mm	1.0 0.8 0.1	Wellington Environmental Planning Study " "	
VERAISON (RIPENING) (FEB – MAR)		**0.35**	Chalmers, Y. DPI, Mildura	Weights reflect average water use of grape vine during phonological stage.
	< 75 mm 75 – 95mm > 95mm	1.0 0.8 0.1	Wellington Environmental Planning Study. Gladstones, J. 1997. Viticulture & Environment. " "	
HARVEST – POST HARVEST (APR – MAY)		**0.15**	Chalmers, Y. DPI, Mildura	Weights reflect average water use of grape vine during phonological stage.
	< 85mm 85 – 100mm > 100mm	1.0 0.7 0.3		
TEMPERATURE (MIN – MAX)		**0.45**	Gladstones, J. 1997. Viticulture & Environment. Dry, P.R. Coombe, B.G. 2005. Viticulture: Volume 1 - Resources	The majority of values obtained for this section have been obtained through either *Viticulture & Environment (Gladstones, J. 1997)* or *Viticulture Volume 1 – Resources (editors Dry, P.R & Coombe, B.G. 2005).*
MINIMUM TEMPERATURE		**0.5**	Gladstones, J. 1997. Viticulture & Environment.	During ripening if the range between min and max exceeds 10C colouring is greatly inhibited. Thee less variation in temp leads to greater colouring.
BUDBURST – FLOWERING (AUG – NOV)		**0.2**		
	7 – 15 15 – 20 or 2 – 7 < 2 > 20	1.0 0.7 0.2 0		during flowering and throughout the growth of the berries, extremes of heat can cause: premature veraison (change of colour and start of the accumulation of sugars); high grape mortality through abscission; enzyme inactivation; and partial or total failure of flavour ripening (Mullins et al., 1992)

GROWING – FRUIT SET (DEC – JAN)		**0.4**		
	13 – 16	1.0	Hall, A. Jones, G.V. 2008. Hawker, J.S. 1981. Buttrose, M.S. Hale, C.R. 1971. Gladstones, J. 1997. Viticulture & Environment.	
	16 – 20	0.8	Hawker, J.S. 1981. Buttrose, M.S. Hale, C.R. 1971. Gladstones, J. 1997. Viticulture & Environment. Mullins et al., 1992	during flowering and throughout the growth of the berries, extremes of heat can cause: premature veraison (change of colour and start of the accumulation of sugars); high grape mortality through abscission; enzyme inactivation; and partial or total failure of flavour ripening (Mullins et al., 1992)
	10 – 15 or 20 – 25 7 – 10	0.5 0.2		
	< 7 or >25	0	Hawker, J.S. 1981. Buttrose, M.S. Hale, C.R. 1971. Mullins et al., 1992	prolonged temperatures above 10 ◦C initiates spring vegetative growth and thus determines the start of the growing season (Mullins et al., 1992)
VERAISON (RIPENING) (FEB – MAR)		**0.4**		
	14 – 17	1.0	Gladstones, J. 1997. Viticulture & Environment.	During the maturation stage, a high diurnal temperature range leads to the beneficial synthesis of grape tannins, sugars, and flavours (Gladstones, 1992).
	9 – 14 or 17 – 23	0.7	Mullins et al., 1992	during flowering and throughout the growth of the berries, extremes of heat can cause: premature veraison (change of colour and start of the accumulation of sugars); high grape mortality through abscission; enzyme inactivation; and partial or total failure of flavour ripening (Mullins et al., 1992)
	5 – 9	0.4		
	< 5 or > 23	0	Mullins et al., 1992	prolonged temperatures above 10 ◦C initiates spring vegetative growth and thus determines the start of the growing season (Mullins et al., 1992)
MAXIMUM TEMPERATURE		**0.5**	Gladstones, J. 1997. Viticulture & Environment.	During ripening if the range between min and max exceeds 10C colouring is greatly inhibited. Thee less variation in temp leads to greater colouring.

BUDBURST – FLOWERING (AUG – NOV)		**0.2**		
	15 – 20	1.0	Palma, B.A. Jackson, D.I. 1981. Mullins et al., 1992	during flowering and throughout the growth of the berries, extremes of heat can cause: premature veraison (change of colour and start of the accumulation of sugars); high grape mortality through abscission; enzyme inactivation; and partial or total failure of flavour ripening (Mullins et al., 1992)
	10 – 15 or 20 – 25 < 7 or 25 – 30 > 30	0.7 0.2 0		
GROWING – FRUIT SET (DEC – JAN)		**0.4**		
	18 – 21	1.0	Hawker, J.S. 1981. Buttrose, M.S. Hale, C.R. 1971	
	21 – 25	0.8	Hawker, J.S. 1981. Buttrose, M.S. Hale, C.R. 1971	
	14 – 18 or 25 – 30	0.5		during flowering and throughout the growth of the berries, extremes of heat can cause: premature veraison (change of colour and start of the accumulation of sugars); high grape mortality through abscission; enzyme inactivation; and partial or total failure of flavour ripening (Mullins et al., 1992)
	10 – 14 or 30 – 35	0.2		
	<10 or >35	0	Hawker, J.S. 1981. Buttrose, M.S. Hale, C.R. 1971	prolonged temperatures above 10 ◦C initiates spring vegetative growth and thus determines the start of the growing season (Mullins et al., 1992)
VERAISON (RIPENING) (FEB – MAR)		**0.4**		
	17 – 24	1.0	Gladstones, J. 1997. Viticulture & Environment.	During the maturation stage, a high diurnal temperature range leads to the beneficial synthesis of grape tannins, sugars, and flavours (Gladstones, 1992).
	15 – 17 or 24 – 30	0.7		
	12 – 15 or 30 – 33	0.2	Mullins et al., 1992	during flowering and throughout the growth of the berries, extremes of heat can cause: premature veraison (change of colour and start of the accumulation of sugars); high grape mortality through

	<12 or > 33	0		abscission; enzyme inactivation; and partial or total failure of flavour ripening (Mullins et al., 1992)
HEAT DEGREE DAYS		**0.15**		
	< 1950	1.0	Gladstones, J. 1997. Viticulture & Environment. Dry, P.R. Coombe, B.G. 2005. Viticulture: Volume 1 - Resources	
	1950 – 2200	0.2	Gladstones, J. 1997. Viticulture & Environment. Dry, P.R. Coombe, B.G. 2005. Viticulture: Volume 1 - Resources	
	> 2200	0	Gladstones, J. 1997. Viticulture & Environment. Dry, P.R. Coombe, B.G. 2005. Viticulture: Volume 1 - Resources	

8. Appendix C – Validation Results for Land Suitability Analysis Model

In each of the two methods, actual production years were analysed[11]. According to statistical production figures, reported in agricultural censuses carry out by the Australian Bureau of Statistics (ABS), a 'production year' encompasses the months of July to December of one calendar year and January to June in the following calendar year. By validating in this fashion, a consistency between actual ABS data and generated data is obtained.

Each method utilises the same time periods. The years for both the climate sensitivity analysis method and Pearson's product-moment correlation coefficient encompass three periods during the baseline coverage; 2001-2002, 2003-2004 and 2005-2006. Climate maps based upon the three studied climatic variables were produced through SILO data for each corresponding production year.

The LSA output for grapes in the period of 2001-2002 (**Figure C1**) indicate that most areas are potentially high in suitability to produce a yield within the desired yield range, with a modest area denoting a moderate suitability. The majority of land in the Goulburn Broken shows suitability in the range of 80% to 90%, no areas show 100% suitability. Moderate suitability (in the range of 50% to 70%) principally occurs in the northern half of the region, with land around Euroa showing the largest area of moderate suitability. Land to the east of Alexandra and west of Kilmore also show moderate suitability. Higher land suitability, at 90%, is only seen in the south of the Goulburn Broken south of Euroa.

The resulting map in 2003-2004 (**Figures C2**) has similarities to the previous map. Alike to the 2001-2002 outputs, most of the region is considered of high suitability (within the 80% to 100% range). The same basic distribution of suitability is also seen between the two outputs. There are differences in the amount of land either considered moderate (50% to 70%) or high (80% and 90%) across the region. The main differences is the expansion of the land considered moderate to the north of Violet Town and north of Shepparton, and also a reduction in the high suitability range (90%) to the lower category of 80% in the south of Seymour and Mansfield.

The period of 2005-2006 (**Figures C3**) is virtually identical to the 2003-2004. The majority of the output maps do indicate that there is a high suitability (80%) for the production of wine grapes. Lands categorised as moderate in suitability are more concentrated in the northern regions with scattered areas north of Violet Town and Euroa. The main difference between this period and the previous period is a slight reduction in suitability east of Seymour from a high suitability of 90% to a lower ranking of 80%. A similar reduction in suitability is also likely to the southeast of Mansfield. Other, similar reductions may also occur in the south of the region.

[11] The use of a single year for validation differs to the 10 year baseline average (1996 – 2005) that is utilised in the overall LSA model. Due to a lack of data, a 10 year average of data could not be obtained and hence single years were used and compared against single year LSA outputs. This may have implications in production outputs seen in the LSA data, as the previous years climatic conditions can have a minor impact on tree growth in the following year.

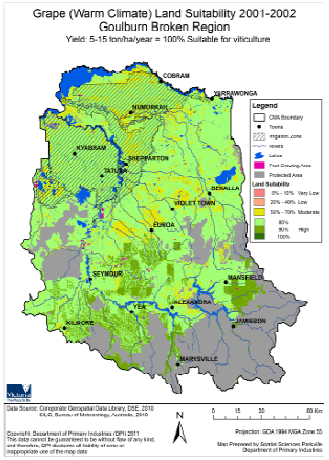


Figure C1 **Grape land suitability for Goulburn Broken Region – 2001-2002**

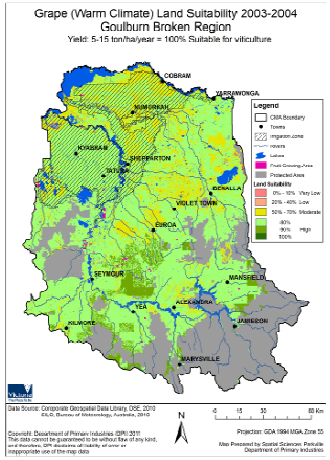


Figure C2 **Grape land suitability for Goulburn Broken Region – 2003-2004**

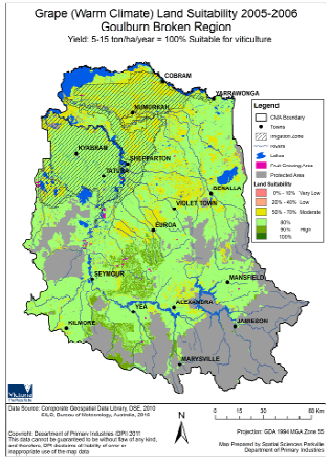


Figure C3 **Grape land suitability for Goulburn Broken Region – 2005-2006**

Climate Sensitivity - Historical Climate Observations

This analysis focuses upon the resultant land suitability maps and the sensitivity they have to climatic variables. The Climate Branch in the AHP hierarchy has the greatest weighting (i.e., 60%; see Figure 3.4) and, hence the largest influence upon any output maps. Consequently, there should be a response within the output models to any climatic changes. This means that the land suitability across the region, for each year that is analysed, should change in response to changes in climate.

A comparison between the three suitability maps for grapes (**Figures C1** to **C3**) indicates that the 2001-2002 production period is predicted as a better growing season compared to those in the 2003-2004 and 2005-2006 periods. This change between the three seasons is analysed through comparison of the climate conditions in the 2001-2002, 2003-2004 and 2005-2006 periods.

For each production year and for each climatic variable, maps have been produced using data provided by the Department of Natural Resources and Mines, Queensland, in conjunction with the BOM weather recordings, through their SILO program

Figures C4 to **C6** show maximum temperatures, respectively, for the 2001-2002, 2003-2004 and 2005-2006 production periods. Maximum temperatures were relatively constant in the northern areas of Goulburn Broken in the range of 22ºC - 24ºC, but generally became cooler in the more southern areas, in particular in the alpine areas, where ranges were from 10ºC - 12ºC. The main differences between the three periods are the southerly extent of the higher range maximum temperatures seen in the north of the region. In the 2003-2004 period, this extent is not as great as in the other two periods. Average maximum temperatures, as high as 24ºC, are seen only in the top quarter of the Goulburn Broken Region. The majority of the region has experienced maximum temperatures in the range of 20ºC to 22ºC. The distribution of average maximum temperatures in the 2001-2002 period indicate that the high temperatures in the north have a more southerly extent than those seen in the 2003-2004 period. Temperatures in the range of 20ºC to 22ºC across the central region have diminished, but they do not extend any further south than in the 2003-2004 period. Distribution of maximum temperatures in the 2005-2006 period indicates that this period was warmer than the other two periods. The high value ranges in the north now extend over the top third of the region, also the central distribution of temperatures are seen further south than seen in the other two years. This also has led to slightly elevated temperatures in the alpine regions to the south.

Figures C7 to **C9** show minimum temperatures, respectively, for the 2001-2002, 2003-2004 and 2005-2006 production periods. As with the maximum temperatures seen in these time periods, there are similar patterns seen over the three years. The 2003-2004 year can be was the cooler of the three periods. High minimum temperatures in the range of 8ºC to 9ºC occurred in the top third of the Goulburn Broken Region. The temperature decreased within the 7ºC to 8ºC range across the majority of the central and southern portions of the region, with cooler minimum temperatures below 6ºC observed in the alpine regions. The 2001-2002 and 2005-2006 periods were very similar in the distribution of maximum temperatures. The top half of the region had minimum temperatures from 8ºC to 9ºC, which also extended into the southwest. This southerly increase in minimum temperatures was reflected in increase temperatures in the southeast alpine regions. Also observed, primarily in the 2005-2006 period, is a small portion of the northern areas experiencing an average minimum temperature from 9ºC to 10ºC.

Figures C10 to **C12** show total annual rainfall, respectively, for the 2001-2002, 2003-2004 and 2005-2006 production periods. The 2001-2002, compared against the other two time periods, has experienced the lower amount of total rainfall. The top third of the study region, in this year, details rainfall below 400mm, with the lowest values of about 200mm seen in the northwest. This increases to, on average, 500mm in a diagonal band across the central portions of Goulburn Broken. This steadily increases in value into the alpine regions where total rainfalls well above 1200mm were observed. The 2003-2004 and 2005-2006 periods are very similar in the spatial distribution of total annual rainfall. For both periods, the lowest values of below 400mm are experienced in the northwest. This value does not fall below 300mm in this area. The central diagonal band of rainfall between 400mm and 600mm is larger than in the 2001-2002 period and the total annual rainfalls towards the southeast alpine regions are higher, well above 1400mm.

The analysis of the climate[12] between the three studied intervals and the land suitability output maps indicates that changes in the maximum and minimum temperatures and in the total rainfall cause a change in grape land suitability. However, between the 2003-2004 and 2005-2006 periods, the rainfall distribution pattern is similar but the maximum and minimum temperatures vary. Even with these differences, the results of land suitability are comparable. This suggests that other climatic factors (acting in conjunction with temperature and rainfall) may be also influencing land suitability ratings over these three periods.

The main relationship between land suitability and climate to observe between the three periods is the influence of rainfall in the 2001-2002 period compared against the 2003-2004 and 2005-2006 periods. In the earlier time frame, across the northern areas, the suitability is seen to be higher than in the latter years. Similarly, the total annual rainfall in this earlier year is lower than in the later years. This is primarily due to the fact that the rainfall experienced is in the optimal ranges preferred for grape vines. This can also be partially attributed to the maximum and minimum temperature ranges observed in this time period, which are slightly better than the later two time periods for optimal grape growth.

The distribution of higher rainfall values in the 2003-2004 and 2005-2006 periods, across the south western regional areas can also be linked to the reduction of land from a land suitability rating of 90% to 80%. Comparison of these later time periods against the 2001-2002 year, it can be seen that as rainfalls increase into ranges not preferred by grapes for optimal growth, there is a subsequent reduction in land suitability.

The temperature variance between the three time periods is not considered extreme, the changes observed do produce responses within the model but are not extreme enough alone to cause major variation in predicted land suitability. This indicates that the temperature related criteria and associated range classes have sufficient granularity to be sensitive to seasonal weather patterns and should perform for the longer term climate change analysis. The same situation is observed for rainfall criteria and class ranges. These can be seen in the land suitability outputs between the 2001-2002, 2003-2004 and 2005-2006 periods. What is primarily seen is that if rainfalls are within the optimal ranges, then, the land suitability is in the higher ranges. If the rainfall falls outside the optimal ranges, as in the 2003-2004 and 2005-2006 periods, then, there is a reduction in the land suitability ratings.

[12] As defined by the IPCC (2007), climate is "the average weather, or more rigorously, the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind". The use of climate within this section is in accordance with this definition as yearly averages of the analysed variables are considered.

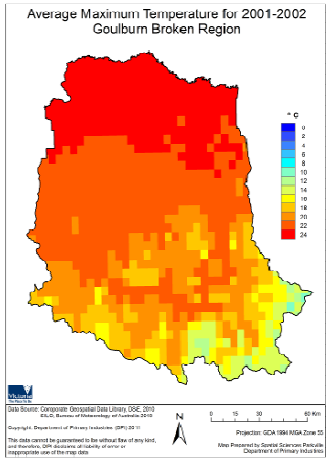


Figure C4 **Average Maximum Temperature for Goulburn Broken Region – 2001-2002**

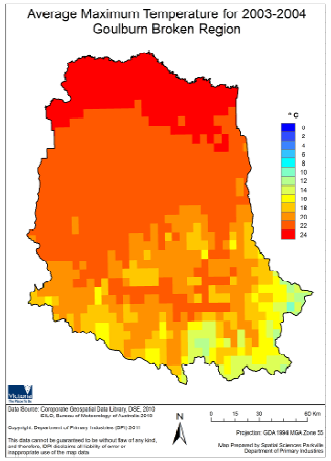


Figure C5 **Average Maximum Temperature for Goulburn Broken Region – 2003-2004**

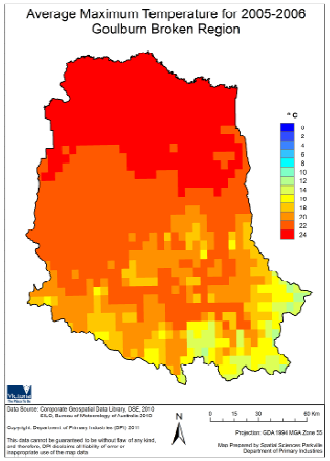


Figure C6 **Average Maximum Temperature for Goulburn Broken Region – 2005-2006**

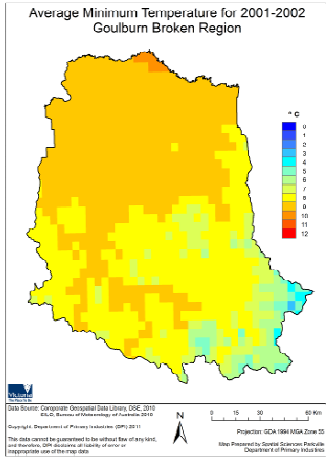


Figure C7 **Average Minimum Temperature for Goulburn Broken Region – 2001-2002**

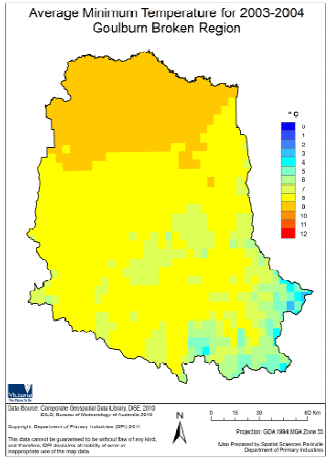


Figure C8 **Average Minimum Temperature for Goulburn Broken Region – 2003-2004**

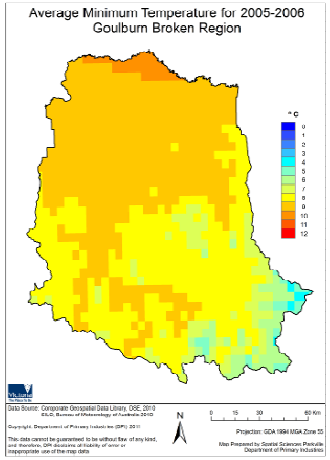


Figure C9 **Average Minimum Temperature for Goulburn Broken Region – 2005-2006**

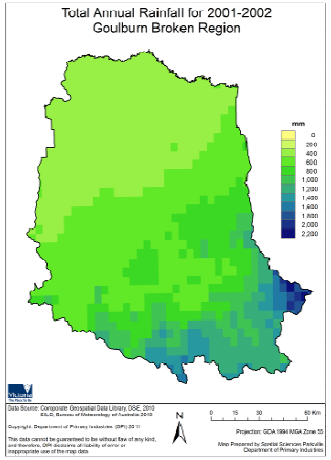


Figure C10 **Total Annual Rainfall for Goulburn Broken Region – 2001-2002**

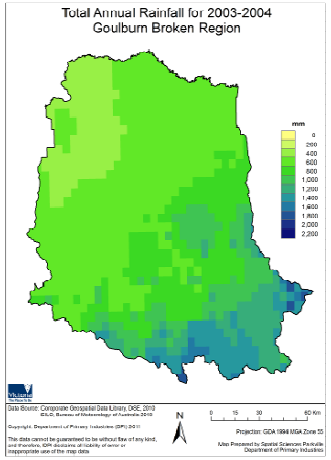


Figure C11 **Total Annual Rainfall for Goulburn Broken Region – 2003-2004**

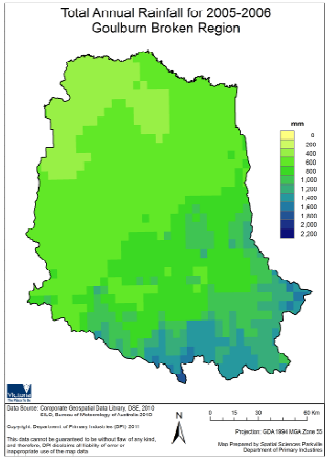


Figure C12 **Total Annual Rainfall for Goulburn Broken Region – 2005-2006**

Validation through Correlation – Pearson's Coefficient

This validation method is deployed to ascertain if the AHP hierarchy and resultant LSA outputs are performing as expected. The *Pearson's product-moment correlation coefficient* provides a measure of the linear correlation between two variables. In this instance, the two variables being tested are changes in land suitability due to climate, landscape and soils and grape production in terms of yield.

Census data on total grape production from the ABS was used at the statistical local area (SLA) across the Goulburn Broken Region (**Table C1**)[13]**.** Three production years, 2001-2002, 2003-2004 and 2005-2006, were chosen on the basis of data availability and also in terms of volume of production. In this method, the yield per SLA is used, which is a result of dividing the production by the area.

Table C1 Grape production per SLA for Goulburn Broken Region – 2001-2002, 2003-2004 and 2005-2006

	2001-2002			2003-2004			2005-2006		
SLA	Production (ton)	Area (ha)	Yield (ton/ha)	Production (ton)	Area (ha)	Yield (ton/ha)	Production (ton)	Area (ha)	Yield (ton/ha)
Moira - West	1,648.80	190.20	8.67	687.50	102.40	6.71	654.00	98.00	6.67
Moira - East	71.90	14.00	5.14	130.00	20.00	6.50	88.00	24.00	3.67
Campaspe - Kyabram	4.00	2.10	1.90	10.00	2.00	5.00	725.00	93.00	7.80
Campaspe - South	1,189.20	676.90	1.76	2,474.50	664.00	3.73	7,388.00	1,078.00	6.85
Gr. Shepparton - Pt A	382.60	166.60	2.30	211.50	42.10	5.02	88.00	43.00	2.05
Gr. Shepparton - Pt B East	713.40	163.80	4.36	1,245.50	165.20	7.54	954.00	154.00	6.19
Gr. Shepparton - Pt B West	221.00	88.00	2.51	499.00	74.80	6.67	282.00	50.00	5.64
Delatite - Benalla *	67.00	7.20	9.31	27.00	7.20	3.75	28.00	8.00	3.50
Delatite - North *	598.60	115.10	5.20	340.70	76.00	4.48	162.00	60.00	2.70
Delatite - South *	419.20	86.30	4.86	983.90	97.40	10.10	837.00	99.00	8.45
Strathbogie	6,738.40	1,139.80	5.91	9,360.50	1,159.70	8.07	7,708.00	1,231.00	6.26
Mitchell - North	353.10	88.30	4.00	390.60	83.00	4.71	110.00	50.00	2.20
Mitchell - South	106.20	56.80	1.87	334.80	57.70	5.80	258.00	80.00	3.23
Murrindindi - North	27.30	12.30	2.22	62.00	14.40	4.31	47.00	17.00	2.76
Murrindindi - South	813.80	212.10	3.84	1,576.80	221.20	7.13	902.00	234.00	3.85
Overall	13,354.50	3,020	4.42	18,334.30	2,787	6.58	20,231.00	3,319	6.10

* Delatite – Benalla is Benalla – Benalla in 2003-2004 and 2005-2006, Delatite – North is Benalla – Balance in 2003-2004 and 2005-2006, Delatite – South is Mansfield in 2003-2004 and 2005-2006.

Calculation of the correlation coefficient was carried out in several steps. The LSA output maps were broken down into their constituent SLAs. From these SLAs, the cell count statistics were obtained - these counts were in the form of land suitability categories. From these cell counts, a percentage of how much lies in each land suitability class, over the whole SLA, can be calculated. This can then be used to divide the ABS data for SLA grape production and area up per suitability class, as defined by the calculated percentages of each land suitability class. From the broken down figures the correlation coefficient can be calculated upon the end result grape yields. Microsoft EXCEL was deployed in the calculation of the Pearson's correlation coefficient between land suitability and production[14].

[13] Total grape production for the Goulburn Broken Region includes the production of both white and red grape varieties. Grapes can include both red and white varieties. Hence values reported are total production values for all grapes produced. Also these values are only for grape production for wine making purposes only.

[14] The formula for the calculation of the Pearson's correlation coefficient is:

$$r = \frac{\sum XY - \frac{\sum X \sum Y}{N}}{\sqrt{\left(\sum X^2 - \frac{(\sum X)^2}{N}\right)\left(\sum Y^2 - \frac{(\sum Y)^2}{N}\right)}} \qquad (2)$$

where X is land suitability class, Y is production, N is number of classes per SLA over the entire region and r is the correlation coefficient.

The eventual outcome is the correlation coefficient which is denoted as 'r'. As mentioned, the r-value has a range between -1 and 1. A strong positive or negative r-value would indicate that there is a correlation present between the two variables being tested (land suitability and yield in a given year). An r-value close to or equal to 0 indicates that there is no correlation present. Using the correlation coefficient and the number of land suitability classes in that given year a t-value can be calculated. The t-value is derived from a t-test, which is used to test whether the null hypothesis is true or false[15]. In this instance, the null hypothesis is that the land suitability (combination of climate, soils and landscape) in a given year is not related to grape production. From the t-value the probability (p-value) can be calculated, the p-value being the probability of obtaining a similar or more extreme r-value. The lower the p-value, the less likely the result if the null hypothesis is true, subsequently the more significant the result is.

According to statistical common practice, significance at the level of 5% (p-value 0.05 or lower) will be used for this method. That is, if the statistical significance is 5% and below, it is deemed significant and the null hypothesis is rejected – land suitability has an affect on grape production in a given year. If the statistical significance is above 5%, it is deemed not significant and the null hypothesis is accepted.

Table C2 Pearson's Correlation Coefficient (r) between Land Suitability and production – grapes

Year	Number	r	t	p
2001-2002	57	0.3010	2.3412	0.0114
2003-2004	56	0.5001	4.2439	0.00004
2005-2006	55	0.3018	2.3048	0.0126

r = Pearson's correlation coefficient, t = t-statistic, p = probability (p-value)

The results recorded in **Tables C2** show that there is a strong positive relationship between land suitability and grape production in a given year; as land suitability in a particular area increases or decreases, grape production will increase or decrease in response.

[15] The formula for the calculation of a t-value is:

$$t = \frac{r}{\sqrt{\frac{\left(1 - r^2\right)}{\left(n - 2\right)}}}$$

where t is the t-value, r is the Pearson's Correlation Coefficient and n is the number of classes per SLA over the entire region.

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Climate Adaptation Options for Viticulture in Sunraysia

Dr Alexandria Sinnett

DEPARTMENT OF PRIMARY INDUSTRIES

Outline

- Background
- Aim
- Method
- Results
- Conclusions

Background

- Annual average temperature in the main viticulture areas, in Australia, will rise in the order of:
  - 0.3 to 1.7^{o}C by 2030
  - 0.8 to 5.2^{o}C by 2070. (Webb 2006)
- Without adaptive measures it is expected that wine grape quality in Australia could decrease by up to 7% to 39% by 2030. (Webb 2006)

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Research suggests that there will be a significant rise in temperature in the future throughout the world. According to Webb *et al.* (2006) in Australia annual average temperature will rise in the order of 0.3 to 1.7°C by 2030 in the main viticulture areas. By 2070 mean annual temperatures are expected to increase in the main viticulture areas by 0.8 to 5.2°C.

Webb *et al.(2008)* found that without adaptive measures wine grape quality in Australia will decrease by up to 7% to 39% by 2030.

There are two ways temperature can impact on viticulture. One way is through an increase in the mean annual temperature. The other way is through an increase in the frequency of extreme heat events. White *et. al* (2006) found that an increase in the frequency of heatwaves had a much greater impact on the wine grape sector compared with an increase in mean annual temperature. He stated:

'… increase 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.'

Such findings have prompted the researchers to question what options do growers have available to them to combat temperature change and how economic are the different adaption options available to them.

Aim

1. To find out what the expected impact on wealth and return on investment could be from an increase in temperature on a wine grape farm business in Sunraysia; and

2. To calculate the expected costs and benefits of different adaptation options for this wine grape farm business.

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This lead to the aim of this research.

This research needs to be undertaken now because it takes time for farmers to adapt their business to a change. By thinking about it today, by 2030 there should be some possible options for the challenges farmers are going to face.

Method

- Develop key assumptions
  - Farm assumptions
  - Operating assumptions
- Analyse options and scenarios for one wine grape farm
  - Using discounted net cash flow analysis, with @RISK overlayed
- Discuss key findings

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This project was carried out using the principals of farm management economics. It involved using a case study as the methodology. One medium to large sized wine grape farm business was used to explore the impact of an increase in temperature (represented through a loss in income) and to explore two different adaptation options. The details of this farm business were provided to the researchers at a visit to the farmers property. The price data, the yield and cost data were based on records from the last 10 years.

Using @Risk (an add-in program for Microsoft Excel) probability distributions were set around the price and yield data. A 15 year discounted net cash flow budget was developed, which allows the return to be calculated from investing in a farm business for certain scenarios. To calculate the return the capital investment yields the farm business is purchased in year one and sold in year 15.

Why do case studies?

Case studies of real and representative farm businesses, as they currently operate and as they could operate, provide information about real world phenomena that facilitates understanding them. Such understanding can be used to check against current theoretical understandings about how parts of the real world work. Thus, case study research is used to generalize to theory, and the analysis can inform other farmers running similar systems on their future options. The results of a real case study analysis are either consistent with theory, and add support to the explanations of current theory, or they are not consistent with theory and challenge accepted wisdoms.

The attributes and goals of farm families and the systems they run are unique. Emphasis on the uniqueness of farm businesses that justifies the use of case study approaches has a corollary: how can the findings about the state of affairs on one farm be useful and used to help farmers running other different farms? In summary, all of these different farms are subject to the same laws of nature affecting the internal workings of the farm business, and the same laws of economics and finance and effects of risk and uncertainty that operate in the external environment.

Some confusion about using results from case study research and development comes from the notion that an aim of extension is to say 'You should do this'. The more useful approach is to say to a potential farm innovator: 'This is the information generated about future options from examining this case study farm; these are the methods used; this is the way to think about whether a change like the one in question is a good thing to do or not, and this is the way to use the information generated. If you want to test out the advantages and disadvantages of this innovation on paper, here is a set of farm budgets, put your own numbers in them'.

Why include risk analysis?

Risk analysis is necessary when there are variables in the model that have a range of possible values. For example the average weighted price of chardonnay has varied from $873/t in 2004 to $300/t in 2009 (according to the Australian Regional Wine Grape Crush Survey). Using only one value to define wine grape price does not allow for full consideration of all the possible outcomes that could occur. Therefore it would be beneficial to include in the model a range of wine grape prices that all have different chances of occurring.

@Risk (an add-in program in Microsoft Excel) allows a range of values and the relative likelihood of each value to be entered for each uncertain variable. @Risk uses these values in each simulation. Simulation, in this sense is letting the computer recalculate the worksheet over and over again, each time using different randomly selected sets of values. Essentially, the computer is trying all valid combinations of the values of input variables to simulate all possible outcomes. It is equivalent to running hundreds or thousands of 'what if' analyses on the worksheet at the one time. For this analysis the model was run 1000 times.

Assumptions about the farm

- Farm size: 62 hectares
- Water share: 9.144 ML per hectare (crop water use 5.5ML/ha red and 6ML/ha white)
- The average yield t/ha, (and price $/ha) for the varieties grown:
  - Cabernet 12t/ha ($457/t)
  - Chardonnay 21t/ha ($496/t)
  - Shiraz 10 t/ha ($540/t)
- Costs $6,000 per hectare (variable and overhead)
- Walk in walk out value of the farm $26,000/ha (made up of land valued at $5,000/ha, water share valued at $1,950/ML and buildings/sheds/pumps valued at $200,000)

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The key assumptions about the case study farm are presented in this slide. The farm has a mix of red and white grapes, the tonnage and price data shown on this slide is based on the mean amount. Yield data is based on a log-normal distribution from the yields the farm has experienced over the past 10 years; price data is based on a distribution from the price data the farmer has received over the past 10 years.

The prices this farmer received were lower than the average presented on the Regional Wine Grape Crush Survey. The mean wine grape crush price data over the last 10 years shows that Cabernet Sauvignon would have had a mean price of $506/ha, Chardonnay would have been $572/ha and Shiraz would have been $556/ha.

The price the grower received was lower, but this has been because he has been financially unable to renovate some blocks, which has meant that some grapes have been of a poorer quality, which lowers the overall average price received.

This will increase the impact a fall in income will have.

To help balance this, throughout the presentation, in the notes pages, information has been provided about a farm that has prices that accord to the Regional Wine Grape Crush Survey and has the same costs as this farm.

The crop water use data accords with industry average in the area (generally it is assumed that irrigation use would be on average 5-7 ML/ha/year for all three varieties)

The yield data also accords with general industry average (generally it is assumed that crop loads would be anywhere from 10-20 t/ha (mostly depending on which winery you sell to).

Costs data are based on the costs the business has experienced and accords with the general rule of thumb of costs being around $6000

The land value is based on a real estate agents estimate, we have also added an extra $200,000 to cover the cost of buildings, sheds, pumps etc.

The value of permanent water is based on the amount the government was paying for permanent water at the time of the analysis.

Assumptions about the operating environment

- Climate B (CSIRO definition of medium climate change)
- Impact of temperature change is represented through a fall in income. Three scenarios were explored:
  - 10 % straight line cut to income
  - 20 % straight line cut to income
  - 30 % straight line cut to income

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In this slide it shows what assumptions have been made about the climatic conditions the farm is operating in (which impact on water allocation and the expected impact of a temperature change).

If it is assumed that the temperature is going to be hotter, then it would also be expected that there will be lower inflows into water storages and necessarily there will be lower water allocations. The CSIRO have modelled a number of water availability scenarios for different climate events. CSIRO developed three scenarios – Scenario A (low climate change) Scenario B (medium climate change) and Scenario C (high climate change) to consider the affect on water availability in the future. These scenarios are calculated through applying a percentage reduction, determined by CSIRO predictions, to the entire historic inflow record (July 1890 to June 2007). Frontier economics used this information on water availability and developed a model to work out the expected water allocations to farm businesses.

The research presented here used continuous probability distributions to describe the water reliability profiles generated by Frontier Economics for climate B . @Risk was then used to select random water right allocation sequences for each year over the fifteen years. That is, in the spreadsheet model used for this analysis, it was assumed the farm business was operating under medium climate change (as defined by CSIRO), which equated to a higher probability of lower water allocations over the 15 year period.

It was also assumed that an increase in temperature, and/or an increase in the frequency of extreme heat events, will lead to a fall in quality and/or yield, which ultimately reduces income. So for the economic analysis, a straight line fall in income is applied every year. Three different scenarios were carried out to assess the impact of an increase in temp – a 10% cut, a 20% cut or a 30% cut to income. These scenarios were based loosely on the work of Webb 2006 who found that a temperature change will cause income to fall somewhere in the range of 8% to 30% for farmers in Sunraysia.

Total income could decrease because of one or all of the following reasons:

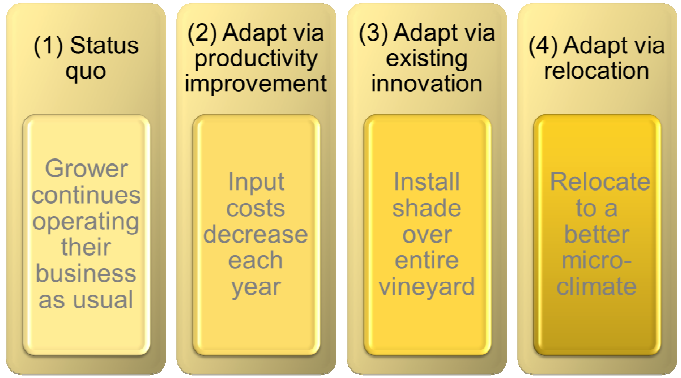
•Growing season is shortened because of an increase in mean annual temperature, this then causes the grapes to be of poorer quality, which then decreases price.

•Water requirement increases because of less rainfall, therefore there is not as much water to sell.

•Water requirement increases because of an increase in mean annual temperatures and there is not as much water to sell.

•Yield falls because the farmer might sacrifice some vines to focus on the better (younger) vines.

The options explored



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Research has suggested that the ways a grower could adapt to an increase in temperature is to:

•Relocate the farm business to a more suitable micro-climate (Webb 2008, Cahill 2008, Thomson and Tomkins 2011).

•Switch to a variety that can cope with a higher Mean January Temperatures (MJT). (Webb 2008, Cahill 2008, Thomson and Tomkins 2011)

•Change annual management (such as adding canopies to shield grape vines from extreme sun exposure (Cahill 2008)

We have considered these different options and equated it into four options – doing nothing, some new productivity improvement (technology, management practice or variety), installing shade and relocation.

This slide shows the different adaptation options.

Option 1 assumed that the grower does nothing about the increase in temperature and it shows what the expected impact is on the business returns. In reality the majority of farmers will do something, they will act to reduce the impact. This simplistic option is purely to demonstrate the potential impact on net wealth and return to should there be an increase in mean annual temperature. It was assumed that the impact of an increase in temperature is reflected through a fall in income (as mentioned earlier three scenarios will be considered: a 10%, or 20%, or 30% cut in income and costs will remain unchanged).

Option 2 explores what size productivity factor is needed to combat this fall in income caused by an increase in mean annual temperatures. It is assumed this productivity factor will come through the form of lowering costs (the fall in costs could be the result of discovering better more efficient technology, or more efficient management practices or a new variety that results in lower costs or increased returns). Such an advancement will take years for it to be taken up on farms; that is why there is need to start thinking about it now. For example, some have argued that it could take 20 to 30 years for consumers to accept a new wine variety (Webb 2008, Cahill 2008, Thomson and Tomkins 2011). It is assumed that this new advancement will not cost extra money.

Option 3 analysed the net benefits/costs of an existing adaptation strategy, which was to install shade. It was assumed that shade would mitigate against an increase in temperature; resulting in income not decreasing as a result of a temperature change.

Option 4 analysed the net benefits/costs of relocating the farm to a better micro climate and higher winegrape prices. For this option an analysis of the stream of cash flows was undertaken in order to work out what the grower should pay for their capital and then an assessment of cash flow available and equity available was undertaken to work out what the grower could afford to pay. This was then compared with the current market rate of land in different production regions.

The expected impact of an increase in temperature on the net wealth accumulated from investing in a wine grape farm without making any changes to the farm

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As stated earlier an increase in temperature is expected to decrease income. The affect of this is shown in the following slide. This is based on the assumption the farmer does nothing – which I understand may not apply to all farms in practice, but this slide is used to show how much a business would be affected by a change in temperature.

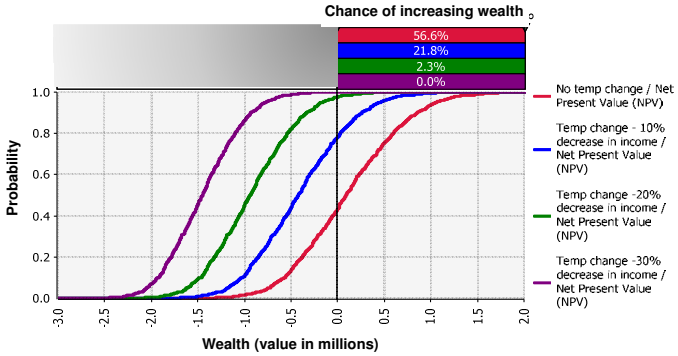
Interpreting the results

@Risk presents the results of the 1000 simulations in the form of a probability distribution. It organises the results so a decision maker can see the likelihood of different levels of returns.

In this analysis a Cumulative Distribution Function (CDF) was used to assess each scenario for a representative farm. Each point on a CDF shows the probability of earning that corresponding level of return or less. Further, plotting CDF's from different scenarios for the same representative farm on the one graph allows for a powerful analytical tool to assess which scenario has the greater business risk and which scenario will make the most efficient use of capital. The higher the IRR (internal rate of return) the more efficient the use of the capital invested. The scenario that generates a CDF that lies furthers to the right when plotted on the same axis as an alternative scenario makes more efficient use of that capital. That is, a CDF for one option located to the right of the CDF of another option is said to be a stochastically dominant option. This means that for the same level of risk, the option promises higher return, or, for the same return, lower risk (Hardaker *et al.* 2004). The investment that promises greater return at any given level of risk is said to 'stochastically dominate' the other investments. For someone who is risk averse, the stochastically dominant option is preferable.

At this point it is important to define business risk. Business risk refers to the volatility of factors affecting the business such as yields, prices, costs, weather events, disease events, and so on (Makeham and Malcolm 1993). In this project variability of irrigation water (that is dry years getting drier) does not change as a result of an SDL (XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX). This is because the SDL (as defined under Activity 2) is a constant percentage reduction in water across the consumptive pool. However, the reliability of receiving full entitlement changes as a result of the SDL. A direct consequence of this is that costs increase (or if costs do not increase yields decrease). If costs increase there is a risk that the business will not be able to pay for its inputs, to service debt and to appropriately reward labour and management and receive an adequate return on capital.

Expected impact of an increase in temperature on wealth (NPV) at 5% discount rate



An increase in temperature, decreases the probability of this farmer increasing his wealth from investing in this farm business and it increases this farmers business risk

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This slide shows the impact an increase in temperature would have on the bag of money (wealth) the case study farmer is expected to have at the end of the 15 years.

As expected a decrease in income has a negative affect to the returns of the business.

The following slide will break down the information presented in this graph into more refined picture.

Expected impact of an increase in temperature on wealth (NPV at 5% discount rate)

		Case study farmers' chance of adding to his wealth		
	Wealth earned after 15 years	**Positive addition to wealth (>$0)**	**$250,000 or more**	**$500,000 or more**
Increase in temperature impacts	**No change to income**	60%	40%	25%
	10% decrease	20%	10%	4%
	20% decrease	2%	0%	0%
	30% decrease	0%	0%	0%

How to read this table:

In a world without an increase in temperature the case study farmer has a 60% chance of adding to his wealth from this investment; if the case study farmer wanted to earn $250,000 or more he has a 40% chance, and he has a 25% chance of adding $500,000.

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This slide is a way to understand the messages coming out of the graph on the previous slide.

•In a world without a temperature change the farmer has a 60% chance of adding to his wealth

•If there is an increase in temperature (which causes income to fall) the chance of the farmer adding to his wealth falls considerably (for example the farmer now only has a 20% chance of adding to his wealth in a world where temperature has caused income to decrease by 10%).

Regional Wine Grape Crush Survey 2011 Data

Expected impact of an increase in temperature on wealth

		Average farmers' chance of adding to his wealth		
	Wealth earned after 15 years	**Positive addition to wealth (>$0)**	**$250,000 or more**	**$500,000 or more**
Increase in temperature impacts	**No change to income**	90%	80%	62%
	10% decrease	57%	34%	17%
	20% decrease	11%	4%	0%
	30% decrease	0%	0%	0%

Using grape prices from the Regional Wine Grape Crush Survey, a farmer has a 90% chance of adding to his wealth from this investment; if the case study farmer wanted to earn $250,000 or more he has a 80% chance, and he has a 62% chance of adding $500,000.

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Wine grape crush prices

If the grower had prices that were closer to the prices of the reported in the Regional Wine Grape Crush Survey (**but had the same cost structure as the case study farm**), it is still expected that an increase in temperature will reduce the probability of a farmer adding to their wealth. However if there was a 10% fall in income, caused by an increase in temperature, it is expected that the farmer would add to his wealth 57% of the time. As one would expect, the size of the impact depends on the commodity price the grower receives and the costs of inputs.

Temperature change and land values

- It is expected that if there was a change in temperature (and no on-farm adaptation implemented), which led to a fall in income then land values would fall
- For example, on this case study farm it is expected that if income fell by 10% the walk in walk out value of this property would fall from $26,000 to $13,000 (in order for the property to still generate a return of 5 per cent nominal)

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The researcher used the stream of cash flows generated after there has been a temperature change to analyse how much the grower should now pay for their property in order to still earn their desired rate of return of 5% nominal.

Adapt via productivity – the expected returns to a wine grape business under different levels of productivity improvements

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In agriculture costs increase at a greater rate than prices, leading to a fall in cash flow over time if the farmer is not making continual improvements (either through more efficient management practices, more efficient use of inputs and so on). In all the budgets used to analyse these questions the implicit assumption behind these analyses is that the farmer is continually adapting his management practices, or uses of machinery, or uses of inputs in order to maintain profits.

This next series of analyses considers directly how much costs need to fall by in order for this business to earn the same rate of return (5% nominal) as it did before there was an increase in temperature. S

Research and Development (RD&E) will be required to develop more efficient practices that lead to productivity gains (either lower input costs of higher returns) to ensure the future rate of return.

An existing adaptation strategy:

eg. installing shade over vines

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Mean return (IRR) to the farm business under different productivity improvement factors and different levels of income

		Annual decrease to input costs, compounded over time					
	Productivity gain p/a	0%	1%	2%	3%	4%	… 7 %
Increase in temp impacts	No change to income	6%	8%	9%	10%	11 %	14%
	10% decrease in income	2%	4%	6%	7%	8%	11%
	20% decrease in income	-1%	1%	3%	4%	5%	8%
	30% decrease in income	-5%	-2%	-0.6%	1%	2%	5%

If income fell by 10% and there **was no** tools/techniques available that increased productivity then it is expected the business would earn 2% return

If income fell by 10% and there **were** tools/techniques available that increased productivity (lowered costs by 2% compounded per annum) then it is expected the business would earn 6% return

For this farm business to adapt to a world with an increased temperature (still earn 5% nominal return) then it is expected that either a 2%, or 4% or 7% productivity gain will be required (dependent on whether it is a 10%, 20% or 30% cut to income).

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For this analysis costs have been reduced at a compounding amount per annum in order to explore how much productivity improvement is needed for this farm to still earn 5% return (IRR – internal rate of return) 50% of the time.

A number of different scenarios have been explored to investigate the size of the reduction in costs needed to still earn the desired 5% nominal return on capital.

The RED boxes show when the farm is not earning the desired level of return,

The GREEN boxes show when the farm is earning the at or above desired level of return.

Costs would need to reduce by 1.5% for the farm to earn 5% return on their business 50% of the time, under an increase in temperature that has caused income to fall by 10%. If income fell by 20% costs would need to fall at a compounding rate of 4% per annum in order for this business to earn 5% nominal return 50% of the time. If income decreased by 30% costs would need to fall at a compounding rate of 7% per annum in order to earn 5% nominal return 50% of the time.

Technological change, varietal change, farm management practice change – all take time to implement; it is not a case of inventing them and seeing them fully implemented on farm the next day. That is why it is important to start investing research dollars today to help growers in 2030.

Wine grape crush survey data

If the farm had prices that accorded closer to the wine grape crush (and the same cost structure) then the above table would like more like:

	0%	1%	2%	… 5%
No change	**10%**	11%	13%	16%
10% decrease in income	**6%**	8%	9%	12%
20% decrease in income	2%	4%	**5%**	9%
30% decrease in income	-2%	0%	2%	**5%**

For a farm that had prices that more closely aligned to the wine grape crush survey then this farm would need either a 2% or 5% lift in productivity

The size of the productivity gain required will differ for every different farm – depending on the

Mean return (IRR) to the farm business under different productivity improvement factors and different levels of income

		Annual decrease to input costs, compounded over time			
	Productivity gain p/a	0%	1%	2%	… 5%
Increase in temp impacts	No change to income	10%	11%	13%	16%
	10% decrease in income	6%	8%	9%	12%
	20% decrease in income	2%	4%	5%	9%
	30% decrease in income	-2%	0%	2%	5%

Based on Regional Crush Survey data, If income fell by 10% and there **were** strategies available that increased productivity by 2% compounded per annum, then the business would earn 9% return (compares with 6% for the case study farm.

Based on grape prices from the Regional Wine Grape Crush Survey, a farmer earns more and requires a lower productivity gain to realise a 5% IRR

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Wine grape crush survey data

If the farm had prices that accorded closer to the wine grape crush (and the same cost structure) then the above table would like more like:

	0%	1%	2%	… 5%
No change	**10%**	11%	13%	16%
10% decrease in income	**6%**	8%	9%	12%
20% decrease in income	2%	4%	**5%**	9%
30% decrease in income	-2%	0%	2%	**5%**

For a farm that had prices that more closely aligned to the wine grape crush survey then this farm would need either a 2% or 5% lift in productivity

The size of the productivity gain required will differ for every different farm – depending on the prices they receive and the costs of their business.

Installing shade to mitigate against the impacts of an increase in temperature

- An existing adaptive strategy is shading grapes.
- Assumed shade would mitigate against temperature (i.e. no fall in income).
- However, installing shade is costly
- For shade cloth to be worthwhile commodity prices need to be higher.
- If income was 20 per cent higher and the shade cost $40,000 /ha, the grower could earn 5% IRR

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One option for this farmer that is available today is for them to build some type of shade structure to combat an increase in temperature. The analysis was carried out to explore different costs of this shading system. It was assumed that this shade would mitigate against the increase in temperature (that is, income would not be reduced). The problem with building shade over the vineyard is the cost. A shading structure that costs $100,000 per hectare or one that costs $50,000 per hectare is not a viable option for this farm business to use to mitigate against an increase in temperature.

If the farmer could invest in some sort of shading that cost $40,000 per hectare, and had no additional ongoing costs, the farm would also need some sort of productivity improvement which either raises income by 20% or lowers costs by 5% compounded over time in order to earn the same returns the business is expected to earn before the increase in temperature.

Wine grape crush survey

Even using the higher commodity prices associated with the wine grape crush survey, shading is still a very costly exercise and not one that the business can afford.

It is expected that income would need to be increased by around 9% for the wine grape farm to earn their desired rate of return, or for costs to be reduced by 2% compounded per annum.

Adapt via relocation to a better micro-climate in a commercial agricultural region

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In the literature on the impacts of temperature on wine grapes, researchers have explored growers relocating to a better microclimate (whereby there is better conditions for the grapes and therefore the grower should receive a higher price for his commodity). The following slides explore this further.

The price a grower should pay for a farm to earn 5% return on capital if moving to a better climate

	Impact of a favourable increase in temperature in a another part of Victoria (represented through an increase in income)			
	0% increase in income	10% increase in income	20% increase in income	30% increase in income
Land price, in order to earn 5% return	$27,000 per hectare	$40,000 per hectare	$55,000 per hectare	$70,000 per hectare

If a grower moved to a better micro climate and income from growing wine grapes was 20% higher than in Mildura, then a grower could pay $55,000 per hectare and expect to earn 5% return on the investment .

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Webb et al estimated that wine growers in some parts of Victoria will experience an increase in their income because conditions are now more favourable.

For this analysis we considered what price per hectare the farmer should pay for this stream of income, on the next slide we compare this with what the market expects for land in a better micro-climate.

If the grape price was 20% higher than the grower currently receives they could afford to pay $55,000 per hectare for land at the new location.

Land prices ($/ha) at a more favourable location resulting in increased income to achieve 5% IRR

	Impact of an increase in temperature in a another part of Victoria (represented through an increase in income)			
	0% increase in income	10% increase in income	20% increase in income	30% increase in income
Land price, in order to earn 5% return	$40,000 per hectare	$55,000 per hectare	$72,000 per hectare	$902,000 per hectare

If a grower moved to a better micro climate and income from growing wine grapes was 20% higher than in Mildura, then a grower could pay $72,000 per hectare and expect to earn 5% return on the investment

Based on Regional Wine Grape Crush Survey, 20112 data

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If the grower was receiving prices more in line with the Regional Wine Grape Crush Survey, i.e. higher prices than the case study farmer, they could afford to buy land at $72,000 per hectare if they were able to realise a 20% increase in income by moving.

Market value of farmland

- It is expected that a better micro-climate would be somewhere south of Mildura.
- One option is to buy a small dairy farm in Gippsland.
- A 40 hectare farm in Pound Creek, which is not planted to wine grapes, is advertised at $775,000.
  - To develop it into vineyard it would cost around $1,800,000
  - That is equivalent to $45,000/ha (including $25,000/ha to develop into a vineyard)

Whether a wine grape grower can buy land in a better micro-climate will depend on where the better micro-climate is and what other sectors are competing for that land

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Given farm land has many competing uses, the value of that land may be higher than this farmer should pay for what he will use the land for.

Farm income and interest rates influence demand for farm land. There are also other factors that influence the price of farm land, such as:

•Development potential for housing

•Hobby farming/ recreational demand potential

•Tourism potential

•Supply of farmland

What a farmer could pay

for a 62 ha farm, based on a 15 year loan at 8% interest

		Scenarios of extra income			
		No extra income	10% extra income	20% extra income	30% extra income
Scenarios of equity available and cash flow available to service debt	100% equity in existing enterprise, all cash flow available to invest	$2.3 million	$2.7 million	$3 million	$3.4 million
	65% equity in existing enterprise, all of cash flow available to invest	$1.7 million	$2.1 million	$2.5 million	$2.8 million
	50% equity in existing enterprise, all cash flow available to invest	$1.5 million	$1.9 million	$2.2 million	$2.6 million
	100% equity in existing enterprise, 2/3 of cash flow available to invest	$2 million	$2.3 million	$2.6 million	$2.8 million
	65% equity in existing enterprise, 2/3 of cash flow available to invest	$1.5 million	$1.7 million	$2 million	$2.2 million
	50% equity in existing enterprise, 2/3 cash flow available to invest	$1.2 million	$1.5 million	$1.7 million	$2 million

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The previous slides looked at what the farmer should pay for farmland for certain level-of-income streams, and what the market is asking for land in areas that have been noted as being the suitable for wine grapes in the future.
Now, we will consider what the farmer could actually pay (given a number of different financial scenarios).
This is based on working out how much the farmer could receive from the sale of his current farm, and the expected cash flow for the farm in the new location (micro-climate).

The numbers (a mixture of equity and debt servicing capacity) in this table show how much a farmer could pay for a 62 hectare farm.
That is, the numbers are based on the equity the farmer invests from selling his farm in Sunraysia and the stream of cash flow expected from the new farm that can be used to service debt.
That is, if a farmer had 100% equity in his existing enterprise, then he could invest $1.6 million from the sale of his existing farm and could service a debt of $700,000 if he had no extra income and he could use all of his cash flow to service debt.
If the farmer only had 65% equity in his existing enterprise then he could invest $1 million dollars from the sale of his existing farm and could service a debt of $700,000 if he no extra income and used all his cash flow to service debt.
Equity available to invest from existing farm (rounded)
100% equity: $1,600,000
65% equity: $1,000,000
50% equity: $800,000
Based on the following scenarios the size of debt the farmer could service if all the cash flow was available is:
No extra income: $700,000
10% extra income: $1,000,000
20% extra income: $1,400,000
30% extra income: $1,800,000
Based on the following scenarios the size of debt the farmer could service if 2/3 of cash flow was available is:
No extra income: $460,000
10% extra income: $700,000
20% extra income: $950,000
30% extra income: $1,200,000
This table shows what amount the farmer could pay for a 62ha farm on a 15 year loan at 8% interest for the assumed income stream. Subject to the income stream expected and how much the farmer will have available to service debt, and the amount of equity the farmer has to invest.
The amount the farmer could pay varies between $3 million dollars (approximately $50,000 per hectare) and $1.5 million dollars (approximately $25,000 per hectare).

The amount the farmer could pay depends on the equity capital available, the cash surplus available to service debt and the length of the loan and the interest rate.

What a farmer could pay

for a 62 ha farm, based on a 15 year loan at 8% interest (Crush 2011 data)

		Scenarios of extra income			
		No extra income	10% extra income	20% extra income	30% extra income
Scenarios of equity available and cash flow available to service debt	100% equity in existing enterprise, all cash flow available to invest	$2.7 million	$3.1 million	$3.5 million	$3.9 million
	65% equity in existing enterprise, all of cash flow available to invest	$2.1 million	$2.5 million	$2.9 million	$3.3 million
	50% equity in existing enterprise, all cash flow available to invest	$1.9 million	$2.3 million	$2.7 million	$3.1 million
	100% equity in existing enterprise, 2/3 of cash flow available to invest	$2.3 million	$2.6 million	$2.9 million	$3.1 million
	65% equity in existing enterprise, 2/3 of cash flow available to invest	$1.8 million	$2 million	$2.3 million	$2.6 million
	50% equity in existing enterprise, 2/3 cash flow available to invest	$1.5 million	$1.8 million	$2.1 million	$2.3 million

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Above table using the wine grape crush survey

	0% extra income	10% extra income	20% extra income	30% extra income
100% equity in existing enterprise, all cash flow available to invest	2,704,733	3,092,995	3,502,613	3,912,232
65% equity in existing enterprise, all of cash flow available to invest	2,139,305	2,527,566	2,937,185	3,346,804
50% equity in existing enterprise, all cash flow available to invest	1,896,979	2,285,240	2,694,859	3,104,477
100% equity in existing enterprise, 2/3 of cash flow available to invest	2,341,659		2,600,500	2,873,579
65% equity in existing enterprise, 2/3 of cash flow available to invest	1,776,230		2,035,071	2,308,151
50% equity in existing enterprise, 2/3 cash flow available to invest	1,533,904	1,792,745	2,065,824	2,338,903

Amount cash flow to service debt …	0% extra income	10% extra income	20% extra income	30% extra income
Amount available to service 100% cash available			1,089,224	1,477,485
	1,887,104	2,296,723		
Amount available to service 67% cash available (two thirds)	726,149		984,990	
	1,258,069	1,531,148		

Factors that could potentially impede relocation

- History of the farm
- The goals of the grower and his family
- The stage of family life
- The stage in a growers career
- Technical factors such as:
  - quality of the soils for growing wine grapes
  - pests and disease issues

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When interpreting the results it is important to recognise that the human/social factors also impact on the decision a farmer makes. The history of the farm, could be very important. On one visit to see a number of growers, we met a few who would not sell their farms because their great grandfather had started this farm and they still had some of the original vines he planted. There is a strong tie to this property. For others the goals of the grower and his family may impact strongly and the decision he/she makes. Some farmers are profit maximisers who would prefer to invest their money in an alternative investment rather than lose money on the farm. Others have a range of goals, profit being one. Factors such as lifestyle and the enjoyment of farming may be equally as important. These farmers may be more likely to adapt by adjusting to a lower return or increasing their income through changing things on the farm or working off the farm.

The stage in the family life will impact on the decisions a grower makes, as will the stage in a growers career – this will steer the direction they take.

Conclusion

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Questions still to be answered

- How much does the temperature have to rise for it to lead to a decrease in income of 10%, 20% or 30%?
- What is the typical size of annual productivity gain achieved through research and development?
- What other sectors will be competing for land in the better micro climates? What is the expected cash flow from these businesses and how does that compare to a wine grape business? How much should or could these businesses pay for the land?

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This slide is designed to ask questions about many unknowns that are generated from this analysis. This analysis has shed a little bit of light onto the impact of temperature on wine grapes but there are still a lot of significant assumptions. A lot more research is needed into quantifying the income affects of an increase in temperature on wine grapes, and into the size of productivity gain that is achievable.

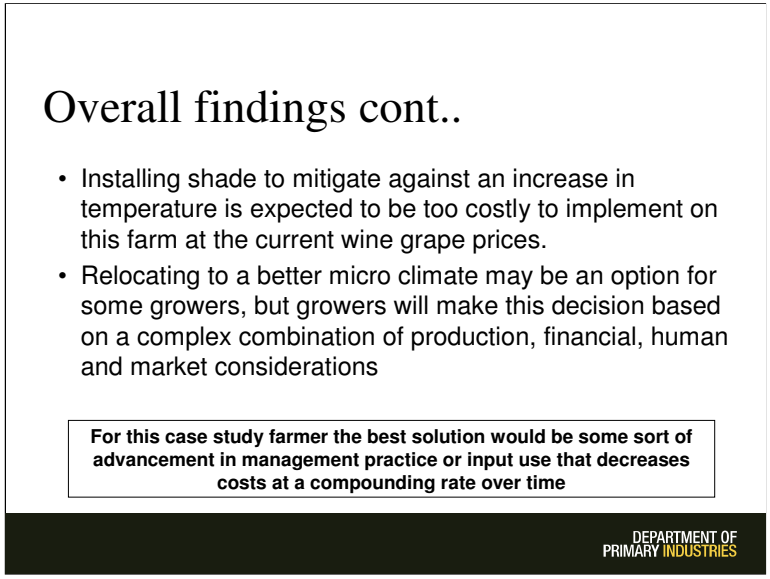
Overall findings

- An increase in temperature, which causes income to fall, is expected to decrease the wealth earned from investing in this farm business. Further, it is expected to decrease the value of the land.
- An increase in productivity (through decreasing input costs) is expected to reduce the impact of a fall in income

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These findings are true no matter which price scenario we draw from (whether it be the prices the farmer has received or the average prices in the wine grape crush survey).

Based on these models the ideal scenario for this farm business is for researchers to find the on-farm change or technology change that enables a “productivity” gain for the farm such that the net result is a 2% decrease in costs over time. There is expected to be a level of temperature change by 2030, but a much more significant temperature change occurring by 2050.



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Based on these models the ideal scenario for this farm business is for researchers to find the on-farm change or technology change that enables a “productivity” gain for the farm such that the net result is a 2% decrease in costs over time. There is expected to be a level of temperature change by 2030, but a much more significant temperature change occurring by 2050.

Viticulture in a changing climate

D. J. Unwin[1], G. E. Thomson[2] and M. O. Downey[1]

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Introduction

- CSIRO climate change model "The science of tackling climate change" (September 2009).
  - 2030 average temperature increase 0.6 to 1.5° C
  - 2070 average temperature increase 1.0 to 5.0° C
- Research is needed to understand the impacts on viticulture should the temperature rise in areas of Australia.
- This project involves elevating temperatures within vineyards in the Sunraysia region of Victoria.
- Varieties to be treated are Shiraz, Cabernet sauvignon and Chardonnay.

Methods

Year Round Average Temperature Increase

- Open-top chambers have been developed to enclose sections of vines within the vineyard.
- Vine warming modules use a temperature control unit to monitor the internal and external temperature.
- Internal chamber temperature is 3° C above the ambient vineyard temperature.



Figure 1. Trenching the vineyard to install electrical cable. **2.** Three phase electrical outlets installed within the vineyard. **3.** Chambers delivered in flat pack form. **4.** Chamber installed in the Chardonnay trial site.

Heat Wave Impacts

- Vines in smaller open topped chambers will be heated 6 or 10° C above the ambient vineyard temperature.
- Raised temperature applied for five day periods.
- Heat wave periods applied at budburst, pea-sized berries, veraison and pre-harvest.



Figure 5. Treated control module (non heating) – simulating air movement in heated chambers. **6.** Dr Mark Downey demonstrating a warming treatment to visiting scientists Duncan Farquhar and Dr Dennis Greer of the National Wine and Grape Industry Centre and Jason Cappello of Industry and Investment NSW. **7.** Radiation shield housing temperature and relative humidity sensors **8.** Smaller chamber for simulating heat wave events.

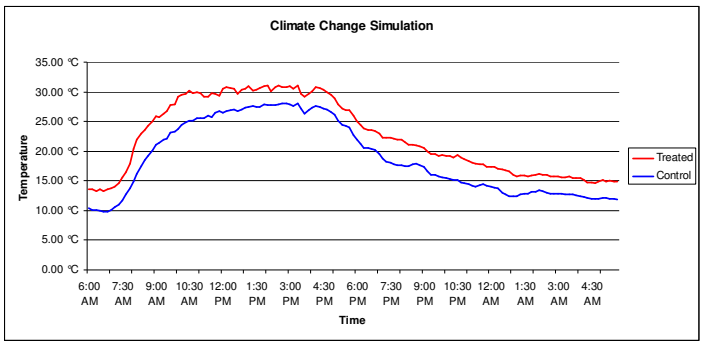


Figure 9. A 24 hour period for simulated temperature increase in the treatment chamber (April 2010).

Measurements include:

- canopy size, temperature and relative humidity
- soil temperature and moisture
- stomatal conductance
- flavonoid analysis at pea-size berries, veraison and harvest
- maturity testing
- yield forecasting and assessments
- wine analysis.

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Australian Government
Department of Agriculture, Fisheries and Forestry

Australian Government
Grape and Wine Research and Development Corporation

Victoria
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DEPARTMENT OF PRIMARY INDUSTRIES | future farming systems research

Impacts of global warming on grape and wine production: Viticulture in a warmer climate.

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Climate change is a contentious issue; whether or not global warming is occurring and whether it is a result of human activity does not alter the challenges faced by grape growers in hot production areas. The Department of Primary Industries (DPI, Mildura) have initiated a project with GWRDC to investigate the effect of elevated temperatures on the quality of the grapes and wine produced. The project compliments ongoing work by SARDI with a similar approach used in both South Australia and the Sunraysia region of Victoria.

The project involves elevating temperatures in sections of Cabernet Sauvignon, Shiraz and Chardonnay vineyards by 2-3° C (50 year projection for the Sunraysia region) all year round for the life of the project. This will be achieved by heating open-topped Laserlite® chambers using custom built air heaters to warm the air space around the vines

This trial will also use the same technique to assess the impact of heatwaves at critical growth stages in viticulture. The grapevines will endure five days of elevated temperatures in the range of 6-10° C above the ambient vineyard temperature.

Results collected from the trials will be used to develop strategies for managing viticulture production in the hotter growing regions of Australia.

Based on the available literature and anecdotal evidence the likely impacts will be early budburst and harvest and a shorter period from budburst to harvest. There is also a perception that higher temperatures will decrease colour, flavour and aroma quality attributes in the grapes and wine.

Hot and getting hotter – how will a warming climate affect warm climate viticulture?

Everard J. Edwards[2], Dale Unwin[1], Marica Mazza[1] and Mark O. Downey[1]
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[2]CSIRO Plant Industry, PO Box 350, Glen Osmond, SA 5064.

Introduction

Despite controversy in the media there is a scientific consensus that our planet's climate is warming and that it will continue to do so. There is less clarity over the degree of warming that will occur. The Fourth Assessment Report by the Inter-governmental Panel on Climate Change suggests a worst case scenario, based on emissions continuing to increase at the current rate, will lead to a global temperature rise between 2.4 and 6.4°C during the current century (IPCC 2007). The best case scenario, based on rapid global adoption of new technologies, suggests a rise of between 1.1 and 2.9°C. Even conservative estimates indicate a rise of over 2°C (Schmittner *et al.* 2011). There is little doubt that Australian viticulture will be subjected to increasing air temperatures over the next 30-50 years.

Predictions of the impact of such warming on viticulture vary, but include decreases in both production and wine quality. However, such predictions are largely based on 'ideal' climatic ranges for specific cultivars and have not been tested experimentally. Analyses of vintage records suggest that climate warming is already having an effect on phenology, with harvest dates advancing and vintages becoming shorter over the past 30 years (Petrie & Sadras, 2008; Webb *et al.* 2011). This suggests that winegrapes are reaching the sugar concentrations desired by wineries earlier as the climate warms and is likely to continue.

Unfortunately it is difficult to disentangle the impact of past warming from other factors, such as consumer wine preferences, changes in viticultural practice and natural year to year variation in weather. Although extensive and careful analysis can do this to some extent, it is our belief that only direct field manipulation of air temperature over multiple seasons is able to definitively determine the potential impacts of future climate warming. This is what we are attempting to achieve at the DPI research facility in Mildura as part of a jointly funded project between DPI Victoria, GWRDC and DAFF to examine the impact of future climate warming on warm climate viticulture. To achieve this we have established a facility that allows warming of field-grown mature vines to the temperatures likely to be experienced over the next few decades by a large proportion of Australia's winegrape growers.

The climate warming facility

Building a field-based system to alter the atmospheric temperature around established vines is neither a simple nor inexpensive task. The approach selected utilises an Open Top Chamber (OTC) approach, which involves surrounding the vines with a transparent 'box' consisting of walls but no top (Figure 1). Unlike a fully enclosed system, this allows the air within the chamber to be manipulated without significantly altering its gaseous composition or the light quality, as well as preventing uncontrollable heating. On the other hand it requires a much higher energy input to maintain a given temperature due to losses from convection and bulk movement of air.

An OTC system provides minimal solar heating, so an active heating system is required. In our case each OTC contains three 2.4 kW air heating elements in a custom ducting system, which uses a fan to draw air in at ground level and then blow it out through a diffuser system that runs along the row. Temperature sensors are placed within the canopy, both in- and outside the chamber, with heating control being achieved by setting the desired temperature difference between the two. In addition, air temperature, relative humidity, vapour pressure deficit (VPD) and soil temperature are separately monitored within each OTC. Other sections of vine row have been assigned as controls, with an equal number as there are OTCs. These are instrumented in the same way, but, not having a chamber, are subject only to ambient environmental conditions.

The responses of three of the varieties most widely grown in the warm climate regions, are being examined: Chardonnay, Cabernet Sauvignon and Shiraz, with three heating OTCs installed within each variety planting, providing nine in total. All the vines are part of mature blocks on sandy loams, typical for the region, and are managed as commercial plots at the DPI Victoria Mildura vineyard. The varietal blocks are approximately half a hectare in size and were planted in the mid-late 1990s on a mixture of rootstocks (Chardonnay/Ramsey, Cabernet Sauvignon/1103 Paulsen, Shiraz/140 Ruggeri). The vines are all on drip irrigation, receiving standard applications for the region, with a seasonal total of 5.1-5.3 ML ha^{-1}, depending on variety.

The OTC itself has some potential to influence vine growth and productivity as the walls are impacting normal air movement and can affect the light quality reaching the lower canopy and vineyard floor. Furthermore, the fans used to disperse the warm air in the chamber generate air currents that would not naturally occur and could also have some degree of effect on the vine. To allow for any such effects to be determined, a matching set of nine OTCs have been installed in the same blocks of vines, containing a fan system identical to that in the heating OTCs, but without the actual heat unit. Consequently, by comparing the fan only OTC results to those from the ambient controls and the heating OTCs we can determine whether responses are indeed due to the temperature differences or an artefact of the system itself, which is a further advantage of the active heating approach.

The heating OTCs provided approximately 2°C of heating throughout the day and throughout a season, with no consistent influence of time of day or year. The Copenhagen Accord, released in late 2009 and signed by over 138 countries, includes a commitment to limit climate warming to 2°C. Consequently, the imposed treatment is a realistic scenario for Australian growers in future years, with little chance of climate warming being less than this. Figure 2 provides a typical two week data set, with a week of warm bright weather followed by a week of cool cloudy weather. Much of the hour to hour variation is likely to be due to wind, with less heating being achieved during windy periods. The impact of the fan only OTCs on air temperature was minimal, generating around 0.2°C of heating when averaged over the season.

Relative humidity (%RH) is directly dependant on air temperature and, not surprisingly, there was an effect of the heating OTCs on %RH. When averaged over the season this amounted to a reduction of around 6%, compared with the ambient controls. This in turn equated to a small increase in vapour pressure deficit (VPD) of approximately 0.3 kPa. Soil warming was limited, with soil temperatures in the heating OTCs less than 1°C warmer than the ambient controls at a depth of 10 cm. Despite this effect, no consistent difference in soil moisture between the treatments was observed.

The OTC system was run throughout the 2010-11 season, having been originally started at flowering 2009 in the Cabernet Sauvignon and at leaf fall 2010 in the Shiraz and

Chardonnay vines, thereby allowing the direct effect of climate warming on the vine and the wine to be examined.

Impact on the vines

Air temperature and vapour pressure deficit (VPD) can both have an impact on leaf physiology as well as on fruit development. However, no consistent differences were seen in leaf photosynthesis, stomatal conductance or leaf transpiration. Therefore, at the leaf level at least, there was no evidence of a change in carbon gain, water use or stress in the heated vines. It is not uncommon for plant species to adjust their physiology to a change in temperature (e.g. Edwards *et al.* 2004) and it appears that all three varieties were able to acclimate to the imposed 2°C of warming.

The heating OTCs maintained higher air temperatures throughout the winter prior to the 2010-11 season and, despite the acclimation of leaf physiology, warming resulted in an advancement of phenology in all three varieties. For instance, budburst was three to four days earlier in the two red varieties and up to 11 days earlier in Chardonnay (Figure 3). It has been suggested that climate warming will not actually alter 'last frost' dates in SE Australia as drier air makes frost more likely (Hayman *et al.* 2009). Thus, perhaps counter-intuitively, Chardonnay in particular could become more likely to suffer from a frost event in the future rather than less. Anthesis was even further advanced by heating, with 50% capfall being eight to nine days earlier in the red varieties and 12 days earlier in Chardonnay. Veraison was also advanced in all three varieties in the heated chambers. In Chardonnay, veraison occurred a week earlier in the heated chamber compared to the control, while veraison was nine days earlier with heating in both Shiraz and Cabernet Sauvignon.

Fruit were harvested when total soluble solid (TSS) concentration was 23°Brix for Chardonnay and Cabernet Sauvignon, and 24°Brix for Shiraz. Differential harvests were required for Chardonnay as fruit from the Chardonnay controls were only 17°Brix when the heated vines were harvested. Control Chardonnay fruit were harvested seven weeks later and still had a slightly lower TSS concentration than those from the heating OTC vines. However, there were only a slight differences in TSS between heated and control fruit in the two red varieties, although this may have been due to the low growing season temperatures and record rainfall in Sunraysia during 2010-11, which resulted in an unusually late harvest.

Yields from the OTCs, heated or not, were generally lower than the ambient controls (Figure 4a). However, this was not due to the temperature treatments *per se*, but to differential impacts of disease. A very high incidence of downy mildew was reported throughout South-Eastern Australia and this was also true of Sunraysia. The physical constraints of working in the chambers created difficulties in disease management, resulting in greater infection rates in OTC vines than in the ambient controls. It is interesting to note that in all three varieties the small impact on %RH of the warming treatment noted above was enough to significantly reduce the OTC disease impact, producing a higher yield in the heated OTCs than in the fan only OTCs in each case.

As well as sugar concentration, there were differences between treatments in a range of measured fruit parameters, such as berry size, pH, titratable acidity, colour and skin tannins. However, due to the differential impact of downy mildew on the three treatments it is difficult to ascertain whether these differences were caused by temperature or disease.

Impact on the wines

Research wines were made from the heating OTC and ambient control treatments for each variety, but not from the fan only controls. All fruit from a given variety/treatment were combined and then used to create three making wine replicates. Despite the driver of treatment differences in yield being loss of fruit from disease rather than an effect of temperature, there was still a strong inverse correlation between yield and wine colour density (Figure 5b). The colour density of the Shiraz wines from the heating OTCs was almost half that of the controls, whereas there was little difference between the Cabernet wines. In contrast, total phenolics were much higher in all the wines from heated vines, including Chardonnay, but total anthocyanin content was similar, despite the colour density effects (Figure 4c). Finally, tannins were an order of magnitude higher in the Cabernet Sauvignon wines from heating OTCs than any other wine. While it is tempting to attribute these differences to the heating effect of the chambers, the increased disease pressure from the very wet 2010-11 season is also a likely cause of increased phenolics in both the fruit and wines as one of the roles of phenolic compounds in the grape is defence against microbial attack. As data from the current and future seasons is collected, the impact on wine colour, tannin and other phenolics will become clearer.

Climate warming or climate variability?

An increase of 2°C in air temperature seems small compared to the day-to-day differences in air temperature observed in any given growing season, but a 2°C increase each day would lead to many more days when the temperature is in the range currently considered 'extreme'. Consequently, what is now considered a 'heatwave' would become commonplace. Furthermore, climate modelling regularly suggests (IPCC 2007; Min *et al.* 2011) that seasonal variability will increase as a result of climate change. Consequently, it is possible that impacts of moderate climate warming on viticulture could be outweighed by the effects of climate variability. Our project includes a component to examine this. Using a portable OTC, capable of heating up to 10°C above ambient, we can impose a short-term 'heatwave' on a group of vines in the same way as we are imposing long-term warming (Figure 5).

Conclusions

The 2010-11 growing season was the first full season of simulated climate warming being applied to all of the varieties included in this study. Despite being the first season, advancement of phenology was seen in all three varieties, with budburst and fruit-set occurring earlier in each case. Harvest was also well advanced in Chardonnay, but the extreme 2010-11 season meant that the red varieties were all harvested late at moderately low sugar content. On the other hand, leaf level physiology appeared to acclimate to the temperature, with no treatment effects observed. The results to date are consistent with previous modelling that indicates a significant advance in phenology with a relatively small increase in the average daily temperature.

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Figures



Figure 1: Dr Mark Downey (DPI Mildura) standing in the Open Top Chamber (OTC). The chamber is constructed from a mild steel frame and Laserlite™ panels, with a custom built heating unit/ duct running the length of the chamber to circulate the warmed air.

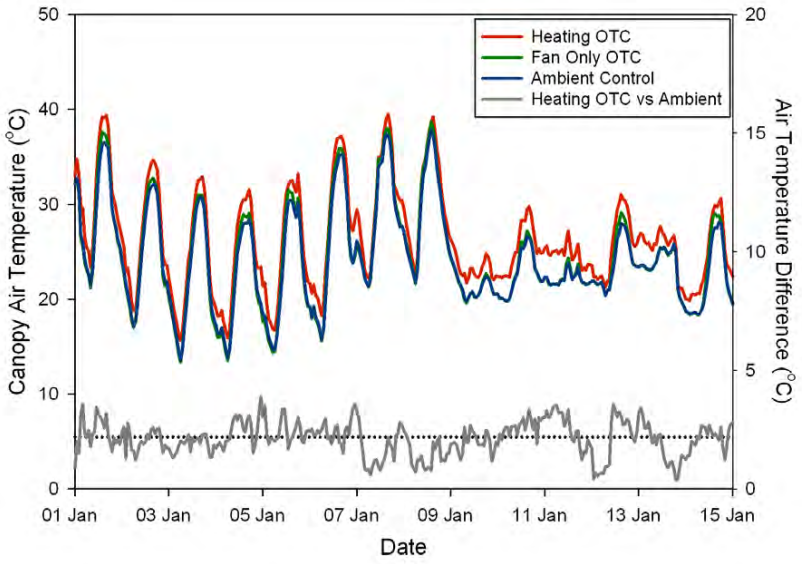


Figure 2: Sample data illustrating OTC performance. Lines are means of three replicates.



23/9/11 28/10/11 29/12/11

Figure 3: Budburst, capfall and veraison in Cabernet Sauvigon vines subject to 2°C warming (bottom row) and ambient conditions (top row). Pairs of photographs were both taken on the day as indicated.

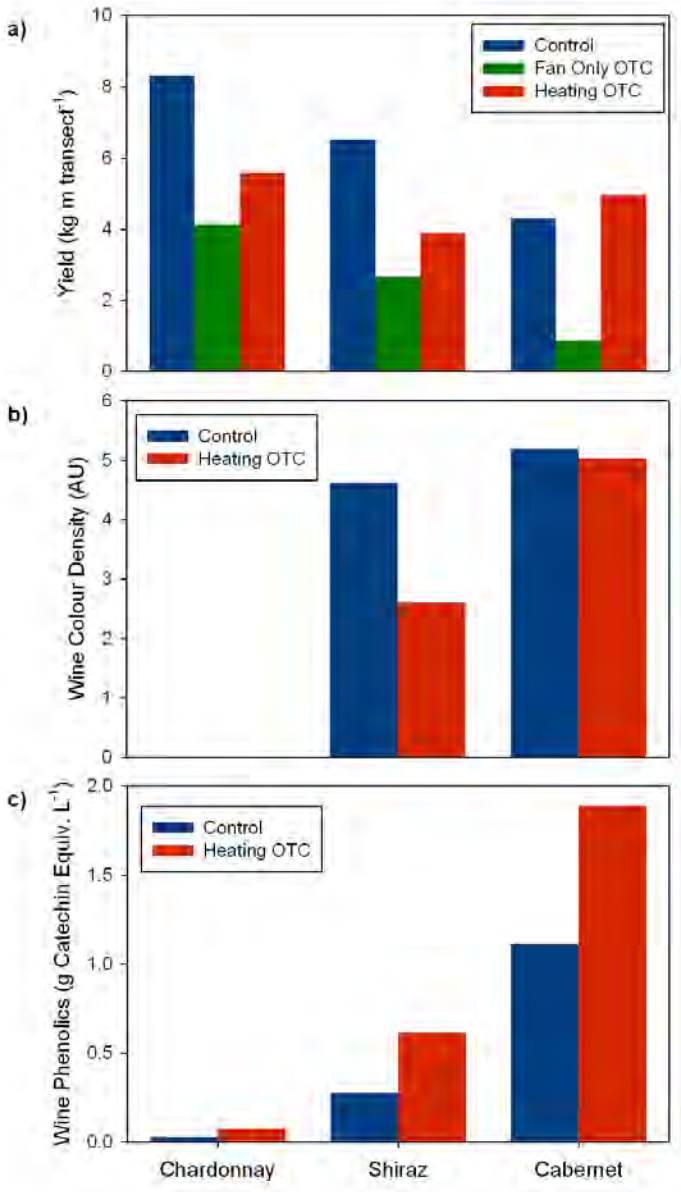


Figure 4: Harvest yield, a, wine colour density, b, and wine total phenolic content, c, of the three varieties studied. Wines were not made for the Fan Only OTC treatments.

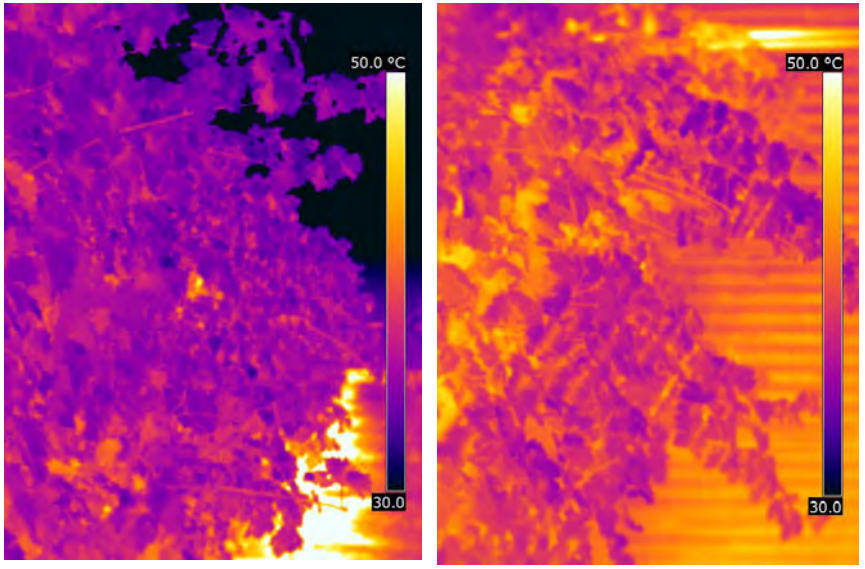


Figure 5 (alternative 1). IR photos of heatwave leaves compared to control leaves.

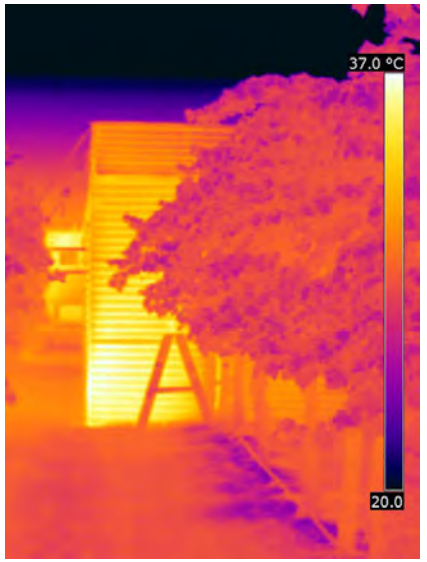


Figure 5 (alternative 2). IR photo of heatwave chamber.

Mediaportal Report

Wine grape research
Wimmera Mail Times, 15/01/10, General News, Page 8
By: None

Clip Ref: **00063131441**
88 words

ABC South Western Victoria (Warrnambool)
08:30 News - 12/01/2010 8:32 AM
Newsreader

Scientists from the DPI are trying to find how climate change could affect Vics wine industry. The four year study is being conducted in North West Vic. Dr Mark Downey, DPI, says a hotter climate could damage the wine quality.

Interviewees: Dr Mark Downey, DPI
Duration: 0.45
Summary ID: W00037472517
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Demographics	
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Female:	600
AB:	400
GB:	500
All People:	900

ABC South Western Victoria (Warrnambool)
06:30 News - 12/01/2010 6:33 AM
Newsreader

The DPI is hopeful that a new study will help the Vic wine industry adapt to climate change. The study involves the growing of common winegrape varieties in a facility which allows them to raise the temperature around the crop.

Interviewees: Dr Mike Downey, Spokesman, DPI
Duration: 0.38
Summary ID: W00037470254
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GB:	600
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Investigating effect of climate change on wine
Wangaratta Chronicle, 11/01/10, General News, Page 17
By: None

Clip Ref: **00063017478**
365 words

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ABC Ballarat (Ballarat)
National Rural News - 7/01/2010 12:09 PM
Newsreader

Demographics
Demographics are not available as the media outlet has not commissioned audience research into this timeslot.

Last year was the second hottest year on record since 1910 and has prompted concern about the future viability of growing grapes in a warmer climate. Mark Downey, Vic Department of Primary Industries, says farmer in hotter climates will need to consider the varieties they can grow.

Interviewees: Mark Downey, Vic Department of Primary Industries
Duration: 0.29
Summary ID: W00037430781
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Wimmera Mail Times
15-Jan-2010
Page: 8
General News
Region: Horsham VIC
Circulation: 8944
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M-W-F--

Wine grape research

A DEPARTMENT of Primary Industries scientist in Mildura is doing research which could improve wine grape varieties grown in the Wimmera.

Dr Mark Downey is studying how increased temperatures may affect wine from varieties commonly grown in the Wimmera such as chardonnay and shiraz.

''We know temperatures will increase but we don't know anything about how and when increased temperatures will impact on grape and wine quality,'' he said.

''The answers to these questions will enable the Victorian wine industry to plan for long-term viability of their industry.''

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Wangaratta Chronicle
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General News
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M-W-F--

Investigating effect of climate change on wine

WITH climate change raising temperatures, investigations are being made into the effect on Victorian wine quality.

The Department of Primary Industries (DPI) investigation into the effect of climate change on the quality of wine produced includes how increased temperatures may affect wine from commonly grown wine grape varieties.

DPI scientist Mark Downey said most wine grape varieties grown in Victoria were based on traditional European varieties, such as chardonnay, cabernet sauvignon and shiraz, bred for cool stable climates.

"With climate change projections forecasting rising temperatures, there is a real need to know the potential impacts this may have on the grape varieties we are growing," Dr Downey said.

He said the project would look at the sorts of future conditions likely in 20 to 30 years time.

The availability, prices and quality of future wine supplies were likely to be influenced by continually warmer conditions in our current wine growing regions.

"Our work is aimed at avoiding potential future slumps in wine production and quality that would affect the economies of grape-growing regions and potentially damage wine export sales," he said.

"To simulate the potential impact of future climatic conditions on commonly grown wine grape varieties, we are enclosing established vines in vineyards in large temperature control chambers.

"We have panels of three cabernet sauvignon vines heated to three degrees Celsius above ambient air temperature both day and night throughout the year, based on CSIRO climate change projections.

"The chambers are open-topped and artificially heated, designed to alter temperature only, allowing us to examine vine growth, berry development and grape and wine quality in response to increased temperatures.

"In future years we will investigate extreme heat wave impacts with temperature ranges raised to six to 10 degrees above ambient for short periods."

Data from the four-year project will inform the industry of when and to what extent climate change will affect the quality of wine grapes and wine in the glass.

This project is managed by DPI and the Grape and Wine Research and Development Corporation, with funding from Federal Department of Agriculture, Fisheries and Forestry's climate change initiative.



HOT TOPIC: DPI scientist Mark Downey is investigating the effect of climate change on wine grapes.

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