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Climate change and winegrape quality in Australia

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ABSTRACT: Various agricultural sectors are likely to be sensitive to projected climate change. Winegrapes are particularly sensitive to climate change because of the intrinsic link between the climate and the characteristic and often unique quality of the resulting wine. Here we present results from a study exploring the impact of projected climate change on the Australian wine industry. In the present study, impact models based upon existing viticultural and winegrape market data are used to estimate how projected regional temperature increases might affect the winegrape and wine industry throughout Australia by 2030 and 2050. The effect on winegrape quality is determined for different premium winegrape varieties separately. Differential impacts were determined across a range of base-climates, climate change regimes and varietal crush profiles. This represents the first national study of the impact of climate change on winegrape quality that is regionally specific, and that integrates varietal differences in temperature sensitivity. The impact of warming was found to be negative overall, assuming no adaptation is implemented, for all Australian winegrowing regions. It is found that the reduction to winegrape quality varied regionally, with greater quality reductions calculated for the inland regions. Without adaptation, winegrape quality may be reduced at a national scale in Australia from 7 % with lower warming to 39 % with higher future warming by the year 2030, and from 9 % with lower warming to 76 % with higher warming by the year 2050 (all uncertainties considered).

KEY WORDS: Climate change · Winegrape quality · Winegrape varieties

1. INTRODUCTION

Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level (IPCC 2007). It is very likely that most of the global warming since the mid-20th century is due to increases in greenhouse gases from human activities (IPCC 2007). The Intergovernmental Panel on Climate Change third assessment report (IPCC 2001b) concluded that the agricultural sector is particularly vulnerable to climate changes, with potential negative impacts on the amount of produce, quality of produce, reliability of production and on the natural resource base on which agriculture depends. This vulnerability requires high levels of adaptive responses (Howden et al. 2003).

Accurate determinations of the magnitude of climate change impact on winegrape quality and productivity are an essential basis for the development of appropriate adaptive responses for the Australian wine industry. Viticulture is one agricultural sector that has a very close association with climate because the production of fine wine is intimately wed to the concept of 'terroir'. This concept involves matching premium winegrape varieties to particular combinations of climate, landscape and soils to produce unique wines of particular styles (Seguin 1986, Pomerol 1989). Changes in climate will alter these terroirs and potentially affect the quality of winegrapes produced (Seguin & de Cortazar 2005).

While previous climate change impact modelling studies have examined qualitative impact on wine quality (Nemani et al. 2001, Pincus 2003, Jones et al. 2005, White et al. 2006), the impact on winegrape yield

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(Bindi et al. 1996), or shifting regional suitability for viticulture (Kenny & Harrison 1992, Hayhoe et al. 2004), none have directly and quantitatively assessed the impact on winegrape quality, nor attempted to determine the impact at a national industry scale.

Earlier studies have discussed the impact of climate change on the wine industry without any detailed spatial modelling of projected impacts, or projection uncertainties (Dry 1988, Smart 1989, Schultz 2000, Pincus 2003). Both global and regional climate change projection uncertainties are examined in this assessment. A range of greenhouse gas (GHG) emission scenarios and also a selection of global climate models (GCMs) is utilised to incorporate uncertainties in climate projections. We have undertaken a spatial assessment and included 9 future climate possibilities and 2 outlook periods. Because projected climate change is not anticipated to be uniform across Australia, with more warming inland than near the coast (Whetton & Hennessy 2001), we applied spatially varying climate projections to a fine-resolution grid of baseline temperature. This allows unique regional impacts to be calculated. The method also enables an analysis of the sensitivity of the industry to different future climates.

In a recent study, Hayhoe et al. (2004) addressed the spatial variation of climate change across California for 2 warming levels in a qualitative analysis of impact to winegrape quality and found that quality would be reduced. Our modelling approach expands on their assessment by quantifying the impact on winegrapes and at the same time integrating the knowledge of variations in grapevine varietal sensitivity to climate (Webb et al. 2008, this issue).

This assessment of national- and industry-scale impact assessment of climate change is informative for 2 main reasons. Firstly, it can illustrate the urgency for possible adaptive action, and, secondly, the sensitivity, at an industry scale, to a range of possible greenhouse gas emission scenarios can be shown.

2. DATA AND METHODS

2.1. Climate data

Winegrapes are grown in a wide range of climates in Australia, from very hot to very cool (Smart et al. 1980). Geographical indications of wine regions are similar to the Appellation naming system used in Europe, but less restrictive in terms of viticultural and winemaking practices. In fact, the only restriction is that wine which carries the GI must include at least 85% fruit from that region (AWBC, http://www.wineaustralia.com/Australia/). These can be seen overlaying the climate maps in Fig. 1a.

An assessment of the climate variables affecting winegrape quality, with a view to determination of the impact of climate change, has been conducted for the Australian wine industry (Webb et al. 2008). Mean January temperature (MJT), a climate index commonly used in the Australian wine industry (Smart & Dry 1980), was the climate variable selected in the development of the model defining the link between climate and winegrape quality and will be used in this assessment. It is projected changes to this climate variable and how this will relate to winegrape quality that is explored in this analysis.

The regional climate data used for this analysis were derived from the OzClim climate scenario generator (Page & Jones 2001). The observed base climatology incorporated in the OzClim package is spatially interpolated from climate station data of the Bureau of Meteorology (1961 to 1990) (BoM, www.bom.gov.au/climate/averages/climatology/gridded-data-info/gridded-climate-data.shtml), on a 25 × 25 km grid. OzClim can be used to produce projected climate data in gridded format for a range of climate parameters, emission scenarios, climate models and outlook periods. Estimates of future changes are derived from climate model patterns of change per degree of warming, which can be scaled for a given year by multiplying the patterns by the IPCC (2000) range of warming for a given year.

2.2. Climate change projection uncertainties

Future warming of the climate system depends on the level of emissions globally, and the sensitivity of the climate to these emissions. This study addresses future warming uncertainty by considering impacts from the following scenarios:

- High greenhouse gas emissions and high climate sensitivity: denoted A1FI high.
- Mid-greenhouse gas emissions and mid climate sensitivity: denoted A1B mid.
- Low greenhouse gas emissions and low climate sensitivity: denoted B1 low.

Added to the global emissions uncertainty is the uncertainty related to regional climate change simulated by GCMs. Using various GCMs in a climate change impact study allows for an estimation of uncertainty due to climate model variability (Whetton et al. 2005). To capture regional detail from the global projections, 11 GCMs were assessed and, of these, 3 were found to satisfy the following requirements (see Table 1):

- Models must perform well in the Australian winegrowing regions (for performance assessment see Whetton et al. 2005).
- Models from a given institution must be <5 yr old.

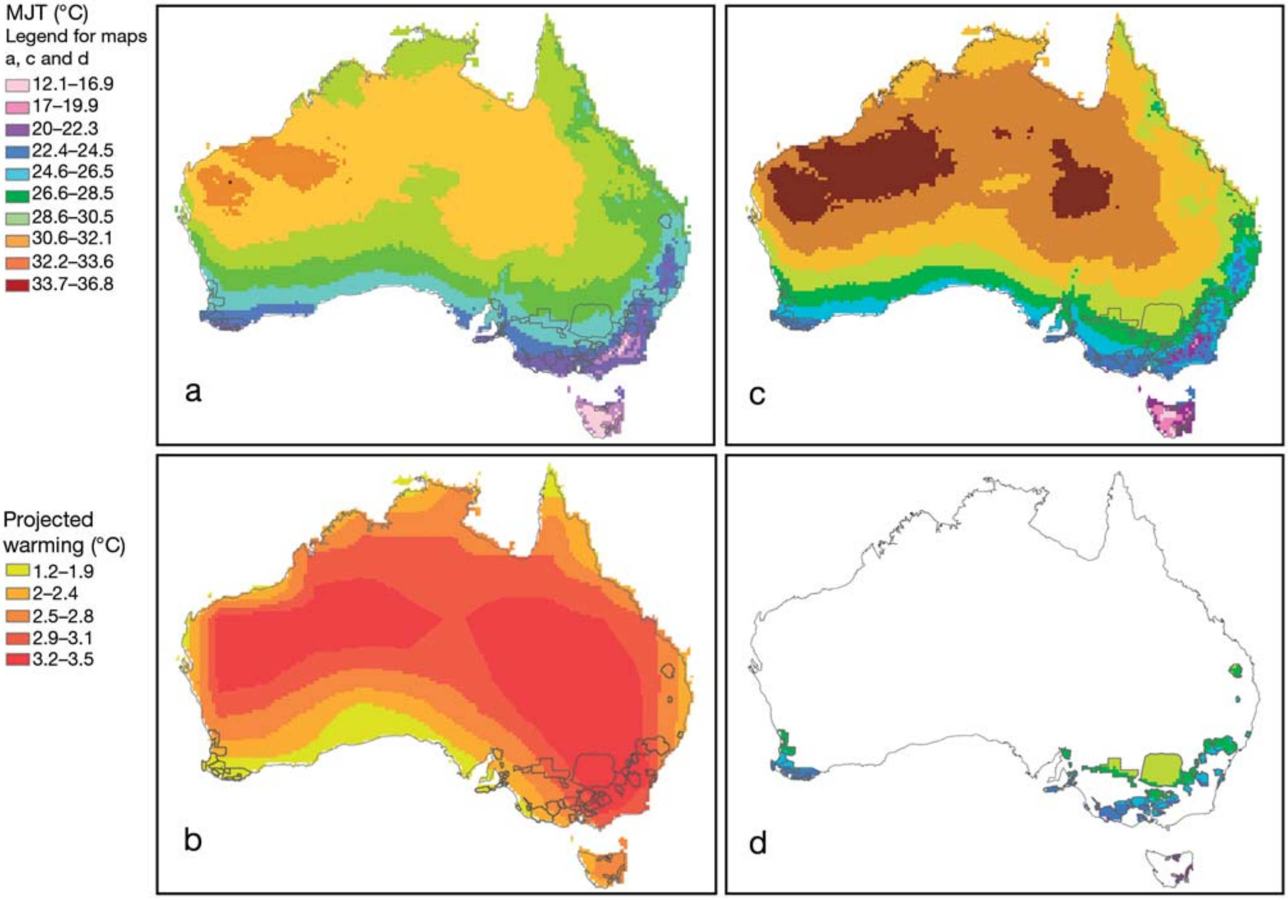

Fig. 1. An example of how OzClim simulates climate change. (a) 1961–1990 mean baseline MJT (mean January temperature), (b) projected warming (2050), (c) projected MJT, (d) extracted projected MJT. Data are °C. The addition of projected warming to the base MJT (mean January temperature) for Australia (1961 to 1990) results in the projected MJT (2050). The climate model pattern and the global warming factor will vary due to the projection uncertainty. In this example, projected warming for January for the year 2050 was calculated using the A1FI greenhouse gas emission scenario, high climate sensitivity and the HADCM3 climate model. The map showing the projected MJT is an example of the ArcGIS method of extraction of climate data for Australian winegrape growing regions. The winegrape growing regions (grey lines) are as defined as Geographic Indication regions (AWBC)

Table 1. Climate models selected for use in studying the impact of projected climate change on the Australian wine industry

Climate model	Horizontal grid spacing (km)	Forcings used in model simulations	Rate of warming within the 11 models available for the present study:	Further information
Coupled global climate model: CSIROMk3	175	Well mixed greenhouse gases, ozone and sulphate direct	Mid range temperature change (greatest simulated temperature increase in south-west Western Australia)	www-pcmdi.llnl.gov/ipcc/model_documentation/CSIRO-Mk3.0.htm
Regional climate model: DARLAM125 km	60	Well mixed greenhouse gases, ozone and sulphate direct	Lowest simulated temperature increase over the Australian continent	Regional model driven at its boundary by the CSIROMk3 GCM
Coupled global climate model: HadCM3	275	Well mixed greenhouse gases, ozone and sulphate direct and indirect	Largest temperature increase (mid-range cf. other models in south-west Western Australia)	http://www-pcmdi.llnl.gov/ipcc/model_documentation/HadCM3.htm

This will account for superseded models from any research organization.
- Models were compared with the aim of capturing the range of uncertainty in projected future climate change for the regions of interest, that is in the southwest and mid- to south-eastern sections of Australia (see rate of warming description, Table 1).

2.3. Projected climate

One of the warming projections for 2050 that was used in this analysis, with a high greenhouse gas emission scenario (A1FI), combined with high climate sensitivity and the HadCM3 climate model, is shown in Fig. 1b. OzClim calculates the projected climate by adding future changes to the base climatology (Fig. 1c).

Though the resolution of the GCMs is much coarser than the baseline climate data, it has been shown that when these projections overlay the finer baseline data, simulations of change are realistic, and that spatially explicit modelling can be accomplished even with coarse projections (CSIRO 2007).

Climate data were extracted by 'intersecting' the particular climate map from the OzClim database with a map of the Australian geographical indication wine regions (AWBC) using GIS overlay techniques (Fig. 1d). In all, 35 regions were analysed. Projected MJT values were calculated for each of the regions using the 3 emission scenarios, 3 climate models and the 2 outlook periods. The steps involved in the extraction of climate data (using ArcGIS 9.0 software) are shown in Fig. 1. Because the grid resolution in OzClim is 25 × 25 km, and the wine region map layers do not align exactly over the grid, when the climate maps are dissected by the wine region maps, not all grid sections are intersected completely. To account for this, an area-weighted average of the climate variable was calculated from the grid.

The results are presented for specific times in the future. For this Australian wine industry assessment the years 2000 (baseline), 2030 and 2050 were selected as being relevant to vineyard planning horizons. The baseline climate for OzClim is centred on the year 1990. Since the baseline climate for our analysis for this project was centred on the year 2000, the OzClim baseline climate data were adjusted with mid-range greenhouse gas forcing levels appropriate to the year 2000.

2.4. Winegrape quality impact modelling

While some process models existed for estimating possible impacts of climate change on vine growth and yield in the wine industry (Williams et al. 1985, Godwin et al. 2002), the impact on winegrape quality was assessed to be more pertinent. For this reason, temperature-sensitivity models defining the relationship between temperature and winegrape quality were specifically created to enable determination of a warming impact on premium varieties of winegrapes in Australia (Webb et al. 2008).

The magnitude of projected climate changes, especially for those later in the century, were assessed to be more aligned to interregional differences in climate than the inter-annual climate variability within a region. For this reason inter-regional differences in quality were assessed. Though a spatial quality–climate relationship was revealed in the study (Webb et al. 2008), this relationship is used here to predict a temporal change in quality. The spatial climate–quality relationship describes a biophysical interaction between temperature and grape quality. This biophysical relationship is assumed to be stable through time due to the genetic stability of the plant (clonal reproduction), even as the climate changes.

Furthermore, the selection of temperature as the climate driver of the impact model was done after a rigorous exploration of a range of climate indices (Webb et al. 2008). Of course, other factors vary regionally, and these may also influence the differences in winegrape quality between regions. These factors may not be influenced by increasing concentrations of greenhouse gasses in the atmosphere. However, due to the extensive viticulture literature identifying temperature as the major driver of the winegrape quality indices (Alleweldt et al. 1984, Haselgrove et al. 2000, Marais 2001, Marais et al. 2001, Spayd et al. 2002, Carey et al. 2003, Coombe & Iland 2004), effects from other variables not projected to change in the future, e.g. insolation, were assumed to be embedded in temperature indices.

In the Webb et al. (2008) assessment, hedonic measures for quality, previously described by Oczkowski (1994) and Schamel & Anderson (2003), were employed. The hedonic quality surrogate used is the average price paid for winegrapes in a region. The winegrape price data used to create the temperature-sensitivity model were obtained from nationwide survey results. The survey is known as the Australian regional winegrape crush survey and is conducted annually (AWBC). Data from 1999 to 2003 inclusive were averaged for each region and winegrape variety. Price was shown to positively correlate with winegrape colour (for red winegrapes), glycosyl-glucose (a flavour and aroma precursor compound found in winegrapes) and the climate index MJT. The sensitivity of winegrape quality to temperature is variety dependent, and, for this reason, temperature-sensitivity relationships developed separately for each premium winegrape variety in Australia (Webb et al. 2008) are employed here.

Due to the differential varietal impact to changing temperature, variations in the proportions of winegrapes grown in the different winegrowing regions (AWBC) were used to weight the regional results. Different winegrowing regions grow different proportions of varieties of winegrapes because of the variation in the suitability of varieties to different climates (Jackson & Lombard 1993). Fig. 2 illustrates the differences in the mix of varieties grown in each region. For example, the proportion of Cabernet Sauvignon in Coonawarra, South Australia, is nearly 50%, compared to about 19% in the Yarra Valley (Victoria), and 4% in the Hunter Valley (NSW).

The regional impacts of warming on winegrape quality are calculated by weighting the varietal impact by the proportion of each variety produced in a region. Impact is described as percent impact to quality, or percent cost to quality. The concepts of 'quality' and impact to 'quality' are not simple to grasp. For example, we consider a 10% impact as meaning 10% less suitable for winemaking, say, where a 100% impact would mean that the winegrape would have no redeeming qualities and be unusable for the purpose of making wine.

The uncertainty of the variation of quality as it varies with temperature has been indicated in the temperature-sensitivity graphs and described mathematically (Webb et al. 2008). The results for the impact to grape quality are calculated here for these 90% confidence intervals (CIs), as well as for the 'best fit' regression describing the relationship.

As with national assessments of climate-change impact with regard to wheat production in Australia (Howden et al. 1999), the impact to winegrape quality can be further up-scaled to a national level by weighting the regional impact with the proportion that each region contributes to the annual national winegrape

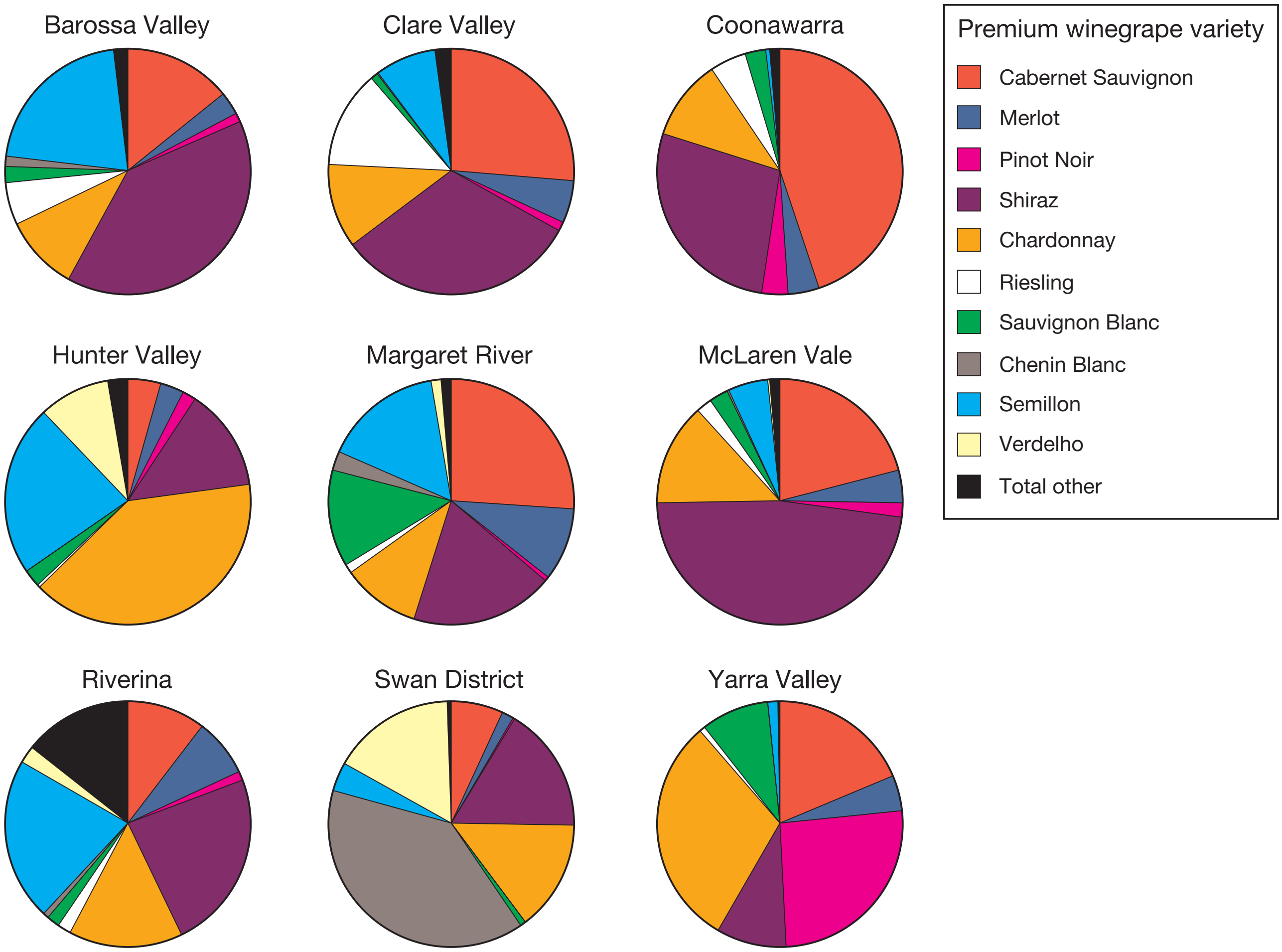

Fig. 2. The proportion of each variety of winegrape in the annual regional crush for some winegrape growing regions of Australia (AWBC)

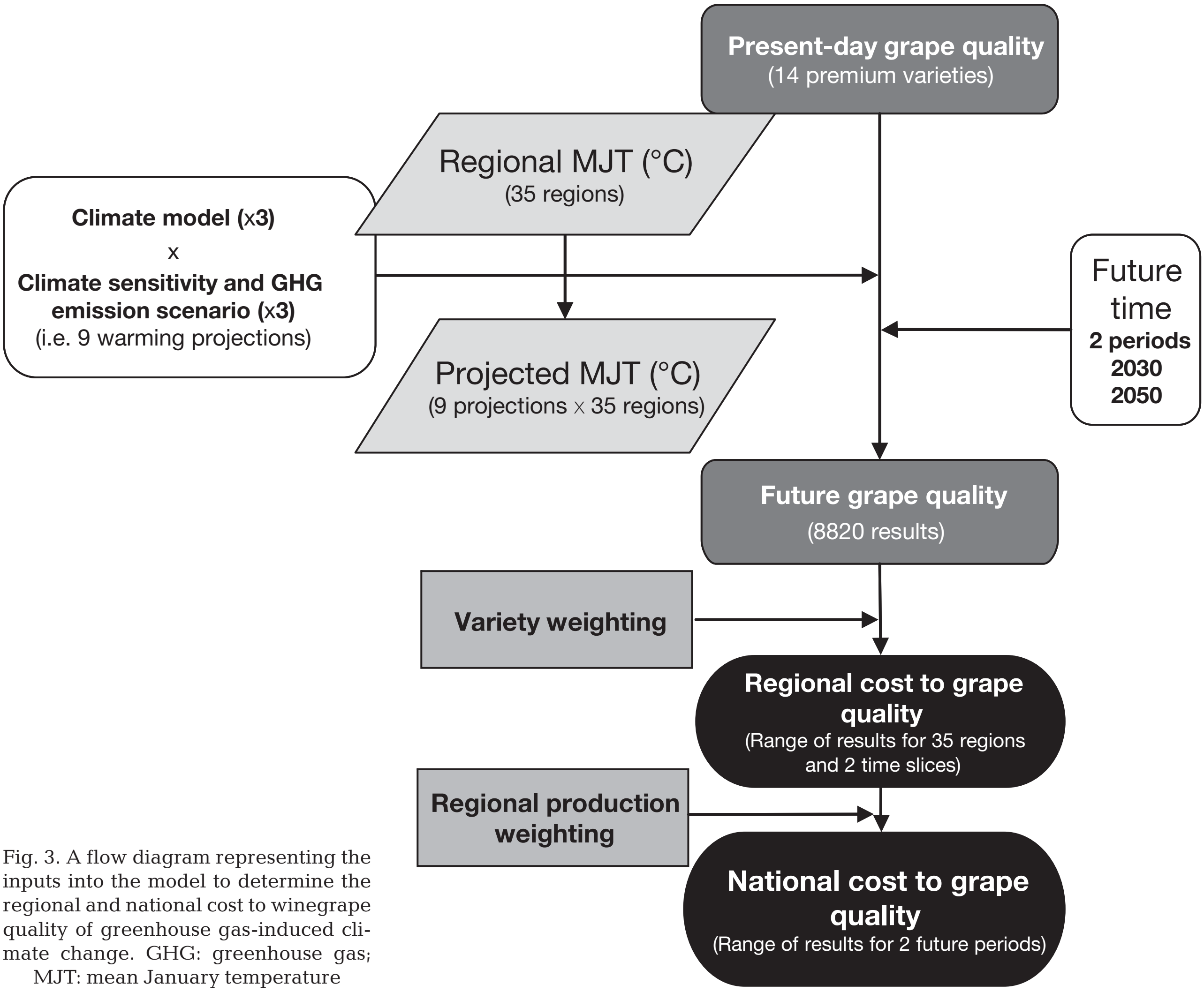

Fig. 3. A flow diagram representing the inputs into the model to determine the regional and national cost to winegrape quality of greenhouse gas-induced climate change. GHG: greenhouse gas; MJT: mean January temperature

crush. A flow diagram of the modelling procedure used is presented in Fig. 3.

The assumptions that have been made in determining the impact of projected temperature change on winegrape quality are as follows:

- Spatially averaged MJT of a region represents the average MJT for vineyard plantings.
- Impacts are calculated using present production (tonnes), and this production is assumed to remain static.
- There will be no adaptive strategies implemented within the projection timeframe (to 2050) to counter negative impacts, e.g. variety substitution.
- A spatial climate–quality relationship is explored and defined, and this is used to quantify a temporal change in quality. Many other factors not assessed in the Webb et al. (2008) study will vary spatially; examples include solar radiation, soil type, latitude effects, viticultural practices (to some extent), prevalence and strength of wind. If any of these are linked to MJT — and the modelled relationship defining quality is actually driven by this untested factor, not temperature at all — then future changes to temperature may not cause the modelled impacts given in the present study. We see no reason to believe that any such effect will be large.

3. RESULTS AND DISCUSSION

3.1. Regional impact of warming on individual winegrape varieties

Winegrape prices were modelled, for each winegrape variety in each region, using current MJT and the potential future MJT values (depending on the emission scenario and climate model). Fig. 4 shows the relationship between regionally averaged MJT and

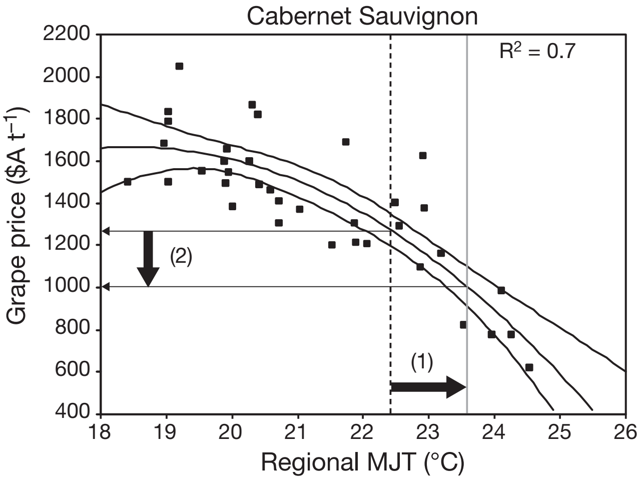

Fig. 4. The relationships between Cabernet Sauvignon winegrape price (1999 to 2003) and the mean regional MJT for Australia. Each point represents a region. The upper and lower 90% CI of the model is indicated by the outer lines. See 'Results and Discussion' for a description of the operation of the model

regionally averaged price ($A t^{-1}) for Cabernet Sauvignon. Price sensitivity to temperature change is calculated whereby Arrow (1) depicts one possible projected greenhouse gas-induced temperature increase (from the dashed line to the grey line). This will vary depending on the region, climate model and greenhouse gas emission scenario used. Arrow (2) represents the projected impact of the temperature increase on winegrape quality (as defined by the quality surrogate price; Webb et al. 2008). Note that if the temperature for a region differs (dashed line), the impact of the same temperature increment would be different. Calculations of model uncertainty are made using the equations describing the 90% CI (see Webb et al. 2008). The quadratic nature of the response of winegrape quality to temperature, for some winegrape varieties, means that where temperatures are already high, a small temperature shift can have a large negative impact (Webb et al. 2008).

Modelled responses of grape price calculated using the temperature-sensitivity equations developed in Webb et al. (2008), and average regional MJT for the years 2000, 2030 and 2050 are presented (Figs. 5 to 7). The extent of the impact of warming resulting from projections made using the CSIRO Mk3 climate model and the A1FI (high warming) emission scenario can be observed. The error bars shown are calculated using results from running the models for the upper and lower 90% CIs of the temperature-sensitivity model for each variety (the equations describing the CIs are presented in Webb et al. 2008). The magnitude of the model error varies across regions and varieties, with the greater error being found in the hottest and coolest regions included in the study (see broader confidence range in Fig. 4).

The projected impact to quality varies for the different varieties grown in a region. This is illustrated in the example of the Barossa Valley impact (Fig. 5), where,

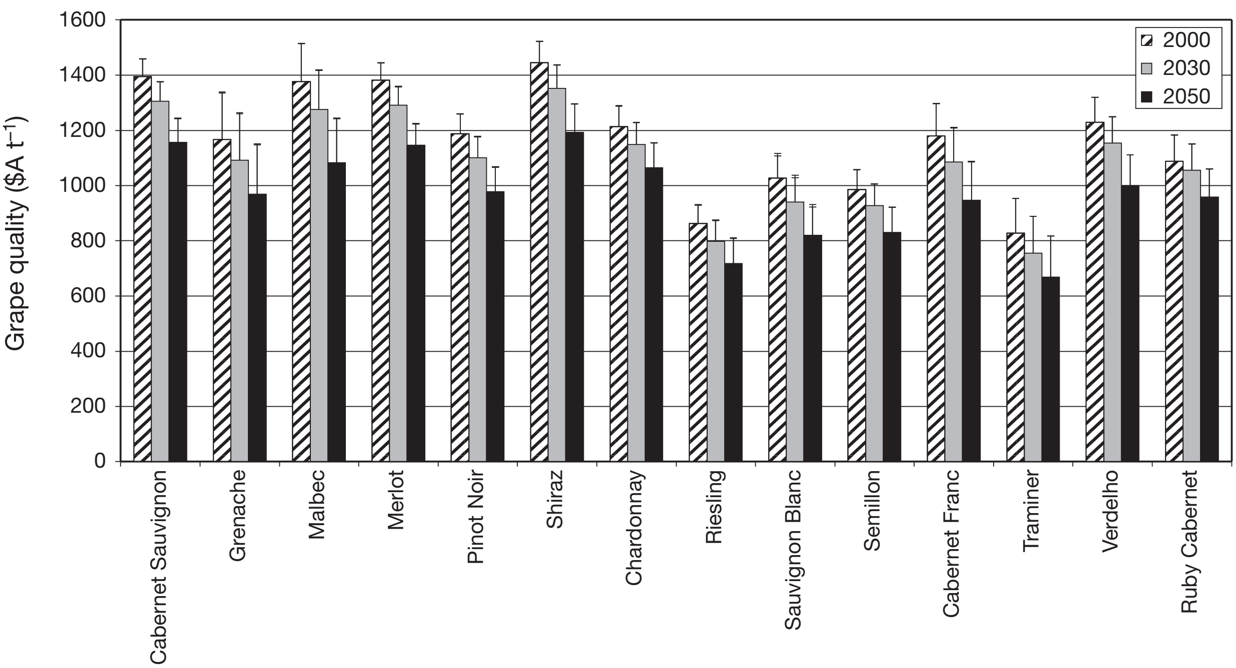

Fig. 5. Shift in winegrape quality (measured in $A t^{-1}) of premium winegrapes from the Barossa Valley (South Australia) as a result of projected climate change (CSIRO Mk3 model and the A1FI emission scenario, high climate sensitivity). Error bars: 90% CI of the model. Negative error bars (not shown) are of the same magnitude

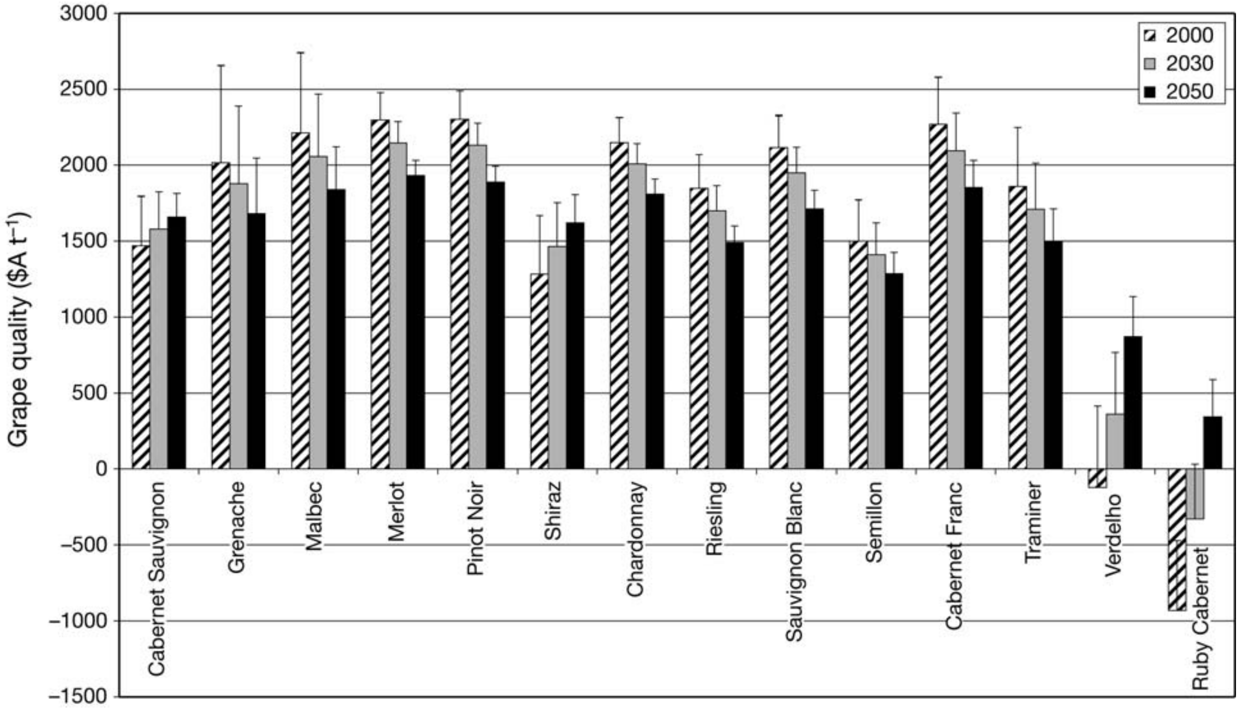

Fig. 6. Shift in winegrape quality (measured in $A t^{-1}) of each winegrape variety in Tasmania as a result of projected climate change (CSIRO Mk3 model and the A1FI emission scenario, high climate sensitivity). Though there is some indication of a negative price, this is unrealistic and would not occur in practice. Error bars: 90% CI of the model. Negative error bars (not shown) are of the same magnitude

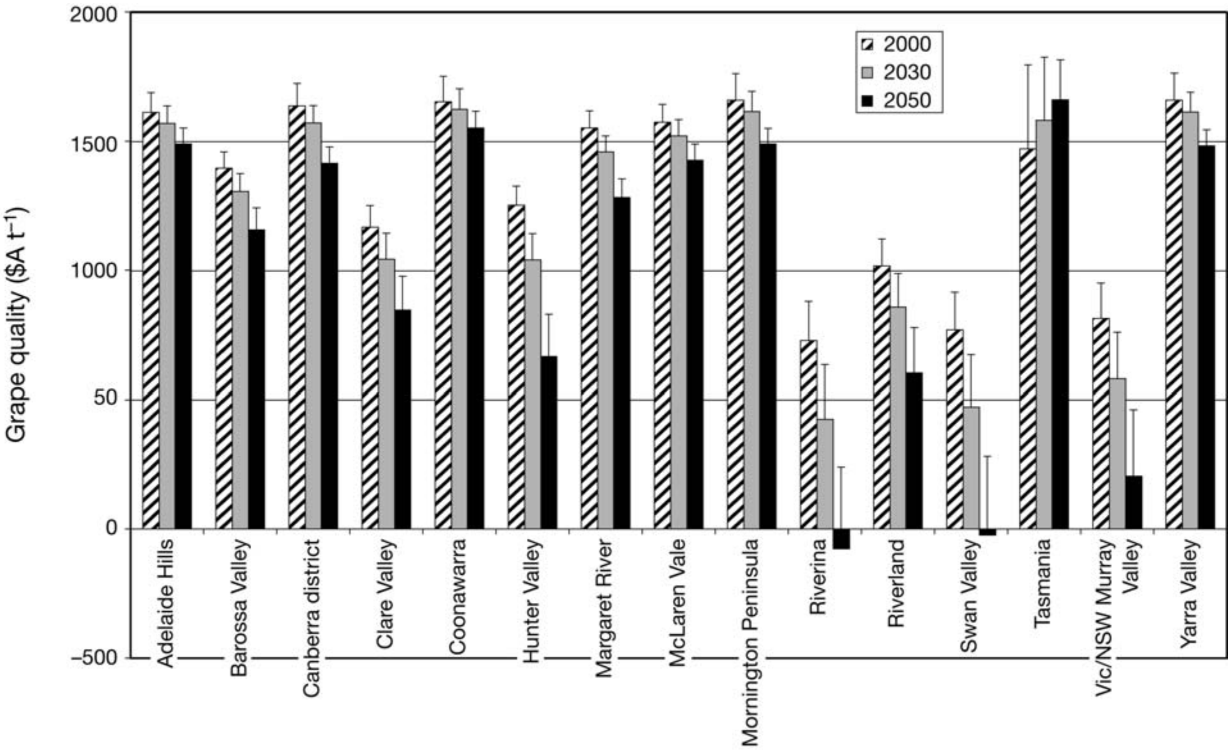

Fig. 7. Shift in winegrape quality (measured in $A t^{-1}) of Cabernet Sauvignon for selected regions as a result of projected climate change (CSIRO Mk3 model and the A1FI emission scenario, high climate sensitivity). Though there is some indication of a negative price, this is unrealistic and would not occur in practice. Error bars: 90% CI of the model. Negative error bars (not shown) are of the same magnitude

by 2030, we estimate a 5 to 7% decrease in the quality of Chardonnay (allowing for model uncertainty), a 6 to 7% decrease in the quality of Cabernet Sauvignon, and a 9 to 11% decrease for Traminer. By 2050, the decreases are 12 to 16, 11 to 19 and 19 to 26%, respectively.

For some cool climate regions, and some varieties, a positive impact of warming can be seen for some varieties (Fig. 6). For example, in Tasmania, there is a potential improvement in quality for varieties like Cabernet Sauvignon, Merlot, Malbec, Shiraz, Semillon, Verdelho and Ruby Cabernet. For other varieties — Pinot Noir, Chardonnay, Riesling, Sauvignon Blanc and Traminer — projected warming will have a negative impact on quality. Varieties like Verdelho and Ruby Cabernet, now unsuitable for planting in Tasmania, may be grown by 2050 under a high warming scenario. The overall impact for winegrapes currently grown in the Tasmanian region is negative.

The impact on the quality of Cabernet Sauvignon can vary from positive in some cooler regions (Tasmania), to minor (Adelaide Hills, Coonawarra) and major in the currently warm winegrowing regions (e.g. Riverina and Swan Valley) (Fig. 7). This range of impacts is observed because of the non-uniform nature of projected warming across the winegrape growing regions of Australia and also the present climate of a region.

3.2. Regional impact of warming on winegrape quality

Using results from the varietal analysis above, we can estimate the regional cost of climate change to the

Table 2. Range of cost to premium winegrape quality when taking into account the 3 greenhouse gas emission scenarios and the 3 climate models (climate projection uncertainty), followed by results representing all of the climate uncertainty and also the temperature-sensitivity model uncertainty for the outlook period 2030 and 2050 (result capped at 100%). Vic: Victoria; NSW: New South Wales

Region	Percent of crush (2002)	Cost to quality incorporating climate projection uncertainty (%)		Cost to quality incorporating climate projection and quality sensitivity uncertainty (%)	
		2030	2050	2030	2050
Riverland	24.35	−7 to −24	−12 to −63	−5 to −32	−9 to −87
Vic/NSW Murray Valley	24.17	−11 to −33	−19 to −87	−8 to −48	−13 to −100
Riverina	13.32	−14 to −45	−24 to −100	−9 to −73	−16 to −100
Barossa Valley	3.74	−3 to −11	−6 to −29	−3 to −13	−5 to −35
McLaren Vale	3.44	−2 to −6	−3 to −17	−2 to −6	−3 to −18
Langhorne Creek	2.93	−2 to −6	−3 to −17	−2 to −6	−3 to −18
Coonawarra	2.06	−1 to −4	−2 to −13	−1 to −5	−1 to −14
Padthaway	1.89	−3 to −8	−4 to −21	−3 to −8	−4 to −23
Hunter Valley	1.83	−5 to −17	−8 to −45	−4 to −21	−7 to −57
Clare Valley	1.51	−5 to −17	−9 to −44	−4 to −21	−7 to −58
Margaret River	1.39	−3 to −7	−5 to −19	−3 to −7	−5 to −20
Mudgee	1.18	−4 to −17	−8 to −48	−4 to −20	−7 to −58
Adelaide Hills	0.94	−2 to −7	−4 to −19	−2 to −8	−4 to −20
Cowra	0.91	−7 to −25	−12 to −67	−5 to −33	−9 to −90
Wrattonbully	0.90	−2 to −6	−3 to −17	−1 to −6	−3 to −18
Yarra Valley	0.74	−3 to −9	−6 to −24	−3 to −10	−5 to −24
Eden Valley	0.68	−2 to −8	−4 to −21	−2 to −8	−4 to −23
Great Southern	0.68	−2 to −6	−4 to −15	−2 to −6	−3 to −15
Orange	0.50	−3 to −12	−6 to −36	−3 to −13	−5 to −41
Adelaide Plains	0.42	−5 to −15	−8 to −39	−4 to −19	−6 to −51
Swan Valley	0.40	−15 to −37	−27 to −99	−10 to −59	−17 to −100
Goulburn Valley	0.39	−6 to −18	−10 to −49	−5 to −21	−9 to −60
Manjimup	0.38	−2 to −7	−4 to −18	−2 to −7	−4 to −19
Rutherglen, Glenrowan	0.37	−7 to −24	−12 to −69	−6 to −30	−10 to −88
Pemberton	0.35	−2 to −6	−4 to −16	−2 to −6	−3 to −16
Geographe	0.27	−5 to −11	−8 to −30	−4 to −13	−7 to −36
Henty	0.25	−1 to −3	−2 to −10	0 to −4	−1 to −12
Tasmania	0.24	−2 to −7	−4 to −16	−2 to −8	−3 to −19
Bendigo	0.20	−3 to −10	−6 to −30	−3 to −10	−6 to −34
Blackwood Valley	0.12	−3 to −8	−5 to −23	−3 to −9	−5 to −26
South Burnett	0.10	−11 to −29	−19 to −78	−8 to −41	−13 to −100
Mornington Peninsula	0.07	−4 to −9	−6 to −23	−3 to −9	−6 to −23
Canberra district	0.04	−2 to −10	−4 to −28	−2 to −10	−4 to −29
Granite belt	0.01	−4 to −12	−7 to −34	−4 to −14	−6 to −40
National impact	91	−7 to −25	−12 to −58	−5 to −36	−9 to −68

Australian wine industry for the years 2030 and 2050 (Table 2). By calculating the sum of the individual varietal impacts, as they vary with the climate projection, weighted by the proportion of varieties grown in a region, the range of regional impacts can be determined. For example, the projected warming in McLaren Vale ranges from 0.3 to 0.7°C by 2030, and this could result in a 2 to 6% reduction to winegrape quality. However, a projected warming of 0.4 to 1.7°C by 2050 could reduce quality by 3 to 17%. In the Riverina, projected warming between 0.4 and 1.2°C by 2030 may result in a 16 to 52% reduction in quality, while a warming of 0.7 to 3.0°C by 2050 could result in a 27 to 100% reduction in quality.

Two regions, Riverina and Swan Valley, have costs to quality exceeding 100% for some model scenario combinations. In these 2 cases the cost curves are extrapolated to temperatures beyond where grape production data exist for Australia. Though it may be postulated that quality diminishes to a level that suitability of winegrape production is zero, this theory remains to be tested. For this reason, cost to quality is capped at 100% when calculating national impacts.

Uncertainty with regard to the temperature quality model was calculated and is presented in Table 2. As expected (as a result of the CIs of the model being broader in the warmer and cooler regions — see Fig. 4), there is more uncertainty for the results in these warmer and cooler regions. When the uncertainty of the quality responses are included in the results for the hotter regions like the Riverland, the range of potential impact increases from –7 to –24% by 2030, to the broader range of –5 to –33%, for example. For the regions in the mid-climatic range like Langhorne Creek, the inclusion of the lesser uncertainty in the temperature quality model (see narrower CIs in the mid-temperature range in Fig. 4) has a flow-on negligible effect in adding to the climate response uncertainty. By 2030, the range due to uncertainty in the climate projections of –2 to –6% of impact to quality is not affected by including the quality model uncertainty for Langhorne Creek.

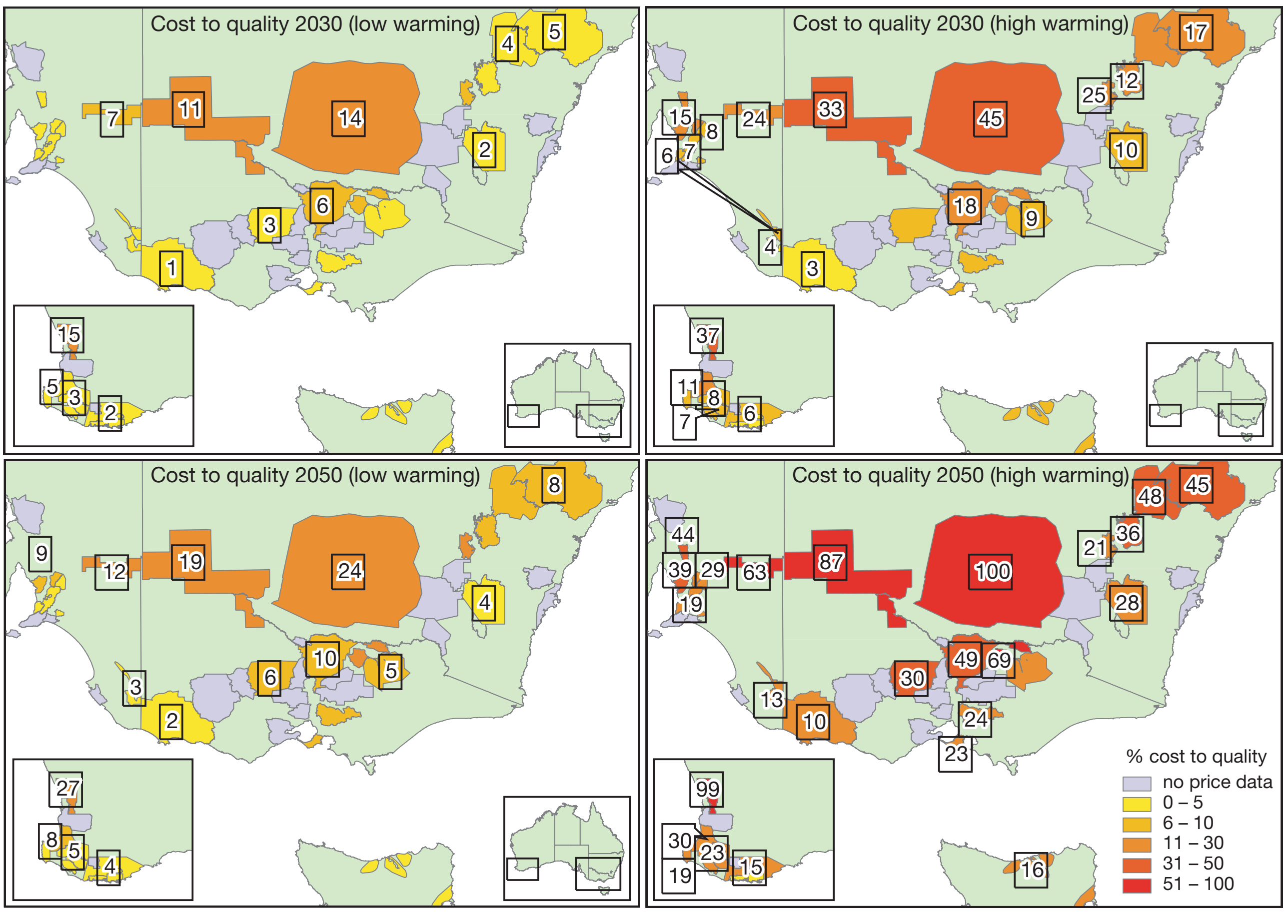

Fig. 8. Range (incorporating climate projection uncertainty) of impact of projected climate change to quality as it varies regionally (measured by quality surrogate $A t^{-1}) by the year 2030 (top) and 2050 (bottom) under low- (left) and high-warming (right) scenarios. Numbers in boxes are actual figures for selected regions

Maps of the Australian winegrowing regions (with Western Australia in the inset) showing the range of percent cost to quality with only the climate projection uncertainty addressed (Table 2) are depicted in Fig. 8.

The ranges of results for declining winegrape quality incorporate uncertainties in projecting the future climate. Managing this uncertainty is difficult. For instance, a 16% decline in quality may be seen as affordable, and regional planning or development may not be affected, while a 52% decrease could see the industry reassessing its investment in a given region. Methods of probabilistic climate change impacts research are being developed that give probability of particular outcomes by using a Monte Carlo method of sampling a large number of possible future climates (Luo et al. 2005). Using probabilistic climate projections in an assessment of impacts on winegrape quality would be useful. Our analysis does enable us to focus on regions where adaptive strategies may be needed sooner, or also regions where viticultural suitability may be reducing, or improving, in the future. This may assist with infrastructure investment decisions.

3.3. National impact of warming on winegrape quality

Each winegrape growing region contributes to the national winegrape crop with varying production totals. More than 75% of the national crush (Table 2) comes from just 8 regions (Riverland, Victoria/New South Wales Murray Valley, Riverina, Barossa Valley, McLaren Vale, Langhorne Creek, Coonawarra and Padthaway). It follows that the impact on quality calculated for these regions will have a greater bearing on the national impact.

If the uncertainties due to the climate projections are considered, by the year 2030, for the B1 low scenario, the impact to national winegrape quality is that of a reduction of >7%, and for the A1FI high scenario this reduction could be as much as 26%. By the year 2050, the national reduction in winegrape quality is 14 and 63%, depending on the level of projected warming. Note that only 91% of the 2002 winegrape crop was assessed to determine the regional production weightings in calculating the national impact; some of the less productive regions were not included. The range of impact increases if the temperature-sensitivity model uncertainty is included in the calculation of impact. By 2030 this negative impact of projected climate change on winegrape quality is from 7 to 39%, or 9 to 76% by 2050.

Though we studied winegrapes, not wine, it was found that in most regions winegrapes are grown at either their optimum temperature, or even above their optimum temperature. A warming climate will therefore have a negative impact on winegrape quality if no adaptive strategies are implemented. These results agree with the findings of Jones et al. (2005). For this analysis, no adaptive strategies were included when calculating 'cost to quality'. We believe stakeholders and relevant local, regional and national government agencies need to consider possible adaptive strategies to avoid at least some of the impacts resulting from the changing climate. Climate is not the only factor that will affect winegrape quality. Soil type, canopy management, irrigation regimes, fertilizer and pest management can all affect winegrape quality as well. Various crushing, pressing and fermentation processes, yeasts, secondary fermentation and storage time can all have an impact on the resulting quality, not to mention the blending of winegrape varieties within a wine. Exploitation of all of these factors can be made to minimize the impact of higher temperature on winegrape quality.

The impact on winegrape quality is presented here as an impact on price ($A t^{-1}). One way to view these data could be to extrapolate this through to vineyard profit, but this would be erroneous. In the first instance, factors such as 'cost of production' can vary significantly from region to region. In one survey, results show the average 'cost of production' in the Sunraysia (warm climate) during 1999/2000 was $9663 ha^{-1} or $524 t^{-1}. In the 'cooler' regions of the 'rest of Victoria', the average 'cost of production' was $12 893 ha^{-1} or $1688 t^{-1} (Thompson 2001). To link price paid for winegrapes with vineyard profitability is not possible as it only deals with the revenue side of the equation and neglects costs.

The other factor that makes an economic analysis more problematic is that many possible variables have been assumed to stay static in this impact assessment. One of these is the demand and supply balance. If quality is impacted in a negative way, demand may be reduced and price may be impacted even more than is estimated in the present study. Another possibility is that world-wide wine supply and demand balance may change. Warming projections for the Northern Hemisphere are greater than for the Southern Hemisphere (IPCC 2001a). There is also a greater potential expansion capacity in the Northern Hemisphere due to the greater high-latitude land mass. For this reason, the Northern Hemisphere winegrape growing potential may increase relative to that in the Southern Hemisphere. This may affect world wine trading and have effects on global wine prices. Attempts to forecast this are very complex. Hence, the price information used in this analysis is to be interpreted only in the capacity as a winegrape quality surrogate.

Though this study has focused on the wine regions of Australia, the relevance of these impacts of climate change on winegrape quality are global. Negative impacts on winegrape quality are likely, that is, for winegrape varieties now suited to their growing conditions. The global viticulture community will benefit from assessment of potential impacts and from considering these impacts in any future planning.

4. CONCLUSIONS

Without adaptation, winegrape quality may be reduced at a national scale in Australia from 7 to 39% by the year 2030, and from 9 to 76% by the year 2050 (all uncertainties considered). With this information now available to wine industries, actions to address and possibly minimise this impact can be considered.

Three of the most obvious methods for addressing this negative impact on winegrape quality of projected warming have been examined in some detail (Webb 2006, Webb et al. 2007). These are:

- Yield compensation strategies: increase winegrape yield, using grapevine management techniques, for a given region to compensate for lower prices.
- Shift the sites of vineyards to maintain, as far as possible, the same climate as currently utilized.
- Variety substitution could be seen as an adaptive strategy, especially in cooler climates, where a positive impact of climate change for some varieties could be realized.

The amount of effort that will be required to implement these adaptation strategies and their benefit to the wine industry remains to be seen. By highlighting the potential risk of climate change to the wine industry, this study highlights the urgency of considering such adaptive responses.

Global climate change will challenge wine production in all wine regions of the world in both a viticultural and regulatory sense. For example, wine law in major European winegrowing regions allows for only certain winegrape varieties to be grown in certain regions, if wines are to be awarded the regional quality classification due to the Appellations Contrôlées system (France) and the Denominazione di Origine Controllata (Italy). Australian wine law does not have variety restrictions, which may enable the industry to be more flexible in adjusting to the effects of climate change.

What might be a concern for the Australian wine industry is just how much winegrape production will come from the regions with — by world winegrowing standards — very warm climates. The projected climate regime for these regions is unprecedented, and the potential for the wine industry to adapt to this climate regime is untested. Examination of viticulture production in some countries where these hotter climates may be experienced presently may prove useful to provide information on the adaptive potential in these warmer sites.

The Australian wine industry has achieved a high level of growth in the past 2 decades, as a result of innovation in both vineyard and winery, to produce wines of consistently high quality at low prices. This detailed spatial analysis of the potential impacts of future climate change presents an opportunity to the Australian industry to develop suitable adaptation strategies to ensure its international competitiveness is maintained or enhanced.

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