

Resilience of grapevine yield in response to warming

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Abstract

Aim: To evaluate the effect of elevated temperature on the yield of Shiraz vines in the Barossa Valley of Australia.

Methods and results: We compiled and analysed 37 pair-wise yield comparisons between heated and control vines spanning seven consecutive vintages from 2009-10. Heating with open-top chambers increased daily average temperature by approx. 2 °C above ambient in realistic vineyard conditions, in comparison to 0.9 to 2.9 °C projected warming for south-eastern Australia (2030-2070). The combination of seasons, varieties, fruit loads, pruning times, and water regimes returned an 8.5-fold variation in the yield of unheated vines. Warming had no statistically significant effect on yield in 32 out of 37 comparisons, reduced yield in 2 and increased yield in 3.

Conclusion: Projected warming is unlikely to cause widespread reduction of yield in environments with thermal regimes similar to Barossa Valley; extrapolation to cooler or warmer regions is not warranted.

Significance and impact of the study: The relevance of this finding is three-fold. First, it demonstrates vine resilience against the target of the Paris Agreement setting a long-term goal of holding global warming below 2 °C. Second, further research on adaptation to warming needs to focus on logistic issues such as early harvest, and fruit composition with implications for wine quality, rather than yield. Third, this summary data set is a robust reference to benchmark time-series and modelling analysis of vine yield in response to warming.

Key words: projected warming, grapevine, yield, modelling analysis, adaptation

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Introduction

As with most horticultural crops, the growers of premium wine grapes regulate yields to achieve higher quality and profit (Lentz, 1998); management practices to regulate grapevine yield (Clingeleffer, 2010) need to be considered in the context of global warming. Evidence from time-series analysis of realised warming, experiments, and modelling projections into future climates indicate the potential for elevated temperature to affect yield, fruit traits and wine attributes (Barnuud *et al.*, 2014; Bergqvist *et al.*, 2001; Bindi *et al.*, 1996; Bonada *et al.*, 2013; Bonada *et al.*, 2015; Bowen *et al.*, 2004; Hannah *et al.*, 2013; Rienth *et al.*, 2016; Sadras and Moran, 2012; Sadras and Moran, 2013; Sadras *et al.*, 2013a; Sadras *et al.*, 2013b; Santos *et al.*, 2013; van Leeuwen *et al.*, 2013). Different approaches and assumptions used in modelling and time-series studies lead to results of varying reliability, as reviewed by Bonada and Sadras (2015). These authors also emphasised two distinct effects of global warming: the gradual increase in background temperature, and the increasing incidence of heat waves; this paper deals with the former.

As a perennial, the fruit yield of grapevines is determined by the conditions over successive seasons, where multiple developmental stages are responsive to the environment, genotype, management, and their interactions (Dry, 2000; Dunn, 2005; Vasconcelos *et al.*, 2009). Generally higher temperature increases the number of bunches and the number of berries per bunch, hence increasing yield (Srinivasan and Mullins, 1981). However, most of these relationships are non-linear (Buttrose, 1974) and at some developmental stages high temperature can reduce yield components; for example, high temperature immediately prior to budburst can reduce flower number (Petrie and Clingeleffer, 2005). Intra-specific variation in thermal adaptation in grapevine is large; for example, increasing temperature from 20 to 30 °C increased the weight of bunch primordia 4-fold in Riesling, but did not change the size of bud primordia in Shiraz (Dunn, 2005). Canopy growth, mostly driven by water availability and management practices such as pruning, interacts with the environment to influence yield (Dry, 2000).

In comparison to annual crops where robust models are used routinely in studies of climate change (e.g. Asseng *et al.*, 2013), we have a limited ability to predict yield and its responses to temperature in long-lived perennials including grapevine, where models are less developed (Bindi *et al.*, 1996; Santos *et al.*,

2011). Hence, the experimental quantification of the effect of high temperature on yield is particularly important in perennials.

We have devised open-top chambers (Fig. 1ab) to increase daily average temperature by approx. 2 °C above ambient in realistic vineyard conditions (Sadras and Soar, 2009; Sadras *et al.*, 2012a). This compares with the range from 0.9 to 2.9 °C for projected global warming depending on the time frame (2030, 2070) and modelling scenario (Webb *et al.*, 2013). Using these systems, we measured and reported yield response to warming from three experiments comprising 20 pair-wise comparisons between heated and control treatments in the vintages 2009-10 to 2011-12 (Sadras and Moran, 2013). The aim of this article is to consolidate this data set, and expand it to 37 pair-wise comparisons including four additional vintages from 2012-13 to 2015-16. First, we compare actual and long-term temperature records to identify potential bias in the environments sampled during the experiments; for example, actual temperatures below long-term average would bias results in the direction of more likely positive warming effect on yield. Then, we analyse the pair-wise yields of heated and control vines for the whole data set in the seven vintages from 2009-10.

Background temperature

Way and Oren (2010) reviewed the response to temperature of trees in a meta-analysis showing enhanced growth in deciduous more than in evergreen trees and in temperate and boreal species more than in their tropical counterparts. This highlights the differential impact of elevated temperature depending on the background temperature; 2 °C warming, for example, is more likely to return positive effects in a cool viticultural region, and more likely to return negative effects in an already hot region (Bentzen and Smith, 2009; Deluze, 2010; Jones *et al.*, 2005).

To account for background temperature in our trials, we compared the long-term climate records and the actual temperature during the seven vintages when we measure yield (Fig. 1c). The experiments spanned the climatic range from percentiles 10th to 90th at the beginning (September) and end of the season (March). The core of the season, from October to February, was mostly close to or above the median long-term temperatures. October 2013 and 2014, November 2009 and 2012, and December 2015 were particularly hot, with monthly means above the 90th percentile. In only one out of seven seasons, January temperature was below median, and February

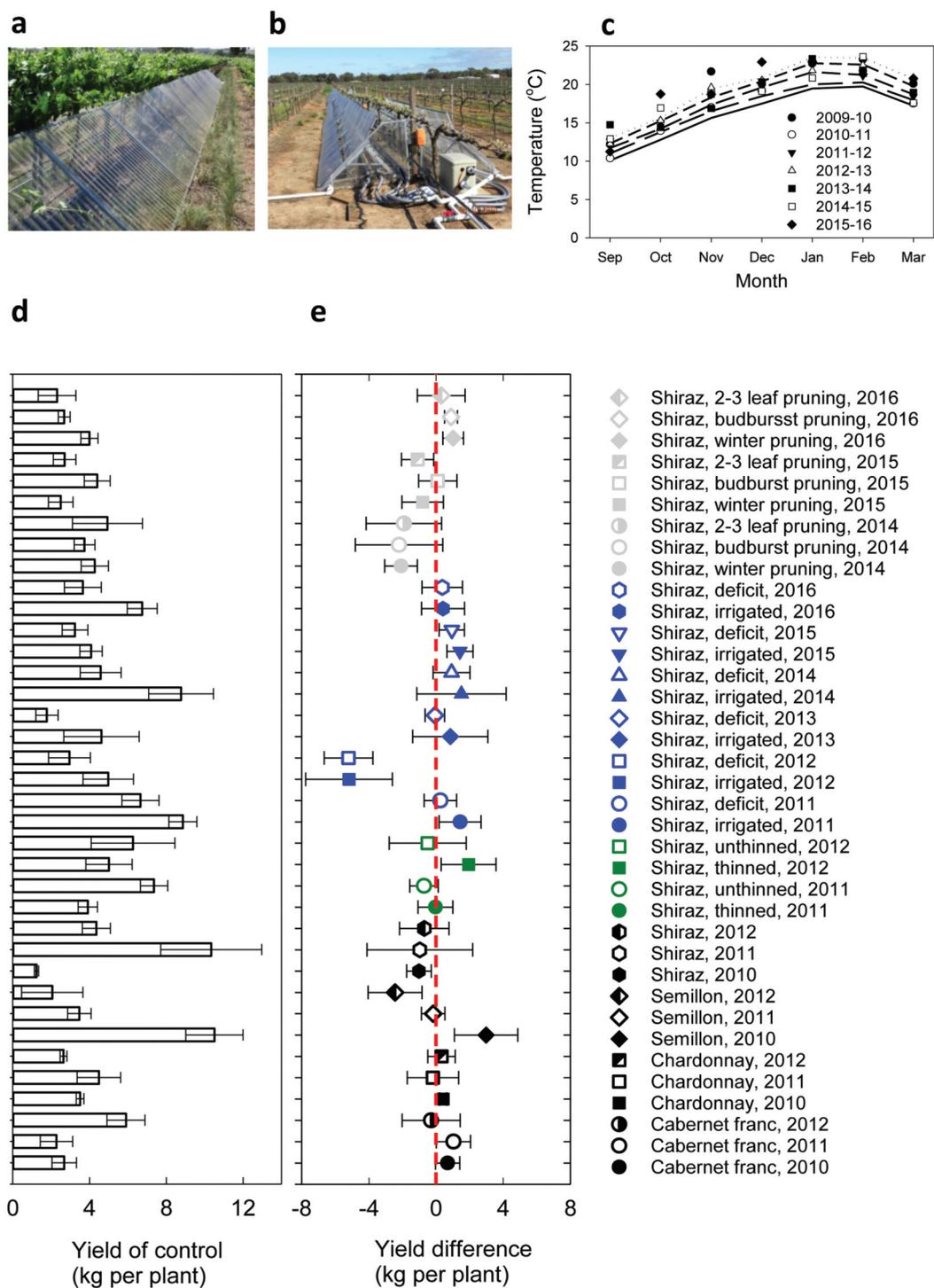


Figure 1 - Resilience of grapevine yield in response to warming.

(a, b). Large-scale open-top chambers used in experiments 1, 2 and 4 (a), and 3 (b). (c) Comparison of actual mean monthly temperature in seven growing seasons (points) and long-term (1957-2016) monthly temperature (lines) in the Barossa Valley, Australia. Lines are, from bottom to top, 10th, 25th, 50th, 75th and 90th percentiles. (d) Yield of unheated controls, and (e) difference between heated and control treatments in experiments where two thermal regimes (heated, control) were combined with either: (exp. 1, black symbols) four varieties over three seasons (2009-10 to 2011-12), (exp. 2, green symbols) two fruit loads over two seasons (2010-11, 2011-12), (exp. 3, blue symbols) two water regimes over six seasons (2010-11 to 2015-16), and (exp. 4, grey symbols) three pruning times over three seasons (2014-15 to 2015-16). Error bars are two standard deviations and asterisks indicate significant warming effect (t-test, $P \leq 0.05$). Sources: (a) Sadras and Soar (2009); (b) Sadras *et al.* (2012a); (c) Queensland Government SILO Climate Data (www.longpaddock.qld.gov.au/silo/); (d-e) Sadras *et al.* (2013a, b); Sadras *et al.* (2014); Sadras *et al.* (2015); Moran, Petrie and Sadras (unpublished).

temperature was never below median. The prevailing warmer-than-median conditions during the experiments (Fig. 1c) indicates that bias, if any, was in the direction of over-estimating the negative impact of the heating treatment.

Measured yield response to warming

We conducted four experiments, where two thermal regimes (heated, control) were combined with either: (1) four varieties over three seasons (2009-10 to 2011-12), (2) two fruit loads over two seasons (2010-11, 2011-12), (3) two water regimes over six seasons (2010-11 to 2015-16), and (4) three pruning times over three seasons (2014-15 to 2015-16). Experiment 1 included Cabernet franc, Shiraz, Semillon and Chardonnay, and experiments 2-4 were with Shiraz. Clones and rootstocks, planting pattern, vineyard practices, experimental design and detail of thermal regimes and vine water status have been presented previously (Sadras *et al.*, 2012b).

The combination of seasons, varieties, fruit loads, pruning times, and water regimes returned an 8.5-fold variation in the yield of unheated vines (Fig. 1d). Figure 1e shows the pair-wise comparisons for all these combinations. Warming had no significant effect on yield in 32 out of 37 cases, reduced yield in 2 and increased yield in 3 ($P = 0.05$). Reductions in yield were 22% for Shiraz in 2010 (exp. 1), and 34% for vines pruned at budburst in 2016 (exp. 4). Warming increased yield 2.0-2.8 fold in both irrigated and water-deficit vines in 2012 (exp. 3), and 1.5 fold in winter-pruned vines in 2014 (exp. 4). This asymmetry, whereby the magnitude of yield enhancement was larger than the magnitude of reduction, was noticed and discussed previously (Sadras and Moran, 2013).

Interpretation of our results and extrapolation to other sites needs caution because plant responses to warming are influenced by background temperature, as discussed before, and other factors such as water and nutrient availability and interactions with pathogens (Ac *et al.*, 2015; Downey, 2012; Ko *et al.*, 2010; Piedallu *et al.*, 2016; Sadras and Moran, 2013; Xu and Zhou, 2005). Our trials were limited to a red brown earth (Northcote, 1979) on a single site; this may restrict conclusions for other soils, particularly important to capture interactions between temperature and water availability. Experiment 3, however, combined thermal and water regimes over six seasons, where yield was reduced from 2.6-8.9 kg/plant in irrigated vines to 1.8-4.6 kg/plant under water deficit (Fig. 1d). Despite these severe water restrictions, warming did not reduce yield in five

seasons, and substantially increased yield in both irrigated and water-deficit vines in 2012 (Fig. 1e, blue symbols). Wet weather in 2010-11 favoured fungal diseases in south-eastern Australia, and vines under elevated temperature showed lower incidence of Botrytis bunch rot (*Botrytis* spp) in the Barossa Valley (Sadras and Moran, 2013) and lower incidence of downy mildew (*Plasmopara viticola*) in the trials at Sunraysia (Downey, 2012) in comparison to vines under ambient temperature.

We conclude that projected warming is unlikely to be detrimental for vine yield in environments with thermal regimes similar to Barossa Valley (Fig. 1c) for vineyards in a range from 1.2 to 10.5 kg/plant (Fig. 1d). Occasional yield reductions are likely to be compensated by yield enhancement, depending on seasonal conditions. The relevance of this finding is three-fold. First, it demonstrates vine resilience (*sensu* Doring *et al.*, 2015) against the target of the Paris Agreement setting a long-term temperature goal of holding the global average temperature increase to well below 2 °C (Schleussner *et al.*, 2016). Second, research effort on adaptation to warming needs to focus on logistic issues such as early harvest, and fruit composition with implications for wine, rather than yield. Third, this summary data set is a useful reference to benchmark time-series and modelling analysis of vine yield in response to warming, and more broadly, the yield response of long-lived perennial plants. Extrapolation to cooler or warmer regions is not warranted.

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