Advancement of grape maturity: comparison between contrasting cultivars and regions

W. CAMERON[1], P.R. PETRIE[2], E.W.R. BARLOW[1], C.J. PATRICK[3], K. HOWELL[1] and S. FUENTES[1]

[1] Faculty of Veterinary and Agricultural Sciences, University of Melbourne, Parkville, Vic., 3010, Australia; [2] South Australian Research and Development Institute, Waite Research Precinct, Urrbrae, SA, 5064, Australia; [3] Statistical Consulting Centre, University of Melbourne, Parkville, Vic., 3010, Australia

Corresponding author: Ms Wendy Cameron, email wtinson@student.unimelb.edu.au

Abstract

Background and Aims: As grapegrowers move to adapt to climate change, they need more detailed information on what cultivars to plant and where to plant them. The aims of this study were to understand how different cultivars in different regions are responding to changes in climate, in order to inform future cultivar selections.

Methods and Results: Trends in the day of year maturity (DOYM) between 1999 and 2018 were analysed for 23 grape cultivars (covering at least 7 years) and four Victorian vineyard regions against vintage year, seasonal growing degree day ($GDD_{Sep–Mar}$) and Spring Index. In most cases there were significant trends in DOYM advancement as a function of $GDD_{Sep–Mar}$ and spring index. Temporal advancement of DOYM was more variable. One cultivar showed a significant advancement at two of three sites and another showed a significant delay. Different cultivars advanced DOYM at significantly different rates at a given site, later ripening cultivars advanced DOYM faster than earlier ripening cultivars and for a cultivar grown across several sites, the DOYM advancement was faster at cooler sites.

Conclusions: Grapevine cultivars respond to warming temperature differently and the advancement of grape maturity is predicted to slow as temperature further increases.

Significance of the Study: The study showed diversity in the phenological response of cultivars to temperature, which may be utilised to better adapt to climate change.

Keywords: *compression of the harvest period, day of year maturity, grapevine, growing degree day, spring index*

Introduction

Grapevine phenology has advanced across many winegrowing regions in recent decades (Duchêne and Schneider 2005, Jones et al. 2005, Webb et al. 2007). One ramification is earlier grape harvests (Jones and Davis 2000, Petrie and Sadras 2008, Tomasi et al. 2011, Webb et al. 2011). Earlier harvests mean that grapes may ripen during a warmer time period, with possible effects on grape composition, quality and wine style (Mira De Ordña 2010, Sadras et al. 2013). An indirect consequence is the phenomenon of compression of the harvest period, causing logistical and infrastructure constraints (Webb et al. 2007, Petrie and Sadras 2016). A possible outcome is that grapes are harvested according to when they can be scheduled to be processed at the winery, rather than at optimum maturity, potentially affecting grape and wine composition.

Harvest has been described as a 'false phase' (Menzel et al. 2006), as this decision is made by the grapegrower or winemaker based on several factors, including grape phenology, harvest and processing logistics, and the forecast weather. To provide some uniformity in the study of grape maturity, the metric 'day of year maturity' (DOYM) has been used by several researchers (Petrie and Sadras 2008, Webb et al. 2011, Jarvis et al. 2017). Day of year maturity describes the date (or day of the year) at which winegrapes reach a designated sugar concentration (°Baumé, °Bé), which may vary between cultivars, or indeed for the same cultivar in different regions, depending on the normal product requirements (Jarvis et al. 2017). The use of the word 'maturity' in this context does not imply that the grapes are mature as such but is the terminology used to describe this chosen metric for the study.

Previous studies in an Australian context have largely focussed on the temporal change of DOYM, and by inference, temporal advancement of DOYM and the associated regional season growing temperature have been linked (Petrie and Sadras 2008, Webb et al. 2011, Jarvis et al. 2017). The responsiveness of individual grape cultivars directly to temperature indices will help to understand the degree of cultivar diversity available to grapegrowers and to predict or anticipate how cultivars may respond either in another setting or in the same environment with a changing climate. Grapevines appear to be well adapted to the changing climate and the large number of grapevine cultivars that are currently cultivated globally in different climatic settings suggests that there already is the potential cultivar diversity required to cope with climate change, provided we better understand these cultivar differences and diversity (Wolkovich et al. 2018).

The purpose of this study was to analyse maturity data from a broad range of cultivars grown in commercial vineyards across a range of climatic zones, and to develop an understanding of how grapevines respond to a warming climate. Specifically, the aims were to determine whether there were differences between the rate of advancement of DOYM for different cultivars in the same vineyard or between cultivars common to different vineyards, both temporally and as a function of the temperature indices,

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seasonal growing degree days ($GDD_{Sep–Mar}$) and the spring index (Jarvis et al. 2017). The role of yield on the timing of DOYM was investigated to further advance previous attribution studies. This research will help to describe the degree of genetic variation between grape cultivars to assist in planting decisions and, thus, help grapegrowers adapt to climate change.

Materials and methods

Data collection

Data from four vineyard locations, Banksdale, Milawa, Heathcote and Mystic Park, representing different regions and different climatic parameters from across Victoria, Australia (Table 1) and 23 grape cultivars were analysed. The data for each cultivar cover a range of time periods between 1999 and 2018 (Table 2), and only cultivars where there were seven or more years data during this overall period were included. The vineyards were all managed using practices that were typical for their region and received irrigation. Being commercial vineyards, some blocks of fruit were removed, and some were planted during the time period of this study. Only data commencing from the third vintage after planting were included. Although it is acknowledged that in those cases the vines were not fully mature, Nader et al. (2019) found that younger vines were consistently 2 or 3 days more advanced for budburst, flowering and veraison compared to that of older vines. One could reasonably expect the DOYM to be later as these vines further aged, a trend which would work against most of the findings in this study.

Sugar concentration was inferred from total soluble solids (TSS) measured by densitometry (°Baumé, °Bé) and collected from the historical records of a commercial winegrowing business over many vineyard sites for the period. These had been recorded and saved in spreadsheets as part of the annual winery operations. Where available, handwritten records held at the vineyards were used to compare with and verify the winery record. When there were discrepancies, the hand-written record was used.

Vineyard staff mostly assessed TSS in the field. It is worth noting that for Banksdale and Heathcote, the same staff member was responsible for this sampling, testing and recording of °Baumé over the entire time period of the analysis. For Mystic Park, only two people were responsible during the measurement period. Meeting fruit specification was a key performance indicator for the vineyard managers so accurate grape sampling and testing was important for them.

Individual blocks of fruit were assessed using a representative sampling technique with sampling beginning after veraison, continuing every week and increasing in frequency as the fruit approached the target TSS. Thirty bunches were collected at random from at least 30 vines and from at least four different rows spread across the block, kept cool before being crushed and the TSS of the juice measured by refractometry with automatic temperature adjustment. Occasionally samples were taken by vineyard staff and sent to the winery laboratory for TSS analysis. In these cases, the samples were collected in the same way, transported cool, pressed at the winery laboratory using a bench bladder press and the juice analysed by refractometry with temperature adjustment (Hamilton and Coombe 1992).

Seasonal growing degree days and spring index

Traditionally, the seasonal growing degree day index (GDD) related to the heat accumulation above a base temperature of 10°C from April to October (Amerine and Winkler 1944) in the northern hemisphere and October to April in the southern hemisphere. More recent studies by Jarvis et al. (2017), who compared several temperature-based viticultural indices in Australian regions with DOYM, demonstrated a better correlation between $GDD_{Sep–Mar}$ and DOYM than between $GDD_{Oct–Apr}$ and DOYM, with the earlier period September to March perhaps better reflecting the growing window and the changes in climate that have already occurred. Sadras and Petrie (2011) used $GDD_{Sep–Mar}$ in their study for the relatively warmer Australian regions, so for these reasons, this updated version of the GDD index was adopted in this study. One criticism of the GDD calculation is the use of 10°C as the base temperature (Moncur et al. 1989, Nendel 2010, Parker et al. 2011, Zapata et al. 2017); research by Pouget (1968) demonstrated a range of 4.3–11°C for the growth threshold for different grape cultivars. As most researchers have continued to use the 10°C base temperature, for comparative purposes, it has been accepted in this study.

In the Jarvis et al. (2017) study, it was also found that the best correlations were between DOYM and the 'spring index'. The spring index is the summation of maximum daily temperature for the southern hemisphere spring months, September, October and November. The additional advantage of including the spring index in these analyses is that it is a period of time before maturity, in contrast to $GDD_{Sep–Mar}$ that covers a time period that ends after many grapes in these vineyards had been harvested so may not as well reflect the actual seasonal conditions for a cultivar or vineyard. Regardless, as the aim here was to identify trends of DOYM with temperature indices, $GDD_{Sep–Mar}$ was included, being an index that is relatively well known. The analyses described below for $GDD_{Sep–Mar}$ were repeated using the time frame of September to January for GDD and the trends and significance were found to be similar (Equations 1–3).

Table 1. Climate summary and temperature index trends for four vineyards located in Victoria, Australia for the period 1999–2018.

Vineyard	Average MJT 1999–2018 (°C)	Average rainfall Sep–Mar (mm)	Average $GDD_{Sep–Mar}$ (°C days)	Average spring index (°C)	Temporal trend for $GDD_{Sep–Mar}$ (°C days/year)		Temporal trend for spring index (°C/year)	
					Slope	*P*-value	Slope	*P*-value
Banksdale	21.72 ± 1.55	477	1520	1760	8.68	0.116	7.69	0.103
Milawa	23.56 ± 1.58	340	1850	2010	11.24	0.042	7.62	0.122
Heathcote	23.26 ± 1.41	258	1880	2020	16.19	0.008	10.79	0.028
Mystic Park	24.67 ± 1.50	193	2160	2190	15.42	0.011	10.15	0.036

Temperature data were obtained from Scientific Information for Land Owners (Jeffreys et al. 2001). $GDD_{Sep–Mar}$, average seasonal growing degree days September to March, $\sum_{1\,Sep}^{30\,Mar} GDD$; MJT, mean January temperature ± 95% confidence interval; spring index, $\sum_{1\,Sep}^{30\,Nov}$TMax.

Table 2. Rate of change of day of year maturity as a function of Vintage Year, seasonal Growing Degree Days September to March ($GDD_{Sep–Mar}$) and Spring Index for individual cultivars at four vineyard sites located in Victoria, Australia.

			Rate of change DOYM as a function of Vintage Year		Rate of change DOYM as a function of $GDD_{Sep–Mar}$		Rate of change DOYM as a function of Spring Index	
Cultivar	Period of data	Designated maturity (°Bé)	Slope ± 95% CI (days/year)	*P*-value	Slope ± 95% CI (days/°C days)	*P*-value	Slope ± 95% CI (days/°C)	*P*-value
Banksdale, Victoria 36.67S 146.32E								
Cabernet Sauvignon	1999–2018	12.0	−0.375 ± 0.975	0.426	−0.069 ± 0.031	<0.001	−0.075 ± 0.042	0.001
Chardonnay	1999–2018	12.0	−0.470 ± 1.050	0.359	−0.065 ± 0.026	<0.001	−0.081 ± 0.025	<0.001
Pinot Grigio	2000–2018	11.0	−0.290 ± 0.970	0.540	−0.048 ± 0.029	0.002	−0.078 ± 0.023	<0.001
Prosecco	2009–2018	9.0	0.062 ± 3.340	0.967	−0.068 ± 0.064	0.039	−0.101 ± 0.037	0.001
Shiraz†	1999–2012	12.0	−1.198 ± 2.031	0.221	−0.066 ± 0.055	0.021	−0.109 ± 0.063	0.003
Tempranillo†	2007–2018	12.0	1.780 ± 2.159	0.095	−0.091 ± 0.058	0.006	−0.099 ± 0.040	<0.001
Milawa, Victoria 36.45S 146.43E								
Cabernet Sauvignon	1999–2018	12.0	−0.690 ± 1.020	0.173	−0.053 ± 0.032	0.002	−0.069 ± 0.032	<0.001
Chenin Blanc†	1999–2013	11.0	−0.884 ± 1.823	0.305	−0.052 ± 0.034	0.006	−0.063 ± 0.037	0.004
Dolcetto	1999–2017	12.0	−1.100 ± 0.880	0.018	−0.058 ± 0.029	0.001	−0.048 ± 0.042	0.024
Graciano	2001–2018	12.0	−0.817 ± 1.410	0.231	−0.057 ± 0.039	0.007	−0.080 ± 0.033	<0.001
Mondeuse†	1999–2018	12.0	−1.158 ± 1.594	0.142	−0.079 ± 0.046	0.003	−0.120 ± 0.048	<0.001
Shiraz	1999–2018	12.0	−0.860 ± 1.153	0.133	−0.055 ± 0.033	0.003	−0.084 ± 0.024	<0.001
Gewürtztraminer†	1999–2013	11.0	0.530 ± 1.389	0.410	−0.045 ± 0.045	0.052	−0.025 ± 0.045	0.241
Heathcote, Victoria 36.47S 144.78E								
Cabernet Sauvignon	2005–2018	12.0	−0.878 ± 1.480	0.220	−0.050 ± 0.025	0.001	−0.064 ± 0.035	0.002
Carmenère†	2005–2015	12.0	−0.630 ± 3.475	0.692	−0.075 ± 0.060	0.020	−0.091 ± 0.085	0.038
Dolcetto	2004–2018	12.0	−1.720 ± 1.493	0.027	−0.052 ± 0.033	0.005	−0.061 ± 0.048	0.016
Durif	2004–2018	12.0	−0.197 ± 1.805	0.817	−0.041 ± 0.041	0.046	−0.073 ± 0.042	0.003
Malbec	2003–2018	12.0	0.305 ± 1.525	0.673	−0.035 ± 0.035	0.046	−0.063 ± 0.037	0.002
Merlot	2002–2018	12.0	−0.552 ± 1.200	0.344	−0.046 ± 0.024	0.001	−0.066 ± 0.032	<0.001
Montepulciano†	2007–2018	12.0	−0.960 ± 2.625	0.435	−0.073 ± 0.043	0.003	−0.088 ± 0.050	0.003
Petit Verdot†	2003–2013	12.0	−0.704 ± 1.519	0.322	−0.028 ± 0.029	0.055	−0.034 ± 0.038	0.074
Shiraz	2002–2018	12.0	−0.817 ± 1.230	0.178	−0.046 ± 0.027	0.002	−0.066 ± 0.036	0.001
Tempranillo	2004–2018	12.0	−0.370 ± 1.520	0.604	−0.048 ± 0.026	0.002	−0.054 ± 0.038	0.009
Mystic Park, Victoria 35.60S 143.76E								
Cienna	2004–2018	12.0	−0.942 ± 1.780	0.274	−0.050 ± 0.040	0.016	−0.073 ± 0.044	0.003
Crouchen	2001–2018	11.0	0.839 ± 1.307	0.192	−0.019 ± 0.042	0.354	−0.035 ± 0.054	0.186
Dolcetto	2007–2018	12.0	−0.470 ± 2.760	0.706	−0.063 ± 0.044	0.012	−0.075 ± 0.052	0.011
Flora†	2002–2018	11.0	0.311 ± 1.194	0.580	−0.020 ± 0.028	0.149	−0.045 ± 0.034	0.012
Muscat of Alexandria	2012–2018	11.0	1.430 ± 8.850	0.699	−0.089 ± 0.120	0.112	−0.121 ± 0.058	0.011
Orange Muscat	1999–2018	11.0	1.160 ± 0.919	0.017	−0.005 ± 0.036	0.785	−0.008 ± 0.048	0.740
Shiraz	1999–2018	12.0	0.561 ± 1.320	0.386	−0.028 ± 0.043	0.190	−0.055 ± 0.051	0.035
Tarrango	2001–2018	11.0	0.067 ± 1.120	0.900	−0.024 ± 0.032	0.138	−0.047 ± 0.039	0.021

Mixed models were used (response: DOYM from 1 January; random factors: Block and Vintage Year; covariate: Vintage Year or $GDD_{Sep–Mar}$ or Spring Index as appropriate). Cultivars marked † were analysed using linear regression. CI, confidence interval; DOYM, day of year maturity; $GDD_{Sep–Mar}$, average seasonal growing degree days from September to March.

$$GDD = (\{[(T_{max} + T_{min})/2] - T_{Base}\};0) \quad (1)$$

where T_{max} is the daily maximum temperature (°C), T_{min} is the daily minimum temperature (°C), T_{Base} is a baseline temperature (10°C used in this study) and values of GDD ≤ 0 are set to zero.

$$GDD_{Sep-Mar} = \sum_{1\ Sep}^{30\ Mar} GDD \quad (2)$$

where $GDD_{Sep–Mar}$ is in °C days

$$\text{Spring index} = \sum_{1\ Sep}^{30\ Nov} TMax \quad (3)$$

where spring index is in °C.

Temperature data for calculation of GDD and spring index

Although the vineyards had on-site automatic weather stations for the duration of this study, these systems did not function continuously and they were changed and updated over time, hence data were not complete. Therefore, temperature data were obtained from Scientific Information for Land Owners (SILO) (Jeffrey et al. 2001), using the nearest available coordinates to the vineyard location. The SILO data use datasets constructed from the Australian Bureau of Meteorology (BOM) observational data. The ‘data drill’ from SILO was sourced, which is daily time series data consisting entirely of interpolated estimates and which are taken from the gridded datasets. The interpolation method uses a thin plate smoothing spline for the temperature variables used in this study (Jeffrey et al. 2001). To ground truth the SILO data, a sample of comparisons was made between the SILO data and recent available on-site weather station data equipment (Measurement Engineering Australia, Magill, SA, Australia which incorporates the Green Brain web application). When SILO daily GDD values and on-site daily GDD values were subjected to a linear regression, the r^2 values ranged from 0.86 to 0.92 and the slopes of the regression lines ranged from 0.82 to 0.93 for the four vineyards. It was decided to use the SILO data for this study as they are complete, readily available and derived from the accurate weather monitoring equipment of the BOM.

Day of year maturity

Day of year maturity (calculated from 1 January) was derived from the TSS data collected as described. The TSS reading that determined 'designated maturity' varied depending on the cultivar and was based on the usual harvest requirement TSS for that cultivar. In general, the designated maturity was 12°Bé for red cultivars (except Tarrango which was 11°Bé for style purposes) and 11°Bé for white cultivars (except Chardonnay which was 12°Bé and Prosecco which is picked early and was 9°Bé) (Table 2).

In a similar approach to Petrie and Sadras (2008), the DOYM was determined using the two TSS data points on either side of the required designated maturity TSS and a linear interpolation of these points to the designated maturity, unless the actual designated maturity point was available in which case that individual point was used. If data were not available both above and below the required designated maturity TSS, the results from that year by cultivar and block combination data were excluded. In other words, TSS data were not extrapolated from a single TSS point to reach the designated maturity.

Analysis of DOYM data

Linear mixed effects models were used to determine the rate of change of the DOYM for individual cultivars. For models with data from multiple blocks of fruit, Block and Vintage Year were included as crossed random effects. Covariates of either Vintage Year, seasonal Growing Degree Days ($GDD_{Sep–Mar}$), or Spring Index were included as fixed effects. In particular, this means the models with Vintage Year as the covariate also included Vintage Year as a random effect. The random effect of Vintage Year was included to model the dependence between multiple blocks within a given year, while the continuous covariate was included to model an overall linear trend over the time period of the data.

The mixed model, with the inclusion of random effects, ensures that the results take into account any block effect as well as accounting for repeated observations within a vintage. Using a mixed model instead of linear regression avoids any potential concerns about false replication. In vineyards where there was only a single block of fruit, where it was not possible to use the mixed model, linear regression was used.

The initial models considered data from a single cultivar at a single vineyard at a time. To determine if there were differences between rates of change of DOYM at a given vineyard, models were fitted to data from all the relevant cultivars at each vineyard. Cultivar and the relevant interaction term between Cultivar and Vintage Year, $GDD_{Sep–Mar}$ or Spring Index were included as fixed factors in the models described above. A value of $P < 0.05$ for the interaction term would show that there was a significant difference between the rates of advancement of DOYM for those cultivars. Pairwise comparisons of the interaction slopes were done using Fisher's Least Significant Difference (LSD). Any differences in the rate of change of DOYM between different cultivars would illustrate the different response of the cultivars to climate and could help explain the phenomenon of compression of the harvest period (Webb et al. 2007, Petrie and Sadras 2016, Jarvis et al. 2019).

To determine if there were differences between rate of change of DOYM for a given cultivar at different vineyards, a similar approach as above was used except the data subset consisted of the cultivar at the different vineyards, and Vineyard and the relevant interaction term between Vineyard and Vintage Year, $GDD_{Sep-Mar}$ or Spring Index and between Vineyard and Yield if applicable.

Yield data

All fruit received at the winery was weighed at the company weighbridge by truck load, or loads were split and weighed as individual bins if necessary and the mass recorded by cultivar and vineyard for the individual blocks. These weighbridge details were manually entered in the winery management software database (Total Systems for Management, Adelaide, SA, Australia). These records were used for both grower payments and company vineyard records, so were checked and verified carefully. On some occasions fruit was not picked because of winery requirements. In those cases, tonnages were estimated based on the tonnage of the balance of the block (11.3% of cultivar and block combinations) or an adjacent block of the same cultivar (4% of cultivar and block combinations). There were no adjacent block or part block tonnage details in less than 1% of instances, and in these few cases the tonnage was estimated by hand harvesting and weighing the fruit from randomly selected sections of the canopy and using traditional yield estimation methods (Dunn 2010). Yield (T/ha) for each block was calculated using these records. The historical block areas were obtained from the company vineyard identification registers, which were updated annually, and from these the tonnage per area was calculated on a block by block basis for each cultivar at each vineyard. The calculated block yields were also cross checked and verified with the yearly company vintage reports.

To determine the effect of yield on DOYM, linear mixed models were used in the same way as above except that Yield (T/ha) was the covariate. Where there was only one block of fruit linear regression between DOYM and Yield was used.

To further investigate the influence of yield on DOYM trends, another set of models was fitted to the DOYM data with Yield included in the model, along with the covariates Vintage Year, $GDD_{Sep–Mar}$ or Spring Index. For the models which included interaction terms between the primary covariate and Cultivar or Vineyard, interaction terms between Yield and Cultivar or Vineyard were also included.

Results

Vineyard temperature trends

Table 1 shows the spread and seasonal variation for mean January temperature (MJT), rainfall, temperature indices and temporal trends for $GDD_{Sep–Mar}$ and spring index from 1999 to 2018 for these vineyards. Mystic Park was the warmest and Banksdale the coolest site with an average $GDD_{Sep–Mar}$ across the 20 seasons of approximately 2160 and 1520°C days, respectively. For this period, all vineyards showed an increasing trend for $GDD_{Sep–Mar}$ and spring index. These were significant ($P < 0.05$) for all except

Banksdale for the $GDD_{Sep–Mar,}$ trend and for Heathcote and Mystic Park for the spring index trend (Table 1).

Individual cultivars showed distinct DOYM temporal trends

Twenty-one out of the 31 vineyard cultivar combinations had an advancing DOYM temporal trend (Table 2). The only significant advancement trend, however, was for Dolcetto at both Heathcote and Milawa which had advanced at 1.72 (P = 0.027) and 1.10 (P = 0.018) days/year, respectively. In contrast, Orange Muscat at Mystic Park had a significantly delayed DOYM trend of 1.16 (P = 0.017) days/year. For all other cultivars and vineyards, non-significant DOYM temporal trends of different magnitudes occurred in both an advancing and delayed direction over their respective time periods, with six of the ten delayed DOYM trends being at Mystic Park the warmest vineyard,.

Individual cultivars showed distinct DOYM temperature index trends

All cultivars at all vineyards showed an advancing trend for DOYM against both temperature indices (Table 2). In other words, as $GDD_{Sep–Mar}$ or spring index increased, DOYM advanced. These trends were significant for all cultivars at Banksdale and for all but Gewürztraminer at Milawa and Petit Verdot at Heathcote, Gewürztraminer and Petit Verdot having the lowest rate of DOYM advancement of the cultivars at their respective vineyards as a function of both temperature indices, $GDD_{Sep–Mar}$ and spring index. It should be noted that the trends for Gewürztraminer and Petit Verdot were significant at $P < 0.1$, except Gewürztraminer as a function of spring index. At Mystic Park, however, while all cultivars showed advancing DOYM trend for $GDD_{Sep–Mar}$, these were significant for only two of the eight cultivars, Dolcetto and Cienna. Most other cultivars at Mystic Park showed smaller non-significant trends in DOYM advancement as a function of $GDD_{Sep–Mar}$ except Muscat of Alexandria which showed a larger trend, but it was not significant (Muscat of Alexandria data covered a shorter time period 2012–2018). The DOYM advancement trend as a function of spring index unit was significant for six of the eight cultivars at Mystic Park, but there was no evidence for a change in DOYM for Crouchen or Orange Muscat as a function of the spring index unit.

Yield showed an independent influence on DOYM trends

Yield has been implicated in DOYM trends (Pearce and Coombe 2004, Webb et al. 2012) but the relationship is unclear (Petrie and Sadras 2008). There were 26 out of 31 positive trends for DOYM as a function of Yield, indicating that as yield increased, the DOYM was later (Table 3). Thirteen of these 26 positive trends were significant and none of the negative trends were significant.

In the models including both Yield and another covariate (Vintage Year, $GDD_{Sep–Mar}$ or Spring Index), yield had a significant association with DOYM for many cultivars (shown in bold in Table 4), controlling for the effects of the other covariates. The results for the change of DOYM as a function of the covariates Vintage Year, $GDD_{Sep–Mar}$ and Spring Index when Yield was included as a second covariate in the model for the individual cultivars, are also shown in Table 4.

A comparison between Tables 2 and 4 indicates some differences in advancement DOYM trends when Yield was included in the models. For the temporal trends, the major differences were that the advancement trends for DOYM/year for Pinot Grigio at Banksdale and Montepulciano at Heathcote became larger and significant (0.85 days/year, P = 0.044 and 2.67 days/year, P = 0.036, respectively) and the magnitude of the significant delayed trend for DOYM for Orange Muscat at Mystic Park reduced from 1.16 to 1.07 days/year and was no longer significant (P = 0.052 when yield was included). Four cultivars, Prosecco, Malbec, Flora and Muscat of Alexandria changed from delayed trends to advancing DOYM trends and Shiraz at Banksdale changed from an advancing trend to a delayed DOYM trend when yield was included as a second covariate, but none of these trends either way was significant. Otherwise, although there were some changes in the magnitude of the DOYM trends, the significance and direction of the DOYM trend was relatively unchanged when yield was included in the models, despite there being many instances when the Yield covariate was significantly associated with the DOYM (Table 4 data shown in bold). (*Note*: There may be some differences between the numbers in Tables 2 and 4 just due to the different structure of the mixed models). Dolcetto at Heathcote and Milawa, Pinot Grigio at Banksdale and Montepulciano at Heathcote were the only significant DOYM temporal trends, and these were advancing, when Yield was included in the models.

When Yield was included in the models as a second covariate with the temperature indices, the only notable changes were that the advancing trend of DOYM as a function of Spring Index for Crouchen increased in magnitude to become significant, and the significant advancement DOYM trends for Carmenère (Heathcote) as a function of both $GDD_{Sep–Mar}$ and Spring Index became smaller and non-significant as did the trend for Chenin Blanc (Milawa) as a function of Spring Index. All other trends remained much the same in terms of trend magnitude and significance.

Yield therefore did have a significant positive association with DOYM but when Yield was included in the models the DOYM trends as a function of Vintage Year, $GDD_{Sep–Mar}$ and Spring Index were largely maintained, suggesting that the yield effect on DOYM did not account for the effects of the other covariates. These findings were in the context of a range of average yields across the cultivars and vineyards and many examples where cultivar yield (T/ha) had increased significantly over the time period.

Advancement trends of grapevine cultivars

The data were further analysed for interaction effects between cultivar and the covariates Vintage Year, $GDD_{Sep-Mar}$ or Spring Index to determine whether these DOYM advancement trends identified for the individual cultivars were significantly different. The data set for the mixed model included all cultivars at each vineyard and cultivar was included as a fixed factor in the model and analysed with and without Yield as an additional covariate. Values of P less than 0.05 for the interaction term between cultivar and the covariate Vintage Year, $GDD_{Sep-Mar}$ or Spring Index showed that there were significant differences between those cultivars for the rate of DOYM advancement as a function of the relevant covariate at that vineyard.

Table 5 records these P-values and shows that, as a function of Vintage Year, Mystic Park and Heathcote had significant differences between cultivars in the rate of advancement of DOYM. When Yield was included in these models Mystic Park, Heathcote and Banksdale all had

Table 3. Yield details for cultivars in four vineyards in Victoria and showing rate of change of day of year maturity as a function of Yield, yield trend per year, average yield and number of data points.

Cultivar	Rate of change of DOYM as a function of Yield [days/(T · ha)]	*P*-value	Rate of change of yield as a function of Vintage Year [(T · ha)/year]	*P*-value	Average yield (T/ha)	No. of data points
Banksdale, Victoria 36.67S 146.32E						
Cabernet Sauvignon	1.22 ± 1.02	0.024	−0.11 ± 0.23	0.342	11.01	27
Chardonnay	0.52 ± 0.24	<0.001	0.45 ± 0.29	0.004	15.10	73
Pinot Grigio	0.86 ± 0.42	<0.001	0.57 ± 0.38	0.006	16.49	47
Prosecco	0.71 ± 0.70	0.005	0.99 ± 1.09	0.086	23.52	38
Shiraz†	2.66 ± 2.10	0.018	−0.44 ± 0.45	0.054	10.55	15
Tempranillo†	2.04 ± 2.75	0.127	0.43 ± 0.47	0.069	10.34	12
Milawa, Victoria 36.45S 146.43E						
Cabernet Sauvignon	0.02 ± 0.91	0.954	0.33 ± 0.28	0.024	8.60	27
Chenin Blanc†	1.54 ± 0.61	<0.001	0.02 ± 0.79	0.954	18.79	15
Dolcetto	0.74 ± 1.33	0.079	0.00 ± 0.29	0.973	13.92	28
Graciano	0.03 ± 1.63	0.967	0.14 ± 0.22	0.188	6.34	30
Mondeuse†	4.24 ± 2.80	0.006	−0.25 ± 0.22	0.029	9.12	19
Shiraz	−0.15 ± 0.54	0.572	0.15 ± 0.25	0.229	10.04	41
Gewürtztraminer†	1.90 ± 1.56	0.022	−0.10 ± 0.61	0.742	14.86	15
Heathcote, Victoria, 36.47S 144.78E						
Cabernet Sauvignon	0.84 ± 1.09	0.117	−0.05 ± 0.31	0.710	8.12	28
Carmenère†	−0.24 ± 2.76	0.836	−0.16 ± 0.86	0.665	5.38	8
Dolcetto	1.44 ± 3.23	0.365	0.00 ± 0.34	0.999	10.83	30
Durif	−0.17 ± 1.97	0.852	0.00 ± 0.36	0.995	9.80	21
Malbec	1.23 ± 1.31	0.063	0.22 ± 0.38	0.235	10.51	23
Merlot	−0.07 ± 0.40	0.731	0.39 ± 0.29	0.011	9.07	80
Montepulciano†	1.99 ± 2.27	0.079	0.51 ± 0.83	0.201	14.03	11
Petit Verdot†	−1.03 ± 1.52	0.158	0.35 ± 0.66	0.263	10.34	11
Shiraz	0.66 ± 0.59	0.029	0.16 ± 0.17	0.065	7.63	132
Tempranillo	1.00 ± 0.90	0.031	−0.07 ± 0.41	0.725	6.59	34
Mystic Park, Victoria 35.60S 143.76E						
Cienna	0.24 ± 0.27	0.074	0.36 ± 0.51	0.175	19.69	96
Crouchen	0.55 ± 0.41	0.009	1.02 ± 0.61	0.003	23.46	74
Dolcetto	0.40 ± 1.13	0.466	0.69 ± 0.45	0.005	13.69	37
Flora†	1.21 ± 1.03	0.025	0.50 ± 0.38	0.012	17.42	19
Muscat of Alexandria	0.77 ± 0.56	0.014	2.42 ± 1.42	0.004	35.74	24
Orange Muscat	0.01 ± 0.35	0.957	1.17 ± 0.33	<0.001	18.46	51
Shiraz	0.10 ± 0.84	0.810	0.56 ± 0.20	<0.001	16.20	41
Tarrango	0.19 ± 0.45	0.399	0.83 ± 0.69	0.021	22.46	53

Rate of change DOYM as a function of Yield was determined using mixed models (response: DOYM; random factors: Block and Vintage Year; covariate: Yield) other than those cultivars indicated with a † which were analysed using linear regression with DOYM versus Yield. Rate of change of Yield as a function of Vintage Year was determined using mixed models (response: Yield; random factors: Block and Vintage Year; covariate: Vintage Year) other than those cultivars indicated with a † which were analysed using linear regression with Yield versus Vintage Year. Average yield was the arithmetic average of the individual block yield for each vintage year. DOYM, day of year maturity.

significant differences between cultivars in the rate of advancement of DOYM.

Mystic Park, Milawa and Banksdale had significant differences in the rate of advancement of DOYM between their respective cultivars, both as a function of $GDD_{Sep–Mar}$ and Spring Index, when Yield was not included as a covariate. When Yield was included as a second covariate in the model, the interactions were significant for Mystic Park and Banksdale for the $GDD_{Sep–Mar}$ interaction and for Mystic Park and Milawa for the Spring Index interaction. For the Heathcote vineyard there was no significant difference between those cultivars in their rate of advancement of DOYM against either temperature index, with or without Yield.

Pairwise comparisons of the interaction slopes using Fisher's LSD were done to show the actual difference in DOYM advancement between the cultivars. These cultivar differences are shown in Figure 1 (without Yield). For example, Dolcetto advanced DOYM as a function of Vintage Year significantly more than Malbec at Heathcote. Cienna advanced DOYM significantly more than Orange Muscat or Crouchen at Mystic Park. As a function of both temperature indices, Muscat of Alexandria advanced DOYM significantly more than Orange Muscat or Flora at the Mystic Park vineyard. As a function of both temperature indices, Mondeuse advanced DOYM significantly more than Gewürtztraminer at the Milawa vineyard and Shiraz advanced DOYM significantly more than Pinot Grigio at the Banksdale vineyard.

These differences of rate of change DOYM as a function of the two temperature indices were maintained to a large extent when Yield was included in the models (Figure S1), although as indicated in Table 5 the differences were no longer significant for Banksdale as a function of Spring Index or for Milawa as a function of $GDD_{Sep–Mar}$. The results for rate of change of DOYM as a function of Vintage Year vary more when Yield was included in the models. For example, at Banksdale the inclusion of Yield resulted in Pinot Grigio showing a significant greater advancement DOYM than Shiraz, whereas the non-significant trend without Yield was the opposite of that result. These differences are consistent with the trend changes shown for the individual cultivars in Tables 2 and 4 for Pinot Grigio and Shiraz.

There have been some indications that later ripening cultivars have a higher rate of DOYM advancement than earlier ripening cultivars (Petrie and Sadras 2016), which if

Table 4. Rate of change of day of year maturity as a function of Vintage Year, seasonal Growing Degree Days September to March and Spring Index for individual cultivars at four vineyard sites in Victoria, Australia with Yield included as a covariate in the mixed models.

	Rate of change DOYM as a function of Vintage Year		Rate of change DOYM as a function of $GDD_{Sep–Mar}$		Rate of change DOYM as a function of Spring Index	
Cultivar	Slope ± 95% CI (days/year)	*P*-value	Slope ± 95% CI (days/°C days)	*P*-value	Slope ± 95% CI (days/°C)	*P*-value
Banksdale, Victoria 36.67S 146.32E						
Cabernet Sauvignon	**−0.290 ± 0.940**	0.522	−0.059 ± 0.035	0.002	−0.064 ± 0.046	0.008
Chardonnay	**−0.550 ± 0.965**	0.240	**−0.062 ± 0.024**	<0.001	**−0.076 ± 0.023**	<0.001
Pinot Grigio	**−0.850 ± 0.825**	0.044	**−0.047 ± 0.025**	0.001	**−0.074 ± 0.017**	<0.001
Prosecco	**−0.512 ± 3.135**	0.718	**−0.061 ± 0.061**	0.048	**−0.095 ± 0.034**	<0.001
Shiraz†	**1.200 ± 2.740**	0.351	**−0.054 ± 0.045**	0.024	−0.083 ± 0.075	0.032
Tempranillo†	1.270 ± 1.270	0.291	−0.084 ± 0.053	0.006	−0.090 ± 0.039	0.001
Milawa, Victoria 36.45S 146.43E						
Cabernet Sauvignon	−0.660 ± 1.495	0.355	−0.058 ± 0.034	0.004	−0.068 ± 0.041	0.003
Chenin Blanc†	**−0.598 ± 0.917**	0.174	**−0.030 ± 0.019**	0.006	**−0.024 ± 0.041**	0.222
Dolcetto	−1.060 ± 0.794	0.012	−0.051 ± 0.031	0.003	−0.044 ± 0.038	0.023
Graciano	−1.100 ± 1.380	0.107	−0.053 ± 0.035	0.007	−0.073 ± 0.038	0.001
Mondeuse†	**−0.651 ± 1.388**	0.327	**−0.057 ± 0.047**	0.022	−0.105 ± 0.078	0.013
Shiraz	−0.610 ± 1.465	0.385	−0.061 ± 0.042	0.008	−0.088 ± 0.033	<0.001
Gewürztraminer†	**0.794 ± 0.975**	0.097	−0.031 ± 0.041	0.121	−0.011 ± 0.040	0.546
Heathcote, Victoria 36.47S 144.78E						
Cabernet Sauvignon	−0.833 ± 1.395	0.217	−0.047 ± 0.024	0.001	**−0.062 ± 0.031**	0.001
Carmenère†	−1.465 ± 2.265	0.157	−0.045 ± 0.067	0.143	−0.068 ± 0.122	0.208
Dolcetto	−1.788 ± 1.448	0.020	−0.056 ± 0.030	0.002	−0.066 ± 0.046	0.008
Durif	−0.217 ± 1.875	0.805	−0.044 ± 0.041	0.038	−0.073 ± 0.040	0.002
Malbec	−0.030 ± 1.340	0.963	**−0.041 ± 0.029**	0.009	**−0.070 ± 0.026**	<0.001
Merlot	−0.535 ± 1.215	0.364	−0.046 ± 0.024	0.001	−0.066 ± 0.032	0.001
Montepulciano†	**−2.670 ± 2.450**	0.036	**−0.069 ± 0.034**	0.002	−0.080 ± 0.059	0.014
Petit Verdot†	−0.398 ± 1.634	0.590	−0.023 ± 0.036	0.173	−0.027 ± 0.042	0.174
Shiraz	**−0.950 ± 1.183**	0.107	**−0.047 ± 0.025**	0.001	**−0.065 ± 0.035**	0.001
Tempranillo	**−0.360 ± 1.400**	0.578	**−0.045 ± 0.023**	0.001	**−0.057 ± 0.028**	0.001
Mystic Park, Victoria 35.60S 143.76E						
Cienna	**−1.010 ± 1.750**	0.235	**−0.053 ± 0.038**	0.010	**−0.076 ± 0.041**	0.001
Crouchen	**0.548 ± 1.315**	0.394	**−0.031 ± 0.037**	0.089	**−0.060 ± 0.042**	0.012
Dolcetto	−0.860 ± 2.910	0.531	−0.067 ± 0.045	0.010	−0.075 ± 0.055	0.017
Flora†	**−0.249 ± 1.136**	0.639	**−0.020 ± 0.022**	0.071	−0.035 ± 0.031	0.030
Muscat of Alexandria	**−0.135 ± 8.000**	0.968	**−0.090 ± 0.091**	0.054	**−0.110 ± 0.047**	0.003
Orange Muscat	1.070 ± 1.08	0.052	−0.005 ± 0.036	0.758	−0.015 ± 0.045	0.494
Shiraz	0.576 ± 1.395	0.402	−0.029 ± 0.043	0.167	−0.056 ± 0.050	0.030
Tarrango	0.227 ± 1.225	0.702	−0.027 ± 0.031	0.082	**−0.057 ± 0.034**	0.003

Mixed models were used (response: DOYM from 1 January; random factors: Block and Vintage Year; covariate: Vintage Year or $GDD_{Sep–Mar}$ or Spring Index as appropriate and Yield (T/ha) was a second covariate in all cases). †A general linear model was used (response: DOYM from 1 January; covariates: Vintage Year or $GDD_{Sep–Mar}$ or Spring Index as appropriate and Yield). The results in bold are those for which the Yield covariate was significant ($P < 0.05$). Period of data and the designated maturity (TSS) are shown in Table 2. CI, confidence interval; DOYM, day of year maturity; GDD, growing degree days.

true, goes some way to explain the phenomenon of compression of the harvest period. To investigate this further, mean DOYM was obtained for each cultivar, adjusted for the main covariate (Vintage Year, $GDD_{Sep–Mar}$ or Spring Index) but not Yield. These were graphed against the rates of advancement of DOYM for each cultivar from the interaction models with and without Yield as an additional covariate (Figure 2). Note that the designated maturity TSS varied for different cultivars, so only cultivars with the same designated maturity TSS were included. Figure 2 shows some trends to suggest that later maturing cultivars advanced their DOYM at a faster rate than earlier ripening cultivars as a function of Vintage Year, $GDD_{Sep–Mar}$ and Spring Index, with and without Yield. The interpretation of these trends is unclear and for most vineyards are based on just a few cultivars. Regression analyses for the values used in the graphs give significant negative trends for Mystic Park for both temperature indices with and without Yield, and for Banksdale as a function of $GDD_{Sep–Mar}$, Heathcote as a function of Spring Index and Milawa as a function of Vintage Year, all without Yield. Mystic Park as a function of Vintage Year without Yield has a *P*-value of 0.05. This relationship, however, between rate of advancement of DOYM for early and later ripening cultivars is not necessarily a linear relationship, and it may depend on the temperature conditions and how they change between earlier and later ripening cultivars at each vineyard. Regardless, Figure 2 does suggest a pattern of later ripening cultivars having a faster rate of DOYM advancement.

Vineyard trend differences

The data were explored to identify whether, for the few common cultivars, there were differences in the trends of DOYM between vineyards. The data set for the mixed model included the cultivar at each vineyard and vineyard was included as a fixed factor in the model and analysed with and without Yield as an additional covariate. Values of *P* less than 0.05 (Table 6) for the interaction terms between vineyard and the covariate Vintage Year, $GDD_{Sep–Mar}$ or Spring Index, showed that there were significant differences between those vineyards for the rate of change of DOYM advancement as a function of the relevant covariate

Table 5. *P*-values for the interaction terms between Cultivar and Vintage Year, seasonal Growing Degree Days September to March and Spring Index for four vineyards in Victoria, Australia.

		Covariate * Cultivar interaction *P*-values					
		Vintage		$GDD_{Sep–Mar}$		Spring Index	
Vineyard	**Cultivars**	**No yield**	**Yield**	**No yield**	**Yield**	**No yield**	**Yield**
Banksdale	Cabernet Sauvignon, Chardonnay, Pinot Grigio, Prosecco, Shiraz, Tempranillo	0.340	0.016	0.004	0.001	0.010	0.098
Milawa	Cabernet Sauvignon, Chenin Blanc, Dolcetto, Graciano, Mondeuse, Shiraz, Gewürztraminer	0.089	0.191	0.022	0.266	<0.001	0.014
Heathcote	Cabernet Sauvignon, Carmenère, Dolcetto, Durif, Malbec, Merlot, Montepulciano, Petit Verdot, Shiraz, Tempranillo	0.010	<0.001	0.509	0.762	0.798	0.915
Mystic Park	Cienna, Crouchen, Dolcetto, Flora, Muscat of Alexandria, Orange Muscat, Shiraz, Tarrango	<0.001	<0.001	0.009	0.022	0.002	0.004

Mixed models fitted were (response: DOYM from 1 January; random factors: Block and Vintage Year; fixed factors: Cultivar; covariates: Vintage Year, seasonal Growing Degree Day ($GDD_{Sep–Mar}$) or Spring Index with and without Yield included as a second covariate). The interaction terms included were Vintage Year * Cultivar and Yield * Cultivar (if applicable), $GDD_{Sep–Mar}$ * Cultivar and Yield * Cultivar (if applicable) or Spring Index * Cultivar and Yield * Cultivar (if applicable)). $P < 0.05$ for the interaction term indicates there was a significant difference between the cultivars and their rate of change of day of year maturity at that vineyard relative to the covariate. DOYM, day of year maturity.

at that vineyard. Table 6 shows that there were significant differences for the rate of change of DOYM for Shiraz between the four vineyards as a function of all covariates, with and without Yield. There were also significant differences for Cabernet Sauvignon (Banksdale, Milawa and Heathcote) as a function of Vintage Year (without Yield) and $GDD_{Sep–Mar}$ (with and without Yield) and for Tempranillo (Banksdale and Heathcote) as a function of Vintage Year and Spring Index (without Yield) and $GDD_{Sep–Mar}$ (with Yield). There were no significant differences for the rate of change of DOYM for Dolcetto between vineyards.

The actual differences between vineyards for rate of change DOYM are shown in Figure 3 (without Yield). One

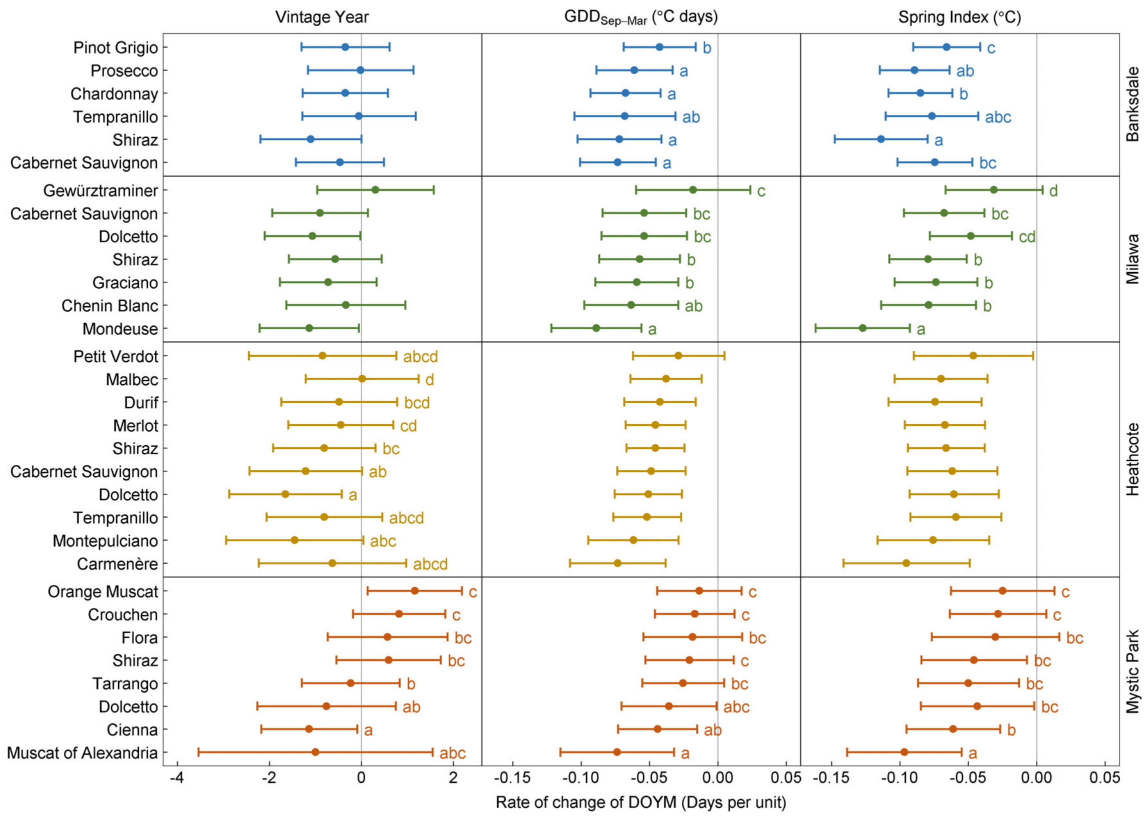

Figure 1. Comparison of rate of change of day of year maturity (DOYM) between cultivars as a function of the covariates Vintage Year, seasonal Growing Degree Day ($GDD_{Sep–Mar}$) and Spring Index with interaction terms. Mixed models fitted were response: DOYM from 1 January; random factors: Block and Vintage Year; fixed factor: Cultivar, covariate: Vintage Year, $GDD_{Sep–Mar}$ or Spring Index. Interaction terms were Vintage Year * Cultivar, $GDD_{Sep–Mar}$ * Cultivar or Spring Index * Cultivar as appropriate. The vineyards are: Banksdale (——), Milawa (——), Heathcote (——) and Mystic Park (——). Rate of change of DOYM values were separated with pairwise comparisons using Fisher's LSD test. Rate of change of DOYM values that do not share a letter are significantly different and indicate therefore that the cultivars have advanced DOYM differently as a function of the covariate for that vineyard. The error bars show 95% confidence intervals. Vineyards that show no letters for the cultivars indicate there were no significant differences for rate of change of DOYM between those cultivars at that vineyard. The *P*-values for these comparisons are shown in Table 5. Yield is not included in these models.

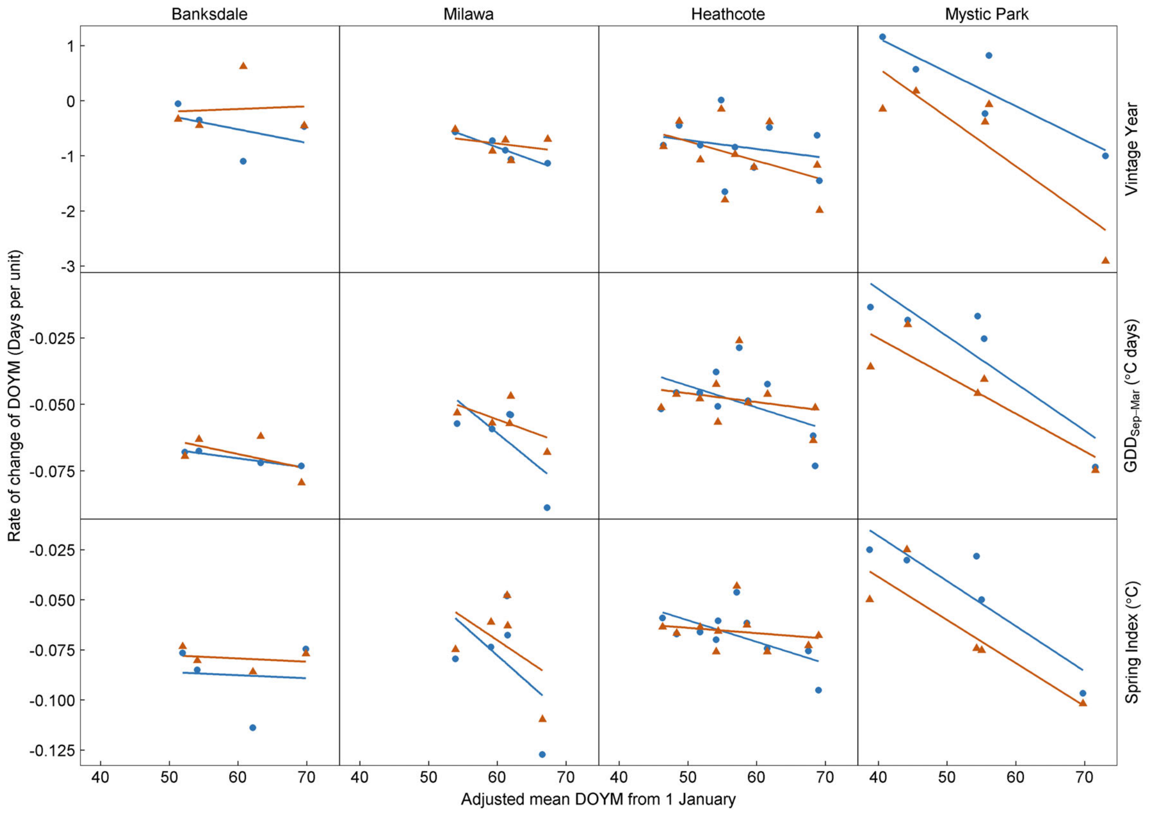

Figure 2. Relationship between the adjusted mean day of year maturity (DOYM) and rate of change of DOYM as a function of Vintage Year, seasonal Growing Degree Day ($GDD_{Sep–Mar}$) and Spring Index by vineyard, with Yield (——) and without Yield (——) included. The cultivars included in these graphs have the same designated maturity TSS; 12°Bé for Banksdale, Milawa and Heathcote and 11°Bé for Mystic Park (see Table 2 for cultivar details). Each data point represents a different cultivar. Rates of change DOYM values come from Figure 1 and adjusted mean DOYM values were determined from the same interaction models that were used to derive those rates.

might have expected that for the temporal trend, the rate of change of DOYM would be larger at the warmer sites, but this varied between cultivars. This was the case for Cabernet Sauvignon. Tempranillo showed a delayed DOYM at Banksdale, the cooler vineyard, yet Shiraz showed a delayed DOYM at Mystic Park.

Interestingly, there was a general trend that at the cooler vineyard, Banksdale, the rate of change of DOYM as a function of the temperature indices was greater than that at the warmer vineyard. This was significant for Shiraz as a function of both temperature indices and for Cabernet Sauvignon as a function of $GDD_{Sep–Mar}$ and Tempranillo as a function of Spring Index. These trends are despite or perhaps due to the cooler vineyard having a smaller increase in the temperature index over the time period (Table 1).

When Yield was included in these models (Figure S2), the main change was for Shiraz at Banksdale, which changed its rate of change of DOYM as a function of Vintage Year from advancing 1.49 days/year to being delayed 1.42 days/year. Otherwise the direction of trends was much the same with and without Yield except that the difference for rate of change of DOYM for Tempranillo at Banksdale and Heathcote as a function of Vintage Year and Spring Index was no longer significant, but as a function of $GDD_{Sep–Mar}$ was significant. The *P*-value for the Cabernet Sauvignon Vintage

Table 6. The *P*-values for the interaction terms between Vineyard and Vintage Year, seasonal Growing Degree Days September to March and Spring Index for the cultivars Shiraz, Dolcetto, Cabernet Sauvignon and Tempranillo that were common to two or more of the four vineyards located in Victoria, Australia.

		Covariate * Vineyard interaction *P*-values					
		Vintage		$GDD_{Sep–Mar}$		Spring Index	
Cultivar	**Vineyards**	**No yield**	**Yield**	**No yield**	**Yield**	**No yield**	**Yield**
Shiraz	Banksdale, Milawa, Heathcote, Mystic Park	<0.001	<0.001	<0.001	0.020	<0.001	0.034
Dolcetto	Milawa, Heathcote, Mystic Park	0.597	0.187	0.100	0.135	0.135	0.120
Cabernet Sauvignon	Banksdale, Milawa, Heathcote	0.021	0.051	0.006	0.022	0.061	0.138
Tempranillo	Banksdale, Heathcote	0.008	0.268	0.088	0.039	0.043	0.069

Mixed models fitted were response: DOYM from 1 January; random factors: Block and Vintage year; fixed factor: Vineyard; covariates: Vintage Year, $GDD_{Sep–Mar}$ or Spring Index with and without Yield included as a second covariate. The interaction terms included were Vintage Year * Vineyard and Yield * Vineyard (if applicable), $GDD_{Sep–Mar}$ * Vineyard and Yield * Vineyard (if applicable) or Spring Index * Vineyard and Yield * Vineyard (if applicable). $P < 0.05$ for the interaction term indicates there were statistically significant differences between the vineyards and their rate of change of day of year maturity for that cultivar, relative to the covariate. GDD, seasonal growing degree day.

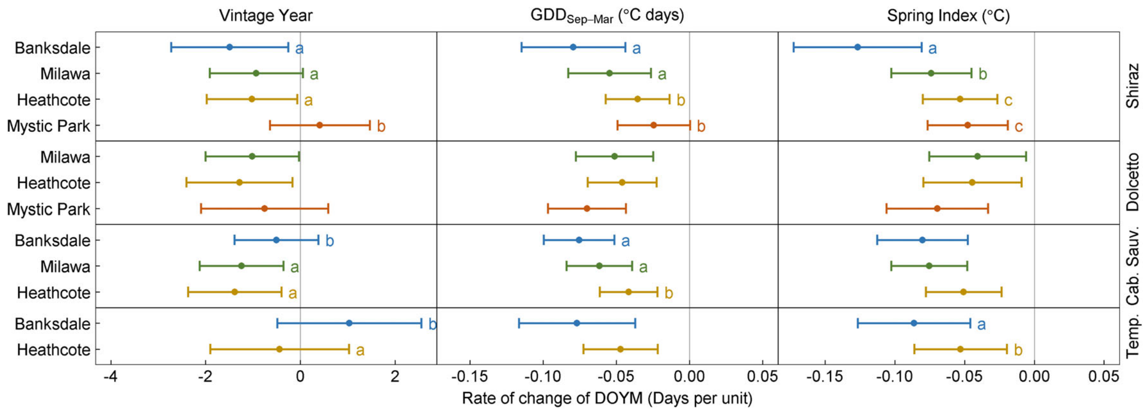

Figure 3. Comparison of rate of change of day of year maturity (DOYM) between vineyards as a function of the covariates Vintage Year, seasonal Growing Degree Day ($GDD_{Sep–Mar}$) and Spring Index with interaction terms. These comparisons were done for each cultivar that was common to the vineyards, that is Shiraz, Dolcetto, Cabernet Sauvignon and Tempranillo. Mixed models fitted were response: DOYM from 1 January; random factors: Block and Vintage Year; fixed factor: Vineyard; covariates: Vintage Year, $GDD_{Sep–Mar}$ or Spring Index and the interactions Vintage Year, $GDD_{Sep–Mar}$ or Spring Index * Vineyard as appropriate. The vineyards were: Banksdale (——), Milawa (——), Heathcote (——), and Mystic Park (——). Rate of change of DOYM values was separated with pairwise comparisons using Fisher's LSD test. Different letters for the rate of change of DOYM indicate that the rate of advancement for the cultivar was different between the vineyards. The error bars show 95% confidence intervals. Cultivars that show no letters for the vineyards indicate there were no significant differences in the rate of change of DOYM between those vineyards for that cultivar. The *P*-values for these comparisons are shown in Table 6. Yield is not included in these models.

Year relationship also changed from 0.021 to 0.051, meaning that the difference in rate of change of DOYM for Cabernet Sauvignon was no longer significant between those vineyards.

Discussion

This research used a data set that consisted of 23 grape cultivars planted in four climatically different vineyard regions in Victoria, Australia to examine DOYM trends against four covariates, Vintage Year, $GDD_{Sep–Mar,}$ Spring Index and Yield and to investigate whether different cultivars and/or vineyards were advancing their DOYM at different rates, and whether changes in the rate of DOYM advancement were related to the time of ripening. It should be noted that while these four vineyards studied here did not capture the full range of climates across Australian viticultural regions, they do represent a substantial range within the Australian context.

Vineyard temperature trends

All four vineyards had increasing trends for $GDD_{Sep–Mar}$ and spring index over the time period examined here, 1999–2018. The temperature trends found here were consistent with increasing growing season temperature trends shown by Webb et al. (2011) for all but one Australian viticultural region studied, and with general warming trends shown in Eastern Australia (Jones et al. 1990). Temperature index increases were more pronounced and significant ($P < 0.05$) at the warmer vineyards, Mystic Park, Heathcote and Milawa for $GDD_{Sep–Mar}$ and for Mystic Park and Heathcote for the spring index trends (Table 1). At the cooler Banksdale vineyard, although $GDD_{Sep–Mar}$ and spring index increased during this time period, these increases were not as great and were not significant. While the time period covered by the data here was relatively short in climate terms, and this exact trend of temperature index increase may vary over the next 20 years, data from the seasons studied here will inform future projections of climate change and warming.

Individual cultivar DOYM temporal trends

As might be expected for this relatively short time frame, where it is possible that a few outlier points might skew an underlying trend (Petrie and Sadras 2008), there were few significant results for the trends of DOYM for individual cultivars as a function of Vintage Year and these were found to be both advancing and receding. Dolcetto at both Heathcote and Milawa showed significant DOYM advancement trends with and without Yield included as did Pinot Grigio at Banksdale and Montepulciano at Heathcote when Yield was included in the model. The advancement of Dolcetto was 1.79–1.72 days/year at Heathcote (with and without Yield) and 1.06–1.10 days/year advancement at Milawa (with and without Yield, respectively). In contrast, at the warmer site Mystic Park, Dolcetto only advanced between 0.86 and 0.47 days/year (with and without Yield included) and neither of those advancing trends were significant. The advancement of DOYM for Dolcetto as a function of both temperature indices at all three vineyards was significant and these temporal and temperature association observations show that Dolcetto was responsive to the changing temperature conditions. This contrasts with Orange Muscat, a cultivar which has not appeared in previous published research on this topic, which showed a significant delayed DOYM temporal trend. This trend became non-significant ($P = 0.052$) when Yield was included in the model. This trend towards a later DOYM was despite the Mystic Park vineyard having significant increasing trends for both $GDD_{Sep–Mar}$ and spring index during the time period for Orange Muscat in the study, 1999–2018. Nor did Orange Muscat show any evidence for an advancement of DOYM as a function of either temperature index with or without Yield. It appears notable too that, six out of eight cultivars at Mystic Park had delayed DOYM trends (Table 2 – only Orange Muscat significant) and that none of those six cultivars with delayed trends had a significant association between DOYM and $GDD_{Sep–Mar}$ (Table 2). Gewürztraminer at Milawa also showed a delayed temporal trend and had no significant change of DOYM as a function of either temperature index (with or without Yield) indicating a lack of responsiveness to temperature for this cultivar.

The temporal advancement trends found here were of similar magnitudes as reported by previous research (Petrie and Sadras 2008, Webb et al. 2011) but these delayed

DOYM temporal trends have not previously been described. Webb et al. (2011) identified one trend towards a later DOYM for Cabernet Sauvignon in Margaret River, Australia, however, that trend was not significant, nor was there any warming trend observed for that region. The delayed DOYM temporal trends shown in this study were despite significant warming trends at the Mystic Park vineyard.

Studies of the effect of heat on berry sugar accumulation have been conducted using a range of techniques (greenhouse, growth chamber and in field), temperature and cultivars (Bonada and Sadras 2015). These studies have given variable results. Kriedemann (1968) demonstrated that the optimum temperature for photosynthesis for Sultana vines was 25°C for glasshouse-grown vine leaves and 30°C for fully exposed leaves, declining rapidly above 35°C falling to zero between 45 and 50°C. In a controlled environment, Greer and Weston (2010) found that berries stopped ripening in Sémillon vines that were heat treated (40/25°C day night temperature) for 4 days during veraison or mid ripening and proposed this was due to a decreased supply of carbon to the berry. In field experiments using polyethylene sleeves, applied during the spring period, to increase ambient temperature with Merlot vines, fruit maturation advanced 7–26 days, site dependent (Bowen et al. 2004). In other field experiments, Soar et al. (2009) found that extreme heat treatments of ~40°C for 3 days during four phenological stages including veraison and pre-harvest, did not affect sugar accumulation for Shiraz. Only a temperature above 42°C in one post-set period was found to reduce sugar accumulation. These varying results may reflect the difference in experimental method – controlled versus field experiments, timing of heat application and the actual temperature used in the studies but may also be due to differences in response by the cultivars being studied. Certainly, the contrasting Dolcetto and Orange Muscat results here point to cultivar diversity with respect to rate of change of DOYM in response to temperature. In addition, the contrasting results for Dolcetto between vineyards, moving from a larger significant DOYM temporal advancement at Heathcote and Milawa to a smaller non-significant temporal DOYM advancement trend at the warmer Mystic Park vineyard suggest the potential for some phenotypic differences (although note these differences were not found to be significantly different for the data set). In addition, the differences found between vineyards with other common cultivars at each vineyard, suggest some phenotypic differences between cultivars because of temperature. As these differences appear to result in the vine being less responsive in the warmer environment, it suggests that the rate of DOYM advancement, in response to temperature may slow, as temperature at a given site continues to increase and as the cultivar matures in a warmer, earlier part of the year.

Trends of DOYM for temperature index and individual cultivars

The advantage of analysing DOYM trends directly with a temperature index is that it provides some additional insight as to how cultivars might change in future climate projections or how a cultivar might respond in a new location.

For this data set, all cultivars at all locations showed an advancing trend of DOYM when this was assessed against the temperature indices $GDD_{Sep–Mar}$ and spring index. These trends were significant, for all cultivars at Heathcote (except Petit Verdot), Milawa (except Gewürztraminer) and at Banksdale with the significant results ranging from 0.035 (Heathcote Malbec) to 0.091 (Banksdale Tempranillo) days advancement as a function of $GDD_{Sep–Mar}$ unit and from 0.048 (Milawa Dolcetto) to 0.120 (Milawa Mondeuse) days advancement as a function of Spring Index for those three vineyards. The lack of significance for Petit Verdot and Gewürztraminer could be because of data being available for a shorter time period, both having been removed from their respective vineyards in 2013. Chenin Blanc at Milawa, however, also removed in 2013, had a larger, significant rate of advancement of DOYM as a function of both temperature indices which suggests that in fact Petit Verdot and Gewürztraminer were less responsive to the influence of warming temperature.

In contrast, at Mystic Park, only two cultivars, Cienna and Dolcetto, had significant advancing trends against $GDD_{Sep–Mar}$ (Table 2). When the Spring Index was used as the covariate (Table 2), although most of the cultivars had significant advancing DOYM trends (e.g. Muscat of Alexandria 0.121 days as a function of Spring Index unit) there was no evidence for a change in DOYM for Crouchen or Orange Muscat as a function of Spring Index, despite associated increasing spring index trends for that vineyard.

While these values of rate of change of DOYM as a function of temperature index might appear to be small, if Mystic Park has a trend line of warming at a rate of 10.15 spring index °C/year (Table 1), a value of 0.121 (Mystic Park Muscat of Alexandria) days per spring index °C equates to a DOYM advancement of 1.2 days/year, which is of practical significance.

These results for individual cultivar DOYM trends show both advancing and delayed DOYM trends and a lack of evidence of DOYM advancement as a function of temperature index for some cultivars. This points to differences between cultivars and their response to increasing temperature. Gewürztraminer at Milawa and Crouchen and Orange Muscat at Mystic Park do not appear to have responded to the same extent to the warming temperature trends with delayed DOYM temporal trends and no significant association of DOYM advancement with either temperature index. Petit Verdot at Heathcote had an advancing DOYM temporal trend but had no significant temperature index DOYM trend. These trends were despite increasing temperature index trends at all three vineyards. Dolcetto was responsive to temperature changes both temporally and when measured as a function of temperature index. Although Muscat of Alexandria had variable non-significant DOYM temporal trends with large confidence intervals (the Muscat of Alexandria data covered a shorter time period) the DOYM advancement trends for Muscat of Alexandria measured as a function of the temperature indices were significant and were larger than other cultivars at the same vineyard.

Yield

It has been suggested that larger yields are associated with later DOYM (Wolf et al. 2003, Pearce and Coombe 2004) and similarly Webb et al. (2012) attributed some of the DOYM advancement trend to decreasing yields. When associations between yield and DOYM were considered on an individual cultivar basis, there were found to be positive relationships between yield and DOYM in 26 out of the 31 cases, 13 of which were significant (Table 3). When the relationship between yield and DOYM was investigated by incorporating Yield as a second covariate into the models, although there were several cases where Yield had a significant association with DOYM (these are shown in bold in Table 4), the inclusion of Yield did not markedly or consistently change the degree nor the significance of the trends, despite there being a range of yield increases over the time period and a range of average yields (Table 3). This suggests therefore that although yield can significantly influence the DOYM, the effect of the primary covariates of interest (Vintage Year, $GDD_{Sep–Mar}$ or Spring Index) was maintained when controlling for Yield. Petrie and Sadras (2008) were not able to show a link between yield and maturity. Links between yield and maturity have been demonstrated experimentally by Hannam et al. (2015) who showed that crop thinning could be used to hasten ripening, although this was more successful when the un-thinned vines carried a higher yield. As early as 1954 Winkler (1954) linked overcropping with a delay in maturity in California vineyards, however, it is not surprising that in commercial vineyards such as this and those of Petrie and Sadras (2008), that yield is not always significantly associated with DOYM. Unlike the experimental or overcropping situations, usually when yields (a strong sink) are increased in these commercial vineyards, other factors are increased to support the higher yield, such as canopy size (the source), water or fertiliser application.

Cultivar DOYM trend differences at a given vineyard site

Interaction effects in the mixed models provided insight as to whether the apparent differences in the rates of DOYM advancement for individual cultivars discussed above were in fact significantly different. Any significant differences in the rate of advancement between cultivars at the same vineyard or in fact between vineyards gives additional evidence for the diversity provided by different cultivars and a further explanation for compression of the harvest period.

Out of the 24 analyses comparing cultivars at each vineyard, (Table 5), 15 showed significant cultivar differences in the DOYM advancement. Mystic Park showed significant differences in the rate of change of DOYM as a function of Vintage Year, $GDD_{Sep–Mar}$ and Spring Index, between the cultivars, with and without Yield included in the model. Heathcote showed significant differences between cultivars as a function of Vintage Year, with and without Yield, but not as a function of the temperature indices. The cultivars at Milawa had significant differences as a function of Spring Index (with and without Yield) and as a function of $GDD_{Sep–Mar}$ without Yield. The differences between cultivars at Banksdale were significantly different for all interactions except as a function of Vintage Year (no Yield) and Spring Index (with Yield) (Table 5).

Evidence for differences between cultivars in their rate of advancement was also observed by Petrie and Sadras (2008) who showed apparent 'environment-by-cultivar interactions', although these were not quantified in the same way as in this study. These differences between cultivars found here also support the work by Ruml et al. (2016) who showed, in a long term study (1986–2011) in Serbia, that different cultivars had different degrees of advancement for harvest [harvest in their study, however, was defined as stage 89 'berries ripe for harvest' on the BBCH scale (Lorenz et al. 1995) which, as already discussed, is a subjective decision, in contrast to the DOYM metric, used in this study].

The relationship between mean DOYM and rate of DOYM advancement (Figure 2) provided some evidence that later ripening cultivars advanced their DOYM at a faster rate, as a function of the three covariates Vintage Year and the two temperature indices, than the earlier ripening cultivars. This result indicating that later ripening cultivars have a higher rate of DOYM advancement than earlier ripening cultivars is in contrast to that found by Tomasi et al. (2011) who showed that early maturing cultivars changed their DOYM at a slightly higher rate. Their data covered a much longer period from 1964 to 2009, in Veneto, Italy, from a large collection of cultivars that included Italian and internationally recognised cultivars. Their contrasting result could be influenced by the longer and not as recent time frame, by the different cultivar mix and by the different climate. It was not clear for the Tomasi et al. (2011) study how their analysis was carried out. The trend found here supports Petrie and Sadras (2016) who found that the later ripening Cabernet Sauvignon had advanced DOYM more rapidly than Chardonnay per year. To further substantiate a trend of later ripening cultivars advancing their DOYM more rapidly than earlier ripening cultivars in response to temperature, more cultivars may be needed at each vineyard with a wider range of DOYM.

Differences between vineyards

The significant difference in the rate of advancement of DOYM when comparing the cultivars that were common to different vineyards has not been reported previously. As a function of Vintage Year, Shiraz advanced significantly more at the cooler Banksdale vineyard than at the warmer Mystic Park vineyard, where it was delayed. Cabernet Sauvignon and Tempranillo, however, advanced significantly less at Banksdale than at the warmer Heathcote site (in fact Tempranillo had a delayed DOYM at Banksdale in this model).

As a function of the temperature indices, Shiraz, Cabernet Sauvignon and Tempranillo had a greater advancement of DOYM at the cooler Banksdale vineyard than at the warmer Heathcote and Mystic Park sites (significant for Shiraz and Cabernet Sauvignon as a function of $GDD_{Sep–Mar}$ and Shiraz and Tempranillo as a function of Spring Index). This is despite there being a smaller relative increase in the temperature indices at Banksdale. This may appear counter intuitive because in general one might expect a warmer temperature to hasten the advancement of maturity. If the cultivar, however, is growing in an optimal temperature range at the cooler site it can be more responsive to the warming temperature, whereas at the warmer sites, the temperature may be more often beyond the optimum range for the cultivar, and indeed above 35°C, found by Kriedemann (1968) to inhibit photosynthesis. These vines growing more often outside their optimum temperature range would therefore be less responsive to the temperature. This result further supports the hypothesis that the advancement of DOYM seen to date may slow as cultivars and vineyards reach a temperature at which they can no longer respond to the same degree and where increasing temperature may lead to a slowing advancement of maturity or even perhaps a delayed maturity.

Compression of the harvest period

Early references to the potential for compression of the harvest period were made by Webb et al. (2007) and the problems of compression of the harvest period were, in 2016, one of the most reported vintage problems through The Australian Wine Research Institute help desk (Coulter et al. 2016). Despite this, it has been difficult to clearly demonstrate the phenomenon of compression of the harvest

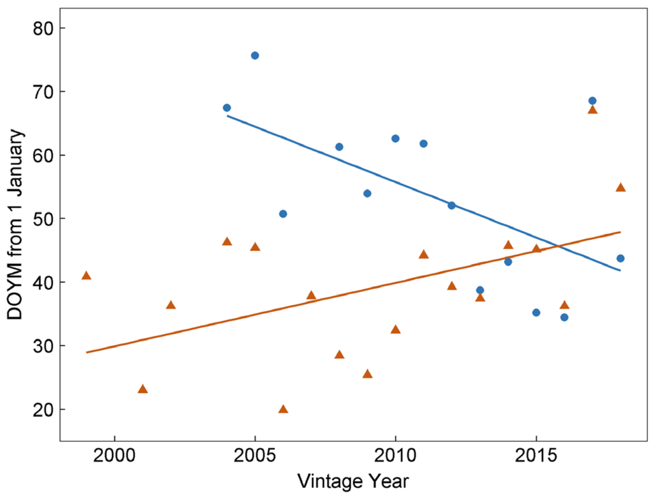

Figure 4. An example of the potential for compression of the harvest period. Day of year maturity (DOYM) from 1 January versus Vintage Year using linear regression. Dolcetto at Heathcote (——) (slope = –1.74, $r^2 = 0.36$, $P = 0.024$) and Orange Muscat at Mystic Park (——) (slope = 1.00, $r^2 = 0.25$, $P = 0.035$). The DOYM has changed from being about 30 days apart to now coinciding.

period. Petrie and Sadras (2016) presented evidence for compression showing that later ripening cultivars were advancing at a more rapid rate than earlier cultivars and Jarvis et al. (2019) showed variable evidence for compression by comparing a reference cultivar with other cultivars to determine a harvest date anomaly, and from these anomalies, determining compression trends.

This research has provided explanations for the phenomenon of compression of the harvest period. First, it has shown that different cultivars at the same vineyard have advanced DOYM at significantly different rates. Furthermore, some cultivars are not advancing, rather, showing a delayed DOYM. Figure 4 illustrates this aspect of compression of the harvest period using data from two cultivars used in this study, Dolcetto at Heathcote which had an advanced temporal DOYM and Orange Muscat which had a delayed DOYM trend, and shows that the two cultivars have changed, over a period of about 10 years, from being about 30 days apart in terms of DOYM to now coinciding. This study also showed that different vineyards had different rates of DOYM advancement for a given cultivar, with the warmer vineyards having a slower rate of DOYM advancement as a function of temperature index. There was also evidence that later ripening cultivars had a more rapid rate of DOYM advancement than earlier ripening cultivars. These different observations combine and point to the potential for a changing ripening pattern for individual cultivars and vineyards and shows that the experience of compression of the harvest period will depend on the cultivar mix and the region (Webb et al. 2011, Jarvis et al. 2019) and the season, as well as any viticultural practices or adaptation strategies that are put in place by vineyards to delay maturity, such as double pruning (Palliotto et al. 2017) or delayed pruning (Petrie et al. 2017).

Conclusion

Historical data collected by wineries allows the study of the grapevine response to a changing climate. For the 20 year period 1999–2018 there was a range of both advancing and delayed DOYM trends but there had been significant temporal advances of DOYM for Dolcetto at two vineyards and evidence of a delayed DOYM trend for Orange Muscat. All cultivars showed a DOYM advancement trend at the Heathcote, Milawa and Banksdale vineyards as a function of both temperature indices $GDD_{Sep–Mar}$ and the Spring Index (21 out of 23 were significant). At the warmest vineyard site, Mystic Park, although all cultivars showed an advancement trend of DOYM as a function of temperature index, only two of eight cultivars were significant for DOYM trend as a function of $GDD_{Sep–Mar}$ (four out of eight for $GDD_{Sep–Jan}$ data not shown) and six out of eight as a function of Spring Index. This suggests that at this warmest site the cultivars are less responsive overall to the temperature increases. Although yield may have a significant effect on DOYM with higher yields sometimes associated with a delayed DOYM, these effects did not account for the effects of other covariates. It was found that at three of the four vineyards, the cultivars advanced DOYM at significantly different rates as a function of the temperature index (without Yield). Two of the four vineyards had significantly different rates of advancement of DOYM between cultivars as a function of Vintage Year (without Yield). Later ripening cultivars advanced faster than earlier ripening cultivars. There were differences in the rate of DOYM advancement for the same cultivars at different vineyards, with the advancement as a function of temperature index being slower at the warmer vineyards. This showed that the advancement of DOYM may slow as temperature further increases and raises the possibility that the response may vary between cultivars. The differences in DOYM advancement both as temporal trends and as a function of a temperature index suggests that there is some degree of cultivar diversity that might be important to any adaptation strategies for climate change. Further research with more cultivars from other regions is needed to further understand the cultivar diversity available to adapt to climate change, the understanding of which will enable future planting and management decisions.

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References

Amerine, M. and Winkler, A. (1944) Composition and quality of musts and wines of California grapes. California Agriculture **15**, 493–675.

Bonada, M. and Sadras, V.O. (2015) Review: critical appraisal of methods to investigate the effect of temperature on grapevine berry composition. Australian Journal of Grape and Wine Research **21**, 1–17.

Bowen, P.A., Bogdanoff, C.P. and Estergaard, B. (2004) Impacts of using polyethylene sleeves and wavelength-selective mulch in vineyards. II. Effects on growth, leaf gas exchange, yield components and fruit quality of *Vitis vinifera* cv. Merlot. Canadian Journal of Plant Science **84**, 555–568.

Coulter, A., Cowey, G., Petrie, P., Essling, M., Holdstock, M., Stockley, C., Simos, C. and Johnson, D. (2016) Vintage 2016 – observations from the AWRI helpdesk. Wine & Viticulture Journal **31**(**4**), 43–45.

Duchêne, E.H. and Schneider, C. (2005) Grapevine and climatic changes: a glance at the situation in Alsace. Agronomy for Sustainable Development **25**, 93–99.

Dunn, G.M. (2010) Yield forecasting fact sheet (Grape and Wine Research and Development Corporation: Adelaide, SA, Australia).

Greer, D.H. and Weston, C. (2010) Heat stress affects flowering, berry growth, sugar accumulation and photosynthesis of *Vitis vinifera* cv. Semillon grapevines grown in a controlled environment. Functional Plant Biology **37**, 206–214.

Hamilton, R.P. and Coombe, B.G. (1992) Harvesting of winegrapes. Coombe, B.G. and Dry, P.R., eds. Viticulture. Practices Volume 2 (Winetitles: Adelaide, SA, Australia) pp. 302–327.

Hannam, K.D., Neilsen, G.H., Neilsen, D. and Bowen, P. (2015) Cluster thinning as a tool to hasten ripening of wine grapes in the Okanagan Valley, British Columbia. Canadian Journal of Plant Science **95**, 103–113.

Jarvis, C., Barlow, E.W.R., Darbyshire, R., Eckard, R. and Goodwin, I. (2017) Relationship between viticultural climatic indices and grape maturity in Australia. International Journal of Biometeorology **61**, 1849–1862.

Jarvis, C., Darbyshire, R., Goodwin, I., Barlow, E.W.R. and Eckard, R. (2019) Advancement of winegrape maturity continuing for winegrowing regions in Australia with variable evidence of compression of the harvest period. Australian Journal of Grape and Wine Research **25**, 101–108.

Jeffrey, S.J., Carter, J.O., Moodie, K.B. and Beswick, A.R. (2001) Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environmental Modelling and Software **16**, 309–330.

Jones, G.V. and Davis, R.E. (2000) Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. American Journal of Enology and Viticulture **51**, 249–261.

Jones, P.D., Groisman, P.Y., Couglan, M., Plummer, N., Wang, W.-C. and Karl, T.R. (1990) Assessment of urbanizations effects in time series of surface air temperature over land. Nature **347**, 169–172.

Jones, G.V., Duchêne, E., Tomasi, D., Yuste, J., Braslavska, O., Schultz, H., Martinez, C., Boso, S., Langellier, F., Perruchot, C. and Guimberteau, G. (2005) Changes in European winegrape phenology and relationships with climate. Proceedings of the XIV international GESCO viticulture congress; 23–27 August 2005; Geisenheim, Germany (Groupe d'Etude des Systemes de Conduite de la Vigne (GESCO): Geisenheim, Germany) pp. 54–61.

Kriedemann, P.E. (1968) Photosynthesis in vine leaves as a function of light intensity, temperature and leaf age. Vitis **7**, 213–220.

Lorenz, D.H., Eichhorn, K.W., Bleiholder, H., Klose, R., Meier, U. and Weber, E. (1995) Growth stages of the grapevine. Phenological growth stages of the grapevine (*Vitis vinifera* L. ssp. *vinifera*) – codes and descriptions according to the extended BBCH scale. Australian Journal of Grape and Wine Research **1**, 100–103.

Menzel, A., Sparks, T.H., Estrella, N., Koch, E., Aasa, A., Ahas, R., Alm-Kübler, K., Bissolli, P., Braslavská, O.G., Briede, A., Chmielewski, F.M., Crepinsek, Z., Curnel, Y., Dahl, Å., Defila, C., Donnelly, A., Filella, Y., Jatczak, K., Måge, F., Mestre, A., Nordli, Ø., Peñuela, J., Pirinen, P., Remišová, V., Scheifinger, H., Striz, M., Susnik, A., Van Vliet, A.J.H., Wielgolaski, F.-E., Zach, S. and Zust, A.N.A. (2006) European phenological response to climate change matches the warming pattern. Global Change Biology **12**, 1969–1976.

Mira De Ordña, R. (2010) Climate change associated effects on grape and wine quality and production. Food Research International **43**, 1844–1855.

Moncur, M.W., Rattigan, K., Mackenzie, D.H. and Mcintyre, G.N. (1989) Base temperatures for budbreak and leaf appearance of grapevines. American Journal of Enology and Viticulture **40**, 21–26.

Nader, K.B., Stoll, M., Rauhut, D., Patz, C., Jung, R., Loehnertz, O., Schulktz, H.R., Hilbert, G., Renaud, C., Roby, J.-P., Delrot, S. and Gomes, E. (2019) Impact of grapevine age on water status and productivity of *Vitis vinifera* L. cv. Riesling. European Journal of Agronomy **104**, 1–12.

Nendel, C. (2010) Grapevine bud break prediction for cool winter climates. International Journal of Biometeorology **54**, 231–241.

Palliotto, A., Frioni, T., Tombesi, S., Sabbatini, P., Guillermo Cruz-Castillo, J., Lanari, V., Silvestroni, O., Gatti, M. and Poni, S. (2017) Double-pruning grapevines as a management tool to delay berry ripening and control yield. American Journal of Enology and Viticulture **68**, 412–421.

Parker, A.K., De Cortázar-Atauri, I.G., Van Leeuwen, C. and Chuine, I. (2011) General phenological model to characterise the timing of flowering and veraison of *Vitis vinifera* L. Australian Journal of Grape and Wine Research **17**, 206–216.

Pearce, I.-C. and Coombe, B.G. (2004) Grapevine phenology. Dry, P.R. and Coombe, B.G., eds. Viticulture. Resources. 2d ed. (Winetitles: Adelaide, SA, Australia) pp. 150–166.

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

Petrie, P.R. and Sadras, V.O. (2016) Quantifying the advancement and compression of vintage. Australlian & New Zealand Grapegrower & Winemaker (**628**), 40–41.

Petrie, P.R., Brooke, S.J., Moran, M.A. and Sadras, V.O. (2017) Pruning after budburst to delay and spread grape maturity. Australian Journal of Grape and Wine Research **23**, 378–389.

Pouget, R. (1968) Nouvelle conception du seuil de crissance chex la vigne. Vitis **7**, 201–205.

Ruml, M., Korac, N., Vujadinovic, M., Vukovic, A. and Ivanisevic, D. (2016) Response of grapevine phenology to recent temperature change and variablility in the wine producing area of Sremski Karlovci, Serbia. Journal of Agricultural Science **154**, 186–206.

Sadras, V.O. and Petrie, P.R. (2011) Climate shifts in south-eastern Australia: early maturity of Chardonnay, Shiraz and Cabernet Sauvignon is associated with early onset rather than faster ripening. Australian Journal of Grape and Wine Research **17**, 199–205.

Sadras, V.O., Moran, M.A. and Bonada, M. (2013) Effects of elevated temperature in grapevine. I. Berry sensory traits. Australian Journal of Grape and Wine Research **19**, 95–106.

Soar, C.J., Collins, M.J. and Sadras, V.O. (2009) Irrigated Shiraz vines (*Vitis vinifera*) upregulate gas exchange and maintain berry growth in response to short spells of high maximum temperature in the field. Functional Plant Biology **36**, 801–814.

Tomasi, D., Jones, G.V., Giust, M., Lovat, L. and Gaiotti, F. (2011) Grapevine phenology and climate change: relationships and trends in the Veneto region of Italy for 1964–2009. American Journal of Enology and Viticulture **62**, 329–339.

Webb, L.B., Whetton, P.H. and Barlow, E.W.R. (2007) Modelled impact of future climate change on the phenology of winegrapes in Australia. Australian Journal of Grape and Wine Research **13**, 165–175.

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

Webb, L.B., Whetton, P.H., Bhend, J., Darbyshire, R., Briggs, P.R. and Barlow, E.W.R. (2012) Earlier wine-grape ripening driven by climatic warming and drying and management practices. Nature Climate Change **2**, 259–264.

Winkler, A.J. (1954) Effects of overcropping. American Journal of Enology and Viticulture **5**, 4–12.

Wolf, T.K., Dry, P.R., Iland, P.G., Botting, D., Dick, J.O.Y., Kennedy, U. and Ristic, R. (2003) Response of Shiraz grapevines to five different training systems in the Barossa Valley, Australia. Australian Journal of Grape and Wine Research **9**, 82–95.

Wolkovich, E.M., García De Cortázar-Atauri, I., Morales-Castilla, I., Nicholas, K.A. and Lacombe, T. (2018) From Pinot to Xinomavro in the world's future wine-growing regions. Nature Climate Change **8**, 29–37.

Zapata, D., Salazar-Gutierrez, M., Chaves, B., Keller, M. and Hoogenboom, G. (2017) Predicting key phenological stages for 17 grapevine cultivars (*Vitis vinifera* L.). American Journal of Enology and Viticulture **68**, 60–72.

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Supporting information

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Figure S1. Comparison of yield-adjusted rate of change of day of year maturity (DOYM) between cultivars as a function of the covariates Vintage Year, seasonal Growing Degree Day ($GDD_{Sep–Mar}$), Spring Index and Yield, and with interaction terms. Mixed models fitted were response: DOYM from 1 January; random factors: Block and Vintage Year; fixed factor: Cultivar; covariate: Vintage Year, $GDD_{Sep–Mar}$ or Spring Index and Yield as the second covariate. Interaction terms were Vintage Year * Cultivar, $GDD_{Sep–Mar}$ * Cultivar or Spring Index * Cultivar as appropriate and Yield * Cultivar. The vineyards were Banksdale (——), Milawa (——), Heathcote (——), and Mystic Park (——). Rate of change of DOYM values were separated with pairwise comparisons using Fisher's LSD test. Rate of change of DOYM values that do not share a letter are significantly different and indicate therefore that the cultivars have advanced DOYM differently as a function of the covariate for that vineyard. The error bars show 95% confidence intervals. Vineyards that show no letters for the cultivars indicate there was no significant difference for rate of change of DOYM between those cultivars at that vineyard. The *P*-values for these comparisons are shown in Table 5.

Figure S2. Comparison of yield-adjusted rate of change of day of year maturity (DOYM) between vineyards as a function of the covariates Vintage Year, seasonal Growing Degree Day ($GDD_{Sep–Mar}$), Spring Index and Yield and with interaction terms. These comparisons were done for each cultivar that was common to vineyards, that is Shiraz, Dolcetto, Cabernet Sauvignon and Tempranillo. Mixed models fitted were response: DOYM from 1 January; random factors: Block and Vintage Year; fixed factor: Vineyard; covariates: Vintage Year, $GDD_{Sep–Mar}$ or Spring Index and the interactions Vintage Year, $GDD_{Sep–Mar}$ or Spring Index * Vineyard as appropriate and Yield * Vineyard. Vineyards were: Banksdale (——), Milawa (——), Heathcote (——) and Mystic Park (——). Rate of change of DOYM values were separated with pairwise comparisons using Fisher's LSD test. Different letters for the rate of change of DOYM indicate that the rate of advancement for the cultivar was different between the vineyards. The error bars show 95% confidence intervals. Cultivars that show no letters for the vineyards indicate there was no significant difference in the rate of change of DOYM between those vineyards for that cultivar. The *P*-values for these comparisons are shown in Table 6.