Agricultural and Forest Meteorology xxx (2011) xxx–xxx

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Effect of vineyard-scale climate variability on Pinot noir phenolic composition

Kimberly A. Nicholas[a,b,*], Mark A. Matthews[a], David B. Lobell[c], Neil H. Willits[d], Christopher B. Field[b]

[a] Department of Viticulture and Enology, One Shields Avenue, University of California-Davis, Davis, CA 95616-5720, United States
[b] Carnegie Department of Global Ecology, Stanford University, Stanford, CA 94305, United States
[c] Department of Environmental Earth System Science, Stanford University, Stanford, CA 94305, United States
[d] Department of Statistics, University of California-Davis, Davis, CA 95616-5720, United States

ARTICLE INFO

Article history:
Received 10 March 2010
Received in revised form 24 May 2011
Accepted 19 June 2011

Keywords:
Climate change
Vitis vinifera
Wine
Climate sensitivity
Anthocyanins
Phenology
Temperature

ABSTRACT

The sensitivity of agricultural crops to climate change is a major area for climate impact studies. The relationship between climate and three key phenolic compounds in grape skins important to premium wine quality (anthocyanins, tannins, and total phenolics) has not been well-studied. Here we conducted a three-year field study to collect and analyze berry samples from Pinot noir vineyards in the Carneros and Sonoma Valley American Viticultural Areas of California's North Coast wine country, and correlate phenolic measurements with climate statistics derived from hourly temperature measures at each vineyard site. We used several statistical approaches to identify key phenologically-based periods influencing phenolic concentration at maturity, including classification and regression trees, factor screening, principal component analysis, and pairwise correlations.

The results from these statistical models showed that cool conditions following harvest the year before maturity, warm temperatures from budburst to bloom, and cool temperatures from bloom to veraison (the onset of ripening) were positively correlated with concentrations of all three classes of phenolics, although not all trends were statistically significant. Anthocyanins were positively and significantly correlated with temperatures between 16 and 22 °C from veraison to harvest. Tannins were significantly increased by warm nights preceding budburst and warm days from budburst to bloom. We measured relatively high levels of light interception (35% of incident photosynthetically active radiation), and we found that increased light interception was significantly correlated with lower levels of all three classes of phenolic compounds in this study.

For the Pinot noir sites in this study, warm temperatures from budburst to bloom appear to increase phenolic concentrations, which is likely beneficial for wine quality. However, warmer periods during the preceding fall and summer during ripening appear to offset these effects. Given projections for greater summer warming in California with climate change, the overall impact of climate change on winegrowing is likely to be negative.

1. Introduction

The price of premium winegrapes in California varies more than 15-fold and is closely tied to the geographic source of those grapes (California Agricultural Statistics Service, 2007). Implicit in that close relationship is a widely accepted dependence of winegrape composition on the local mesoclimate (climate at the scale of a vineyard block). Temperature affects the rate of development or loss of various biochemical compounds in grapes, including the accumulation of sugar, the loss of acids through respiration, and the synthesis and maintenance of color and flavor compounds.

The amount and proportion of these compounds are essential to winegrape quality. Organic acids are important in wine flavor (Coombe, 1987; Kliewer, 1973). Phenolic compounds, including anthocyanins and tannins, contribute to wine color, bitterness, astringency, and anti-oxidant capacity (Downey et al., 2006; Harbertson and Spayd, 2006). Tannin causes an astringent sensation of drying in the mouth (Green, 1993; Smith et al., 1996; Thomas, 1995), and is perceived as having a bitter taste (Arnold et al., 1980; Peleg et al., 1999). Recent work in Australia has found that higher tannin levels in fruit were strongly positively correlated with commercial quality grading, and that consumers preferred wines with tannin in a specific range from 1.3 to 1.9 g/L (Smith et al., 2008). Tannins also bind with the pigment anthocyanin, which produces color in red wines, to create larger, more stable molecules that give long-term color in aged red wines (Harbertson et al., 2003; Hayasaka and Kennedy, 2003). Webb (2006) demonstrated a strong

* Corresponding author. Current address: Lund University Centre for Sustainability Studies, PO Box 170, SE 221-00, Lund, Sweden. Tel.: +46 46 222 4809.
E-mail address: kimberly.nicholas.academic@gmail.com (K.A. Nicholas).

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doi:10.1016/j.agrformet.2011.06.010

positive correlation between winegrape anthocyanin concentration and price.

There is clear evidence of changing climate worldwide (Intergovernmental Panel on Climate Change, 2007) and in California winegrape production areas (Cayan et al., 2008; Nemani et al., 2001). Warmer temperatures accompanying climate change may shift the timing of the growing season, with decreased quality from earlier harvests at higher temperatures (Webb et al., 2006). In warmer climates, such as in much of California, higher temperatures may result in negative changes in fruit composition. For example, research from vines grown in controlled environments found significantly lower anthocyanin concentrations at maturity in potted grapevines exposed to 30 °C rather than 20 °C temperature treatments (Yamane et al., 2006). Another greenhouse experiment found that high temperatures (35 °C) both inhibit anthocyanin production, and degrade the anthocyanins that are produced (Mori et al., 2007).

Long-standing tradition, and more recently, several classification schemes based on growing degree-days, classify winegrapes as suitable from cool to warm climates. For example, Pinot noir, from the cool and often damp Burgundy region in France, is widely seen as a cool-climate variety. The pioneering study of Amerine and Winkler (1944), which grouped grapes grown all over California from cool to hot regions, classified Pinot noir as most suitable for the coolest areas (Winkler Region I, up to 1388 growing degree-days (°C units) from April 1 through October 31), as compared with varieties more suited to warmer climates (such as Merlot, classified as a Region II variety, suitable for less than 1667 degree-days). Gladstones (1992) used slightly different criteria for degree-day accumulation, but similarly classified Pinot in his Maturity Group 3, requiring 1150 degree-days (°C), with Merlot in Group 5 (1250 degree-days). Varieties that thrive in cool climates may be particularly sensitive to climate warming.

To the extent that fruit quality and price are determined by mesoclimate, a clear and quantitative understanding of the effects of weather on fruit composition is needed. However, not enough is known about the effect of vineyard-scale climate on fruit composition in field conditions. Most studies that report differences in fruit from different mesoclimates do not explicitly measure temperature in the vineyard; rather, they rely on public weather station data which may be tens of kilometers or more away from their sites (Jones and Davis, 2000). Several previous studies on the impact of climate on winegrapes or wine (Hayhoe et al., 2004; Jones et al., 2005; White et al., 2006) use simple assumptions about temperature thresholds for grape production applied at a broad regional scale to estimate an effect of future climate on winegrape "quality," which is often loosely defined, or not defined at all. A better estimate of the temperature sensitivity of specific varieties of winegrapes is needed to support such projections.

Additionally, an analysis of light intensity should be included, as berry temperature increases linearly with exposure to incident light (Bergqvist et al., 2001; Smart and Sinclair, 1974) and the interaction between light and temperature effects on winegrape chemistry is actively being investigated. Increased light has traditionally been thought to contribute to increased phenolic concentrations, particularly anthocyanins (Downey et al., 2006), and light is an absolute requirement for coloration in some grape varieties (Weaver and McCune, 1960), but increased temperatures from over-exposure may lead to reduced berry color, particularly in already warm regions (Winkler et al., 1974). Tannins have also been shown to be affected by fruit shading (Cortell and Kennedy, 2006; Downey et al., 2004). It is still unclear whether these variations are due to light, temperature, or other variables (Kennedy et al., 2007), though Downey et al. (2006) conclude that temperature has a greater effect than light on anthocyanin biosynthesis.

The goal of this study was to collect detailed temperature measurements at the vineyard scale, and light at the vine scale, to analyze the effects of light and temperature on Pinot noir skin phenolic composition.

2. Materials and methods

2.1. Site selection and description

The study took place in private, commercial vineyards in the Sonoma Valley and Los Carneros American Viticultural Areas (AVAs). There were seven vineyards studied in 2005, eight in 2006, and six in 2007. Pinot noir was selected for study because of its reported climate sensitivity (Haeger and Storchmann, 2006; Webb, 2006). We selected sites with vines that were at least five years old, planted between 1998 and 2001 (so that vines would be at full canopy cover and maturity), with similar clones (Dijon 115 and Pommard 5; one ranch each had UCD 4 and UCD 13) and rootstocks (including 101-14, 3309C, and 110R) to minimize biological variation that could affect phenolic composition between sites(Guidoni et al., 2002; Sampaio et al., 2006).

Row orientations were generally northwest–southeast. Site locations were chosen based on reported temperatures to span as wide a range as possible within the region, and ability to obtain research access to private vineyards. We selected three sites in the Los Carneros AVA: one from the western Sonoma edge, one near the Sonoma/Napa county line, and one at the eastern Napa edge, and five sites in the Sonoma Valley AVA, spanning a north/south transect from the southern edge of the AVA to mid-valley near Eldridge, and from the Sonoma Mountain foothills in the west to the eastern border of the AVA with Napa County. All sites spanned an east-west range of 16 km and a north-south range of 12 km. Controlling for factors such as water deficit and soil structure, which have been shown to affect phenolics (Kennedy et al., 2002), and variables affecting vine transpiration and photosynthesis but not well-studied for their effect on phenolics, such as wind (Campbell-Clause, 1998) and humidity (Schultz and Stoll, 2010), was beyond the scope of this study.

2.2. Berry collection protocol

To ensure a representative sampling to draw valid conclusions over the scale of a vineyard, berry samples were collected in the following stratified manner, following the recommendations of Zoecklein (2001) to sample a minimum number of berries from a maximum number of vines and to collect approximately 500 berries per vineyard for an accurate sample. Each vineyard was divided into five blocks covering the full vineyard. Within each block, six randomly selected indicator vines were chosen, from which five berries per cluster were sampled from three clusters along the length of the cordon, for a total N of 450 (15 berries per vine for 30 vines per vineyard). For bilateral cordon-trained vines (the majority of the study vineyards) or cane-pruned vines, the left or right side of the vine was chosen randomly. To ensure a random, unbiased sample was collected, clusters were chosen without looking at the clusters (to avoid being drawn to larger or more fully developed clusters), the canopy depth and exposure position of the cluster (east/west or north/south) was varied randomly. Once clusters were selected, they were flagged, and the same clusters were sampled during each growing season; here we report results from samples taken at full maturity (immediately prior to commercial harvest), as well as samples taken midway between veraison and harvest. Berries were sampled from different positions (shoulder, middle, and tip) and depths (superficial or inner berries) within a cluster. Collecting the required number of berry samples using

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this protocol necessitated multiple workers to perform the collection; all were trained in the sampling protocol and there was no evidence of sampler bias. Berry samples were kept chilled in coolers for transport to the lab, where they were frozen at −20 °C until analysis after all fruit samples had been collected for each season. Freezing fruit up to 3 months at −18 °C has been shown not to significantly affect total anthocyanins, soluble solids (sugar), or total phenolics (Cynkar et al., 2004).

2.3. Berry processing protocol

When ready for analysis, berries were removed from frozen storage, dissected using a razor blade, and mesocarp was scraped from skins. Skins were weighed, liquid nitrogen was added to break open cell walls and ensure full phenolic extraction, and then extracted overnight in 50% ethanol (v/v). The mesocarp was crushed in a hand crusher through cheesecloth to extract juice, which was measured for Brix (total soluble solids) using a digitial refractometer. Seeds were removed from the solid material left behind after crushing, then counted and weighed.

2.4. Phenolic analysis

Skin extracts were analyzed using the Harbertson–Adams phenolic assay (Harbertson et al., 2002). The aromatic ring in phenolic compounds allows absorption in the ultraviolet region, which can be measured using a spectrophotometer and used to calculate the concentration of phenolic compounds present based on absorbance compared to a known concentration from a standard curve. This assay measures anthocyanin at low pH so all pigmented molecules are in their colored (flavylium) form (Cabrita et al., 2000), and is reported in malvidin-3-glucoside equivalents. The Harbertson–Adams assay measures tannin and total iron-reactive phenolic concentrations from absorbance changes based on their reaction with ferric chloride; tannin measurements additionally use a protein precipitation step to isolate the fraction of total phenolics comprised of four or more subunits, which are those that precipitate with salivary proteins, causing perceived astringency (Harbertson et al., 2002). Kennedy et al. (2006) found that protein precipitation methods, and in particular the Harbertson–Adams assay, had the highest correlation with perceived astringency among the common methods tested, so it provides a good link between the laboratory and the consumer experience of the final product. Samples were run in duplicate and re-run if the difference between duplicates was greater than 10% to minimize laboratory error.

2.5. Climate data collection and analysis

One datalogger (Hobo H8 Loggers, Onset Corporation) per vineyard was installed inside solar shields at 1.5 m height (Snyder et al., 2003), which was within the vineyard canopy of each study vineyard. This within-vineyard measurement represents a significant advantage in capturing mesoclimate variability versus using sometimes distant public weather stations. Measurements of temperature and humidity were logged once every 10 min. These 10-min readings were averaged to obtain hourly and daily measurements of minimum, maximum, and mean temperature. These original data were used to calculate ten climate metrics for analysis over phenological periods, as discussed below: minimum, mean, and maximum temperatures; temperature range (difference between maximum and minimum); growing degree-days (base 10 °C); days below 0 °C; days above 30 °C; days above 35 °C; hours above 22 °C; and hours between 16 and 22 °C.

Several different methods of calculating growing degree-days are reported in the literature that use different thresholds to begin counting heat accumulation and to not count or to penalize heat over certain temperatures (Amerine and Winkler, 1944; Gladstones, 1992; Happ, 1999b; McIntyre et al., 1987). We compared our growing degree-day calculations for all days above 10 °C with no upper threshold (Amerine and Winkler, 1944) and for days between 10 and 19 °C (Gladstones, 1992), using both the traditional formulation of (max + min)/2 to get the day's average temperature (Amerine and Winkler, 1944) and the true mean temperature (averaged over all 10-min increment readings over a 24-h period). We found all these methods to be very highly correlated with each other ($R^2 > 0.99$), and thus selected the most widely reported index, that of Amerine and Winkler (1944), which was used to develop the Regions I–V climate classification for California still in use today. A more sensitive measure of heat accumulation was proposed by Happ, who suggested that hours below 16 °C were beneficial to flavor conservation, hours between 16 and 22 °C were favorable to enzyme activity promoting flavor production, and hours above 22 °C were detrimental to flavor retention (Happ, 1999a). We accounted for the effects of high heat through other indices and use the degree-days as a general measure of heat accumulation.

Developing phenologically-based models for grapevine growth allows physiological interpretations of the influence of climate on plant development (Due et al., 1993), and is more useful for future projections than calendar-based approaches when plant development may shift earlier in response to climate change. We made observations of bloom and veraison at each of the 30 study vines per vineyard, using a visual estimate of both the percent of all clusters on each vine having achieved bloom or veraison, and the percent of berries on three randomly selected clusters having achieved the stage. We used these observations for each vineyard to calculate climate statistics for five phenological periods:

1. **Previous fall (PF)**: from harvest of the last year's crop (~September) to the end of the previous calendar year.
2. **Winter (W)**: from January 1 to budburst of the present year (~late March).
3. **Budburst to bloom (BB)**: budburst to bloom (~late May)
4. **Bloom to veraison (BV)**: bloom to veraison (~late July)
5. **Veraison to harvest (VH)**: veraison to harvest (~September).

Bloom and veraison were estimated when 50% of observed vines had achieved capfall and color change, respectively, and harvest dates were recorded. Budburst dates were not observed, so budburst was modeled in two different ways: first, as 177 days before harvest, which was the mean interval between budburst and harvest for a study of 20 Pinot noir vineyards in Carneros from 1993 to 2002 (F. Dewyer, personal communication), and second, as the spring date when mean daily temperatures exceeded 10 °C for five consecutive days (Amerine et al., 1980; Mullins et al., 1992). These two approaches agreed with each other within a few days. The dates for each phenological event across sites were compared between years using ANOVA as reported in Section 3.1 below.

2.6. Climate interpolation and analysis

Because new sites were added during the course of the study, and because some dataloggers were not functioning properly when initially installed in the field due to a software malfunction, temperature measurements started at different dates in different sites for 2005 and 2006. (The 2007 climate record was complete in all sites.) We took two approaches to develop climate statistics to compare between sites. The first was to calculate calibrated climate statistics, starting at the first date where all sites within a year were logging temperatures. The second approach was to estimate the climate at a site for a time period that was not measured by calculating the difference between the climate of the missing site and the climate

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of a nearby site with an intact climate record, using leave-one-out cross-validation (See Appendix A).

2.7. Light data collection and analysis

Photosynthetically active radiation (PAR) was measured at each vine within 1 week of commercial harvest in 2006 and 2007 using a handheld Decagon LP-80 ceptometer. All measurements were taken within 90 min of solar noon on clear, sunny days. Fruiting zone PAR measurements were taken by placing the PAR sensors adjacent to the clusters on the more sun-exposed side of the vine (south or west-facing, depending on row orientation). PAR exposure was calculated as a percentage of full PAR interception, relative to an open-sky reading taken adjacent to the vine immediately after the fruiting zone reading.

2.8. Statistical analysis

Programming for climate data analysis and data visualization was performed in R (R Development Core Team, Vienna, Austria). Statistics were analyzed in JMP 7.0 (SAS Institute, Cary, NC). Because summary statistics for climate could be calculated in an almost infinite variety of ways, there is the danger of overfitting a model correlating climate and grape composition because of the large number of potential predictors. To deal with this, we conducted two forms of exploratory data analysis (classification and regression trees (CART) and factor screening) in JMP to systematically identify potentially significant predictors of grape composition for the two years (2006 and 2007) for which we had complete climate records. These analyses were run using climate calculations for the five phenological periods for the ten metrics described above in Section 2.5 ($N = 50$ metrics per year per site). Predictor variables that were found to be highly and significantly correlated (Pearson's correlation, $p < 0.05$) with grape composition measures were selected for use in regression models. Residuals from these models were evaluated to make sure they met the required assumptions. These predictor variables were also correlated with other candidate climate measures to identify any sources of multicollinearity that might confound interpretation. For 2005, since climate data were collected starting during the summer and we could not use this record to calculate phenologically-based summaries, we used the calibrated data for comparisons.

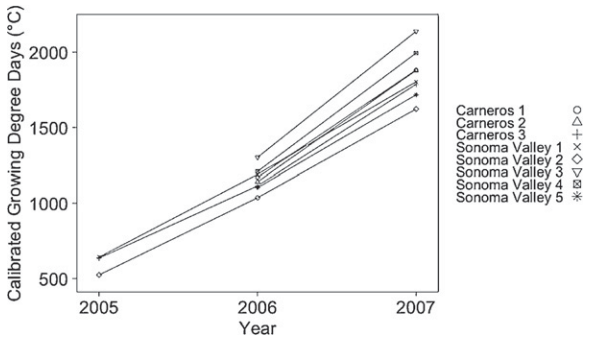

Fig. 1. Calibrated site growing-degree-days. GDD are counted for each year starting on the first day that all stations were recording for that year, so that sites with different record lengths may be compared. For 2005, calculations started on August 25. For 2006, calculations started on July 7. For 2007, calculations began on January 1 (all 2007 records were complete). Lines connect the points representing the same site in different year, showing that the pattern of degree-day accumulation at a site is consistent between years.

3. Results

3.1. Climatic interpolations and differences between years

Generally the temperature patterns between sites were quite consistent (see Fig. 1 for an example using the calibrated data). Overall, 2005 had a warm, sunny spring (based on data from the Carneros CIMIS weather station (http://www.cimis.water.ca.gov), since this was before our instruments were installed in vineyards), a more cloudy summer, and a cool ripening period. Average dates for phenological stages across all vineyards were 19 March for budburst, 12 May for bloom, 27 July for veraison, and 10 September for harvest. We used ANOVA to compare phenological dates between years, and found that 2006 was significantly ($p < 0.05$) delayed compared to 2005; 2007 was slightly, though not significantly, earlier (Table 1). This year produced large berries with a high ratio of skin to total fresh weight (Table 1). The following year, 2006, had a cool and cloudy spring with a hot summer and a cooler ripening period, with significantly ($p < 0.05$) delayed phenological dates (28 March for budburst, 31 May for bloom, 5 August for veraison, and 19 September for harvest). The spring of 2007 was warm and sunny, with a cooler summer and a warmer ripening period. In 2007, the aver-

Table 1
Berry structure and composition parameters averaged across all sites for each year.

Year	2005	2006	2007	Significance
N	7	8	6	
Berry structure				
Skin weight (g/berry)	0.17a	0.11b	0.093b	***
Berry weight (g/berry)	1.11a	1.05a	0.8b	***
Seed weight (g/berry)	0.084a	0.072a	0.044b	***
Seed number (per berry)	1.8a	2.1b	1.4c	***
Ratio skin:berry weight	0.16a	0.11b	0.12ab	*
Berry composition				
Anthocyanin[a]	0.57a	0.67ab	0.85b	**
Iron-reactive phenolics[b]	0.83a	0.57a	0.77a	NS
Tannin[b]	0.42a	0.30a	0.41a	NS
Phenological dates[c]				
Budburst	81a	90b	74a	0.0001
Bloom	146a	155b	139a	0.0001
Veraison	213a	222b	206a	0.0001
Harvest	258a	267b	251a	0.0001

Means with different letters within a row are significantly different by Tukey's HSD test, at $p \leq 0.05$ (*), $p \leq 0.01$ (**), $p \leq 0.001$ (***), or $p \leq 0.0001$ (****). NS, not significant.
[a] mg malvidin-3-glucoside per gram berry.
[b] mg catechin equivalents per gram berry.
[c] Julian day.

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age date for budburst was 12 March, bloom was 15 May, veraison was 20 July and harvest was 3 September. These dates were slightly earlier than 2005, though the difference was not statistically significant. Berries in 2007 were significantly smaller than the other years (Table 1). The total heat accumulation was similar between all three years, although the spring of 2007 was warmer than 2006, and 2006 had more hot days (data not shown).

We tested our interpolation approach for missing climate data using leave-one-out cross-validation with complete climate records, where we used comparisons between sites for two years of data to estimate the third year using the deviation from climate measured at a different site, and compared with the existing climate record. We found very good agreement between observed and simulated data using this approach (R^2(adj) of 0.98 for maximum temperatures and 0.91 for minimum temperatures). We used this approach to fill in complete site climate records from August 2005 through the end of 2007, and used this dataset for analysis of correlations between climate and grape composition as described below.

3.2. Rootstock and clone effects on phenolic compounds

Rootstock and clone differences were tested in an ANOVA model of the three classes of phenolic compounds. They were not significant individually and the overall model was not significant, so we pooled across clones and rootstocks for the analysis of climate effects.

3.3. Climate effect on phenolic compounds

Seven climate variables (listed in the first row of Table 2) were identified as potentially significant to explain variability in grape phenolics through exploratory data analysis using correlation and regression trees and factor screening. These variables were used to develop final regression models based on three criteria: each term in the final model had to be significant at $p < 0.05$, overall model significance and R^2(adj), and accounting for correlation among predictor terms. The selected models were:

$$\text{Anthocyanins} = 3.457 - 0.00347\,(\text{Hours} > 22\,^{\circ}\text{C})_{\text{PF}} - 0.00475\,(\text{Hours } 16 - 22^{\circ}\text{C})_{\text{BV}}$$
$$R^2(\text{adj}) = 0.64;\ p = 0.0013$$

$$\text{Total phenolics} = 3.99 - 0.00412\,(\text{Hours} > 22\,^{\circ}\text{C})_{\text{PF}} - 0.0059\,(\text{Hours } 16 - 22\,^{\circ}\text{C})_{\text{BV}}.$$
$$R^2(\text{adj}) = 0.47;\ p = 0.0119$$

$$\text{Tannin} = -1.04 + 0.084(\text{Range},\ ^{\circ}\text{C})_{\text{BB}} + 0.023(\text{min},\ ^{\circ}\text{C})_{\text{W}}$$
$$R^2(\text{adj}) = 0.56;\ p = 0.0041$$

The subscripts following the variables indicate the phenological period as described above.

Because these models contained terms that were moderately correlated with each other (pairwise correlation, $\rho \sim 0.50$, p close to 0.05; Table 2), we also examined two other sets of models: those suggested by the regression tree approach and by a principal components analysis. For all three classes of phenolics, the variable suggested by the regression tree analysis that explained the most variation in the data was a measure of heat in the previous fall. For anthocyanins and tannins, the threshold was an accumulation of >490 °C growing degree-days above 10 °C in the previous fall; this explained 60% of the variability in the data for anthocyanins ($p = 0.0007$) and 36% of the variability in the tannin data ($p = 0.013$).

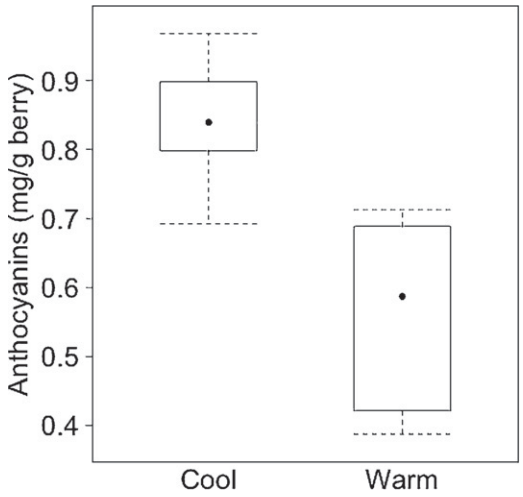

Fig. 2. Mean anthocyanin concentration in fruit from cool and warm sites in 2006 and 2007. The regression tree model identified a threshold that explained the maximum variation in the data as the accumulation of >490 °C growing degree-days in the previous fall. The box plots show the median and upper and lower quartile of the data. The two groups are significantly different at $p < 0.05$.

Sites with a cool previous fall (all the 2007 sites, plus 3 sites from 2006) had significantly higher anthocyanin concentrations (Fig. 2) and tannins than sites with a warm previous fall. The threshold for total phenolics was for sites with a mean maximum fall temperature >20.9 °C. This model explained 45% of the variability in the data for total phenolics ($p = 0.0051$). Sites with a cool previous fall (all 2007 sites and 2 of the 2006 sites) had significantly higher total phenolics.

In the principal components analysis, the first component explained 50.8% of the variability in the climate data, and the second component explained an additional 22.9%. The major contributors to Component 1 were measures of heat during veraison to harvest (negative contribution to Component 1) and measures of heat during the previous fall and from bloom to veraison (positive contribution to Component 1). The major contributors to Component 2 were variables measuring warm spring days (positive) and winter chill (negative) (Table 3; Fig. 3). The climate components in the first principal component were moderately correlated with anthocyanin and iron-reactive phenolic concentrations, though not at $p < 0.05$ (correlation = −0.53, $p = 0.074$, and correlation = −0.51, $p = 0.091$, respectively).

Pairwise Pearson correlations between phenolics and key climate variables showed that several measures of moderate heat from veraison to harvest were positively and significantly related to anthocyanin concentrations (Table 4), but not significant for total phenolic and tannin concentrations. Measures of heat accumulation in the previous fall and from bloom to veraison (two variables that were highly positively correlated; Table 2) were negatively correlated with all three classes of phenolics, and the effect was significant for anthocyanins and total phenolics for hours >22 °C. Tannins were significantly ($p < 0.05$) increased by warm days between budburst and bloom. Increased anthocyanins were correlated with warm days and cool nights during that period, though the correlation was not significant at the selected alpha level ($p = 0.056$).

For the calibrated measures from 2005, which began approximately a month before harvest, sites with higher calibrated GDD and hot days had higher phenolic concentrations. However, the warmer sites included for 2005 were substantially cooler than the hottest sites, which were added for 2006 and 2007.

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Table 2
Pairwise correlations (ρ) between climate variables (first column) and the seven climate variables selected to be included in models to explain phenolic concentrations (top row). All possible climate variables were evaluated in the first column; only those that were significant at $p < 0.05$ for at least one correlation are shown.

Season	Phenological period	PF	PF	PF	W	BB	BV	BV
	Climate variable	Hours >22 °C	GDD	Max	Min	Range	Min	Hours 16–22 °C
	Phenolic compound	A, P	A, T	P	T	T	A, P	A, P
Previous fall (PF)	Days <0 °C	−0.16	−0.58*	−0.29	−0.75**	0.87***	−0.84***	−0.32
	GDD	0.87***					0.76**	−0.54*
	Max	0.94***	0.86***				0.66**	−0.68**
	Mean	0.73**	0.94***	0.77**	0.52	−0.82***	0.87***	−0.33
	Range	0.41	−0.05	0.42	−0.88***	0.35	−0.17	−0.52
Winter (W)	Days <0 °C	−0.09	−0.51	−0.21	−0.85***	0.84***	−0.76**	−0.31
	Hours 16–22 °C	−0.55*	−0.74**	−0.68**	−0.30	0.83***	−0.88***	0.08
	Hours >22 °C	−0.61*	−0.79***	−0.66*	−0.39	0.85***	−0.89***	0.16
	Max	0.23	−0.20	0.25	−0.80***	0.45	−0.31	−0.38
	Mean	−0.11	0.34	−0.12	0.96***	−0.44	0.27	0.24
	Min	−0.06	0.42	−0.04		−0.55*	0.39	0.23
	Range	0.08	−0.40	0.07	−0.99	0.57*	−0.41	−0.27
Budburst-Bloom (BB)	Hours >22 °C	0.42	0.15	0.34	−0.30	0.46	−0.06	−0.72**
	Min	0.49	0.76**	0.62*	0.56*	−0.85***	0.95***	−0.03
	Range	−0.42	−0.72**	−0.52			−0.83***	−0.11
Bloom-Veraison (BV)	Days >30 °C	0.89***	0.79***	0.90***	−0.06	−0.39	0.60*	−0.74**
	Days >35 °C	0.82***	0.76**	0.91***	−0.04	−0.52	0.75**	−0.59*
	GDD	0.73**	0.81***	0.84***	0.21	−0.66**	0.90***	−0.39
	Hours 16–22 °C	−0.78***						
	Hours >22 °C	0.77**	0.78**	0.87***	0.08	−0.53	0.78***	−0.52
	Max	0.89***	0.81***	0.92***	−0.04	−0.45	0.67**	−0.69**
	Mean	0.84***	0.81***	0.91***	0.02	−0.57*	0.80***	−0.54*
	Min	0.54*						−0.05
	Range	0.80***	0.54*	0.75**	−0.32	−0.01	0.18	−0.89***
Veraison-Harvest (VH)	Days >30 °C	0.13	0.03	−0.09	−0.11	0.29	−0.24	−0.35
	Days >35 °C	−0.09	−0.22	−0.16	−0.22	0.37	−0.21	−0.04
	Hours 16–22 °C	−0.82***	−0.56*	−0.73**	0.23	0.02	−0.17	0.89***
	Hours >22 °C	−0.60*	−0.53	−0.75**	0.12	0.48	−0.52*	0.27
	Min	−0.57*	−0.27	−0.66**	0.55*	−0.01	−0.17	0.64*
	Range	0.56*	0.20	0.43	−0.54*	0.35	−0.10	−0.88***

The phenolic compounds are listed as anthocyanins (A), tannins (T), and iron-reactive phenolics (P), for the phenological periods of Previous fall (PF), Winter (W), Budburst-bloom (BB), and Bloom-veraison (BV).
* $p \leq 0.05$;
** $p \leq 0.01$;
*** $p \leq 0.001$.

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Table 3
Eigenvectors for the first two principal components in the analysis of climate variables. (Abbreviations given first by the phenological period then the climate variable as shown in Table 2). These values represent the contribution of each climate variable to the overall principal component. Factor loadings with an absolute value >0.20 are shown in bold to highlight the more important factors. The first principal component (PC1) explained 50.8% of the variability in the climate data, and the second principal component (PC2) explained 22.9%.

Climate variable	PC1	PC2
VH.mean	−**0.230**	0.025
VH.min	−0.197	−**0.221**
VH.hours.over22	−0.196	−0.017
VH.hours.16–22	−0.191	−**0.274**
BB.range	−0.163	**0.283**
BB.hours.16–22	−0.150	0.144
PF.cold.days	−0.142	**0.320**
BV.hours.16–22	−0.132	−**0.322**
VH.max	−0.105	0.173
VH.days.over35	−0.070	0.133
W.min	−0.021	−**0.382**
BB.hours.over22	0.066	**0.337**
PF.hours.16–22	0.070	0.168
W.min	0.151	−**0.322**
BV.min	**0.212**	−**0.223**
PF.hours.over22	**0.228**	0.150
PF.GDD	**0.246**	−0.039
PF.mean	**0.249**	−0.146
BV.days.over30	**0.252**	0.113
PF.max	**0.255**	0.086
BV.max	**0.262**	0.087
BV.GDD	**0.263**	−0.070
BV.hours.over22	**0.263**	0.004
BV.days.over35	**0.268**	0.044
BV.mean	**0.268**	0.010

3.4. Correlations among variables

Across all three years, correlations between anthocyanins and tannins were not very strong ($R^2 = 0.41$; $p = 0.062$). Anthocyanins were slightly more strongly correlated with total phenolics ($R^2 = 0.50$, $p = 0.02$). And of course, since tannins are part of what is measured by the total phenolic reading, tannins and total phenolics were significantly correlated ($R^2 = 0.88$, $p < 0.0001$).

Many of the climate variables were highly correlated with each other, particularly different measures of climate during the same period and adjacent periods (e.g., Fig. 3; Table 2).

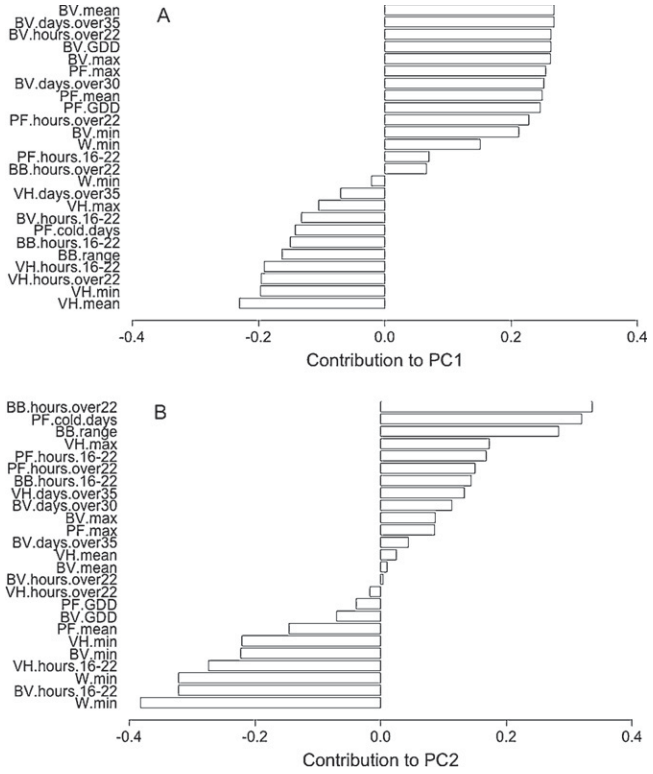

Fig. 3. Principal components analysis of climate variables. There were $n = 8$ sites in 2006 and $n = 6$ sites in 2007. The data are combined into two principal components, or combinations of observed variables along two axes, to summarize patterns of correlations among observed variables. The further from the origin, the more that variable contributes to a component. Points that are close to each other in Panel A contribute similarly to the first component (which explained 51% of the variability in the climate data), and points close to each other in Panel B contribute similarly to the second component (which explained 23% of the variability in the data). Abbreviations for time periods are as given in the text and Table 2.

3.5. Development over the growing season

In 2006, we collected samples approximately midway between veraison and harvest, as well as harvest samples, at six sites. These

Table 4
Pairwise Pearson's correlations between concentrations of phenolic compounds and individual climate variables significant at $p \leq 0.10$. Correlations significant at the $p \leq 0.05$ level are shown in bold.

Season	Climate variable	Phenolic variable						*N*
		Tannin		Iron-reactive phenolics		Anthocyanin		
		Corr	*p*-value	Corr	*p*-value	Corr	*p*-value	
Previous Fall (PF)	Days <0 °C	0.56	0.058	0.23	0.466	0.27	0.389	12
	Days >35 °C	−0.26	0.369	−0.39	0.165	−0.52	0.056	14
	GDD	−0.34	0.231	−0.42	0.134	−**0.6**	**0.025**	14
	Hours >22 °C	−0.37	0.196	−**0.54**	**0.044**	−**0.64**	**0.014**	14
	Max	−0.36	0.208	−0.51	0.061	−**0.63**	**0.015**	14
	Mean	−0.35	0.223	−0.35	0.224	−0.5	0.067	14
Winter (W)	Hours >22 °C	0.5	0.072	0.36	0.213	0.44	0.115	14
	Hours 16–22 °C	0.48	0.083	0.33	0.248	0.49	0.074	14
Budburst-Bloom (BB)	Max	**0.57**	**0.034**	0.47	0.091	0.41	0.142	14
	Range	**0.58**	**0.031**	0.44	0.119	0.52	0.056	14
Bloom-Veraison (BV)	Days >30 °C	−0.28	0.339	−0.38	0.181	−0.51	0.065	14
	Max	−0.32	0.27	−0.39	0.162	−0.51	0.061	14
	Mean	−0.4	0.154	−0.41	0.146	−**0.54**	**0.048**	14
	Min	−0.49	0.072	−0.31	0.284	−0.44	0.114	14
Veraison-Harvest (VH)	Hours >22 °C	−0.02	0.915	−0.05	0.839	**0.63**	**0.002**	21
	Hours 16–22 °C	−0.31	0.168	−0.23	0.318	**0.44**	**0.047**	21
	Mean	0.15	0.524	0.1	0.682	**0.46**	**0.036**	21

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Table 5
Mean and (standard error of the mean) for berry composition and weight from six sites in 2006. Fruit from the same vines was collected approximately 3 weeks before harvest ("Ripening"), and immediately before commercial harvest ("Harvest"). The *p*-value shown is for the paired *t*-test comparing values at the two time points.

	Ripening	Harvest	Percent change	p-value
Berry structure				
Skin weight (g/berry)	0.13 (0.0033)	0.14 (0.0028)	3.8%	NS
Berry weight (g/berry)	1.16 (0.016)	1.03 (0.014)	−11.1%	<0.001
Seed weight (g/berry)	0.090 (0.0015)	0.077 (0.0013)	−14.4%	<0.001
Ratio skin:berry weight	0.115 (0.0033)	0.136 (0.0031)	18.3%	0.031
Berry composition				
Anthocyanin[a]	0.60 (0.016)	0.58 (0.015)	−2.7%	<0.0004
Iron-reactive phenolics[b]	0.75 (0.025)	0.595 (0.022)	−21.1%	<0.0001
Tannin[b]	0.49 (0.015)	0.321 (0.012)	−34.9%	<0.001

[a] mg malvidin-3-glucoside per gram berry.
[b] mg catechin equivalents per gram berry.

Table 6
Parameter estimates from a regression model to explain fruit composition using light measured at the vineyard level, accounting for variability in light at the vine and block level. The parameter estimate represents the change in the dependent variable of fruit composition associated with one percent change in the independent variable of PAR in the fruit zone.

Fruit measure	R^2(Adj)	*p*-value for vineyard light	Parameter estimate
Brix	0.379	0.0357	0.0857
Anthocyanin[a]	0.411	0.0027	−0.0167
Iron-reactive phenolics[b]	0.766	<0.0001	−0.0348
Tannin[b]	0.98	0.0009	−0.00787

[a] mg malvidin-3-glucoside per gram berry.
[b] mg catechin equivalents per gram berry.

samples showed slight declines in anthocyanin concentration and substantial decreases in iron-reactive phenolic and tannin concentrations over time (21 and 35%, respectively; both $p < 0.001$) (Table 5). Although skin weight increased slightly over this time ($p > 0.05$), berry weight declined by 11% ($p < 0.001$), which was enough to increase the ratio of skin to total berry weight by 18% ($p = 0.031$).

3.6. Effects of light on phenolics

The amount of light was found to be highly significant ($p < 0.01$) in explaining all three classes of phenolic compounds measured at harvest, as well as Brix (Table 6). For a model that accounted for within-vineyard variability (i.e., variability from vine to vine and block to block, as random effects), increasing light explained between 41% and 98% of the variability in the decrease of all three phenolics measured, and 37% of the variability in the increase in Brix (Table 6). For example, the model predicts that a 1% increase in PAR would correspond with a decrease of 0.0167 mg malvidin-3-glucoside per gram berry, about 2.5% of the mean anthocyanin concentration at harvest (Table 5). We measured vine light at 561 vines over two growing seasons, and found that average light interception is quite high in these commercial vineyards (Fig. 4).

4. Discussion

4.1. Climate effects on Pinot noirphenolic composition

Several different statistical approaches showed that heat accumulation in the postharvest period a year before maturity, and heat from bloom to veraison, were negatively correlated with the concentration of anthocyanins, tannins, and iron-reactive phenolics. These two periods were highly correlated with each other in this study (Tables 2 and 3), as the postharvest period of 2005 was warm and the period from bloom to veraison in 2006 coincided with a substantial heat spell (with recorded vineyard temperatures exceeding 44 °C), while post-harvest temperatures in 2006 and temperatures from bloom to veraison in 2007 were cool. More years of field evaluations, as well as greenhouse trials to manipulate and control temperature, are needed to evaluate the causative relationships behind these relationships.

We found a positive correlation between anthocyanin concentration and accumulated hours from 16 to 22 °C between veraison and ripening, which has not been reported previously. However, this finding supports the use of the "heat work index" of hour–degrees between 16 and 22 °C proposed by Happ (1999a), who claimed this temperature interval was particularly favorable for enzymatic activity relating to flavor production.

For example, Valladao et al. (1995) observed decreases in tannins and anthocyanins in Pinot noir during the process of maturity, including a decrease of up to 35% following a week with temperatures >35 °C during ripening. Pastor del Rio and Kennedy (2006) showed that increased heat summations between fruit set (immediately following bloom) and veraison was associated with increased tannins in Pinot noir fruit and wines in Oregon. Spayd et al. (2002) found that a higher accumulation of growing degree-days (GDD) between veraison and harvest decreased anthocyanin levels observed in Merlot, and that this factor explained about half of the variation observed.

We also found a significant increase in the skin:berry weight ratio during berry growth (Table 5), in contrast with past work that found that the berry grows proportionally (Roby and Matthews, 2004) and that concentration of phenolic compounds does not change during ripening.

Other research has found winter rainfall to be correlated with wine price in regions that are not irrigated (Ashenfelter, 2008), but

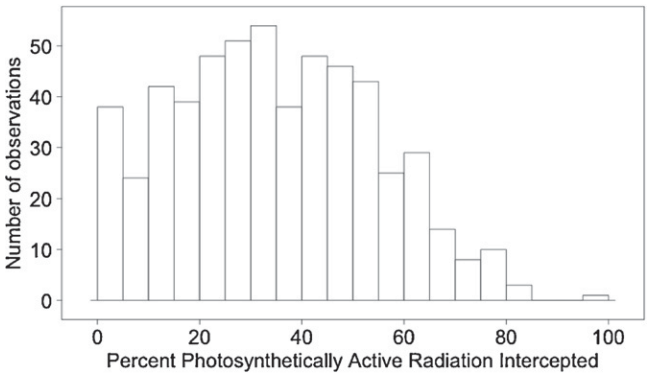

Fig. 4. Light interception in Pinot noir vineyards. Distribution of light interception (fraction intercepted in the fruiting zone versus ambient photosynthetically active radiation, PAR) observed at 561 Pinot noir vines in 2006 and 2007. The mean of the distribution was 35% and the standard deviation was 19%.

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the potential for climate influences in the previous fall to have an effect on grape phenolic composition has not been previously documented. However, due to the two-year reproductive cycle of the grapevine, where the development of floral primordia occurs the first year before cluster development the second year (Srinivasan and Mullins, 1981; Winkler and Shemsettin, 1937), conditions during the previous year have been shown to affect fruitfulness and yields (Buttrose, 1970). Lobell et al. (2007) found that precipitation in the fall preceding harvest increased both wine and table grape yields in California, which they speculated may have been related to relieving nutrient deficiencies and allowing continuing photosynthesis and carbohydrate storage. Unpublished data from a $\partial^{14}C$ labeling experiment by Kliewer and Leach showed that sugars made by the leaves post-harvest and stored as starch in the wood and root tissues were the first carbohydrates used by shoots the following spring (Winkler et al., 1974). The mechanism for the previous fall's climate to affect fruit composition is unclear, and this bears further study to determine if there is a causative relationship, or an artifact of the seasonal patterns during the three years of this study.

4.2. Light and Pinot noir phenolic composition

Vine light interception in the fruiting zone explained more variability for total phenolics and tannins than did measurements of vineyard temperature. The mean light interception of 35% measured in this study is vastly higher than reported in previous studies, and we found these high levels of light correlated with reduced concentrations of anthocyanins, tannins, and total phenolics. In a previous study in a vertically-trained two-wire Cabernet Sauvignon vineyard in California, ambient light interception in the cluster zone largely fell below 10%, and levels as low as 0.3% were measured in dense canopies (Dokoozlian and Kliewer, 1995a; Dokoozlian and Kliewer, 1995b). In our study, 89% of the 561 vine light measurements made were above 10% ambient light interception (Fig. 4). About 49% of the vines we measured fell between the 10% and 40% ambient light interception advocated as optimal for vertically-trained vines in New Zealand (Smart, 1988); nearly 40% were above this level (Fig. 4). Possibly the use of a third training wire and hedging additional shoot growth in these vertically shoot-positioned vineyards removes substantial shading that would otherwise occur from shoots draping over the top wire.

Increased sun exposure was shown to increase levels of both total phenolics and anthocyanins in Pinot noir fruit in the cool climates of Oregon (Valladao et al., 1995) and British Columbia (Mazza et al., 1999). However, several studies have found a decrease in anthocyanin levels with high light levels (Bergqvist et al., 2001; Hunter et al., 1995; Spayd et al., 2002). For one study, anthocyanin accumulation increased with increasing light up to 100 mmol/m^2/s (about 5% of full sunlight), and decreased thereafter (Bergqvist et al., 2001). Less research has focused on the effect of light on tannin accumulation, though Downey et al. (2004) found little effect of bunch exposure on tannin concentrations at harvest.

In experimental conditions where the temperature effects of sunlight were controlled for, skin anthocyanin accumulation was maximized at relatively high light intensities, but high temperatures inhibited color formation (Kliewer, 1970; Kliewer, 1977; Kliewer and Torres, 1972). Bergqvist et al. (2001) found that exposure on the south (sunny) side of the canopy above a threshold of 100 mmol/m^2/s decreased anthocyanin accumulation in Cabernet Sauvignon and Grenache, and high grape temperatures after veraison were linked with lower anthocyanin levels at the same light exposure levels. Spayd et al. (2002) showed that cooling highly exposed fruit increased anthocyanins, while heating less exposed fruit decreased anthocyanins.

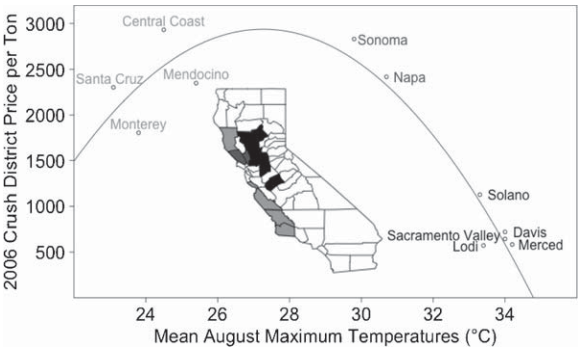

Fig. 5. Relationship between August temperature and California Pinot noir price. Average maximum August county temperatures, 1980–2006, versus 2007 price per ton of Pinot noir for the corresponding Crush District (CASS, 2007). We have included all grape districts producing greater than 200 ton of Pinot noir (thus excluding Los Angeles, Riverside, and Lake Counties and the Fresno and Sierra Foothills region); for comparison, Sonoma produced over 18,000 ton of Pinot noir in 2007. This analysis includes 99.5% of all Pinot noir produced in California (CASS, 2007). Model R^2(adj) is 0.89. For a model comparing 2006 temperatures and 2006 prices, model R^2 was 0.82. We use here regional names for familiarity; the corresponding Crush Districts from CASS (2007) are as follows: Mendocino, District 1; Sonoma, District 3; Napa, District 4; Solano, District 5; Santa Cruz, District 6; Monterey, District 7; Central Coast, District 8; Sacramento Valley, the southern portion of District 9; Lodi, District 11; Merced, District 12; and Davis, District 17.

4.3. Implications for warming and winegrape price in California

Although the sites studied spanned a reasonably wide temperature range within the local region, they represent a small fraction of the full range of climates within which winegrapes, and particularly Pinot noir, are grown. While most of the relationships between climate and grape composition that we describe were linear, it is likely that thresholds may exist, causing the full relationship to be polynomial (e.g., warmer spring temperatures may increase tannins only up to a certain point, beyond which they decline). State-level data on fruit composition is only available for Brix (CASS, 2007), as phenolic compounds are not systematically measured or reported. While Brix has been used as a measure of quality in cool climates, where fruit does not ripen adequately in cool years, we believe price is a more appropriate measure of quality in warmer climates like California.

Price has been used as an indicator of grape quality in Australia (Webb et al., 2006; Wood and Anderson, 2006), France (Jones and Storchmann, 2001), and California (Lima, 2006). Other analyses use price as an independent variable and expert quality ratings as the dependent variable measuring quality (Horowitz and Lockshin, 2002). However, this approach does not explain as much variability in the data as does the hedonic approach, where price is taken as the dependent variable in a multivariate analysis. Work by Haeger and Storchmann (2006) showed that, while climate did not explain as much variation in wine price for American Pinot noir as for Bordeaux wines (with an R^2 of about 0.52 versus 0.8), climate factors still explained nearly twice as much variation in wine price as did the combination of all non-climate factors studied (including variables for winemaker and brand, vineyard and appellation designation, amount of production, and critical ratings).

To examine the relationship between temperature and winegrape value at the state rather than the local scale, we present available data comparing climate and Pinot noir pricein California (Fig. 5). The price data are available at the Crush District level, of which there are 17 in the state (California Agricultural Statistics Service, 2007). To obtain matching climatology, we used the mean August temperature from 1980 to 2006, derived from 382 weather stations across the state and averaged at the county level (data from

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Lobell et al., 2007), then further aggregated where needed to match the scale of the Crush District data. For example, Napa and Mendocino counties each represent their own crush district, while the Central Coast District comprises Santa Barbara, San Luis Obispo, and Ventura counties. We chose August temperatures because they occur during a critical period of grape ripening, and because regional temperature differences are maximized in this month (data not shown). We found great consistency between years in temperature rankings (i.e., the same areas were consistently warm or cool), while price data were more variable, so we chose not to average those data because it obscured regional differences.

Fig. 5 shows that the cool Central Coast region command the highest price in the state for Pinot noir fruit ($2932 per ton); Sonoma is the second-highest at $2831 per ton, and prices in warmer Napa are about 15% lower. Napa and Sonoma, with about a third of the state Pinot noir tonnage, are on the side of the curve where further warming is likely to reduce prices, whereas cooler coastal areas may see a slight price increase from warming. The warmer Central Valley regions earn much less (from $1127 per ton for Solano County to $400 per ton in Kings County). This supports the observation that Pinot noir is usually grown in the cooler winegrowing regions of the world, and is particularly sensitive to climate warming.

Warmer winter and spring temperatures have been observed in California in recent decades (Cayan et al., 2008; Nemani et al., 2001). However, future estimates for statewide temperatures project substantially more warming in summer than in winter in seven out of eight realizations (Cayan et al., 2008; Hayhoe et al., 2004). These projections use three climate models with varying climate sensitivities (PCM, HadCM3, and GFDL) driven by three IPCC emissions scenarios – low (B1), medium–high (A2), and high (A1fi) (see Cayan et al. (2008) and Hayhoe et al. (2004); not all models were run for all emissions scenarios). While the lowest emission scenario with the least sensitive model projects about equal warming in summer and winter, the remaining combinations project summer warming of 3.3–6.4 °C for Northern California, compared with winter warming of 2.3–3.4 °C (Cayan et al., 2008). Warming of this scale would be likely to have a substantial, negative impact on winegrape prices in California. Approximately 4 °C currently separates mean August temperatures in the coolest Pinot noir regions in California (Santa Cruz and Monterey) and the temperature associated with maximum grape prices (Fig. 5). The same amount separates Napa and Sonoma today from the low-price regions in the Central Valley (Fig. 5).

5. Conclusion

This study represents a first step in the analyses needed to make more informative, region- and variety-specific projections of the effects of climate, and the potential effects of climate change, on the wine industry. Future work should pursue questions at both the vineyard and the regional scale. At the vineyard scale, environmental measurements at individual vines for variables such as canopy or cluster temperature and light, and plant and soil water status, would help to explain the tremendous variability observed within vineyards and elucidate the role of climate and particularly temperature on fruit composition. Further, improved observations and models of grapevine development and the drivers of grapevine phenology are important for accurate projections of climate change impacts.

On the regional and larger scale, a robust examination of climate effects on viticulture would require a large-*N* study over many sites and years to detect trends. This approach would be well-suited to partnerships with private vineyard owners to share historical climate and grape data. New studies on the scale of Amerine and Winkler's (1944) ambitious assessment of winegrowing in California would be tremendously helpful to account for all the changes in varieties, technology, and management, as well as climate, since that pioneering study.

In terms of management implications, desirable phenolic compounds in this study were decreased by the quite high exposure to light and by higher temperatures during critical periods in the postharvest period the previous year, and from bloom to veraison. Given this finding, viticultural practices developed to increase light exposure and cluster temperature in the Old World, where often cool, wet weather was an impediment to ripening, must be critically examined for their applicability to New World winegrowing. Canopy management to increase shading might increase color and phenolic concentrations in these highly light-exposed Pinot noir vineyards. Viticulturists may want to examine changing trellising styles, irrigation practices, and other techniques to promote shadier and cooler conditions in Pinot noir vineyards in Napa and Sonoma, while they prepare for the warmer conditions ahead.

Acknowledgements

KAN was supported by a David and Lucile Packard Foundation Stanford Graduate Fellowship and an Interdisciplinary Program in Environment and Resources fellowship. Funding for research instrumentation and assistants came from Stanford School of Earth Sciences McGee and Rudolf Grants. Mark Krasnow at UC Davis helped with lab analyses. The contributions in the field and lab of research assistants Eva Dehlinger, Jill Bible, Emily Humphreys, Lisa Kashiwase, Lisanne Leask, Elizabeth Chan, Martha Kimber, and Jennifer Zeek were essential in completing this research. Greg Hirson provided invaluable advice and programming assistance to create the figures in R. Thanks to the participating growers and winery owners who allowed access to their vineyards, including Mike Cox at Schug Carneros Estate Winery, Chris Bowen at Hunter Farms, Jean Arnold and Bob Sessions at Hanzell Vineyards, Ned Hill of La Prenda Vineyards Management, and all other anonymous participants.

Appendix A. Algorithm for multiple imputation of climate data

Describing the approach

To calculate the temperature for missing days, the following approach was taken.

1. Take daily temperature data (min, max, mean, range) for all sites for each year.
2. Examine correlations between existing data to determine which site is most highly correlated with others to serve as a baseline station (Sonoma Valley 1). This station is at the southwestern edge of the Sonoma Valley AVA, within 16 km of all other stations.
3. Calculate daily absolute difference (degrees) between baseline site (Sonoma Valley 1) and site to interpolate (for example, Carneros 2) for all dates with available data for both sites.
4. Calculate monthly mean of daily differences for all years with available data. For example, daily August maximum is 1.2 °C cooler for Carneros 2 than the baseline Sonoma Valley 1 site, based on observations at both Carneros 2 and Sonoma Valley 1 in August 2006 and August 2007.
5. Apply monthly mean difference for each site to the baseline data from Sonoma Valley 1 site to impute missing data. For example, for all missing values for August 2005 at Carneros 2, subtract 1.2 °C from the measured daily max at Sonoma Valley 1.

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Validating the approach

Use leave-one-out cross-validation to generate a modeled climatology for a site with existing data. For example:

1. Carneros 3 has observed data available for 2005, 2006, and 2007.
2. Delete the 2005 data from the dataset.
3. Calculate differences between Carneros 3 and the baseline site, Sonoma Valley 1, based on the average of 2006 and 2007 data.
4. Use these calculations to estimate a climatology for Site 3 for 2005, based on imputations from the baseline Sonoma Valley 1 in 2005.
5. Compare modeled record for 2005 for Carneros 3 site with observed 2005 data.

References

Amerine, M.A., Winkler, A.J., 1944. Composition and quality of musts and wines of California grapes. Hilgardia 15 (6), 493–673.
Amerine, M.A., Berg, H.W., Kunkee, R.E., Ough, C.S., Singleton, V.J., Webb, A.D., 1980. The Technology of Wine Making. AVI Publishing Company, Inc, Westport, CT.
Arnold, R.A., Noble, A.C., Singleton, V.J., 1980. Bitterness and astringency of phenolic fractions in wine. Journal of Agricultural and Food Chemistry 28, 675–678.
Ashenfelter, O., 2008. Predicting the quality and price of Bordeaux wine. The Economic Journal 118 (529), F174–F184.
Bergqvist, J., Dokoozlian, N., Ebisuda, N., 2001. Sunlight exposure and temperature effects on berry growth and composition of Cabernet Sauvignon and Grenache in the central San Joaquin Valley of California. American Journal of Enology and Viticulture 52 (1), 1–7.
Buttrose, M., 1970. Fruitfulness in grape-vines: the response of different cultivars to light, temperature, and daylength. Vitis 9 (2), 121–125.
Cabrita, L., Fossen, T., Andersen, O.M., 2000. Colour and stability of the six common anthocyanidin 3-glucosides in aqueous solutions. Food Chemistry 68 (1), 101–107.
California Agricultural Statistics Service, 2007. Grape crush report: Final 2006 crop, California Department of Food and Agriculture, Sacramento, CA.
Campbell-Clause, J.M., 1998. Stomatal response of grapevines to wind. Australian Journal of Experimental Agriculture 38 (1), 77–82.
Cayan, D.R., Maurer, E.P., Dettinger, M.D., Tyree, M., Hayhoe, K., 2008. Climate change scenarios for the California region. Climatic Change 87 (Suppl 1), S21–S42.
Coombe, B.G., 1987. Influence of temperature on composition and quality of grapes. Acta Horticulturae 206, 23–35.
Cortell, J.M., Kennedy, J.A., 2006. Effect of shading on accumulation of flavonoid compounds in *Vitis vinifera* L. Pinot noir fruit and extraction in a model system. Journal of Agricultural and Food Chemistry 54, 8510–8520.
Cynkar, W.U., Cozzolino, D., Dambergs, R.G., Janik, L., Gishen, M., 2004. The effects of homogenisation method and freezing on the determination of quality parameters in red grape berries of *Vitis vinifera*. Australian Journal of Grape and Wine Research 10, 236–242.
Dokoozlian, N.K., Kliewer, W.M., 1995a. The light environment within grapevine canopies. I. Description and seasonal changes during fruit development. American Journal of Enology and Viticulture 46 (2), 209–218.
Dokoozlian, N.K., Kliewer, W.M., 1995b. The light environment within grapevine canopies. II. Influence of leaf area density on fruit zone light environment and some canopy assessment parameters. American Journal of Enology and Viticulture 46 (2), 219–226.
Downey, M.O., Harvey, J.S., Robinson, S.P., 2004. The effect of bunch shading on berry development and flavonoid accumulation in Shiraz grapes. Australian Journal of Grape and Wine Research 10 (1), 55–73.
Downey, M.O., Dokoozlian, N.K., Krstic, M.P., 2006. Cultural practice and environmental impacts on the flavonoid composition of grapes and wine: a review of recent research. American Journal of Enology and Viticulture 57 (3), 257–268.
Due, G., Morris, M., Pattison, S., Coombe, B.G., 1993. Modelling grapevine phenology against weather: considerations based on a large data set. Agricultural and Forest Meteorology 65 (1–2), 91–106.
Gladstones, J., 1992. Viticulture and Environment. Winetitles, Adelaide, South Australia, pp. 310.
Green, B.G., 1993. Oral astringency: a tactile component of flavor. Acta Psychologica 84, 119–125.
Guidoni, S., Allara, P., Schubert, A., 2002. Effect of cluster thinning on berry skin anthocyanin composition of *Vitis vinifera* cv. Nebbiolo. American Journal of Enology and Viticulture 53 (3), 224–226.
Haeger, J.W., Storchmann, K., 2006. Prices of North American Pinot Noir wines: climate, craftmanship, critics. Agricultural Economics 35, 67–78.
Happ, E., 1999a. Indices for exploring the relationship between temperature and grape and wine flavor. Australian Wine Industry Journal 14 (4), 68–75.
Happ, E., 1999b. Story time: no grape needs heat in the ripening cycle. Australian Wine Industry Journal 14 (6), 68–73.
Harbertson, J.F., Spayd, S., 2006. Measuring phenolics in the winery. American Journal of Enology and Viticulture 57 (3), 280–288.
Harbertson, J.F., Kennedy, J.A., Adams, D.O., 2002. Tannin in skins and seeds of Cabernet Sauvignon, Syrah, and Pinot noir berries during ripening. American Journal of Enology and Viticulture 53 (1), 54–59.
Harbertson, J.F., Picciotto, E.A., Adams, D.O., 2003. Measurement of polymeric pigments in grape berry extracts and wines using a protein precipitation assay combined with bisulfite bleaching. American Journal of Enology and Viticulture 54 (4), 301–306.
Hayasaka, Y., Kennedy, J.A., 2003. Mass spectrometric evidence for the formation of pigmented polymers in red wine. Australian Journal of Grape and Wine Research 9 (3), 210–220.
Hayhoe, K., Cayan, D., Field, C.B., Frumhoff, P.C., Maurer, E.P., Miller, N.L., Moser, S.C., Schneider, S.H., Kimberly, N.C., Cleland, E.E., Dale, L., Davis, F., Drapek, R., Hanemann, R.M., Kalkstein, L.S., Lenihan, J., Lunch, C.K., Neilson, R.P., Sheridan, S.C., Verville, J.H., 2004. Emissions pathways, climate change, and impacts on California. Proceedings of the National Academy of Sciences of the United States of America 101 (34), 12422–12427.
Horowitz, I., Lockshin, L., 2002. What price quality? An investigation into the prediction of wine-quality ratings. Journal of Wine Research 13 (1), 7–22.
Hunter, J.J., Ruffner, H.P., Volschenk, C.G., le Roux, D.J., 1995. Partial defoliation of *Vitis vinifera* L. cv. Cabernet Sauvignon/99 Richter: effect on root growth, canopy efficiency, grape composition, and wine quality. American Journal of Enology and Viticulture 46, 306–314.
Intergovernmental Panel on Climate Change, 2007. Summary for Policymakers. In: S. Solomon et al. (Eds.), Climate Change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 1–18.
Jones, G.V., 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 (3), 249–261.
Jones, G.V., Storchmann, K.-H., 2001. Wine market prices and investment under uncertainty: an econometric model for Bordeaux Crus Classes. Agricultural Economics 26 (2), 115–133.
Jones, G.V., White, M.A., Cooper, O.R., Storchmann, K., 2005. Climate change and global wine quality. Climatic Change 73, 319–343.
Kennedy, J.A., Matthews, M.A., Waterhouse, A.L., 2002. Effect of maturity and vine water status on grape skin and wine flavonoids. American Journal of Enology and Viticulture 53 (4), 268–274.
Kennedy, J.A., Ferrier, J., Harbertson, J., Peyrot des Gachons, C., 2006. Analysis of tannins in red wine using multiple methods: correlation with perceived astringency. American Journal of Enology and Viticulture 57 (4), 481–485.
Kennedy, J., Robinson, S., Walker, M., 2007. Grape and wine tannins: production, perfection, perception. Practical Winery and Vineyard, 57–67.
Kliewer, W.M., 1970. Effect of day temperature and light intensity on coloration of *Vitis vinifera* L. grapes. Journal of the American Society for Horticultural Science 95 (6), 693–697.
Kliewer, W.M., 1973. Berry composition of *Vitis vinifera* cultivars as influenced by photo- and nycto-temperatures during maturation. Journal of the American Society for Horticultural Science 98 (2), 153–159.
Kliewer, W.M., 1977. Influence of temperature, solar radiation and nitrogen on coloration and composition of Emperor grapes. American Journal of Enology and Viticulture 28 (2), 96–103.
Kliewer, W.M., Torres, R.E., 1972. Effect of controlled day and night temperatures on grape coloration. American Journal of Enology and Viticulture 23 (2), 71–77.
Lima, T., 2006. Price and quality in the California wine industry: an empirical investigation. Journal of Wine Economics 1 (2), 176–190.
Lobell, D.B., Nicholas Cahill, K., Field, C.B., 2007. Historical effects of temperature and precipitation on California crop yields. Climatic Change 81 (2), 187–203.
Mazza, G., Fukumoto, L., Delaquis, P., Girard, B., Ewert, B., 1999. Anthocyanins, phenolics, and color of Cabernet Franc, Merlot, and Pinot noir wines from British Columbia. Journal of Agricultural and Food Chemistry 47 (10), 4009–4017.
McIntyre, G.N, Kliewer, W.M., Lider, L.A., 1987. Some limitations of the degree-day system as used in viticulture in California. American Journal of Enology and Viticulture 38 (2), 128–132.
Mori, K., Goto-Yamamoto, N., Kitayama, M., Hashizume, K., 2007. Loss of anthocyanins in red-wine grape under high temperature. Journal of Experimental Botany 58 (8), 1935–1945.
Mullins, M.G., Bouquet, A., Williams, L.E., 1992. Biology of the Grapevine. Biology of Horticultural Crops. Cambridge University Press, Cambridge, UK, pp. 239.
Nemani, R.R., White, M.A., Cayan, D.R., Jones, G.V., Running, S.W., Coughlan, J.C., Peterson, D.L., 2001. Asymmetric warming over coastal California and its impact on the premium wine industry. Climate Research 19, 25–34.
Pastor del Rio, J.L., Kennedy, J.A., 2006. Development of proanthocyanidins in *Vitis vinifera* L. cv. Pinot noir grapes and extraction into wine. American Journal of Enology and Viticulture 57 (2), 125–132.
Peleg, H., Gacon, K., Schlich, P., Noble, A.C., 1999. Bitterness and astringency of flavan-3-ol monomers, dimers and trimers. Journal of the Science of Food and Agriculture 79, 1123–1128.
Roby, G., Matthews, M.A., 2004. Relative proportions of seed, skin and flesh, in ripe berries from Cabernet Sauvignon grapevines grown in a vineyard either well irrigated or under water deficit. Australian Journal of Grape and Wine Research 10, 74–82.

Please cite this article in press as: Nicholas, K.A., et al., Effect of vineyard-scale climate variability on Pinot noir phenolic composition. Agric. Forest Meteorol. (2011), doi:10.1016/j.agrformet.2011.06.010

Sampaio, T., Kennedy, J.A., Vasconcelos, M.C., 2006. Effect of rootstocks on anthocyanins and tannins in grapes and wine. American Journal of Enology and Viticulture 57 (3), 388–389.
Schultz, H.R., Stoll, M., 2010. Some critical issues in environmental physiology of grapevines: future challenges and current limitations. Australian Journal of Grape and Wine Research 16 (s1), 4–24.
Smart, R.E., 1988. Shoot spacing and canopy light microclimate. American Journal of Enology and Viticulture 39, 325–333.
Smart, R.E., Sinclair, T.R., 1974. Solar heating of grape berries and other spherical fruits. Agricultural Meteorology 17, 241–259.
Smith, A.K., June, H., Noble, A.C., 1996. Effects of viscosity on the bitterness and astringency of grape seed tannin. Food Quality and Preference 7, 161–166.
Smith, P.A., Mercurio, M.D., Dambergs, R.G., Francis, I.L., Herderich, M.J., 2008. Relationship between tannin concentration, variety, quality, and consumer preferences. Practical Winery and Vineyard, 5–13.
Snyder, R.L., Spano, D., Duce, P., 2003. Weather station siting. In: Schwartz, M.D. (Ed.), Phenology: An Integrative Environmental Science. Kluwer Academic Publishers, Dordrecht The Netherlands, pp. 345–361.
Spayd, S.E., Tarara, J.M., Mee, D.L., Ferguson, J.C., 2002. Separation of sunlight and temperature effects on the composition of *Vitis vinifera* cv. Merlot berries. American Journal of Enology and Viticulture 53 (3), 171–182.
Srinivasan, C., Mullins, M.G., 1981. Physiology of flowering in the grapevine: a review. American Journal of Enology and Viticulture 32 (1), 47–63.
Thomas, C.J., 1995. Astringent subqualities in acids. Chemical Senses 20, 593–600.
Valladao, M., Price, S.F., Watson, B.T., 1995. The phenolic composition of Pinot noir grape skin, seeds, and stems during maturation. American Journal of Enology and Viticulture 46 (3), 408–409.
Weaver, R.J., McCune, S.B., 1960. Influence of light on color development in *Vitis vinifera* grapes. American Journal of Enology and Viticulture 11, 179–184.
Webb, L.B., 2006. The Impact of Projected Greenhouse Gas-Induced Climate Change on the Australian Wine Industry. Ph.D. dissertation Thesis, University of Melbourne, Melbourne, Australia, 277 pp.
Webb, L.B., Whetton, P.H., Barlow, E.W.R.S., 2006. Potential impacts of projected greenhouse gas-induced climate change on Australian viticulture. Wine Industry Journal 21 (4), 16–20.
White, M.A., Diffenbaugh, N.S., Jones, G.V., Pal, J.S., Giorgi, F., 2006. Extreme heat reduces and shifts United States premium wine production in the 21st century. Proceedings of the National Academy of Sciences of the United States of America 103 (30), 11217–11222.
Winkler, A.J., Shemsettin, E.M., 1937. Fruit-bud flower formation in the Sultanina (Thompson Seedless). Hilgardia 10, 589–611.
Winkler, A.J., Cook, J.A., Kliewer, W.M., Lider, L.A., 1974. General Viticulture. University of California Press, Berkeley.
Wood, D., Anderson, K., 2006. What determines the future value of an icon wine? New evidence from Australia. Journal of Wine Economics 1 (2), 141–161.
Yamane, T., Jeong, S.T., Goto-Yamamoto, N., Koshita, Y., Kobayashi, S., 2006. Effects of temperature on anthocyanin biosynthesis in grape berry skins. American Journal of Enology and Viticulture 57 (1), 54–59.
Zoecklein, B., 2001. Grape sampling and maturity evaluation for growers. Vintner's Corner 16 (1).

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