**Impacts of Climate Change on Retail Prices of Coastal California Wines**

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## 1. Introduction

The potential impact of climate change on the world wine industry is of concern. French economist Patrice Geoffron, director of the Energy-Climate team at Paris-Dauphine University, says that climate change will have dire consequences for world wine. Climatologists project large enough changes in growing season temperatures in regions producing luxury wines that the wine qualities from appellations with close to optimal climate will start to decline due to future warming.

Climate change influences characteristics of winegrapes and therefore attributes of wines. Rising temperatures during the fruit maturation stage are likely to increase the beneficial synthesis of grape tannins, sugars, and flavors (Gladstones, 1992). Jones et al. (2005) show that climate change is likely to affect winegrape characteristics by altering conditions suitable for different grape varieties across appellations around the world. Historical evidence and projections signal that climate change is likely to result in changes in wine attributes for wines.

Literature shows that wine prices are often highly related to weather and wine characteristics. Ashenfelter, Ashmore, and Lalonde (1995) (for Bordeaux wines) and Byron and Ashenfelter (1995) (for Australian wines) find that weather conditions during the growing season of the vintage year explain more than 80% of the auction price variation in their sample. However, Ginsburgh, Monzak, and Monzak (2013) find that in addition to weather, third-party classification (1855 classification), soil and other natural endowments, production technologies, and appellation also explain variations in wine pricing. Jones and Storchmann (2001) (for Bordeaux wines) and Oczkowski (2001) (for Australian wines) show that the expert-assessed quality index (i.e. Parker-points or a score based on International Show Judging System) has a high correlation with wine prices. Alston et al. (2011) and Alston et al. (2015) examine whether climate change or changes in production techniques cause a trend toward wines with higher alcohol content. They find rising temperatures to some extent contributed to the higher sugar levels in grapes (potential alcohol), but that changes in wine styles may be the main cause of rising alcohol content in wines.

There is a large literature documenting the effects of climate change on winegrape productivity. Lobell, Schlenker, Costa-Roberts (2011) reviewed the global climate trend and its impact on multiple crops around the globe. They find that in the cropping regions and during growing seasons of most countries (with the exception of the United States), temperature trends from 1980 to 2008 exceeded one standard deviation of historic year-to-year variability. The negative impacts of warming climate trends offset the increases in average crop yields due to technological changes, and the elevated carbon dioxide concentration in the atmosphere. Adams, Wu, and Houston (2003) analyze the temperature effect on California grape (and other crop) yields. Based on a warming simulation scenario of 3°C and elevated carbon dioxide concentration, Adams, Wu, and Houston (2003) project that winegrape yield in the coastal California, including the Napa and Sonoma Valleys, will increase 90% by 2100. This projection by Adams, Wu and Houston (2003) is highly dependent on the methodology and to what extent adaptations are considered.

Ashenfelter and Storchmann (2016) review the abundant literature on the impact of climate change on wine and its economic implications. Climate change affects wine price and quality differently across regions and creates winners and losers for world wine producers. Nemani et al. (2001) suggest that climate change in coastal California between 1951 and 1997 may have benefited the California premium wine industry. Using annual quality ratings from Sotheby for the 1963 to 1996 period, they report an inverse relationship between ratings and number of winter frost days. Jones et al. (2005) analyze the effect of temperature on Sotheby's vintage ratings from 1950 to 1999 for all major wine regions worldwide. They project that with increasing temperatures, wine-growing regions in northern France and Germany will produce higher-quality wine, but that wine-growing regions in Spain (Rioja), California, and South Australia (Barossa Valley) may experience a decline in quality. Storchmann (2005) examines the weather determinants of wine quality of Schloss Johannisberg in the German Rheingau region from 1700 to 2003 and finds that periods of past warming improved the quality of Rheingau wines.

Facing climate change, wine producers adapt to weather outcomes over time. For within season practices, Ashenfelter and Storchmann (2016) review the potential adaptation strategies farmers might undertake in response to climate change. One such strategy is to adjust harvest date based on vines' phenological stages. For long term adaptation, increasing temperatures may induce grape growers to establish vineyards in cooler regions, for example areas further north or south, or into higher elevations. Alternatively, grape growers can change the variety planted for a given location that experiences warming. Ashenfelter and Storchmann (2016) list historical observations including harvest date changes due to heat wave in Australia, location changes of European vineyards in the past century, and variety composition changes in England and Germany winegrape production. However, to our knowledge, there are few empirical studies estimating to what extent the historical adaptations listed by Ashenfelter and Storchmann (2016) are due climate change, rather than technological and consumer preference change.

This paper investigates how weather and climate affect wine prices in Coastal California by examining the cross-sectional and time-series differences in climate and prices of California wines. This paper contributes to the literature by investigating in more detailed weather effects on wine prices in the coastal California appellations between 1996 and 2014. To do this, we use a large longitudinal database (more than 15,000 observations) of four wines varieties (Cabernet Sauvignon, Merlot, Pinot Noir, and Zinfandel) grown in coastal California and rated by Wine Spectator from 2000 to 2017.We investigate to what extent weather and climate influence wine prices and how does it differ across different climate measures.

## 2. Data and summary statistics

The dataset underlying this study is compiled from various sources. We downloaded suggested retail price information for wines produced in California from Wine Spectator's (WS) magazine with issue dates from January 2000 to December 2017. We included wines with vintage years from 1996 to 2014. Wines with vintage years earlier than 1996 were excluded because we consider that these wines are historical and the listed wine prices of these wines by WS magazine may be secondary market prices rather than suggested retail prices. Wines with vintage years later than 2014 were excluded because most of these red wines had not been released by December 2017 which is the latest WS magazine issue date in our dataset.

In total, our longitudinal dataset contains 15,266 wines. Each wine is defined by the information of brand or producer, appellation, vintage year, and winegrape variety. Wines with different vintage years are considered different wines in our dataset. We do not analyze the price development of a particular wine over time because there are very few wines that were repeatedly reviewed by WS magazine. Among the 15,266 wines, 39.1 percent are Cabernet Sauvignon, 10.1 percent are Merlot, 32.4 percent are Pinot Noir, and 18.4 percent are Zinfandel.

The weather data in our dataset are based on long-run gridded daily meteorology data from PRISM Climate Group at Oregon State University. The weather variables include winegrape growing season minimum temperatures, maximum temperatures and growing degree days (GDD) with the winegrape growing season defined as April 1st to October 31st. We extract weather information relevant to the 93 different wine appellations that appeared in the wine dataset from WS magazine. The appellation locations and boundaries are based on American Viticultural Areas Project provided by the libraries of University of California, Davis and University of California, Santa Barbara. We aggregate the grid level (4 km resolution) data to appellation level by taking an area average of gridded weather located in each appellation. Then, we aggregate the daily level data to annual level by taking an average of weather over the growing season.

[Table 1]

Table 1 reports the summary statistics of the variables in our dataset. The wine prices in Table 1 are real prices in 2010 dollars that are deflated using U.S. Consumer Price Index from 2000 to 2017. The average WS price for the entire sample is about 65 US dollars per bottle, while the median price is50 US dollars per bottle, with a standard deviation of about 54 US dollars. The lowest-priced wine in the sample costs 5 US dollars, while the highest sold at 845 US dollars. The fact that the mean price is much larger than the median price implies that the distribution of wine price has a long right tail at the high end of the price spectrum. Among the four types of wines, Cabernet Sauvignon has the highest mean price with the largest standard deviation of 72 US dollars in wine prices. Following the high prices of Cabernet Sauvignon, Pinot Noir has the second highest average wine price closely followed by Merlot. Zinfandel has the lowest average wine prices in our dataset which is 36 US dollars with a standard deviation of 21 US dollars.

The summary statistics for temperature data display a pattern that is consistent with climate expectations for different wine grape varieties. In Coastal California, the average growing season minimum temperature is about 10.36˚C, the average growing season maximum temperature is about 26.27˚C, the average growing season mean temperature is about 18.32˚C, and the average GDDs is about 1794.06˚C. In general, Cabernet Sauvignon, Merlot, and Zinfandel winegrapes are grown in regions that are warmer than regions growing Pinot Noir.

We detect significant warming trend in the growing season climate in coastal California from 1981 to 2017. The period that we estimated climate trend is slightly broader than the available wine price period (1996-2014) because we expect that the historical climate influences wine prices by affecting the reputation of the wine and hence wine prices, say historical climate from 1981 to 1996 affecting the prices of wine produced in 1996. We detect an asymmetric warming trend in coastal California wine appellations from 1981 to 2017, which is similar to findings in Nemani et al. (2001). The trend (1981-2017) in growing season minimum temperature shows a warming of 0.77°C/36 years across wine appellations in coastal California. Readers should note that the winegrape growing season (April - October) climate in our study does not include months in early spring that were included in the annual average temperature estimated by Neimani (2001), and the magnitude of annual warming estimated using our dataset is smaller than the findings by Neimani (2001). In our data, there were no significant changes in growing season maximum temperature and growing degree days from 1981 to 2017.

3. Empirical Strategy

The main empirical model to estimate climate change impact is similar to regression models used in Mérel and Gammans (2018) and Schlenker (2017), which is

$$\log(P_{it}) = \alpha_1 clmt_{it} + \alpha_2 clmt_{it}^2 + \alpha_3 (wthr_{it} - clmt_{it}) + \alpha_4 (wthr_{it} - clmt_{it})^2 + \beta X + \mu_{it} \quad (1)$$

where $\log(P_{it})$ is log value of real wine prices (deflated using CPI to 2010 US dollar) for wines produced in vintage year t with appellation i, the climate variable $clmt_{it}$ is the past 10 year moving average of growing season weather in appellation i in year t, say climate in 1996 is the mean weather from 1986 to 1995. Besides, we include weather variable $(wthr_{it} - clmt_{it})$, which is estimated as the deviation of current year growing season weather from current climate. Other covariant vector $\vec{X}$ include variety fixed effect (effect of wine type), market year fixed effect (effect of marketing), appellation fixed effect (vineyard characteristic effects), age of the wine, and quadratic trend using vintage years (technological change). The $\mu_{it}$ is the random error. The standard error of the estimates are cluster-robust standard errors clustering over the market year and the appellation. Following the suggestions of cluster-robust inference by Cameron and Miller (2015), it is easy to understand why we choose to cluster by appellation because 1) our climate and weather variables are perfectly correlated within an appellation by our data construction method, 2) we expect the prices of wines to be correlated within an appellation, and 3) the correlation could not be eliminated by appellation fixed effect. Similarly, clustering over market year is due to the following reasons: 1) the wine prices released in the same year are likely to be correlated, 2) climate to some extent are correlated within a market year, because most wines are released from 2 to 4 years from vintage year, and the climate within same vintage year is likely to be correlated. 3) the market year fixed effect cannot capture all the correlation within market year.

In the specification (1), our coefficients of interest are $\alpha_1$ and $\alpha_2$ which estimate a quadratic relationship between climate and wine prices. The marginal effect of climate on wine price is $\alpha_1 + 2\alpha_2 clmt_{it}$.The quadratic climate terms allows non-linear impact of climate on the wine price and that the marginal effect of climate on wine prices changes across the spectrum of climate.

There are different channels that climate may influence wine prices. One of such channels is that climate influence wine prices by changing the reputation of wine and cost of production for wines. There is an implicit monetary value of wine reputations that wine producers and grape growers collect premiums from, and consumers are willing to pay for. In many cases, consumers purchase wines based on various resources of wine reputation because they may have imperfect information about the wine before consumption, or they may be inexperienced in evaluating a collection of different wine attributes. An example of the various sources signaling the reputation of a wine is past wine reviews and evaluations made by wine critics for a specific appellation, or wine variety, or wine producer or vintage year. These wine reviews are usually based on subjective attributes of wines, i.e. aroma, color, taste, which are results of chemical attributes of grapes and winemakers' skills. Climate influences the implicit prices of wine reputation by affecting the distribution of grape characteristics and the resulting wine attributes.

In specification (1), the coefficients $\alpha_3$ and $\alpha_4$ estimate a quadratic relationship between weather deviations and wine prices. The marginal effect of weather deviation on wine price is $\alpha_3 + 2\alpha_4 clmt_{it}$. The basic assumption of including the weather deviations teams is that weather influences prices of wines differently compared to climate. One such example is that weather induces additional costs in production when weather deviation from climate produces certain undesirable grape characteristics that are not consistent with the reputation of the wine. In order to produce wines meeting the reputation and benefit from reputation premium, grape growers and wine producers may take additional actions to mitigate any undesirable grape characteristics due to weather extremes. Consequently, increases in marginal cost of product will increase wine prices due to weather extremes of a particular year. Webb et. al (2009) shows one such example of weather extremes that heat wave resulted in an increase in cost of production for Australia grape growers in 2009. The heat wave during late growing season but pre-harvest may result in grape acid drop such that the acid to sugar ratio of winegrapes may become too low if harvested on usual harvest date. In response to the heat wave, Australian grape growers changed harvest date by selectively harvesting grapes and trimming up some bunches to reduce negative impacts on grape characteristics, which however added to the cost of harvest, and hence wine price. However, the sign of the extreme weather impact on wine price may not be always positive. The extreme weather may reduce wine prices when the negative characteristics of grapes could not be mitigated by raising cost of production. For example, a cool growing season at the cold limit of viticulture results in a below-average vintage because of unripe and inferior fruit, and hence lower wine price (Ashenfelter and Storchmann, 2016).

We control additional covariates in the specification to address omitted variable concerns that unobservables may confound the estimates of climate and weather impacts on wine prices. We include quadratic trend terms to capture technological change in wine and grape production for the year of vintage, linear terms of wine age, wine variety fixed effect (four varieties), marketing year fixed effect using the issue year of WS magazine when the wine was tasted, and the appellation fixed effect.

The quadratic trend terms of vintage year are to capture the impact of technological change in wine production on wine price. For example, changes in winemakers' skills may result in changes in wine prices due to either changes in the cost of production, or changes in wine attributes. One such winemakers' skill example is cold fermentation techniques. Wine attributes such as aroma and color are highly sensible during the fermentation stage of winemaking. In the 1880s, when proper fermentation technique with temperature control was first introduced, there was a large improvement in producing desirable wine attributes such as delicate fruit flavors, and clear and translucent color.

The linear term of wine age is to capture the impact of wine age on wine prices. Firstly, age of wine maybe correlated with wine prices. For some collectible wines, age of wine has positive impact on wine prices. However, the age effect on wine prices for table wines (prices on the lower end of the spectrum) may be very small. The overall effect of age on wine prices produced in Coastal California is unclear. In addition, age of wine may associate with different cost of production, for example storage cost. Older wines require higher storage cost. Secondly, climate and weather may negatively influence the age of wine for sale. One such example is that good reputation wines (climate) may be more likely to sell at an earlier age give the high demand. Thus, we control wine age to avoid confounded estimate of the impact of climate on wine prices.

The marketing year fixed effect is to control the impact of shocks due to marketing and branding effort made by the winemakers on wine prices. Events such as innovative marketing strategies and substantial branding efforts in a specific market year greatly influence wine prices. For example. There is large increase in demand for and prices of Pinot Noir wines after the release of the movie "Sideways" in which the actor Paul Giamatti said Pinot Noir is "a hard grape to grow" and "only the most patient and nurturing of growers can do it." These events induce marketing conditions that influence wine prices with lasting impacts on the prices of wines sold in consecutive years after the events.

The appellation fixed effect is to control the impact of vineyard specific characteristics on wine prices. Vineyard characteristics affect wine attributes because grapes harvested from different vineyards can produce wines with different flavors. Even when such biological factors as variety, clone, and rootstock are identical, grape characteristics, and resulting wines are influenced by subtle differences in physical characteristics of the vineyard, including soil type, microclimate, slope, exposure, soil water holding capacity, and drainage (Johnson et al., 2001).

4. Regression Results

[Table 2]

Table 2 shows the results of fixed effect model estimate of climate impact on wine prices using specification (1). We cannot estimate the coefficients for all three-time dimensions (vintage year, market year, and wine age) because the covariate matrix became rank-deficient by including the all three time dimensions. We reported the coefficient estimates by removing the age of wine in Table 2. As can be inferred from the first column, we do not find evidence of wine prices responding average growing season maximum temperature in our sample. The marginal changes in wine prices per vintage year is $\frac{\partial \log(P_{it})}{\partial trend} = 29.18 - 2 \times 0.0073 \times \text{Vintage Year}$ (increase from 1996 to 2001, decrease from 2001 to 2014, maximum wine price in 2001)[1].

The 10-year moving average growing season minimum temperature turns out to be very significant in influencing wine prices. In Column (2), the significant coefficients for the

[1] We used the pre-rounded coefficients to estimate the marginal effect. Readers may not get the same value using the reported coefficients in Table 3 which are rounded to two significant digits.

quadratic terms of average growing season minimum temperature confirms the assumption that there is a quadratic relationship between the 10-year moving average of minimum temperature during growing season and wine prices. By taking the partial derivative and setting it to zero, one can calculate the optimal growing season minimum temperature from

$$\frac{\partial \log(P_{it})}{\partial Tmin_{it}} = \alpha_3 + 2\alpha_4 Tmin_{it} = 0. \quad (2)$$

Thus, the average growing season minimum temperature is 9.30˚C at its optimum for the entire growing season[2], which is substantially lower than the average growing season minimum temperature for most wines in our dataset[3]. Figure 1 displays growing season minimum temperatures for selected appellations and years compared with the 9.30˚C optimum, which is depicted in dashed line. While the minimum temperatures in appellations such as Napa Valley, Los Carneros and Lodi are consistently too high from the optimum, temperatures in Anderson Valley, and Carmel Valley are below the optimal temperature with small deviations.

Based on Column (3), the 10-year moving average growing season mean temperature has important influence on wine prices. We find non-linear response of wine prices with respect to growing season average temperatures. The optimal average growing season mean temperature is 17.38˚C[4], which is substantially lower than the average growing season mean temperatures in appellations in our sample. Figure 2 shows the growing season mean temperature at selected appellations with the 17.38-degree optimum, which is depicted in dashed line. Similar patterns are found comparing Figure 1 and Figure 2 that the 10-year moving average growing season

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[2] The optimal temperature is calculated using the pre-rounded coefficients. Readers may not get the same value using the reported coefficients in Table 3 which are rounded to two significant digits.

[3] The average growing season minimum temperature is 10.36˚C with standard error 0.0010˚C ($= 1.05˚C/1023\ observations$).

[4] The optimal value of growing season mean temperature is calculated using the pre-rounded coefficients. Readers may not get the same value using the reported coefficients in Table 3 which are rounded to two significant digits.

mean temperatures in appellations such as Napa Valley, Los Carneros and Lodi are consistently too high from the optimum, while temperatures in Anderson Valley, and Carmel Valley are below the optimal temperature with increasing deviations in more recent years.

Based on Column (4), the 10-year moving average growing degree days during growing season has non-linear impact on wine prices. The optimal growing degree days is 1579 Celsius Degree days[5], which, again, is substantially lower than the average growing season mean temperatures in appellations in our sample. Figure 3 shows the growing season mean temperature at selected appellations with the 1579-degree day optimum, which is depicted in dashed line. While the growing degree days in appellations such as Napa Valley, Los Carneros and Lodi are consistently too high from the optimum, growing degree days in Anderson Valley, and Carmel Valley are below the optimal degree days.

Table 3 summarizes the 10-year moving average of growing season minimum temperature, growing season mean temperature and growing degree days by appellations from 1996 to 2017. We calculate the average of the three climate measures over the 22 years (1996 – 2017), and the standard error. The time period includes more recent years (2015 – 2017) than the wine price available period (1996 – 2014) to reflect more recent climate of the appellations. We compare the average of the three temperature measures to the optimal temperatures we calculated based on the regression result from Table 2. Among the 93 appellations, there are 8 appellations that have significant lower temperatures than the optimal temperatures in terms all three measures, which are Anderson Valley, Carmel Valley, Cienega Valley, Eagle Peak of Mendocino County, Green Valley of Russian River Valley, Mendocino Ridge, San Benito, and

[5] The optimal value of growing degree days is calculated using the pre-rounded coefficients. Readers may not get the same value using the reported coefficients in Table 3 which are rounded to two significant digits.

York Mountain. Warming in these regions during winegrape growing season increases the wine prices because the temperature is approaching the optimal temperature in all three measures.

For most appellations (67 appellations out of 93 appellations) in our dataset, warming growing season in terms of higher growing season minimum temperature, higher growing season mean temperature and higher growing degree days will result in lower wine price. These appellations include appellations famous for Cabernet Sauvignon wines (a variety suitable for warm climate) such as Napa Valley, Rutherford, Oakville, and also appellations famous for Pinot Noir wines (a variety suitable for cool climate), such as Los Carneros, Russian River Valley, and North Coast.

## 5. Discussion

The trend estimated using the quadratic terms of vintage years in Table 2 consistently show an increasing trend in wine prices before vintage year 2000 and a decreasing trend after vintage year 2000 while taking into account of climate variation over vintage years, based on Column (2), (3) and (4) from Table 2. One possible explanation is that the 1990s (1996 to 2000 in our study) was considered the golden decade for California wine when wine producers realized the high-end wines are more profitable than cheap wines with large production and there was large increase in high-end wine production in the 1990s. The wine prices start to decline after vintage year 2000 when the rapid growth of the California wine industry overcrowded the wine market for California wines and resulted in lower wine prices. As an example to show the large increase in wine production, the number of wineries increased from 944 to close to 4000 different wineries from 1995 to 2005 (data from The Wine Cellar Insider). An alternative but implausible interpretation is that the technological changes produce undesirable characteristics of wines and hence lower wine prices after 2000. We find the second interpretation unlikely because wines produced in coastal California had good standing of rating from various resources (WS score, Parker score, etc.) for the given period.

Our regression results suggest an overall negative impact of warming climate on wine prices. Climate affect wine prices through two ways, 1) marginal cost effect, 2) reputation effect. An unfavorable climate which produce undesirable winegrape characteristics may increase the marginal cost of production that increase the wine prices, but at same time decrease the reputation of wines that decreases the wine prices in future years. Our finding of negative impact of climate suggest that the negative reputation loss due to warming climate is greater than the positive marginal cost effect due to warming. Our finding is consistent with findings from other studies that California wines are at the hot limit of viticulture (Haeger and Storchmann, 2006, Jones et al., 2001) and warmer growing season may become too warm for the existing varieties grown there.

Our find of optimal 10-year moving average of growing season mean temperature of 17.38˚C is lower than the optimal average of growing season mean temperature found in other studies. Gladstone (1992) suggests an average daily average temperature during the growing season of 20-22˚C is optimal for the formation of color, aroma and flavor for red table wines. Wood and Anderson (2006) find the optimal daily average temperature of 18.6˚C for auction price of Australian icon wines (Hill of Grace), conditional on wine age, rainfall during growing season and wind. It is challenging to directly compare the optimal growing season temperature estimates between our study and other studies because the definition of "optimal" varies across different studies, i.e. optimal red wine color, aroma and flavor in Gladstone (1992), optimal auction price in Wood and Anderson (2006), and optimal retail wine price in our study.

We do not find significant weather impact on wine prices after controlling climate impact. One possible reason is that there are mixed signals of weather impact on wine prices because weather deviation from climate may produce both desirable and undesirable grape characteristics such that unclear direction in influencing the cost of production.

We do not offer an interpretation for fixed effect estimates. First, the reason we include market year fixed effects and appellation fixed effect is to control any unobservables that are correlated with climate but are invariant across variety-appellation-year. It is difficult to interpret the fixed effect without the context of unobservables that is correlated with climate. Secondly, different from hedonic price method, the fixed effect coefficients in our study are not implicit prices for appellation or market year. It is true that consumers are likely to choose wines based on the appellation attribute by assigning implicit values to different appellations. However, an appellation represents all characteristics of this particular region, including climate, soil, and terrain. These characteristics jointly determined the implicit value of appellations. One may think of the coefficients of appellation fixed effects as implicit values for time-invariant characteristics of the region, i.e. soil and terrain. However, this interpretation is challenging in the way that these are implicit value for time-invariant characteristics of the region conditional on climate. When the climate differs, the implicit value for a particular bundle of time invariant characteristic of the appellation will change. Thus, directly comparing or ranking the fixed effect coefficients across appellation may be misleading and we do not offer interpretation of the fixed effects.

In this study, we do not investigate how climate will affect the quantity outputs of wine. Viticultural decisions highly influence wine qualities and quantities. For Coastal California wine industry, winemakers' viticultural decisions not to maximize crop yield determine the grape yield for expensive wines more so than weather effects. This contrasts to the situation in California's San Joaquin Valley, where grape growers attempt to compensate for low grape prices by maximizing yield. In that situation, weather may have an important impact on yield.

We do not investigate how climate will affect wine prices by influencing the suitable varieties. Many studies show climate change is likely to affect the suitable grape varieties grown in a given appellation (Ashenfelter and Storchmann 2016; Jones et al., 2005). Most studies define the suitability of a grape variety given a climate in two ways: 1) the biological suitability of the variety, 2) the economic suitability of a variety. However, to our knowledge, there is very few empirical studies actually estimate how much of the changes in winegrape varieties planted were due to climate change in the past. Ashenfelter and Storchmann (2016) review historical changes in winegrape varieties grown in England and Germany from 2004 to 2013. They find vineyards in England and Wales are shifting from cooler varieties (Reichensteiner and Seyval Blanc) to warmer varieties (Pinot Noir and Chardonnay). Vineyards in Germany sees increasing red-to-white ratio of the planted acreage from 1996 to 2014. However, these shifts may be a result of changes in consumer preferences, technological changes, and climate. It is not clear that to what extent the changes in planted acreage across different varieties were due to climate change.

6. Conclusion and future search

This article analyzes climate impact on coastal California wines prices. We find that for California coastal wine appellations, the relation between wine prices and growing season temperatures is not linear but quadratic. Most of the appellations are above the optimal growing season temperatures, and further warming is likely to decrease wine prices for California Coastal wines. Our studies provide limited interpretation on the estimate of climate impact of wine prices. We proposed to think of the climate impact on wine prices as changing reputation of the wines. However, climate may also affect the suitable variety of the region and hence different wine prices, which our study does not investigate.

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Figure 1. Long run (10-year) moving average growing season minimum temperature at selected appellations from 1996 to 2014, temperature in ˚C.

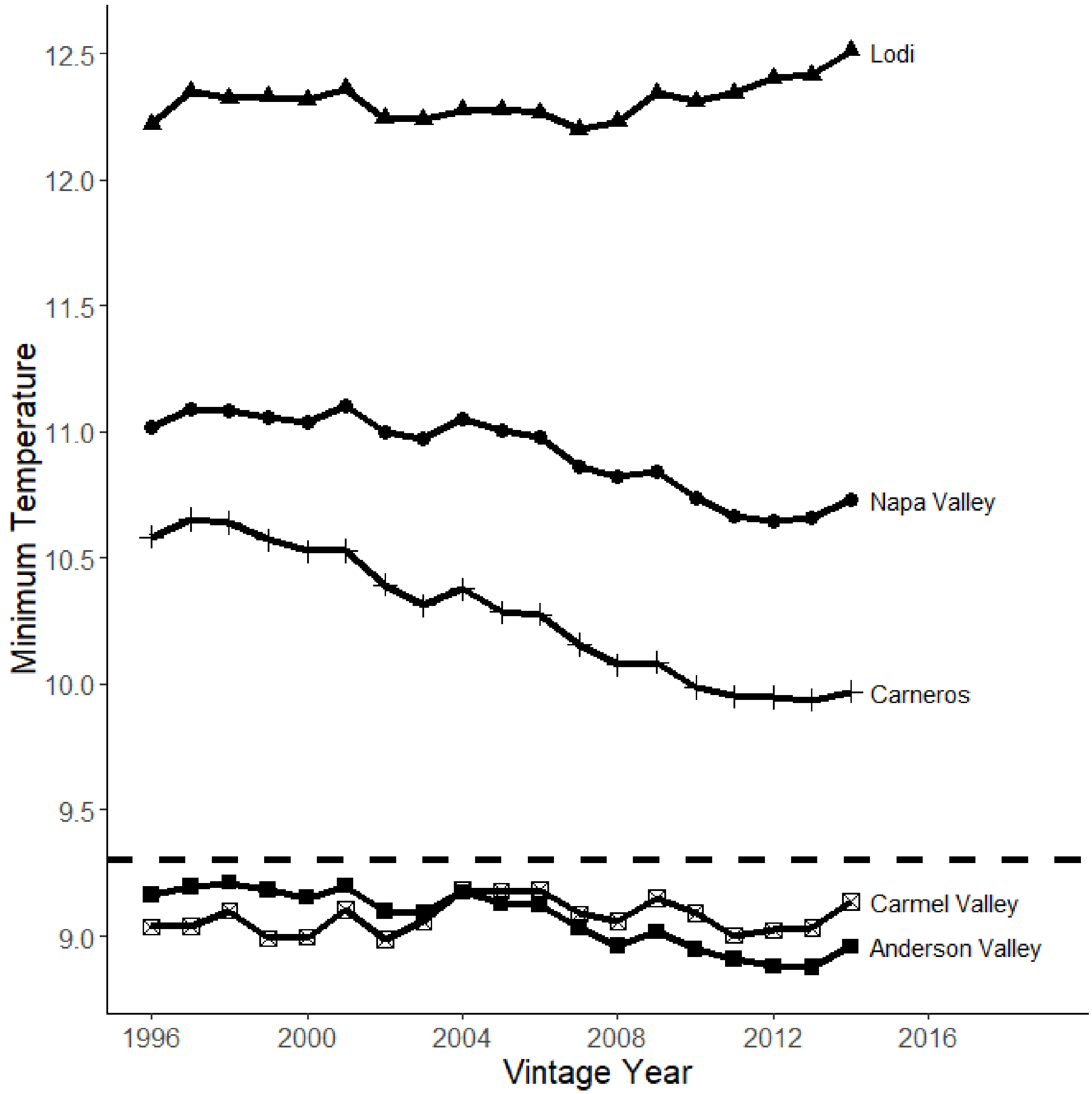

Figure 2. Long run (10-year) moving average growing season mean temperature at selected appellations from 1996 to 2014, temperature in ˚C.

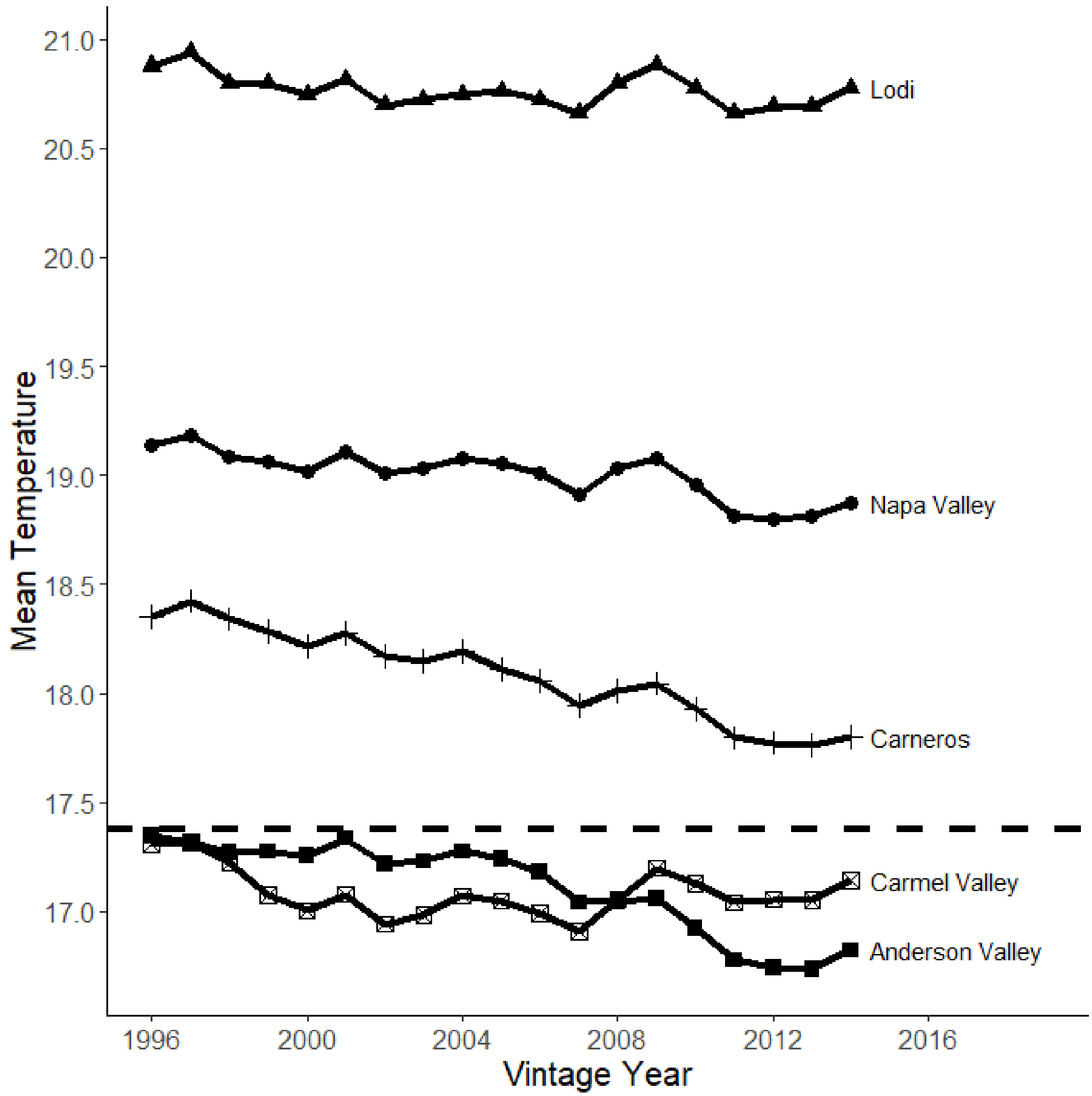

Figure 3. Long run (10-year) moving average growing degree days during growing season at selected appellations from 1996 to 2014, Celsius Degree days.

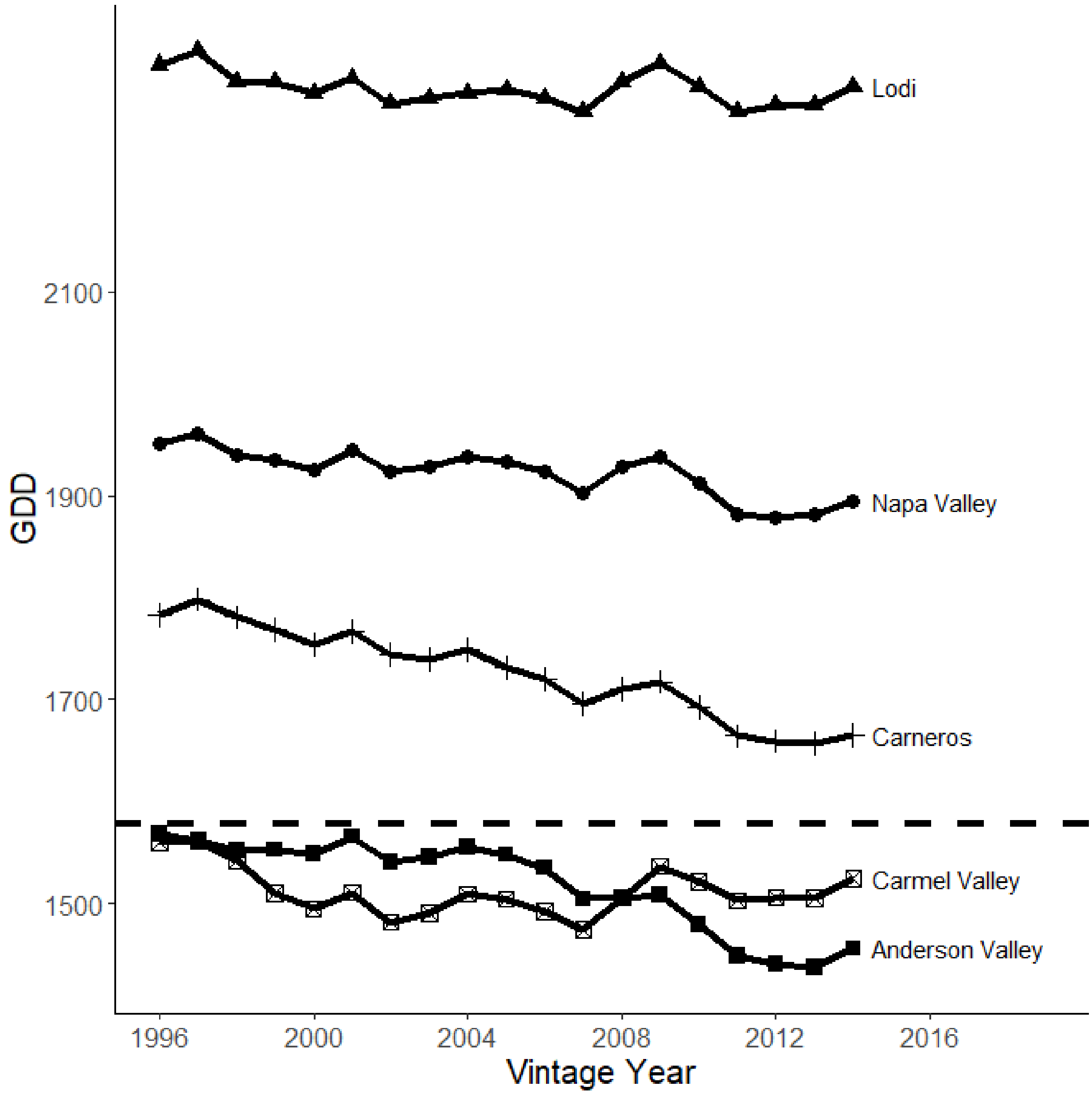

Table 1. Summary statistics of wine price, score and weather of appellations.

| Variables by variety | Obs. | Median | Mean | s.d. | Max | Min |
|---|---|---|---|---|---|---|
| Wine price | | | USD [e] | | | |
| Cab. Sauv. | 5974 | 76.50 | 93.07 | 72.00 | 845.50 | 5.10 |
| Merlot | 1548 | 39.69 | 48.12 | 32.78 | 427.50 | 8.16 |
| Zinfandel | 2802 | 32.31 | 36.39 | 21.48 | 138.15 | 8.40 |
| Pinot Noir | 4942 | 48.00 | 51.00 | 21.24 | 158.75 | 11.20 |
| All wines [a] | 15266 | 49.49 | 64.49 | 54.02 | 845.50 | 5.10 |
| Min. Temperature [b] | | | ˚C | | | |
| Cab. Sauv. | 518 | 10.44 | 10.44 | 0.86 | 14.17 | 7.31 |
| Merlot | 364 | 10.32 | 10.31 | 0.89 | 14.17 | 7.70 |
| Zinfandel | 452 | 10.50 | 10.56 | 1.19 | 15.49 | 7.31 |
| Pinot Noir | 454 | 9.88 | 9.87 | 0.76 | 12.08 | 7.70 |
| All wines | 1023 | 10.31 | 10.36 | 1.05 | 15.49 | 7.31 |
| Max. Temperature [b] | | | ˚C | | | |
| Cab. Sauv. | 518 | 26.58 | 26.70 | 1.41 | 30.94 | 22.81 |
| Merlot | 364 | 26.48 | 26.56 | 1.47 | 30.94 | 21.86 |
| Zinfandel | 452 | 26.56 | 26.61 | 1.73 | 30.97 | 21.69 |
| Pinot Noir | 454 | 25.50 | 25.52 | 1.64 | 30.62 | 20.65 |
| All wines | 1023 | 26.32 | 26.27 | 1.73 | 30.97 | 20.65 |
| Mean Temperature [b] | | | ˚C | | | |
| Cab. Sauv. | 518 | 18.55 | 18.57 | 0.88 | 20.86 | 16.17 |
| Merlot | 364 | 18.42 | 18.44 | 0.96 | 21.53 | 15.67 |
| Zinfandel | 452 | 18.51 | 18.58 | 1.24 | 23.23 | 15.30 |
| Pinot Noir | 454 | 17.67 | 17.70 | 0.95 | 20.68 | 15.28 |
| All wines | 1023 | 18.27 | 18.32 | 1.17 | 23.23 | 15.28 |
| Growing Degree Days [c] | | | ˚C | | | |
| Cab. Sauv. | 518 | 1842.25 | 1843.88 | 185.25 | 2340.54 | 1333.38 |
| Merlot | 364 | 1812.31 | 1816.20 | 199.75 | 2467.65 | 1258.04 |
| Zinfandel | 452 | 1836.00 | 1854.65 | 258.97 | 2830.75 | 1155.55 |
| Pinot Noir | 454 | 1649.89 | 1659.11 | 201.72 | 2286.12 | 1143.90 |
| All wines [d] | 1023 | 1784.90 | 1794.06 | 247.74 | 2830.75 | 1143.90 |

Note: [a] The dataset has total 15,266 wine-year observations based on the wine label and vintage years. For each wine, there is labeled appellation region and wine type. [b] The min/max/mean temperature is the min/max/mean temperature from April 1 to October 31. [c] The growing degree days is based on heat accumulation from April 1 to October 31 with daily temperature above 10 ˚C. [d] The dataset has total 1,023 appellation-year observations based on the 15,266 wine-year labels. There are total 93 appellations, and some of the appellation do not appear in the wine dataset thus the total appellation year is smaller than 1767 (93 appellations for 19 years). [e] The wine prices in US dollars are deflated 2010 dollars.

Table 2. Estimates of climate and weather impact on wine prices using specification (1).

| Dependent variable: log(Wine Price) | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| Explanatory variables | Temp. var: Tmax (˚C) | Temp. var: Tmin (˚C) | Temp. var: Tmean (˚C ) | Temp. var: GDD (100 ˚C) |
| 10 year moving average temperature growing season | 1.32 | 2.96 | 4.30 | 0.86 |
| | (1.43) | (0.54) | (1.47) | (0.30) |
| squared 10 year moving average temperature growing season | -0.025 | -0.16 | -0.12 | -0.027 |
| | (0.028) | (0.028) | (0.042) | (0.0092) |
| temperature deviation from 10 year moving average | -0.0094 | -0.00043 | 0.012 | 0.0060 |
| | (0.015) | (0.018) | (0.025) | (0.012) |
| squared temperature deviation from 10 year moving average | -0.011 | 0.041 | 0.0081 | 0.00085 |
| | (0.010) | (0.025) | (0.020) | (0.0048) |
| trend [a] | 29.18 | 25.58 | 26.12 | 26.13 |
| | (9.00) | (7.72) | (8.69) | (8.69) |
| squared trend [a] | -0.0073 | -0.0064 | -0.0065 | -0.0065 |
| | (0.0022) | (0.0019) | (0.0022) | (0.0022) |
| Fixed effects: market year effects [b] and appellation effects [c] and variety fixed effect [d] | Yes | Yes | Yes | Yes |
| adjusted R2 (include fixed effects) (%) | 41.93 | 42.68 | 42.28 | 42.29 |
| adjusted R2 (exclude fixed effects) (%) | 1.85 | 3.12 | 2.45 | 2.46 |
| Number of observations | 15266 | 15266 | 15266 | 15266 |

Note: value in parentheses are cluster-robust standard error clustering over market year and appellation. [a] The trend and squared trend terms are the linear and quadratic terms of vintage year labeled on the wine. [b] The market year effects are included as dummy variables of the issue year of the Wine Spectator Magazine when the wine is published. [c] The appellation effects are included as dummy variables of appellations labeled of each wine. [d] The variety fixed effects are included as dummy variables of four grape varieties of each wine, including Cabernet Sauvignon, Merlot, Pinot Noir and Zinfandel.

Table 3. The mean and standard error of the 10-year moving average growing season growing degree days, growing season minimum temperature, and growing season average temperature from 1996 to 2017.

| | (1) | | (2) | | (3) | |
|---|---|---|---|---|---|---|
| Appellations | GDD | | Tmin | | Tmean | |
| Adelaida District | 1746.80$^{++}$ | (3.89) | 7.45$^{--}$ | (0.022) | 18.18$^{++}$ | (0.018) |
| Alexander Valley | 1919.38$^{++}$ | (5.37) | 10.83$^{++}$ | (0.020) | 18.99$^{++}$ | (0.025) |
| Amador County | 1825.35$^{++}$ | (8.82) | 10.67$^{++}$ | (0.035) | 18.52$^{++}$ | (0.039) |
| Anderson Valley | 1518.90$^{--}$ | (10.37) | 9.07$^{--}$ | (0.027) | 17.11$^{--}$ | (0.049) |
| Arroyo Grande Valley | 1600.03$^{++}$ | (5.95) | 9.58$^{++}$ | (0.081) | 17.49$^{++}$ | (0.028) |
| Arroyo Seco | 1724.98$^{++}$ | (5.70) | 9.63$^{++}$ | (0.020) | 18.08$^{++}$ | (0.027) |
| Atlas Peak | 1869.53$^{++}$ | (7.12) | 10.68$^{++}$ | (0.039) | 18.76$^{++}$ | (0.033) |
| Bennett Valley | 1683.02$^{++}$ | (6.61) | 10.44$^{++}$ | (0.034) | 17.88$^{++}$ | (0.031) |
| Borden Ranch | 2310.45$^{++}$ | (4.03) | 12.47$^{++}$ | (0.016) | 20.82$^{++}$ | (0.019) |
| Calaveras County | 1949.82$^{++}$ | (11.29) | 11.05$^{++}$ | (0.052) | 19.12$^{++}$ | (0.051) |
| Calistoga | 1960.44$^{++}$ | (7.48) | 10.21$^{++}$ | (0.047) | 19.18$^{++}$ | (0.035) |
| Capay Valley | 2179.44$^{++}$ | (6.50) | 11.90$^{++}$ | (0.021) | 20.21$^{++}$ | (0.030) |
| Carmel Valley | 1512.67$^{--}$ | (5.47) | 9.08$^{--}$ | (0.015) | 17.09$^{--}$ | (0.026) |
| Carneros | 1726.31$^{++}$ | (10.24) | 10.28$^{++}$ | (0.059) | 18.09$^{++}$ | (0.048) |
| Central Coast | 1667.62$^{++}$ | (3.61) | 9.98$^{++}$ | (0.019) | 17.81$^{++}$ | (0.017) |
| Chalk Hill | 1771.87$^{++}$ | (9.55) | 10.16$^{++}$ | (0.062) | 18.30$^{++}$ | (0.045) |
| Chalone | 1807.46$^{++}$ | (10.70) | 8.99$^{--}$ | (0.047) | 18.46$^{++}$ | (0.050) |
| Chiles Valley | 1896.73$^{++}$ | (4.31) | 10.94$^{++}$ | (0.028) | 18.88$^{++}$ | (0.020) |
| Cienega Valley | 1482.16$^{--}$ | (7.46) | 7.66$^{--}$ | (0.027) | 16.94$^{--}$ | (0.035) |
| Clarksburg | 2241.28$^{++}$ | (7.04) | 12.02$^{++}$ | (0.015) | 20.50$^{++}$ | (0.033) |
| Clear Lake | 1820.61$^{++}$ | (6.10) | 9.68$^{++}$ | (0.016) | 18.51$^{++}$ | (0.027) |
| Cole Ranch | 1800.39$^{++}$ | (3.70) | 9.91$^{++}$ | (0.031) | 18.43$^{++}$ | (0.017) |
| Contra Costa County | 1936.04$^{++}$ | (8.95) | 11.98$^{++}$ | (0.023) | 19.07$^{++}$ | (0.042) |
| Coombsville | 1929.04$^{++}$ | (5.42) | 10.96$^{++}$ | (0.046) | 19.04$^{++}$ | (0.025) |
| Cucamonga Valley | 2516.90$^{++}$ | (5.33) | 14.08$^{++}$ | (0.027) | 21.79$^{++}$ | (0.025) |
| Diamond Mountain District | 1959.31$^{++}$ | (7.32) | 10.23$^{++}$ | (0.044) | 19.18$^{++}$ | (0.034) |
| Dry Creek Valley | 1944.94$^{++}$ | (7.97) | 10.81$^{++}$ | (0.041) | 19.11$^{++}$ | (0.037) |
| Dunnigan Hills | 2432.93$^{++}$ | (3.82) | 12.56$^{++}$ | (0.018) | 21.40$^{++}$ | (0.018) |
| Eagle Peak | 1385.32$^{--}$ | (4.24) | 7.80$^{--}$ | (0.019) | 16.43$^{--}$ | (0.026) |
| Edna Valley | 1455.04$^{--}$ | (5.13) | 9.99$^{++}$ | (0.049) | 16.82$^{--}$ | (0.024) |
| Eldorado | 1653.78$^{++}$ | (9.33) | 10.42$^{++}$ | (0.043) | 17.59$^{++}$ | (0.042) |
| Fiddletown | 2028.76$^{++}$ | (7.61) | 11.05$^{++}$ | (0.019) | 19.49$^{++}$ | (0.035) |
| Fort Ross Seaview | 1454.41$^{--}$ | (7.35) | 10.47$^{++}$ | (0.037) | 16.81$^{--}$ | (0.034) |
| Fountain Grove District | 1828.31$^{++}$ | (5.62) | 10.83$^{++}$ | (0.028) | 18.56$^{++}$ | (0.026) |
| Green Valley of Russian River | 1561.59$^{--}$ | (2.51) | 8.90$^{--}$ | (0.030) | 17.31$^{--}$ | (0.012) |
| Guenoc Valley | 2017.28$^{++}$ | (8.52) | 10.55$^{++}$ | (0.016) | 19.45$^{++}$ | (0.040) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Happy Canyon of Santa Barbara | 2080.13$^{++}$ | (4.02) | 10.69$^{++}$ | (0.018) | 19.74$^{++}$ | (0.019) |
| High Valley | 1950.01$^{++}$ | (10.88) | 10.86$^{++}$ | (0.048) | 19.12$^{++}$ | (0.049) |
| Howell Mountain | 1794.55$^{++}$ | (4.92) | 10.61$^{++}$ | (0.025) | 18.40$^{++}$ | (0.023) |
| Knights Valley | 1902.74$^{++}$ | (6.66) | 10.77$^{++}$ | (0.030) | 18.91$^{++}$ | (0.031) |
| Lake County | 1797.32$^{++}$ | (8.08) | 10.38$^{++}$ | (0.023) | 18.39$^{++}$ | (0.035) |
| Livermore Valley | 1834.88$^{++}$ | (7.05) | 11.62$^{++}$ | (0.013) | 18.59$^{++}$ | (0.033) |
| Lodi | 2298.75$^{++}$ | (3.74) | 12.31$^{++}$ | (0.018) | 20.77$^{++}$ | (0.018) |
| Malibu Newton Canyon | 1962.81$^{++}$ | (4.42) | 13.43$^{++}$ | (0.049) | 19.19$^{++}$ | (0.021) |
| Marin County | 1370.08$^{--}$ | (12.47) | 10.33$^{++}$ | (0.054) | 16.42$^{--}$ | (0.058) |
| Mendocino | 1718.15$^{++}$ | (4.27) | 9.78$^{++}$ | (0.021) | 18.04$^{++}$ | (0.020) |
| Mendocino Ridge | 1277.15$^{--}$ | (11.24) | 9.26 | (0.022) | 15.97$^{--}$ | (0.054) |
| Monterey | 1734.44$^{++}$ | (7.94) | 8.99$^{--}$ | (0.041) | 18.12$^{++}$ | (0.037) |
| Moon Mountain | 1836.53$^{++}$ | (9.51) | 10.59$^{++}$ | (0.035) | 18.60$^{++}$ | (0.045) |
| Mount Harlan | 1550.96$^{--}$ | (6.39) | 9.55$^{++}$ | (0.040) | 17.25$^{--}$ | (0.031) |
| Mount Veeder | 1862.40$^{++}$ | (8.73) | 10.90$^{++}$ | (0.036) | 18.72$^{++}$ | (0.041) |
| Napa County | 1966.42$^{++}$ | (4.36) | 11.08$^{++}$ | (0.033) | 19.21$^{++}$ | (0.020) |
| Napa Valley | 1921.91$^{++}$ | (5.56) | 10.91$^{++}$ | (0.037) | 19.00$^{++}$ | (0.026) |
| North Coast | 1641.79$^{++}$ | (5.38) | 9.96$^{++}$ | (0.021) | 17.69$^{++}$ | (0.025) |
| Northern Sonoma | 1765.38$^{++}$ | (4.84) | 10.11$^{++}$ | (0.028) | 18.27$^{++}$ | (0.023) |
| Oakknoll | 1878.56$^{++}$ | (8.58) | 10.53$^{++}$ | (0.054) | 18.80$^{++}$ | (0.040) |
| Oakville | 2002.62$^{++}$ | (8.01) | 10.68$^{++}$ | (0.037) | 19.38$^{++}$ | (0.038) |
| Paso Robles | 1884.02$^{++}$ | (4.21) | 8.21$^{--}$ | (0.026) | 18.82$^{++}$ | (0.020) |
| Paso Robles Willow Creek | 1625.15$^{++}$ | (5.83) | 7.55$^{--}$ | (0.027) | 17.61$^{++}$ | (0.027) |
| Petaluma Gap | 1485.54$^{--}$ | (10.03) | 9.67$^{++}$ | (0.055) | 16.96$^{--}$ | (0.047) |
| Pine Mountain Cloverdale Peak | 1964.95$^{++}$ | (3.93) | 11.65$^{++}$ | (0.032) | 19.20$^{++}$ | (0.018) |
| Potter Valley | 1667.12$^{++}$ | (4.91) | 8.57$^{--}$ | (0.022) | 17.79$^{++}$ | (0.021) |
| Red Hills Lake County | 1986.02$^{++}$ | (11.68) | 11.87$^{++}$ | (0.058) | 19.29$^{++}$ | (0.052) |
| Redwood Valley | 1627.67$^{++}$ | (4.08) | 8.44$^{--}$ | (0.023) | 17.61$^{++}$ | (0.018) |
| Rockpile | 1881.24$^{++}$ | (5.41) | 11.02$^{++}$ | (0.042) | 18.81$^{++}$ | (0.025) |
| Russian River Valley | 1634.53$^{++}$ | (6.20) | 9.52$^{++}$ | (0.048) | 17.66$^{++}$ | (0.029) |
| Rutherford | 2010.66$^{++}$ | (6.22) | 10.78$^{++}$ | (0.019) | 19.42$^{++}$ | (0.029) |
| San Benito | 1555.06$^{--}$ | (6.39) | 8.07$^{--}$ | (0.020) | 17.28$^{--}$ | (0.030) |
| San Bernabe | 1734.44$^{++}$ | (7.94) | 8.99$^{--}$ | (0.041) | 18.12$^{++}$ | (0.037) |
| San Francisco Bay | 1645.74$^{++}$ | (7.26) | 11.23$^{++}$ | (0.013) | 17.71$^{++}$ | (0.034) |
| San Joaquin County | 2295.18$^{++}$ | (3.74) | 12.55$^{++}$ | (0.031) | 20.75$^{++}$ | (0.018) |
| San Luis Obispo county | 1824.70$^{++}$ | (4.56) | 9.68$^{++}$ | (0.034) | 18.55$^{++}$ | (0.021) |
| San Mateo County | 1330.08$^{--}$ | (6.12) | 10.22$^{++}$ | (0.018) | 16.23$^{--}$ | (0.029) |
| Santa Barbara county | 1702.96$^{++}$ | (7.49) | 10.97$^{++}$ | (0.016) | 17.98$^{++}$ | (0.035) |
| Santa Clara Valley | 1769.59$^{++}$ | (5.47) | 12.37$^{++}$ | (0.039) | 18.28$^{++}$ | (0.025) |
| Santa Cruz Mountains | 1790.29$^{++}$ | (3.46) | 10.66$^{++}$ | (0.031) | 18.39$^{++}$ | (0.016) |
| Santa Lucia Highlands | 1565.86$^{--}$ | (5.00) | 9.73$^{++}$ | (0.024) | 17.33 | (0.023) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Santa Margarita Ranch | 1764.18$^{++}$ | (7.12) | 8.50$^{--}$ | (0.048) | 18.26$^{++}$ | (0.033) |
| Santa Maria Valley | 1615.25$^{++}$ | (5.19) | 10.15$^{++}$ | (0.027) | 17.57$^{++}$ | (0.024) |
| Santa Ynez valley | 1812.59$^{++}$ | (6.44) | 10.40$^{++}$ | (0.012) | 18.49$^{++}$ | (0.030) |
| Sierra Foothills | 2139.66$^{++}$ | (8.34) | 11.83$^{++}$ | (0.030) | 20.02$^{++}$ | (0.039) |
| Sonoma Coast | 1466.26$^{--}$ | (8.76) | 9.69$^{++}$ | (0.039) | 16.87$^{--}$ | (0.041) |
| Sonoma County | 1650.61$^{++}$ | (5.98) | 10.25$^{++}$ | (0.026) | 17.73$^{++}$ | (0.028) |
| Sonoma Mountain | 1795.89$^{++}$ | (7.03) | 10.48$^{++}$ | (0.022) | 18.41$^{++}$ | (0.033) |
| Sonoma Valley | 1743.21$^{++}$ | (9.59) | 10.39$^{++}$ | (0.041) | 18.16$^{++}$ | (0.045) |
| Spring Mountain District | 1890.56$^{++}$ | (4.70) | 11.01$^{++}$ | (0.020) | 18.86$^{++}$ | (0.022) |
| Stags Leap District | 1936.46$^{++}$ | (10.32) | 10.66$^{++}$ | (0.053) | 19.07$^{++}$ | (0.048) |
| Sta Rita Hills | 1589.77 | (12.79) | 10.16$^{++}$ | (0.016) | 17.45 | (0.060) |
| St Helena | 2014.13$^{++}$ | (4.95) | 10.96$^{++}$ | (0.014) | 19.43$^{++}$ | (0.023) |
| Suisun Valley | 2240.43$^{++}$ | (8.97) | 12.17$^{++}$ | (0.052) | 20.49$^{++}$ | (0.042) |
| York Mountain | 1547.11$^{--}$ | (5.22) | 8.63$^{--}$ | (0.035) | 17.25$^{--}$ | (0.024) |
| Yorkville Highlands | 1725.87$^{++}$ | (5.90) | 10.55$^{++}$ | (0.019) | 18.08$^{++}$ | (0.028) |
| Yountville | 1987.13$^{++}$ | (9.82) | 10.75$^{++}$ | (0.048) | 19.31$^{++}$ | (0.046) |

Notes: 1) Values in parenthesis are standard errors calculated as standard deviation divided by square root of number of observations (22 years from 1996 to 2017). 2) The optimal GDD based on regression result from Table 2 is 1579˚C. In Column (1), appellations with more than two standard errors above the optimal GDD is marked with $^{++}$, and appellations with more than two standard errors below the optimal GDD is marked with $^{--}$. 3) The optimal minimum temperature is 9.30˚C. In Column (2), appellations with more than two standard errors above the optimal minimum temperature is marked with $^{++}$, and appellations with more than two standard errors below the optimal minimum temperature is marked with $^{--}$. 4) The optimal mean temperature is 17.38˚C. In Column (3), appellations with more than two standard errors above the optimal mean temperature is marked with $^{++}$, and appellations with more than two standard errors below the optimal mean temperature is marked with $^{--}$. 5) The optimal temperatures are calculated using the pre-rounded coefficients. Readers may not get the same value using the reported coefficients in Table 2 which are rounded to two significant digits.