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CWE Working Paper number 1001
Reprinted in Journal of Wine Economics, Volume 6, Number 2, 2011, Pages 135–159

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Too Much of a Good Thing? Causes and Consequences of Increases in Sugar Content of California Wine Grapes*

Julian M. Alston[a], Kate B. Fuller[b], James T. Lapsley[c] and George Soleas[d]

Too Much of a Good Thing?
Some wine writers express their dismay
Over high alcohol cabernet
Burning coal, says Al Gore
Not the high Parker score
Is the cause of the rising baumé

Still a 15 percent chardonnay
Will be too hot to drink most would say
Lower Brix on the vine
Spinning tricks with the wine
Or a lie on the label might pay

Abstract

The sugar content of California wine grapes has increased significantly over the past 10–20 years, and this implies a corresponding increase in the alcohol content of wine made with those grapes. In this paper we develop a simple model of winegrape production and quality, including sugar content and other characteristics as choice variables along with yield. Using this model we derive hypotheses about alternative theoretical explanations for the phenomenon of rising sugar content of grapes, including effects of changes in climate and producer responses to changes in consumer demand. We analyze detailed data on changes in

* We are grateful for data provided by the Liquor Control Board of Ontario and Calanit Bar-Am. The work for this project was partly supported by the University of California Agricultural Issues Center. Authorship is alphabetical. We thank the editor and a referee for helpful comments and suggestions.
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the sugar content of California wine grapes at crush to obtain insight into the relative importance of the different influences. We buttress this analysis of sugar content of wine grapes with data on the alcohol content of wine. (JEL Classification: Q54, Q19, D12, D22)

I. Introduction

The sugar content of California wine grapes has increased significantly over the past 10–20 years, and this implies a corresponding increase in the alcohol content of wine made with those grapes. The sugar content of California wine grapes at harvest increased from 21.4 degrees Brix in 1980 (average across all wines and all districts) to 21.8 degrees Brix in 1990 and 23.3 degrees Brix in 2008.[1] Relative to the average sugar content in 1980 this amounts to an increase of almost 7 percent over the most recent 18 years and 9 percent over 28 years. Since sugar converts essentially directly into alcohol, a 9 percent increase in the average sugar content of wine grapes implies a corresponding 9 percent increase in the average alcohol content of wine. These changes might have resulted from changes in climate (e.g., generally hotter weather), cultural changes in the vineyard (e.g., later harvest dates) either in response to perceived demand for more-intense or riper-flavored wines (e.g., as reflected in higher "Parker" scores) or to mitigate the effects of climate change, or some combination of the two.

In this article, we document the increases in the sugar content of wine grapes and their implications for the alcohol content of wine in California, and evaluate the roles of exogenous changes in climate versus human responses (both in the vineyard and the winery) to climate change and other influences in determining the changing sugar content of wine grapes. Our main statistical analysis uses annual data, by variety of grapes and crush district, on the average sugar content of wine grapes at crush, for 1980 through 2008, along with other data on yield, acreage, and production of wine grapes by variety and county. This analysis is buttressed by an analysis of the changes over time in the alcohol content of California wine tested by the Liquor Control Board of Ontario (LCBO), Canada.

II. Evolution of California Winegrape Production

The primary motivation for this work came from the observation of rising sugar content of California wine grapes at harvest. The extent of change varied by variety and growing region, as well as over time, but it is clear that a shift towards higher sugar at harvest became evident in the mid 1990s and through the first decade of the 21st century. In the case of white varieties, which are generally picked at lower

[1] Degrees Brix (°Bx) is a measurement of the relative density of dissolved sucrose in unfermented grape juice, in grams per 100 milliliters. A 25 °Bx solution has 25 grams of sucrose sugar per 100 milliliters of liquid. The percentage of alcohol by volume of the finished wine is estimated to be 0.55 times the °Bx of the grape juice.

sugar than are red grapes, sugar at harvest increased by just under 12%, moving from an average sugar at harvest of 20.7 degrees Brix in the years 1980–1984, to 23.2 degrees Brix for the period 2005–2007. Red grapes increased from 22.2 to 24.3 degrees Brix for the same time period. Average degrees Brix at harvest for red varieties, as a single category, was reduced by the inclusion of Zinfandel, a red variety that is generally harvested at low sugar for the production of white Zinfandel. Indeed, average sugar at harvest barely changed for Zinfandel, rising from 22.0 only to 22.6 degrees Brix between 1980–1984 and 2005–2007. In contrast, Cabernet Sauvignon increased from 22.8 degrees Brix in 1980–1984 to 25.0 in 2005–2007. Figure 1 charts the rise of sugar at harvest for California as a whole.

Various other changes in the California wine and winegrape industry may have had some influence on the changes in the sugar content of winegrapes that are the focus of this article. During the 30 years between 1980 and 2010, California's winegrape vineyards changed dramatically. The most obvious difference was the physical expansion in total acreage and shift in the location of production. Bearing acreage increased by 60%, from 278,935 acres in 1981 to 445,472 acres in 2007.[2] Much of this increase was in the premium regions. Less obvious were the changes in the varietal composition of California's vineyards, with a shift over time to premium varieties used increasingly to produce wine with varietal labels.

Changes in the structure of the bearing and nonbearing age structure of the vineyard give some indication of the trends and cycles in production. Assuming an economic life of 30 years for a vineyard, and allowing that vineyards do not become productive until the fourth year, at any given time non-bearing acreage equal to approximately 10% of bearing acreage is required to replace aging vineyards that are soon to be grubbed out.[3] Figure 2, Panel *a* shows white and red non-bearing acreage as a percentage of total bearing acreage of white and red wine grapes, respectively, and the average price per ton of wine grapes in California.[4] Several points stand out. First, boom and bust cycles are evident, with nonbearing acreage well above 10% of bearing acreage in some periods, but well below in other periods. Second, red and white varieties were not replaced at the same rate.[5] In 1981, white varieties accounted for approximately 38% of the 278,935 bearing acres of wine grapes in California. By 1984, white varieties represented more than 50% of all acreage, and white varieties remained dominant until 1998, when

[2] Acreage figures are derived from the NASS/CDFA (1980–2010b) Grape Acreage Report. Figures for tonnage are derived from the NASS/CDFA (1980–2010a) Grape Crush Report.

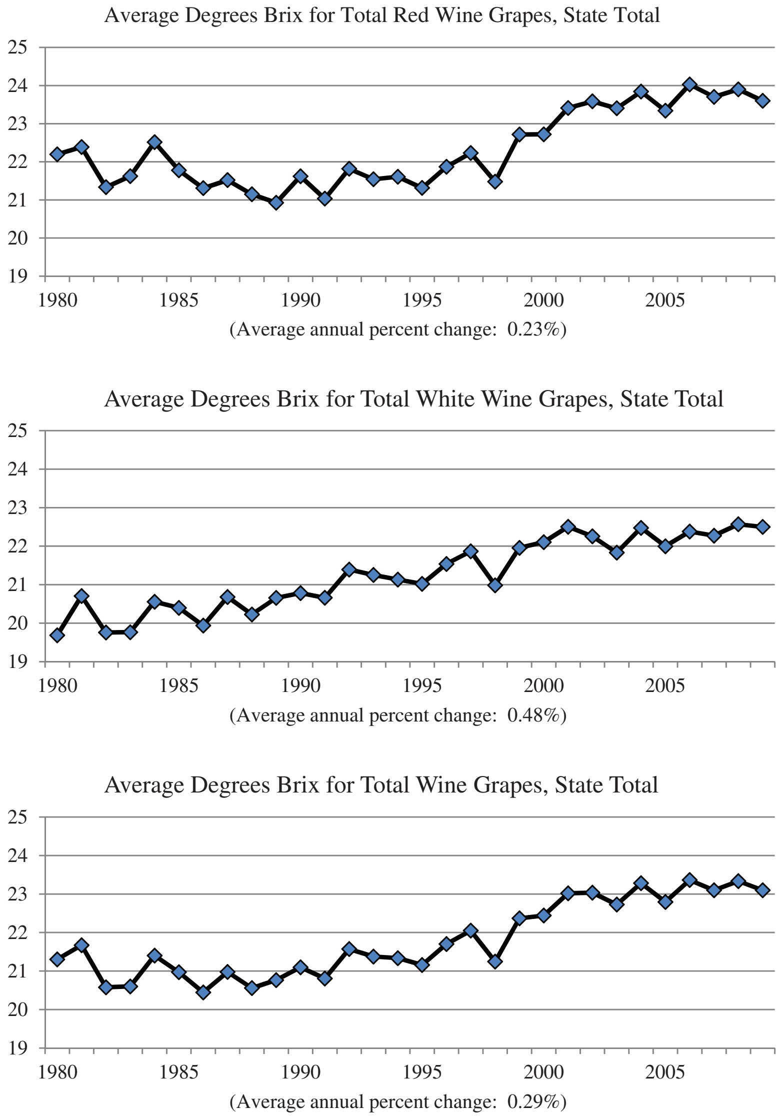
[3] Vineyards can certainly be productive for more than 30 years, but by that age, productivity declines and vineyards are often replanted. Because vineyards are often planted in cycles, vineyard age is not uniform over time and the 10% non-bearing acreage is merely a useful guideline rather than a precise figure.

[4] These prices were deflated using the price deflator for GDP, based in 2008.

[5] These figures treat Zinfandel as a red grape variety, although the vast majority of its fruit has been used to produce white Zinfandel, so it perhaps should be classified as a "white" grape variety.

Figure 1

Trends in Sugar Content (Degrees Brix) of California Wine Grapes, 1980–2008



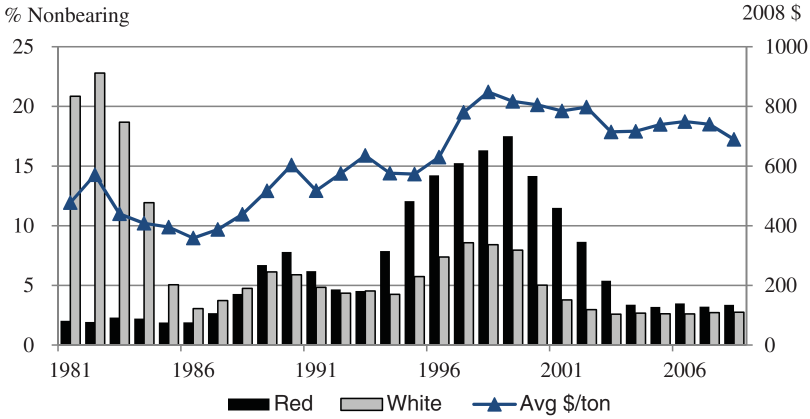
Source: Created by the authors using data from NASS/CDFA Grape Crush Reports, 1981–2010.

red varieties accounted for 50.7%. The trend toward red varieties has continued and in 2007 red varieties claimed just under 62% of all California winegrape acreage.

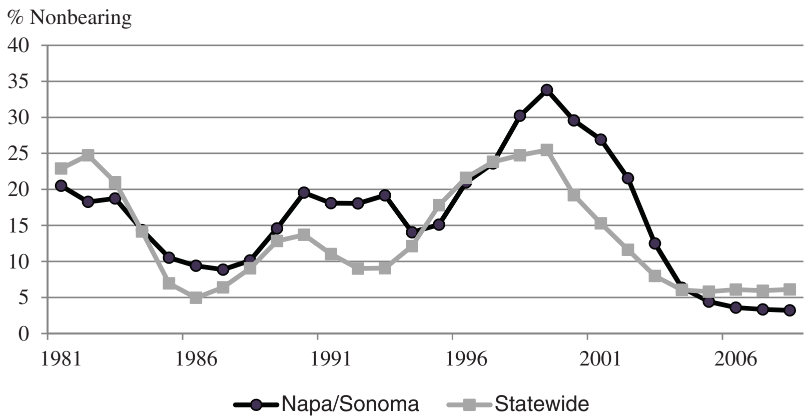
Figure 2

Nonbearing Acreage of Wine grapes as a Percentage of Bearing Acreage

Panel *a*:



Panel *b*:



Source: Created by the authors using data from NASS/CDFA Grape Acreage Reports, 1982–2010.

The state aggregate figures mask significant spatial variation. As can be seen in Figure 2, Panel *b*, in most years during the two decades from 1985 to 2005, Napa and Sonoma counties had a higher percentage of non-bearing acreage than did the state as a whole. These counties suffered a phylloxera infestation in the 1980s and 1990s, necessitating replanting of existing vineyards as well as new vineyard plantings to meet increased demand. During this period, wine consumers in the United States increasingly chose varietally labeled wine, leading to the dominance of "premium" varieties such as Chardonnay, Cabernet Sauvignon, Zinfandel, and Merlot. In 1985, only 19% of California table wine carried a varietal label, but within 15 years, by 2000, varietally labeled wine accounted for 71% of all California table wine by volume (Shanken, 2001, p. 97).[6] Although costly in materials and lost harvest revenue, the replanting in Napa and Sonoma roughly coincided with a market swing to red wine in the 1990s, and allowed vineyard owners to convert their vineyards to red varieties, especially Cabernet Sauvignon and Merlot, while adopting higher planting densities and new trellising systems.

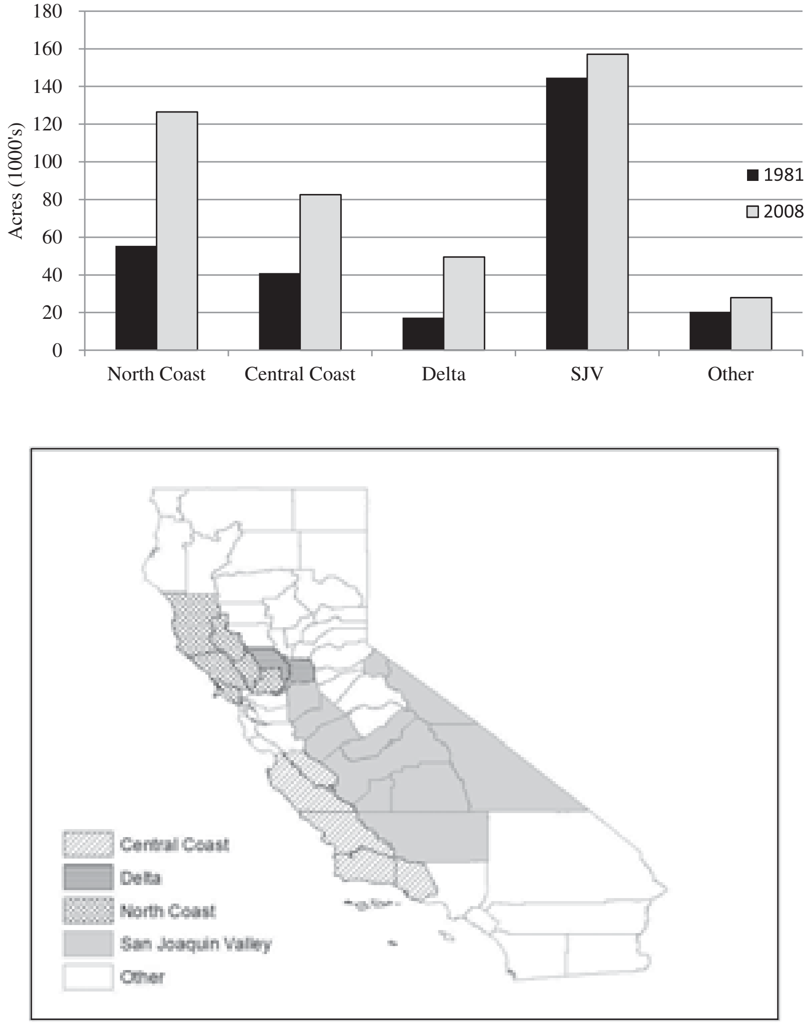
The trend to grow premium varieties of red wine was accompanied by a shift to produce a greater share of production in the premium regions. In 1981 slightly more than 50% of California's winegrape acreage was located in the southern San Joaquin Valley but by 2008, this percentage had fallen to slightly more than 33% of acreage. While total California winegrape vineyard acreage had expanded by 164,756 acres (a 59% increase), San Joaquin Valley acreage had increased by only 12,422 acres, or 8.5%. As can be seen in Figure 3, the areas experiencing the greatest percentage growth in acreage were the Delta, which grew by 185% from 17,355 acres in 1981 to 49,558 acres in 2008; the North Coast, which expanded by 128% from 55,474 acres in 1981 to 87,726 acres in 2008; and the Central Coast, which doubled in size from 41,015 acres in 1981 to 82,600 acres in 2008.[7]

California's vineyard regions differ significantly in yield and in perceived quality, which is reflected in the average price per ton paid for grapes from different regions. Figure 4 shows the average price per ton for Cabernet Sauvignon and Chardonnay wine grapes for five California viticultural areas in 2008. The price ranged from an average price of $4,648 a ton for Cabernet Sauvignon grown in Napa County, to a low of $363 a ton for the same variety grown in district 14, which is located at the southern end of the San Joaquin Valley. The higher prices paid for Cabernet from Napa and Sonoma counties reflect the very real compositional differences, such as higher acidity, deeper color, and greater intensity, relative to grapes grown in California's warm interior valley. To some extent the prices also are indicative of yield. In 2008, Napa County vineyards delivered 2.4 tons of Cabernet per acre, and neighboring Sonoma County yields were only a bit higher at 2.8 tons. In the warm interior valley, Delta vineyards produced 7.6 tons per acre of Cabernet while district 14 yielded 15.1 tons per acre. Monterey and San Benito counties in California's Central Coast, yielded 4.4 tons per acre.

[6] Under U.S. law, varietally labeled wine must contain at least 75% of the named variety.
[7] For the present purpose, we have divided California into five viticultural areas: (1) the "North Coast," including Napa, Sonoma, Mendocino, Lake and Marin counties; (2) the "Central Coast," including Monterey, San Benito, San Luis Obispo, and Santa Barbara counties; (3) the "Delta," which includes the northern portion of San Joaquin County and southern portions of Yolo and Sacramento counties adjacent to California's delta; (4) the "San Joaquin Valley," comprising southern San Joaquin County, Stanislaus, Merced, Madera, Fresno, Tulare, Kings and Kern counties; and "Other" which includes the Sierra foothills, southern California, and the northern Sacramento Valley (in aggregate the "Other" area comprises approximately 6% of vineyard acreage and 3.5% of total tonnage).

Figure 3

Regional Distribution of California Winegrape Acreage, 1981 and 2008

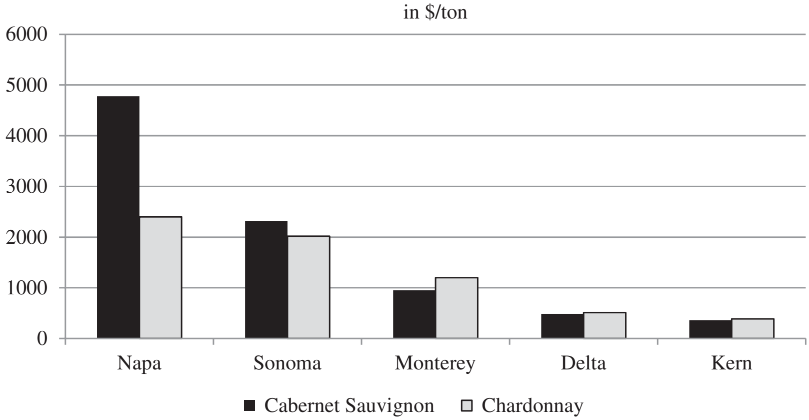


Source: Created by the authors using data from NASS/CDFA Grape Acreage Reports, 1982–2010.

In Figure 5, Panel *a* shows the percentage of tons by region while Panel *b* displays the percentage of value by region in 2008. The North Coast, which accounted for just less than 10% of all grapes crushed, commanded over 38% of all revenue. It is followed by the Central Coast, which grew 9.4% of all tons crushed and claimed 18.8% of revenue. The Delta, the coolest area of California's interior valley, delivered 17.1% of all grapes crushed, and received 13.5% of the revenue.

Figure 4

Price of Cabernet Sauvignon and Chardonnay in Various Places, 2008



Source: Created by the authors using data from NASS/CDFA Grape Crush Reports, 1981–2010.

The southern San Joaquin Valley, responsible for producing 61% of California's harvest, received just under 27% of the revenue. Clearly growing grapes is a significantly different business in Napa than in the San Joaquin Valley.

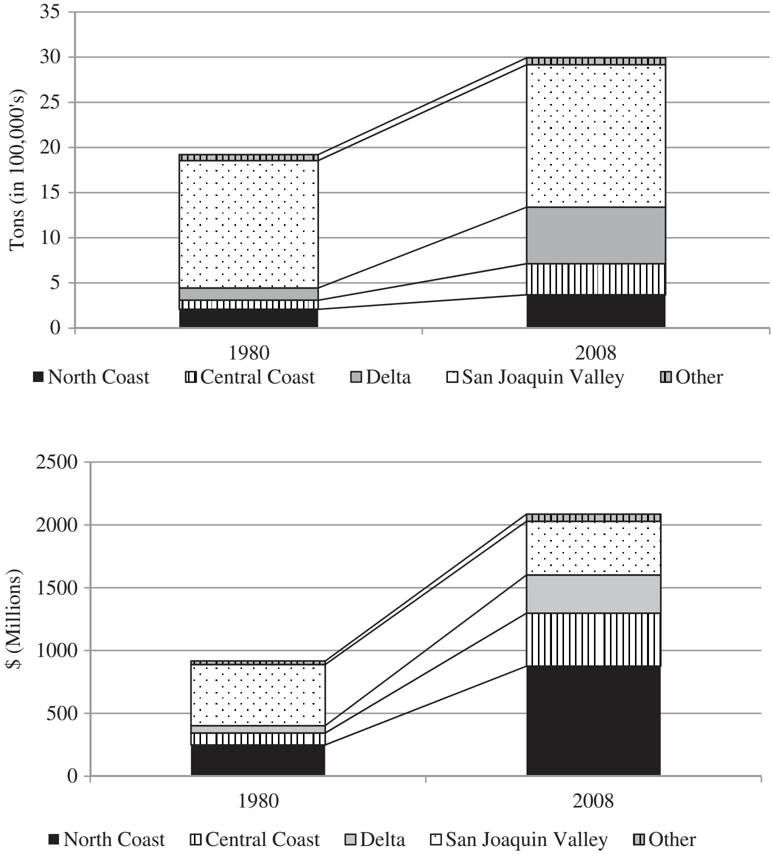
III. A Simple Model of Determinants of Sugar in Wine Grapes

It is unclear why sugar has increased at harvest but several contributing factors have been suggested. Global warming is often mentioned. For instance, average minimum temperatures in the San Joaquin Valley rose by about 2.5 degrees Fahrenheit (almost 1.4 °C) from the 1930s to the first years of the 21st century, and most of that increase became apparent during the most recent 20–30 years (Bar-Am, 2012, in process; see also Weare, 2009). Denser coastal vineyard plantings and new trellising systems are also often cited. Some wine makers point to the new rootstock/scion interactions that were introduced following the collapse of the rootstock, AXR to phylloxera, indicating that these new vineyards achieve sugar ripeness prior to reaching phenolic maturity, making it necessary for the grapes to "hang" longer than in the past. Still others claim that higher sugar at harvest is simply a style choice, with no underlying physiological reason to be found in the vineyard.

Whatever, the case, it is clear that higher sugar grapes, if fermented to dryness, result in higher alcohol wines. Higher alcohol in wines may or may not be a desired outcome. The presence of more alcohol can contribute to a perception of "hotness" for some consumers, while for others higher alcohol may add a sense of sweetness to the wine. However, under the United States tax system, wines above 14% alcohol by volume are taxed at $0.50 a gallon more than are wines with less than

Figure 5

Total Tons Harvested and Value in 1980 and 2008, by Region



Source: Created by the authors using data from NASS/CDFA Grape Crush Reports, 1981–2010.

14% alcohol by volume.[8] The demand to reduce alcohol concentrations has given rise to a new business in California, alcohol reduction. Currently two firms, Wine Secrets and ConeTech, specialize in alcohol removal. Use of such technology indicates a demand to reduce the alcohol content of wine.[9]

[8] Federal tax rates are $1.07 per gallon for wine having 7 to 14% alcohol and $1.57 per gallon for wine between 14 and 21% alcohol by volume. See http://www.ttb.gov/tax_audit/atftaxes.shtml

[9] Based on its production of "proof gallons," we estimate that ConeTech alone treated roughly 3.3 million gallons of wine per year for the four years 2005–2008, which represents a finished amount of approximately 16.5 million gallons (assuming 20% of a lot would be treated), or about 3% of California's annual wine production. ConeTech indicates that they have sold their technology to several large California wineries, but declined to name their clients.

In this section we develop a model of winegrape production and quality, including sugar content and other characteristics as choice variables along with yield, which we can use to derive hypotheses about alternative theoretical explanations for the phenomenon of rising sugar content of grapes. Growers' variable profit per acre of wine grapes of variety v grown in crush district d in year t is equal to gross revenue per acre (yield in tons per acre, Y_{vdt} times the price per ton, P_{vdt}) minus variable costs (the quantity of variable inputs used per acre, X_{vdt} times the price per unit of inputs, v_t). That is:

$$\pi^G_{dvt} = P_{dvt}Y_{dvt} - v_t X_{dvt}. \tag{1}$$

The price of wine grapes varies, depending on their sugar content, B (in degrees Brix) and other physical quality characteristics, Q (such as acidity), as well as the variety, V, the district, D, and the year, Y (reflecting market conditions). Thus:

$$P_{dvt} = \mathrm{p}(B_{dvt}, Q_{dvt}, D_d, V_v, T_t). \tag{2}$$

The yield of wine grapes varies among crush districts, varieties, and years, and with changes in the quantity of variable inputs, X; it also depends on weather conditions during the growing season in the crush district, W_{dt} (a complex of rainfall and temperature variables), and management practices applied to the particular variety, M_{dvt}. The yield relationship may also vary over time reflecting year-to-year and secular changes in technology that are not captured in the weather and management variables (e.g., because of changes in climate, rootstocks, pest and disease prevalence, or other factors), and the variable T_t is included to represent these aspects.

$$Y_{dvt} = \mathrm{p}(X_{dvt}, W_{dt}, M_{dvt}, D_d, V_v, T_t). \tag{3}$$

The sugar content of wine grapes (B) and other quality characteristics (Q) depend on the same factors that affect yield.

$$B_{dvt} = \mathrm{b}(X_{dvt}, W_{dt}, M_{dvt}, D_d, V_v, T_t). \tag{4}$$

$$Q_{dvt} = \mathrm{q}(X_{dvt}, W_{dt}, M_{dvt}, D_d, V_v, T_t). \tag{5}$$

Winemakers' variable profit per gallon of bulk wine (or equivalent quantity of wine grapes) produced using variety v grown in crush district d in year t is equal to gross revenue per gallon, G_{dvt} minus (a) the cost of excise taxes per gallon, E, which depend on the alcohol content of the wine, A_{dvt}, (b) the cost of the wine grapes, (c) variable costs of winemaking (the quantity of variable inputs used per gallon, Z_{vdt} times the price per unit of inputs, r_t), and (d) expenditure on removal of alcohol from wine, S_{vdt}.[10] That is:

$$\pi^W_{dvt} = G_{dvt} - E(A_{dv}) - P_{dvt}Y_{dvt} - r_t Z_{dvt} - S_{dvt}. \tag{6}$$

[10] It might be useful to disaggregate into several categories of winemaking inputs for some purposes but for now we treat Z as a scalar aggregate, as we did with X for grape production.

The value of wine per gallon depends on its alcohol content, A, other physical quality characteristics, K, as well as the variety, V, the district, D, and the year, Y.

$$G_{dvt} = \mathrm{g}(A_{dvt}, K_{dvt}, D_d, V_v, T_t). \tag{7}$$

The alcohol content of the wine depends on the sugar content of the wine grapes, but can be modified by the expenditure of effort, S.

$$A_{dvt} = \mathrm{a}(B_{dvt}, S_{dvt}). \tag{8}$$

Other quality characteristics of the wine depend on the same variables, as well as the quality characteristics of the wine grapes, Q, the quantity of winemaking inputs, Z, and oenological management practices in the winery, O.

$$K_{dvt} = \mathrm{k}(Q_{dvt}, O_{dvt}, B_{dvt}, S_{dvt}, A_{dvt}, D_d, V_v, T_t). \tag{9}$$

We draw informally on this model in proposing two hypotheses about the sources of the rise in sugar content of California winegrapes. In each case the increase in sugar content of grapes is seen as an unsought consequence of other factors. The first hypothesis is that exogenous changes in the weather, with generally rising average temperatures, imply increases in sugar content of grapes even without any changes in management of the vineyard.[11] Profit-maximizing responses of growers and wineries to such changes could mitigate the implications for sugar content of grapes but should not be expected entirely to eliminate their impact.

The second hypothesis is that the trend was caused by a market demand (perceived or real) for wines with ripe flavors and lower tannin levels, attributes associated with grapes that are picked at higher degrees Brix. Under this hypothesis, profit-maximizing responses of wineries and growers to changes in demand for quality characteristics of wine required changes in viticultural practices that resulted in unsought increases in sugar content of grapes. For instance, extending the "hang time" and picking the grapes later than they would do otherwise is likely to result in higher sugar content, if only because the grapes are more dehydrated.[12] To some extent *vignerons* can independently manage the sugar

[11] A literature is developing on the implications of climate and climate change for the wine industry, and some of that specific to California. Examples include Nemani *et al.* (2001), Tate (2001), Jones (2005, 2006, 2007), Jones *et al.* (2005), Webb *et al.* (2005), White *et al.* (2006), and Jones and Goodrich (2008). Issues addressed include various aspects of wine quality, yield, and the optimal location of production. Published work to date has not quantified the impacts on sugar content of grapes that are the subject of our work.

[12] More-specifically, influential wine writers, such as Robert Parker of the *Wine Advocate* or James Laube of the *Wine Spectator*, may have encouraged the production of wines with strong, intense, riper fruit flavors, by giving very favorable ratings for such wines. This argument applies more directly to ultra-premium wines than to the large volume end of the market that is not subject to wine ratings, and probably more to red wines than white wines. However, changes in the ultra-premium end of the market might have led to similar subsequent movements in wines in the lower price categories. In addition, some of the market growth of moderately priced wines might have been facilitated by an emphasis on similar styles of wine that are attractive to less experienced wine consumers.

content of grapes and other quality characteristics, but an increase in intensity and ripeness of fruit is likely to come to some extent at the expense of a reduction in tons per hectare and an increase in degrees Brix.[13]

IV. Changing Sugar Content of California Wine Grapes

We assembled a very detailed data set (from annual crush reports and various other sources) that includes (a) annual data by variety of grapes and crush district on the average sugar content of wine grapes at crush, extending from 1980 through 2008, (b) other data on yield, acreage, and production of wine grapes by variety and county, and (c) daily data on temperatures by crush district. Using these data, we estimated variants of the following model to examine the extent of changes in degrees Brix (*BRIX*) over time among crush districts and varieties and the role of climate as represented by a heat index:

$$BRIX_{dvt} = \beta_0 + \beta_h H_{dt} + \sum_{j=1}^{V} v_j VAR_{vj} + \sum_{i=1}^{D} \delta_d DIST_{di} + \tau_0 T_t + \sum_{j=1}^{V} \tau_j^v \left(VAR_{vj} \times T_t\right) + \sum_{i=1}^{D} \tau_i^d (DIST_{di} \times T_t) + \epsilon_{dvt} \qquad (10)$$

In this model, H_{dt} is a weather variable, the "heat index" for crush district d during the growing season in year t. The other variables are dichotomous dummy (or indicator) variables such that $VAR_{vj} = 1$ if $j = v$, 0 otherwise, and $DIST_{di} = 1$ if $i = d$, 0 otherwise), and a time trend, T_t.

A. *Definitions of Variables and Data for the Analysis*

We have data for the years 1980–2008 on average degrees Brix for over 200 varieties in 17 crush districts. (The number of varieties reported changes from year to year and from district to district. Varieties include wine, table, and raisin grapes.)[14] Table 1 reports average annual growth rates over the longer period 1980–2008 as well as 1990–2008, for a selection of important varieties, as well as for all red, all white, and all varieties, in each of the main production regions and for California as a whole. The data in the table are suggestive of the possibility that growth rates may have differed systematically among regions and varieties, an issue that we examine next. The statistical analysis that follows uses only the data for the

[13] A literature on the economic effects of weather and climate on wine quality has developed over the past 20 years, with contributions such as Ashenfelter, Ashmore and Lalonde (1995), Ashenfelter and Byron (1995), Jones *et al.* (2005), Storchmann (2005), Ashenfelter (2008), and Ashenfelter and Storchmann (2010).

[14] These data were compiled from the Annual Grape Crush Reports, published by NASS/CDFA, various issues.

Table 1
Trends in Sugar Content of California Wine Grapes (Degrees Brix), by Variety and Region

(a) 1980–2008

	Region					
Variety	*North Coast*	*Central Coast*	*Delta*	*San Joaquin Valley*	*Southern California*	*California*
	average annual percentage change					
Sauvignon Blanc	−0.02	0.11	0.05	0.51	0.20	0.16
French Colombard	−0.12	–	0.25	0.22	–	0.20
Chardonnay	0.18	0.32	0.29	0.37	0.19	0.18
Chenin Blanc	0.05	0.29	0.30	0.33	−0.11	0.29
All White Varieties	0.30	0.42	0.68	0.40	0.61	0.47
Cabernet Sauvignon	0.30	0.25	0.33	0.23	0.38	0.25
Merlot	0.15	0.32	0.38	0.10	–	0.19
Zinfandel	0.37	0.17	0.07	−0.29	0.07	−0.16
Pinot Noir	0.39	0.30	–	0.72	–	0.42
All Red Varieties	0.36	0.35	0.27	0.17	0.18	0.26
All Varieties	0.34	0.38	0.34	0.22	0.30	0.31

(b) 1990–2008

	Region					
Variety	*North Coast*	*Central Coast*	*Delta*	*San Joaquin Valley*	*Southern California*	*California*
	average annual percentage change					
Sauvignon Blanc	0.18	0.39	0.08	0.37	0.42	0.21
French Colombard	−0.05	–	0.19	0.04	–	0.04
Chardonnay	0.35	0.49	0.39	0.22	0.00	0.32
Chenin Blanc	0.12	0.72	0.23	0.16	0.07	0.20
All White Varieties	0.36	0.63	0.69	0.26	0.25	0.43
Cabernet Sauvignon	0.50	0.49	0.46	0.29	0.53	0.42
Merlot	0.44	0.55	0.44	0.18	0.35	0.40
Zinfandel	1.11	1.01	1.02	0.33	0.60	0.55
Pinot Noir	0.88	0.63	0.75	1.49	0.26	0.87
All Red Varieties	0.72	0.75	0.96	0.31	0.49	0.53
All Varieties	0.57	0.69	0.85	0.36	0.43	0.53

Notes. Entries in this table are average annual percentage changes, computed as ln(final value) – ln(initial value) divided by the number of years and multiplied by 100. For some years and some varieties, records are unavailable. In the table, this is indicated by "—."
Source: Created by the authors using data from NASS/CDFA Grape Crush Reports, 1981–2010.

more recent period, 1990–2008, for which the data are more consistent and more complete, and the estimated relationships are more likely to be stable and meaningful.

The daily measure of growing degrees (GDs) is equal to the average of the daily minimum and daily maximum temperature minus a base temperature of 50°F. The growing season for wine grapes is defined as extending over the six months, April through September. The accumulated total of growing degree units (GDUs) is the sum of GDs accumulated during the season. We use a growing season heat index, *H* defined as the average daily GDs during the growing season, equal to the accumulated GDUs divided by the total number of days.[15] We also experimented with the same variable applied to different periods (e.g., the entire year or particular months).

The data on monthly temperature averages were obtained from NOAA's National Climatic Data Center (NOAA, 2010). From hundreds of NOAA stations within California, we chose one weather station for each of the 17 crush districts. While more localized data would have been preferred, none were available. However, Lecocq and Visser (2006) showed that while highly localized data make for better-fitting models, weather station data approximate the disaggregated data quite well (see, also, Haeger and Storchmann, 2006). We attempted to find stations that were geographically central to wine-growing areas within each district, while making sure that the station locations were not at higher altitudes, or were otherwise different from the areas where winegrapes are grown. In some instances, it was difficult to find a well-located station for which data were available for each month in the entire span of time we are examining. Some stations are relatively new, and so do not have historical data reaching more than several years back. Other stations have been shut down or have large gaps in reporting. As a result, we used some data from stations that were not ideal for our purposes, and we used the same weather station for districts 11 and 12.[16] Faced with a similar

[15] We thank Professor Andrew Walker from the Department of Viticulture and Enology at UC Davis for advising us about the appropriate choice of a heat index for our purpose.

[16] We were able to obtain data from the NOAA website for a number of weather stations in the Napa Valley on monthly average temperatures for the years 1990 through 2007, that we could use to compute our growing season heat index. None of these stations is located in the center of the vineyard area in the Napa Valley, and away from urban and other influences, as would be ideal for the purpose. Temperatures vary significantly within the valley, tending to increase as you go North and East, and consequently particular locations may not be fully representative of the Valley as a whole. In our initial analysis we used data from Markley Cove, which is at a higher altitude on the Eastern edge of Napa County, and somewhat warmer than locations in the Valley floor, especially at the Southern end. Data from Napa City Hospital, at the Southern end of the Valley, reflect a combination of urban influence and generally cooler conditions. Data from Healdsburg, which we used for Sonoma county, are more likely to be representative of the Napa Valley as a whole, because Healdsburg has temperature patterns quite similar to those of St Helena, which is somewhat warmer than the city of Napa, at the Southern end of the Valley. When we tried using data for Healdsburg instead of Markley Cove, the results were essentially identical. Based on this analysis we concluded that the results were not sensitive to the choice, and we report the results we obtained in the first instance, using data from Markley Cover to represent the Napa crush district.

Table 2
Definitions of Regions

Region (average winegrape price in 2008)	*Includes Crush Districts*
Ultra-premium (> \$2,000/ton)	3 (Sonoma) 4 (Napa)
Premium (\$1,000 – \$2,000/ton)	1 (Mendocino) 2 (Lake) 6 (San Francisco area) 7 (Monterey, San Benito) 8 (Santa Barbara area) 10 (Sierra Foothills area) 15 (Los Angeles, San Bernardino) 16 (San Diego area)
Fine (\$500 – \$1,000/ton)	5 (Solano) 9 (Northern California area) 11 (San Joaquin, part of Sacramento) 17 (parts of Yolo, Sacramento)
Ordinary (< \$500/ton)	12 (Merced area) 13 (Fresno area) 14 (Kern, parts of Kings, Tulare)

problem, Storchmann (2005) regressed Rhine wine quality on English weather from 1700–2003.

We tried the model in equation (11) with different aggregations of varieties and districts in preliminary analysis. To reduce the dimensions of the problem of reporting and interpreting results we opted to aggregate crush districts into four larger regions based on the average price of wine grapes in 2008. Table 2 shows the districts as classified. Similarly, rather than model individually every winegrape variety we included various aggregates such as "red" versus "white," and "premium" versus "non-premium" varieties, where "premium" included Cabernet Sauvignon, Merlot, and Chardonnay (we tried including Pinot Noir as well, but the results were not affected much).

B. *Regression Results for Model of Changes in Brix in California, 1990–2008*

Each of the four columns in Table 3 refers to a different variant of the model in equation (12). We estimated each model by ordinary least squares (OLS) but where possible we used Newey-West robust standard errors for hypothesis testing rather than the conventional OLS robust standard errors. We also ran the model with cluster-robust standard errors, but the effect on the results was very small. As well as estimating each model using conventional OLS we also estimated each model using weighted regression, where the data from each crush district were weighted

Table 3
Brix Regression Results, Annual Observations 1990–2008

a: Weighted Observations

Regressor	*(1)*	*(2)*	*(3)*	*(4)*
Constant	20.91**	18.79**	19.25**	0.58**
	(0.107)	(0.447)	(0.418)	(0.424)
	[0.187]	[0.649]	[0.616]	
Trend	0.14**	0.10**	0.02	0.01**
	(0.011)	(0.009)	(0.011)	(0.007)
	[0.020]	[0.015]	[0.018]	
Variety				
Red		0.96**	0.22	0.19**
		(0.087)	(0.158)	(0.091)
		[0.156]	[0.274]	
Premium		1.89**	2.25**	0.36**
		(0.072)	(0.119)	(0.100)
		[0.123]	[0.200]	
Region				
Ultra-premium		1.34**	0.48	0.40**
		(0.121)	(0.176)	(0.116)
		[0.189]	[0.290]	
Premium		1.71**	0.80*	0.50**
		(0.206)	(0.215)	(0.140)
		[0.302]	[0.336]	
Fine		0.28	– 0.91*	0.18**
		(0.137)	(0.265)	(0.154)
		[0.241]	[0.463]	
Heat Index (Growing Season Average Degree Days)		0.04*	0.05*	0.03**
		(0.018)	(0.017)	(0.010)
		[0.027]	[0.025]	
Trend × Region				
Ultra-Premium			0.09**	– 0.01
			(0.014)	(0.009)
			[0.023]	
Premium			0.09**	– 0.00
			(0.013)	(0.009)
			[0.021]	
Fine			0.10**	0.00
			(0.023)	(0.013)
			[0.040]	
Trend × Variety				
Red			0.08**	0.00
			(0.005)	(0.008)
			[0.025]	
Premium			– 0.03**	– 0.02**
			(0.0051)	(0.008)
			[0.019]	
Brix(Year-1)				0.35**
				(0.030)
Brix(Year-2)				0.41**
				(0.029)
Brix(Year-3)				0.17**
				(0.033)
Adjusted R^2	0.14	0.49	0.52	0.91
RMSE	1.94	1.49	1.45	0.63

b: Unweighted Observations				
Regressor	*(1)*	*(2)*	*(3)*	*(4)*
Constant	21.87**	19.97**	20.35**	3.69**
	(0.032)	(0.121)	(0.140)	(0.371)
	[0.049]	[0.173]	[0.206]	
Trend	0.14**	0.13**	0.09**	0.03**
	(0.003)	(0.003)	(0.008)	(0.007)
	[0.004]	[0.004]	[0.013]	
Variety				
Red		1.05**	0.77**	0.21**
		(0.031)	(0.063)	(0.078)
		[0.048]	[0.093]	
Premium		0.70**	0.90**	0.18**
		(0.026)	(0.049)	(0.059)
		[0.039]	[0.072]	
Region				
Ultra-premium		1.28**	1.00**	0.50**
		(0.060)	(0.117)	(0.127)
		[0.091]	[0.174]	
Premium		1.25**	0.97**	0.58**
		(0.057)	(0.091)	(0.088)
		[0.085]	[0.139]	
Fine		0.74**	0.38*	0.41**
		(0.057)	(0.107)	(0.104)
		[0.090)	[0.166]	
Heat Index (Growing Season Average Degree Days)		0.02**	0.02**	0.02**
		(0.005)	(0.005)	(0.004)
		[0.006]	[0.006]	
Trend × Region				
Ultra-Premium			0.03	−0.01
			(0.010)	(0.010)
			[0.015]	
Premium			0.03*	−0.01
			(0.008)	(0.007)
			[0.012]	
Fine			0.03*	−0.01
			(0.010)	(0.009)
			[0.015]	
Trend × Variety				
Red			0.03**	0.01
			(0.006)	(0.006)
			[0.008]	
Premium			−0.02**	−0.00
			(0.005)	(0.005)
			[0.006]	
Brix(Year-1)				0.35**
				(0.032)
Brix(Year-2)				0.28**
				(0.036)
Brix(Year-3)				0.17**
				(0.020)
Adjusted R^2	0.14	0.26	0.27	0.61
RMSE	1.83	1.69	1.68	1.20

OLS robust standard error in parentheses. Newey-West robust standard error in square brackets. **, * Significant at the 1% and 5% levels, respectively, using Newey-West except in column (4). 13,379 observations.

according to shares of California's total production.[17] The rationale for using a weighted regression is that the data we are using are themselves annual averages for particular varieties within individual crush districts, with very different numbers of observations contributing to the average, depending on the volume of the crush. We prefer the estimates from the model using weighted regression, as reported in Panel *a* of Table 3. The results from the same models using the unweighted data are also presented for comparison in Panel *b* of Table 3.

In Table 3, Panel *a*, column (1) includes the results from a regression of Brix against trend for all varieties and regions. The model predicts that on average, sugar content of California wine grapes increased by 0.14 degrees Brix per year over the years 1990–2008 from a base of 21.7 in 1989, a predicted increase of 2.5 degrees Brix, or 11.6 percent over the period. In column (2) the model is augmented with a weather variable (the heat index for the growing season), and various dummy variables for Variety and Region, retaining the assumption of a single trend growth rate applying to all varieties and regions. The trend growth rate in this model is slightly lower, 0.10 rather than 0.14 degrees Brix per year.

The coefficient on the heat index is positive and statistically significant indicating that a 1 degree increase in the index would result in a 0.04 degrees Brix increase in the sugar content of wine grapes. This is a comparatively small effect, since a 1 degree increase in the heat index requires a large temperature increase.[18] The first Variety dummy is set equal to 1 for "red" varieties (including Zinfandel, although significant quantities of Zinfandel are used to make White Zinfandel). The second Variety dummy is set equal to 1 for "premium" varieties (Cabernet Sauvignon, Merlot, or Chardonnay). Regional dummies represent the "fine," "premium," and "ultra premium" regions as defined in Table 2 such that the default region is "ordinary." The coefficients on all of the dummy variables for Varieties and Regions are positive and statistically significant (with the marginal exception of the "fine" region), indicating that red varieties, and premium varieties, and grapes from districts commanding price premia could be expected to have higher sugar content at crush compared with the default category.

In this case we interpret the intercept (18.79) as applying to the default category of "non-premium," "white" varieties from the "ordinary" region (crush districts 12, 13, and 14 in the southern San Joaquin Valley). The counterpart for red varieties is higher by 0.96 degrees Brix, the estimated dummy variable coefficient, and the counterpart for premium varieties is higher by 1.89 degrees Brix. It can be seen that compared with the default region ("ordinary") the other regions have

[17] The weights were calculated using STATA's "aweight" option, with the weights for particular observations equal to the corresponding observation-specific tons crushed as a share of total California tonnage in the same year.

[18] For instance, an increase by 1 degree Fahrenheit in both the average daily minimum and the average daily maximum temperature throughout the six-month growing period would imply 1 degree increase in the index.

higher degrees Brix associated with higher prices for wine grapes: by 0.28 degrees Brix for the "fine" region, 1.71 degrees Brix for the "premium" region and 1.34 degrees Brix for the "ultra premium" region. These results are consistent with the idea that higher sugar content and higher alcohol content are less desirable in lower-priced wine grapes, possibly because of the additional $0.50 cents per gallon tax on wine with more than 14 percent alcohol by volume.

The model in column (3) augments the model in column (2) with variables that interact the time trend with the dummy variables for varieties and regions. In this model the coefficient on the heat index indicates that a 1 degree increase in the index would result in a 0.05 degrees Brix increase in the sugar content of wine grapes, slightly higher than that in the model without interaction terms, but the coefficient on the time trend (the growth rate for the default category) and several of the coefficients on the dummy variables for Varieties and Regions are no longer statistically significant. Still, premium varieties (but no longer red varieties) and grapes from the premium and fine districts (but not the ultra-premium district) could be expected to have higher sugar content at crush compared with the default category.

The interaction terms indicate significantly faster growth rates in sugar content for red varieties and premium varieties, and for grapes from the premium and fine regions, compared with the default; they indicate a slower growth rate for the ultra-premium region. The coefficients on the interaction terms represent the additional growth in degrees Brix per year for the dummy category relative to the default. The default category is non-premium, white varieties in the ordinary wine region, for which the trend growth rate is 0.02 degrees Brix per year from a base of 19.25 degrees Brix. Thus, for instance, for a premium white variety in the premium region, the corresponding estimate is a trend growth rate of 0.14 (0.02 + 0.09 + 0.03) degrees Brix per year from a base of 22.30 (19.25 + 2.25 + 0.80) degrees Brix.

Column (4) of Table 3 represents the same model as in column (3) augmented with lagged values of the dependent variable. We experimented with the number of lags of the dependent variable to include. The adjusted R-squared is maximized and the Akaike Information Criterion (AIC) is minimized when three lags are included, so that is the model we are reporting. In models with lagged dependent variables we could not compute Newey-West measures and so we report the OLS robust standard errors. Notably the coefficients on all three lagged-dependent variables are individually statistically significant, and diminishing with lag length, and they sum to 0.93, which means that in this model shocks have very persistent effects on the dependent variable. In addition, the long-run impact of a shock is on the order of 10–20 times its initial impact.[19] This implication of the model might not be equally plausible for all types of shocks. Otherwise, this model is to be

[19] The long-run multiplier for a permanent increase is equal to the short-run multiplier, divided by one minus the sum of the coefficients on the lagged dependent variable: 1/(1–0.93) = 14.3.

Table 4
Trends in the Heat Index by Crush District and for California, 1990–2008

Crush District	*Annualized Average Change (%)*	*100*Slope from Regression of Ln(Heat) on Trend*
	percent per year	
1	−0.30	−0.23 (0.357)
2	−0.18	0.11 (0.722)
3	0.58	0.75 (0.007)
4	0.01	0.20 (0.374)
5	0.03	−0.01 (0.979)
6	−0.50	−0.16 (0.600)
7	−0.69	−0.55 (0.271)
8	−0.60	−0.05 (0.919)
9	0.02	0.14 (0.445)
10	0.85	1.01 (0.004)
11	−0.19	−0.09 (0.725)
12	−0.19	−0.09 (0.725)
13	0.22	0.25 (0.224)
14	0.22	0.26 (0.312)
15	0.04	0.27 (0.249)
16	−0.31	−0.83 (0.033)
17	0.07	0.28 (0.195)
State Average (Weighted)	0.06	0.12 (0.405)

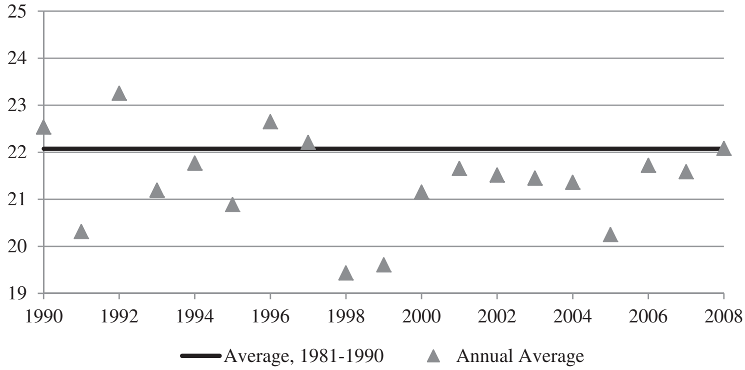
Notes: The weather station is the same for Districts 11 and 12. The annual heat index is a weighted average across crush districts, where the weights are tons crushed in the respective districts as a share of the total California tonnage. Standard errors in parentheses.

preferred, on grounds of its superior statistical performance, to the one in column (3) that omits the lagged values of the dependent variable.

The coefficients for this model are generally plausible, and they are largely consistent with those of the variant in column (3). The coefficient on the heat index indicates that a 1 degree increase in the average heat index would result in a 0.03 degrees Brix increase in the sugar content of wine grapes in the current year. Taking the lagged dependent variables into account, a permanent increase in the heat index by 1 degree Fahrenheit would imply a 0.43 degrees Brix increase in the sugar content of wine grapes in the ultimate long run. Compared with the default variety, non-premium white, for red varieties sugar content is higher by 0.19 degrees Brix and for premium varieties it is higher by 0.36 degrees Brix. As in the other models, compared with the default region ("ordinary") the other regions have higher degrees Brix associated with higher prices for wine grapes: by 0.18 degrees Brix for the "fine" region, 0.50 degrees Brix for the "premium" region and 0.40 degrees Brix for the "ultra premium" region. Importantly, none of the coefficients on interactions of trend with region, or trend with red varieties, is statistically significant. For these categories the coefficient on the trend is the same as for the default category, 0.01 degrees Brix per year. Only for premium varieties is the trend growth rate significantly different: it is lower by 0.02 degrees Brix per year.

Figure 6

Growing Season Heat Index, California Weighted Average, 1990–2008



Notes: The annual heat index is a weighted average across crush districts where the weights are tons crushed in the respective districts as a share of the total California tonnage.
Source: Created by the authors using data from NOAA NCDC Climate Radar Data Inventories, 1980–2009.

Of particular interest here is the relative importance of the heat index as an explanation of the rise in Brix. Across all the models, the results suggest that even a substantial rise in average temperature (or the average of the daily maximum and minimum temperatures) during the growing season would have had only modest effects on the sugar content of wine grapes. In fact, however, our data do not show a substantial rise in temperature between 1990 and 2007, as measured by the heat index. Table 4 includes two measures of the average trend rate in the index for each crush district: (a) the simple average of the annual proportional growth rates as measured by the logarithmic difference, and (b) the trend growth rate, from a regression of the logarithm of the index against a time trend. The estimates are expressed as annual percentage growth rates, and they include a mixture of small positive and negative numbers, none of which is statistically significantly different from zero. This outcome reflects the fact that the year-to-year movements in the index are large relative to any underlying trend that can be discerned. This aspect is revealed clearly in Figure 6, which represents the weighted heat index for California, in which the district-specific indexes are weighted according to the district shares of the total tonnage produced.

Combining the negligible trend in the heat index with its low coefficient in the model, our results imply that warming average temperatures in the growing season did not contribute substantially or significantly to the increase in sugar content of California's wine grapes during the almost twenty-year period 1990–2008. Other factors in the model do account for much of the rise in sugar content, including changes in the varietal mix and location of production. Some is attributed statistically to underlying trends that are not captured by specific variables in the

Table 5
Alcohol Percentage of California Wine Measured by the LCBO: 1990 versus 2000

		Red Wine	*White Wine*	*All Wine*
1990	Number of Observations	329	152	481
	Mean (Standard deviation)	13.14 (0.65)	13.04 (0.96)	13.10 (0.77)
2000	Number of Observations	115	171	286
	Mean (Standard deviation)	13.39 (1.44)	13.41 (0.84)	13.40 (1.12)
	Average Difference in Means (Standard error)	0.25 (0.10)	0.38 (0.10)	0.30 (0.07)
	t_1 (equal variances)	−2.51**	−3.83**	−4.36**
	t_2 (unequal variances)	−1.81*	−3.79**	−3.97**
	F	0.21**	1.32*	0.47**

**, * Significant at the 1 percent and 10 percent levels of significance, respectively.
t_1 and t_2 report the results of t-tests for a paired comparison under assumptions of equal and unequal variances, respectively.
F is the F-value for a test of equal variances.

model and might reflect elements of climate change not well represented by our heat index. Regardless of the cause, the rise in sugar content of grapes implies increases in alcohol content of wine that might not be desired by winemakers or consumers.

V. Changes in Alcohol Content of Wine: Too Much of a Good Thing?

Detailed data on the alcohol content of California wines are not available. While every wine bottle reports a figure for alcohol content on the label, the tolerances are wide and the information content is therefore limited. Specifically, U.S. law allows a range of plus or minus 1.5 percent for wine with 14 percent alcohol by volume or less, and plus or minus 1.0 percent for wine with more than 14 percent alcohol by volume. Wineries may have incentives to deliberately distort the information because the tax rate is higher for higher alcohol wine or for marketing reasons, if consumers prefer particular alcohol percentages. Consequently, label claims concerning alcohol content may be misleading. However, the Liquor Control Board of Ontario (LCBO), which has a monopoly on the importation of wine for sale in the province of Ontario, Canada, tests every wine it imports and records a number of characteristics including the alcohol content. We have obtained access to 18 years of LCBO data comprising information on a total of 129,123 samples composed of 80,421 red wines and 46,985 white wines. For each sample a number of measures are reported including the label claim of alcohol content and the actual alcohol content.

Here we report some preliminary analysis. Table 5 shows the average alcohol content of red wine, white wine, and both red and white wine from California tested by the LCBO in 1990 and in 2008. The data show that the average alcohol percentage increased by 0.30 percent, with a larger increase for white wine (0.38 percent) than for red wine (0.25 percent). This increase in alcohol percentage is consistent with an increase in the sugar content of the grapes used to make that wine of 0.55 degrees Brix, on average. Such an increase in degrees Brix over a

10 year period, while substantial, implies a relatively small growth rate compared with the actual growth. Further work remains to be done to examine the other characteristics of the wine tested.

The LCBO also records the alcohol percentage claimed on the wine label. We compared the true alcohol percentage and the label claims and found some remarkable discrepancies. On average across 7,920 observations of California wines, the actual alcohol percentage (13.35 percent by volume) exceeded the declared alcohol percentage (12.63 percent by volume) by 0.72 percent by volume. Further work is needed to examine more fully the nature of this discrepancy before we can evaluate causes. It seems unlikely that wineries are making consistent errors of this magnitude in measuring the true alcohol content of the wine. One possibility is that wine producers may be attempting to avoid tax, given that tax rates vary with alcohol percentage; another is that there may be marketing advantages from having label claims of alcohol percentages that are consistent with consumers' expectations for given types of wine; a third is that they simply cannot be bothered getting it right.

VI. Conclusion

The work in this paper has documented a substantial rise in the sugar content of wine grapes in California since 1980, and we have analyzed in detail patterns since 1990. All regions of production and all varieties grown have experienced some increase. We investigated the patterns among varieties and regions to try to shed light on the role of nurture, in terms of management choices by vignerons, versus nature, in terms of climate change as factors contributing to this growth. It is difficult to devise clean, definitive tests of these competing possibilities, given the complex relationships involved and the many dimensions for responses and interactions. However, we were able to distinguish some interesting patterns.

Previous studies have shown some increase in measures of temperature in California over the longer term, which may have contributed to changes in winegrape characteristics including sugar content at harvest. We used a measure of heat during the growing season for wine grapes to attempt to account for any direct effect of climate change. This measure itself exhibits large year-to-year swings making it difficult to discern clear trends in it. The variable contributed statistically significantly to the models, and showed that an increase in heat during the growing season would contribute to an increase in the sugar content of grapes. However, the heat index did not exhibit any statistically significant growth during the growing season and, in any event, its coefficient was small. Hence, this variable did not account for much of the growth of the average sugar content of grapes, compared with the other variables in the model.

Sugar content of grapes at harvest was relatively high for red varieties and premium varieties, and for grapes from ultra-premium and premium regions. The same categories tended to show evidence of faster growth rates in sugar content as well, but here the story is a little mixed, depending on the details of the model. In all of the models, however, the analysis shows a higher propensity for growth in sugar content for premium varieties, compared with non-premium varieties, even though premium varieties had higher sugar content to begin with. This feature and the patterns of the level of sugar content among regions and varieties could be consistent with a "Parker effect" where higher sugar content is an unintended consequence of wineries responding to market demand and seeking riper flavored, more-intense wines through longer hang times. A similar story holds for red (versus white varieties) in the models without lagged dependent variables, but not in the models with lagged dependent variables.

Regional patterns are important in relation to the average sugar content of grapes, but less so with regard to trends in sugar content. Using a definition of regions based on the average price of wine grapes, we found that the region with the lowest price of wine grapes (under $500 per ton) had significantly lower average degrees Brix at crush compared with all other regions. This finding could reflect the fact that sugar content is being managed in the vineyard, perhaps with a view to avoiding taxes that are disproportionately high on lower-valued wine. But independent of tax effects it may also be profitable, in producing lower-priced wines, to opt for a higher yield of wine per ton of grapes in exchange for lower Brix.

Preliminary analysis of data from the LCBO indicates that the alcohol content of California wine has risen in concert with the rise in sugar content of wine grapes, although possibly not to the same extent. This result is consistent with the fact that significant effort is being spent in wineries to remove alcohol from wine, which suggests that to some extent at least alcohol is a nuisance by-product in some wines; possibly because of tax implications. The finding that label claims appear systematically to understate the alcohol content of California wine sampled by the LCBO may reflect a perception that higher alcohol content diminishes the consumer value of certain wines.

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