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Wine and Climate Change

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Wine and Climate Change

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Abstract

In this article we provide an overview of the extensive literature on the impact of weather and climate on grapes and wine with the goal of describing how climate change is likely to affect their production. We start by discussing the physical impact of weather on vine phenology, berry composition and yields, and then survey the economic literature measuring the effects of temperature on wine quality, prices, costs and profits and how climate change will affect these. We also describe what has been learned so far about possible adaptation strategies for grape growers that would allow them to mitigate the economic effects of climate change. We conclude that climate change is likely to produce winners and losers, with the winners being those closer to the North and South Poles. There are also likely to be some substantial short run costs as growers adapt to climate change. Nevertheless, wine making has survived through thousands of years of recorded history, a history that includes large climate changes.

I. Introduction

Fine wine is an agricultural product that has characteristics that make it an especially interesting topic for economic analyses against the background of a changing climate. First, the quality and quantity of wine, and thus prices and revenues, are extraordinarily sensitive to the weather where the grapes were grown.[1] Price differences for wines made

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[1] The close relation between weather and wine has also been exploited for reverse inferences. Historical climatologists use data on harvest dates and the phenological stages of ripeness to generate medieval weather data (see, e.g., Garcia de Cortázar-Atauri et al., 2010; Brázdil et al., 2005).

by the same winemaker and coming from fruit grown on the same plot of land can vary by 20 to 1 or more from year to year (e.g., Ashenfelter, 2010) depending on weather conditions.[2] Likewise, in the same year, prices for wines from the same grape type can vary enormously from one place to another place with a more felicitous climate (e.g., Ashenfelter and Storchmann, 2010a).

Grape growing conditions also determine the longevity of a wine. Unlike most other agricultural products fine wine can be stored a very long time and, in some cases, it not only holds its nominal value, it also grows in real value with age. This storability has made fine wine an increasingly desirable alternative asset class, especially for the sake of portfolio diversification (e.g., Sanning et al., 2008; Fogarty, 2010; Masset and Henderson, 2010).

Finally, grape yields are also very sensitive to the weather in a growing season, so that revenues (price times quantity) are also subject to considerable climactic variability.

All of this implies that, absent some adaptation, a changing climate will affect the prices and quantities of wine produced and thus the profit from existing plantings. Although wine farmers have several adaptation options to mitigate or offset the effects of climate change, adjustments to changing climates are likely to be slower for perennial crops like vines than for annual crops such as wheat, cotton, or corn. Vines are perennials with a productive lifetime of more than 25 years; and full production is not attained until five or six years after planting (e.g., Cooper et al., 2012). Many studies suggest that the favorability of a specific vineyard site or grape variety may change within a vine's natural lifetime, which makes short-term losses unavoidable. In addition, in many cases,

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[2] In fact, prices can be astonishingly high. The world's most expensive bottle, a 1787 Chateau Lafite, purportedly formerly owned by Thomas Jefferson, was auctioned by Christie's of London in 1985 for £105,000, which is equivalent to approximately $330,000 in 2012. More typically, reported negociant prices for the top Bordeaux wines of the 2012 vintage, sold after harvest, before bottling, ranged between $300 and 500 per bottle—with retail prices still higher.

vineyards are planted on marginal land, that is, on land with poor and rocky soils and/or on steep slopes, where there are few crop substitution options (e.g., Ashenfelter and Storchmann, 2010a). This will further restrict mitigation options and increase short-term adaptation cost.

In this article we provide an overview of the extensive literature on the impact of weather and climate on grapes and wine. We start by discussing the physical impact of weather on vine phenology, berry composition and yields (Section II). We then survey the economic literature measuring the effects of temperature on quality, prices, costs and profits (Section III). Section IV describes possible adaptation strategies for grape growers, while Section V summarizes our findings and provides some discussion of the implications of our findings for future developments.

II. Physical Impact of Climate and Weather on Wines

A. Temperature

Mean Temperature

Grapevines (*vitis vinifera*) are characterized by a distinct annual growth cycle beginning with bud break (in the northern hemisphere, this is March/April), continuing with bloom (May/June), berry growth and coloring (July/August), maturation (September/October), and culminating in leaf fall in autumn followed by winter dormancy (e.g., Amerine and Winkler, 1944; Winkler et al., 1974; Gladstones, 1992; Jones et al., 2012). Since these phenological growth stages are determined by growing season temperatures, their association with certain calendar dates is only lose and can vary over time.

At temperatures below 10^0C (50^0 F) vines go dormant in order to resist adverse winter conditions. In the dormant stage, grapevines can withstand minimum winter temperatures between -5^0C to -20^0C, depending on variety and cultivar.[3] Although the role of the dormant phase of the growing season for grapevines is not fully understood, we know that winter dormancy affects the vine's vegetative and berry development. A dormancy period helps to synchronize the growth stages for vines. It avoids irregular and patchy

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[3] Sustained temperatures below -20^0C will ultimately destroy the plant.

budburst or maturation for separate plants. In addition, the existence of a dormant period substantially increases the productive lifetime of the vine (e.g., Lavee and May, 2008; Gladstones, 1992). In the tropics the absence of a dormancy period permits grape growers to harvest two or more crops per year. However, aside from the unsuitability of grapes grown in the tropics for wine production,[4] irregular budburst, flowering and grape clusters, low bud fruitfulness, poor wood maturation (lignification), and very short life spans make tropical wine production unprofitable (Possingham, 2004; Possingham et al., 1990).

Extended temperatures above 10^0C in the spring end the vine's dormancy and initiate vegetative growth and bud break. Gladstones (1992) reports that the leaf-stem weight ratio of the vine changes with increasing temperatures. While this ratio is significantly higher than one at low (15^0C day/10^0C night) and high temperatures ($35/30^0$C) it drops to one at mean temperatures of $20/15^0$C. In contrast, the number of stem nodes steadily increases with high temperatures. Therefore, stem thickness and internode stem length decrease at temperatures above $20/15^0$C. It appears that during the vegetative period and at moderate temperatures, the plant directs any surplus sugar to stem growth. Some scientists suggest that the emphasis on stem growth may be a viable survival strategy for plants for which early growth normally occurs at sub-optimal temperatures. Only later in the year, when temperatures and day-lengths are at their maximum or above, does the plant switch its main efforts toward reproduction (Gladstones, 1992). The tendency to higher vigor at hot temperatures may explain the poor lignification (wood growth) in tropical vines.

Temperatures during bloom appear to play a crucial role in fruit–set, ovule fertility, and berry size. Kliewer (1977b) examines various cultivars (e.g., pinot noir, cabernet sauvignon) and compares their behavior at different temperatures, such as $25/20^0$C, $30/25^0$C, $35/30^0$C and $40/35^0$C. He finds that all varieties exhibit lower fruit-set, ovule fertility and berry size as temperatures exceed the $25/20^0$C benchmark. This suggests that warming above a cultivar-specific optimum reduces crop yields.

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[4] The majority of grapes grown in the tropics are table grapes and are not appropriate for wine production.

During véraison (i.e., the onset of ripening and change in berry color) and maturation, temperature affects sugar content, acidity, color and flavor profile of the berries (Amerine and Winkler, 1944; Winkler et al., 1974; Gladstones, 1992; Jones et al., 2012). In general, high temperatures increase grape sugar accumulation (and thus potential alcohol), and reduce grape acidity. This determines the style, balance and potential alcohol of the wine. Sadras, et al. (2012) confirm the influence of temperature on acidity and sugar in a field experiment. Since temperature effects are often confounded with other climatic factors Sadras et al. (2012) isolate the temperature effects by comparing the fruit of heated vines with those of an unheated control group. They find that elevated temperatures accelerate development, increase phenotypic plasticity of stomatal (leaf pore related) conductance, and reduce titratable acidity in mature Australian Shiraz berries.

In addition, during a process called “flavor ripening” various enzymes initiate the physical softening of the berries and, most importantly, contribute to the accumulation of flavors, aromas and pigments. Enzyme activity follows an inverse U-shaped pattern and is low at low average temperatures, high at moderate temperature and falls again at high temperatures. Very high temperatures can inactivate or even irreversibly destroy any enzyme activity (e.g., Kliewer, 1977a).

However, flavor ripening and the other ripening processes are not necessarily optimized at the same temperature. Generally, the optimal flavor temperature lies above the temperature that balances the must’s acidity. That is, full flavor is often not reached before the pH values are too high, i.e., acidity is too low, to obtain a balanced wine. Although an optimum average temperature for flavor and aroma formation in grapes has not been defined, many scientists assume that the ideal ripening temperature lies in the range between 20^0C and 22^0C (see Gladstones (1992) and the literature cited there).[5]

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[5] Interestingly, there is evidence that the 20^0C to 22^0C temperature range is optimal also for other fruits, such as pears, tomatoes, avocados or bananas, that normally ripen in temperature-controlled storage. These parallels suggest that the enzymic biochemistry of ripening is very similar across many fruits (Gladstones, 1992).

Temperature Variability

Temperature variability among seasons and years is a well-recognized determinant of the quality of the wine from a vintage, especially in cool viticultural climates. While a cool growing season at the cold limit of viticulture results in a below-average vintage due to unripe and inferior fruit (e.g., for Bordeaux and Mosel wines, see Ashenfelter (2010) and Ashenfelter and Storchmann (2010a), respectively), the opposite is true for the hot limit of viticulture (for U.S. pinot noir wines, see Haeger and Storchmann, 2006, and for Austrailian shiraz see Byron and Ashenfelter, 1995). Accordingly, increased warming may thus increase the number of good vintages in cold climate wine growing areas and simultaneously decrease the number of good vintages in hot climate growing areas.

However, aside from vintage variations, viticulture is also affected by short-term fluctuations such as diurnal variations (the range between day maxima and night minima) and day-to-day fluctuations in extreme temperatures within a given season.

It is generally thought that a low diurnal temperature variance is favorable for the ripening and coloring process (Gladstones, 1992; Kliewer and Torres, 1972). However, in hot wine growing regions, a greater diurnal range may help to protect the grapes against detrimental heat during the day (Robinson, 2006).

Spring frosts that injure developing shoots, and frosts after budburst that reduce the current season's crop yield, are among the most common detrimental effects of minimum temperature extremes. Winter freezes of below -12^{0}C, which may severely damage or kill fully dormant vines, occur mostly near the northern/southern limit of viticulture (e.g., Washington State, British Columbia).[6]

Similarly, extreme maximum temperatures in summer can cause substantial heat damage by inhibiting photosynthesis and causing sunburn. Exposed grape bunches are

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[6] Extreme minimum temperatures and average minimum temperatures are not always correlated. For instance, in the Walla Walla (Washington) viticultural are, one of the warmest grape growing areas in the U.S. with usually mild winters, the winter freezes of 1991, 1996, 2004 and 2011 each reached temperatures of -20^{0}C and below and destroyed large parts of productive vineyards.

particularly vulnerable to heat damage during véraison. Since red wines more than whites depend on skin-derived components such as pigments and tannins, reds are more affected than whites because the skin is the part of the berry that is most sensitive to heat damage (Gladstones, 1992). A detailed report of the impact of the January/February 2009 heat wave in Southern Australia is provided by Webb et al. (2009).

Temperature Accumulation Indices and Grape Suitability

In order to classify the climatic suitability of a vineyard area, various temperature accumulation indices have been developed. The most commonly used index is the *Winkler Index* as developed by Amerine and Winkler (1944). This index draws on data from a truly remarkable series of field experiments in California's grape growing regions.[7] Each year between 1935 and 1941, Amerine and Winkler made several wines from each of more than 150 different grape varieties, each grown in various climatic environments. Overall, they produced and analyzed more than 3,000 wines. Amerine and Winkler then defined five degree-day regions[8] (Winkler regions) and assessed each variety's suitability for each region. These regions are separated by the following degree-day thresholds:

Region I	2,500 degree days or less
Region II	2,501-3,000 degree days
Region III	3,001-3,500 degree days
Region IV	3,501-4,000 degree days
Region V	above 4,000 degree days

Although the Winkler index is still widely used in the U.S., some modifications have been suggested. Gladstones (1992) calculates a similar degree-day index with the

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[7] Although the Winkler scale was derived from data through only the 1941 vintage, these field experiments continued into the 1950s. This massive data collection effort has never been fully digitized, and much of the data from the later period, for cultivars not included in the earliest report, has never been analyzed. Ironically, computational limits on data manipulation were a serious issue for Amerine and Winkler, while today it is the scale of their experimentation that is hard to imagine.

[8] Degree days are the sum of Fahrenheit degrees above 50° over the growing season period April 1-October 31st (in the northern hemisphere).

imposition of an upper limit of 19^0C on average temperatures and corrects for latitude (solar radiation) and monthly temperature variation. Jones (2006) suggests a simple growing season average index.

Figure 1 reports the suitability of various grape cultivars for different average growing season temperature ranges (Jones et al. 2005). For varieties that were fully tested by Amerine and Winkler (1944), we also report the recommended Winkler regions. The chart shows that, depending on current average temperatures, there may be a substantial substitution potential. For instance, a grape grower currently growing Riesling in Germany, who faces increasingly warm temperatures, can plant different cultivars that require increased temperatures to ripen. In contrast, the options of a Grenache grower in the South of France are limited.

B. CO2

The longest continuously measured CO2 series originates from Mauna Loa, Hawaii and reaches back to 1958. Since the first measurement of 315 parts per million (ppm) in 1958, the atmospheric CO2 concentration has steadily grown to 398 ppm (February 2014; NOAA, 2014). Studies with a variety of plants have shown that CO2 stimulates photosynthesis and plant growth. This could also be confirmed for grapevines. Bindi et al. (2001) fumigated vines with CO2 and found substantial increases in yields, dry biomass, sugar and acidity levels in response to elevated CO2 concentrations. However, the marginal effect of additional CO2 is declining and equals zero at a high enough level (500 μmol mol^{-1}). Similar results are reported by numerous other authors (e.g., Schultz, 2000; Kriedemann et al., 1976; Moutinho-Pereira et al., 2009).

However, when examining the impact of elevated CO2 levels combined with higher temperatures and moderate drought conditions Bindi et al. (1996) found a significantly higher yield variability. In addition, some researchers found reduced CO2 assimilation and declining crops for orange trees (Kimball et al., 2007) and soybeans (Ainsworth et al., 2002) if plants are water stressed. Bindi et al. (2005) found no increased grapevine CO2 assimilation under dryer growing conditions. In short, it is unclear what the effect of increased CO2 levels alone might be on grape quality and quantity.

C. Pests

Warming temperatures are likely to increase disease and pest pressure on grapevines. Pierce's disease, a bacterium that inhibits a vine's water circulation and ultimately kills the plant, is predicted to move toward the North and South Poles as winter temperatures become more hospitable for its main vector, the glassy-winged sharpshooter. In the U.S., Pierce's disease is expected to move from California northward into Oregon and Washington (e.g., Daughtery, 2009; Hoddle, 2004). Other insect pests, such as the light brown apple moth in Australia (Webb, 2006) may expand their habitats into new regions as well.

Likewise, warmer weather may promote fungal diseases such as black rot, downy mildew, powdery mildew, phomopsis, and botrytis. All of these diseases are driven by climatic factors and particularly benefit from warmer night temperatures (Magarey et al., 1994; Maixner and Holz, 2003; Salinari, 2006). However, dryer growing conditions may partially or fully curb the detrimental effects of increasing temperatures.

D. Water

The water balance of the vine is mainly determined by the supply side factors (1) local precipitation (rain, snow), (2) ambient atmospheric humidity and (3) soil water holding capacity (Gladstones, 1992; Jones et al., 2012). On the demand side, water use efficiency (WUE) plays a decisive role in the vine's water requirements (Webb et al., 2011).

The overall quantity of annual rainfall and its distribution over the growing and non-growing season is crucial when vines are not irrigated as is the case in almost all of Europe. When vines are irrigated, as in almost all U.S. west coast wine regions, water supply can be optimized and adjusted to the plant's needs. In general, while ample rainfall during the winter and the early vegetative stage is beneficial, rain during bloom and maturation is deemed detrimental.

However, even irrigated vines experience transpirational (leaf evaporative) restrictions under hot and dry atmospheric conditions, or low relative humidity. Leaf pores (stomata) close in order to conserve moisture and photosynthesis ceases. On the other hand, high humidity may increase the likelihood of fungal diseases.

The water use efficiency (WUE) of grapevines, defined as the ratio between photosynthesis and stomatal conductance, is expected to increase with increasing CO2 levels. However, Schultz and Stoll (2010) find that increasing leaf temperatures may thwart the positive correlation between CO2 levels and WUE.

Although predictions of the total annual amount of precipitation and its annual and regional distribution are much more uncertain than temperature predictions, IPCC (2008) expects increasing water deficiencies in most grape growing regions.

III. Economic Impact

A. Suitability

An analysis by Nemani et al. (2001) suggests that climate changes between 1951 and 1997 over coastal California may have benefited the premium wine industry. They find that the observed temperature warming trends were asymmetric, with greatest warming at night and during spring. Warming was associated with large increases in eastern Pacific sea surface temperatures and rising atmospheric water vapor. Although the average annual warming trend was modest (1.13ºC/47 yr), they observed a 20-day reduction in frost occurrence and a 65-day increase in frost-free growing season length. In the Napa and Sonoma valleys, warmer winter and spring temperatures advanced the start of the growing season by 18 to 24 days per year. Enhanced atmospheric water vapor resulted in a 7% reduction in evaporative demands.[9]

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[9] Studies that analyze the relationship between temperatures and phenological stages for other regions comprise Jones and Davis (2000) for the Bordeaux region, Urhausen et al. (2011) for the Upper Mosel river, Kenny and Harrison (1992) for all of Europe and Webb et al. (2008) for six Australian winegrowing regions. In most cases, climate warming has advanced the grapevine's development and has extended the

However, gains from past warming may turn into losses when the warming trend continues. Based on high-resolution climate data for 1-kilometer grids, White et al. (2006) analyze the impact of climate projections on the suitability distribution of premium wine grape producing region in the United States using Winkler regions (see Chapter II.A.). Based on the IPCC (2000) A2 scenario[10] and using growing season average temperatures they find that the total suitable vineyard area in the United States will decline from about 4.1 million km^2 to 3.5 million km^2 (-14%) by the end of the 21st century. However, when focusing on high-quality growing regions by excluding regions with growing season average temperatures lower than 13^{0}C or above 20^{0}C, extreme temperatures over 35^{0}C during the growing season and diurnal variations of more than 20^{0}C, the authors find reductions in suitable growing areas of up to 81%. In addition, since climate change shifts most of the premium wine production north into the high-precipitation/humidity regions of the Pacific Northwest and the Northeast, the increasing risk of fungal diseases will require substantial (and costly) pest management efforts (White et al., 2006).

Although, the analysis by White et al. (2006) is static and does not account for any adaptations and is, therefore, very pessimistic, it also points at the shortcomings of average temperature analyses. Average temperature analyses hide short-term peaks and troughs and may thus yield biased results. Schlenker and Roberts (2009) show that temperatures exert nonlinear effects on crop yields of corn, cotton and soybeans. To our knowledge, there is no similar research on grapevines.

B. Yields

The study by Adams et al. (2003) is one of the first analyses of temperature's effect on California grapevines (and other crops). For the time period from 1972 to 2000,[11] they

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growing season. However, Webb et al. (2008) report that some regions may have been adversely affected by further warming because dormancy requirements may not be met. As a result, they project a later budburst for some regions (e.g., Margaret River region).

[10] Compared to the 1980-1999 temperature average, the IPCC's A2 scenario expects a temperature increase of 3.4^{0}C for 2090-2099 (IPCC, 2000).

[11] Wine grape yields were only available from 1980 on.

regress crop yields on monthly daytime maximum temperatures and rainfall for the growing seasons from March to September, while disregarding daily minimum and non-growing season temperatures. They report regionally disaggregated results for four areas[12] and 23 crops. Assuming a warming scenario of 3^0C (with CO2 fertilization) Adams et al. (2003) project wine grape crop yield increases of 90% by 2100 for the coastal regions of California, including the Napa and Sonoma valleys. Without CO2 fertilization, the projected crop yield increase is 65%.

This is in stark contrast to the findings of Lobell et al. (2006) who analyze six perennial crops in California: wine grapes, almonds, table grapes, oranges, walnuts, and avocados. Their forecast is based on panel models drawing on county data from 1980-2003 as reported in Lobell et al. (2007). For each crop equation, the months and climatic variables of greatest importance were employed to relate yield to climatic conditions. The crucial difference to Adams et al. (2003) is the inclusion of minimum night temperatures.

Lobell et al. (2006) find that climate change in California is very likely to put downward pressure especially on the yields of almonds, walnuts, avocados, and table grapes by 2050. In contrast, the model projects relatively stable median crop yields for wine grapes (without CO2 fertilization).

The difference between Adams et al. (2003) and Lobell et al. (2006) points at possible nonlinear effects of temperature on crop yields. Schlenker and Roberts (2009) employ a flexible model that can detect nonlinearities and breakpoints for corn, soy and cotton. Based on fine-scaled weather data they calculate the length of time each crop is exposed to each one-degree Celsius temperature interval per day, summed up for all days of the growing season. Clearly, if the temperature-yield relationship is nonlinear, averaging over time or space will only dilute the true temperature response. This way, Schlenker and Roberts find temperature optima for each crop. Temperatures above these thresholds become increasingly harmful. “The slope of the decline above the optimum is significantly steeper than the incline below it.” (Schlenker and Roberts, 2009, 15594).

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[12] Sacramento and delta regions, San Joaquin Valley and desert regions, northeast and mountain regions, and coast region of California.

C. Quality

Some studies focus on wine quality rather than on wine prices or winery profits. 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 employ non-linear squared time series models for each region and show that there are winners and losers of global warming. In general, while winegrowing regions in northern France and Germany will produce better wine quality with increasing temperatures, winegrowing regions in Spain (Rioja), California, and South Australia (Barossa Valley) may suffer from any further warming.

Storchmann (2005) examines the weather determinants of wine quality of Schloss Johannisberg in the German Rheingau region from 1700 to 2003 employing an ordered probit model. He draws on documented vintage classifications (such as "top wine", "sour", "lesser vintage") in historical harvest books, groups them into five quality ranks and regresses these ranks on various weather data. Since instrumental weather data for the covered time period are available only from weather stations in England and, with some restrictions, from The Netherlands he also refers to monthly index data based on paleo-climatic indicators such as tree rings. The results show that (1) English weather data are a good proxy variable for the actual weather conditions in the Johannisberg vineyards[13] and (2) that past warming has improved the quality of Rheingau wines.

One measure of wine quality may be its alcohol, which, in most cases, is closely related to the sugar content of the grape juice (must) it was made from. In general, higher growing season temperatures yield sweeter musts and stronger wines and *vice versa*. However, at extremely hot temperatures vine metabolism may be inhibited and may adversely affect wine aroma and color (e.g., Mira de Orduña, 2010).

Alston et al. (2011) find a substantial rise in the sugar content in California wine grapes

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[13] This squares with the results of an analysis by Lecocq and Visser (2006) who analyze Bordeaux wine prices. They compare the results when drawing on data from only one weather station to those from numerous local stations. They conclude that using localized data does not improve the models' explanatory power.

(measured in Brix). From 1980 to 2005, the Brix levels have increased by an average of 0.23% per year; this increase is twice as high for red as for white grapes. In their econometric analysis, Alston et al. (2011) find that rising temperatures have contributed to the higher sugar levels to some extent, but their explanatory power is comparatively small. Brix levels at harvest were relatively high for red varieties and premium varieties, and for grapes from ultra-premium and premium regions, even though non-premium regions experienced similar temperature changes. In fact, "the lowest price of wine grapes (under $500 per ton) had significantly lower average degrees Brix at crush compared with all other regions" (Alston et al., 2011, 158). This suggests that most of the Brix increase may be caused by vineyard management practices. Wineries can respond to changing market demand by lowering yields by pruning,[14] or by permitting longer hang (ripening) times.

Alston et al. (2011) also find that wine alcohol levels have increased with Brix levels. The informational value of the alcohol level posted on U.S. wine labels is, however, limited. U.S. law allows a bandwidth of plus/minus 1.5% for wine with 14% or less alcohol by volume, and plus/minus 1.0% for wine with more than 14% alcohol by volume. In contrast, the Liquor Control Board of Ontario (LCBQ) analyses every wine sold and posts the "true" alcohol level on the back label. When comparing the U.S. and the Canadian label Alston *et al.* find that Californian wineries systematically understate the alcohol level of their wines.

D. Prices

The first empirical evaluations of the effect of weather on fine wine prices were carried out by Ashenfelter and were published in *Liquid Asset* in the late 1980s (e.g., Ashenfelter, 1986, 1987a, 1987b, 1990; see also Storchmann, 2012). Although he analyses wines from various regions, Ashenfelter focuses on *grand cru* (high quality) wines from the Bordeaux region. In one of the earliest papers studying the economics of wine, published in 1995 but based on work done in the 1980s, (Ashenfelter et al., 1995), Ashenfelter and

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[14] At any given point in time and vineyard, there is a trade-off between crop yield and Brix levels (e.g., Winkler et al., 1974).

collaborators regress cross sectional auction price data for a basket of Bordeaux *grand cru* wines on various weather variables and an age variable. The "Bordeaux equation" in column 2 of Table 1 reports a growing season temperature coefficient of 0.616, i.e., a growing season temperature increase by one centigrade results in a 61.6% price increase. Given that average Bordeaux growing season temperatures after 1945 have ranged between 14.98^0C (1972) and 19.83^0C (2003) large price variations are not surprising. Predicted temperature increases for the European wine growing regions for this century are between 1.5°C and 5°C (e.g., IPCC, 2007; European Commission, 2009), i.e., a variation that is within the already experienced range of regular annual weather fluctuations.

This Bordeaux equation, however, also implies that excess rainfall during the end of the growing season may be harmful to wine prices. Predictions for precipitation changes associated with climate change are less reliable and generally conclude that precipitation will increase in Scandinavia and decrease in Southern Europe; the direction of any precipitation changes in the middle of Europe, including France, is currently uncertain (European Commission, 2009). Assuming future temperature increases and no changes in precipitation, Ashenfelter's Bordeaux equation, therefore, predicts substantial price increases for Bordeaux *grands crus*. In fact, there have been notable temperature increases in the Bordeaux area since the 1980s, and a Bordeaux wine prices are currently at all time highs. It is unclear, however, whether these recent temperature increases reflect climate change or some other unexplained phenomenon.

Jones and Storchmann (2001) confirm the positive effect of global warming on the Bordeaux wine region. They model the effect of weather by estimating cross sectional equations for each of 21 selected *premiers crus* chateaux. Given that each chateau's wine is a unique blend that is either dominated by Cabernet Sauvignon, Merlot or a blend of each,[15] Jones and Storchmann first compute the weather's impact on the sugar and acid level of each of these grape varieties. Taking into account the respective blend

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[15] Many chateaux add smaller quantities of Cabernet Franc, Petit Verdot, Malbec and/or Carménère. For *Chateau Cheval Blanc*, however, Cabernet Franc is the dominant variety.

proportions they then proceed with a price equation. They find that Merlot is more weather-responsive than Cabernet Sauvignon. That is, in a scenario of global warming, Merlot dominated wines such as *Chateau Petrus* would benefit disproportionally.

In a long-run time series analysis covering the time period from 1800-2009, Chevet et al. (2011) study prices and yields of a *premier cru* Chateau in the Bordeaux region. They find a positive impact of temperature on both yields and prices. However, while the temperature responsiveness of crop yields has fallen dramatically over time, prices have become substantially more sensitive to growing season temperature changes.[16] Apparently, technological improvements have helped wine growers to lower the weather's impact on crop levels. However, the findings also suggest that price changes are not a result of quantity changes alone. Increased wine quality and growing market demand seem to have more than offset any effect yield increases due to warmer growing seasons have had on prices.

All the papers noted above employ linear temperature specifications. That is, the marginal effect of temperature on wine prices is implicitly assumed to be constant over the entire observed temperature spectrum. That may be justified for regions in cooler climates, such as Bordeaux and Germany, or when drawing on data from colder time periods such as the "Little Ice Age" of the early and mid 19th century. For warmer regions, especially in the New World, nonlinear specifications may be more appropriate. Byron and Ashenfelter (1995), in their analysis of the Australian wine known as the Grange (see Section IV), use a quadratic regression specification and find that wine prices grow with increasing temperatures but at a decreasing rate. Wood and Anderson (2006) also employ a quadratic temperature specification for Australian icon wine prices. Similarly, Haeger and Storchmann (2006) estimate a quadratic function for U.S. Pinot Noir wines that has a price-maximizing peak at a growing season temperature of 22.2^0C.[17] Many U.S. growing regions already have higher temperatures than this (Salem, Oregon: 23.2^0C; Napa, California: 26.2^0C; Paso Robles, California: 30.3^0C). Further

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[16] While the yield coefficient fell from 0.31 (1847-1900) to 0.08 (1961-2009) the price coefficient grew from 0.004 (1839-1900) to 0.45 (1961-2009) (Chevet, et al., 2011).

[17] From April to September.

warming may thus have detrimental effects on Pinot Noir prices in America's western growing regions. In contrast, Burgundy (Dijon: 22.0^{0}C) as well as the German wine regions (Karlsruhe, Pfalz: 21.3^{0}C) would still benefit from further warming.

E. Revenue and Profit

Many of the above-cited studies are static in nature and disregard the interdependences between quantity and prices. In addition, there are almost no studies that analyze cost or profits as a function of climatic variables.

Webb (2006) analyzes grape gross returns for Australia. In a first step, she generates varietal-specific revenue data (in $/hectare) by multiplying varietal prices by crop yields across all Australian wine regions for 2002. She then regresses these revenue measures on weather data in a cross sectional analysis. She finds significant quadratic relationships between revenue and temperature for Cabernet Sauvignon, Merlot, Shiraz, Chardonnay and Semillon. In a second step, Webb applies the findings to the regional level by weighting varietal results by the respected planted area within each wine growing region. The national effect is computed as the weighted average of the regional results. Depending on the climate change scenario, she finds gross return losses for all of Australia between 9.5% and 52% by 2050. However, since the results neither consider winemaker adaptations, nor varietal substitutions within or across regions, the overall results may be interpreted as a worst-case "dumb farmer" scenario.[18]

Ashenfelter and Storchmann (2010a) analyze the value of land, i.e., discounted future land rents, for vineyards in the Mosel valley of Germany. In a first model of three, they explain the Prussian vineyard classification from 1868. Based on land profits[19] for the time period from 1837 to 1860, the Prussian government assigned one of eight ranks to each vineyard; rank one vineyards commanded the highest wine prices and were highly profitable, while rank eight vineyards yielded the lowest profits (if any). This vineyard

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[18] The "dumb farmer" scenario is a catch phrase to describe a scenario that disregards farmer adaptations in response to changing economic and environmental conditions (see Mendelsohn et al., 1994).

[19] The profit was calculated as the product of wine price and crop yield minus the cost of growing (Ashenfelter and Storchmann, 2010a). Interestingly, Karl Marx, whose parente owned vineyard land in the Mosel, published some critical comments about this calculation method in 1843 (Marx, 1843).

classification was not carried out as an orientation guide for wine aficionados but as a basis for fair and just taxes; high profit land was taxed more than low profit land. Using an ordered probit model, Ashenfelter and Storchmann show that the Prussian ranking (and thus the willingness to pay for wine) can be explained by the most important vineyard physical characteristics: soil type and the land's potential capability to capture incoming solar radiation, i.e., energy. The darker the soil (mainly dark slate that stores heat) and the higher the potential solar energy of a vineyard the better is its rank. The solar radiation a plot of land will capture can be calculated in the same way the energy potential of a solar panel is calculated. This energy potential depends on the vineyard's latitude, slope and orientation. For the German Mosel region, which is located at the northern frontier of professional viticulture, energy is a scarce resource so the best vineyards are south-facing and exhibit a 45-degree slope. Ashenfelter and Storchmann employ the Boltzmann equation to link solar radiation to temperature so that higher temperatures from climate change can be associated with the price effects associated with better vineyards. This implies that higher temperatures will change the likelihood of a certain vineyard being in a high-quality rank. In effect, further warming will shift the rank distribution of all Mosel vineyards from lower to higher quality and will thus increase land prices. Under a warming scenario of 3^0C, the value of vineyards in the Mosel may double.

Ashenfelter and Storchmann (2010a) compare these results with two different time series models. In one model, they regress accounting data on profits for wineries from various West German winegrowing regions on weather variables. Table 2 shows that the marginal effect of temperature on winery profits (excluding subsidies, column 1) is approximately 0.309. A growing season temperature increase of 3^0C would raise profits by about 150%. Interestingly, temperatures do not alter production costs, as column (3) of Table 2 reports. As a result, profit increases are virtually identical with revenue increases.

[Table 1 and Table 2 about here]

In a third model, Ashenfelter and Storchmann (2010a) regress Mosel wine revenues on temperatures. They show that crop yields as well as prices respond positively to higher growing season temperatures. This model suggests that warming of 3^0C may raise revenue by approximately 180%. Figure 2 depicts the suggested temperature impact of all three models, which all show a positive relationship between growing season temperatures and profits, revenues or land values. Given the entirely different nature of the models, the results are remarkably consistent.

In a different paper, Ashenfelter and Storchmann (2010b) show that, depending on the wine sample considered, regressing price on temperature may result in biased results. Comparing auction, retail and wholesale prices yields the strong positive temperature effects for wines sold at auction but much smaller effects for a sample of wholesale price data. Accordingly, the computed revenue effects due to temperature changes exhibit a considerable range. Given that only a tiny fraction of the wines produced are sold at auction (e.g., only those of higher quality) results based on auction prices may overstate the effect of climate warming.

In work similar to Ashenfelter and Storchmann (2010a), Antoy et al. (2010) use accounting data to analyze the climate's impact on various economic grape grower variables. In particular, they draw on the Farm Accounting Data Network (FADN) database of the European Union, which provides accounting data for a sample of test farms that represent approximately 3% of all European wineries. The grape-related data cover 85 European regions (administrative districts) for the time period from 1989 to 2009. However, many time series, especially for Eastern European regions, begin much later than 1989. Temperature and rainfall data were taken from one local weather station in each district. In small districts, such as Luxemburg, the station data may reflect the weather in the vineyard fairly well. However, for larger districts, such as Austria, weather from only one weather station maybe problematic, especially with respect to precipitation data.

Figure 3 reports the 2009 Net Value Added per hectare in selected grape growing regions. The values range from €378 in Yugozapaden (Bulgaria) to €42,396 in the Champagne region (France). In addition to the wide range, the Figure also shows that all low-value regions are located in Southern or Eastern Europe while high-value regions are near the northern frontier of professional viticulture or in close proximity to the Alps. This pattern is even stronger for tax payments. Wineries in only 8 regions are net tax payers while most pay negative taxes, i.e., obtain subsidies. While grape growers in the Champagne sample paid on average €761 in net taxes per hectare, grape growers in Ipiros-Peloponissos (Greece) received €2,022 in net subsidies per hectare.

Table 3 shows the result of several unbalanced panel model regressions where the logarithms of revenue, cost, subsidies and value added are regressed on a quadratic temperature function, various precipitation variables, and a trend variable. All equations contain region-fixed effects. While revenue and value added are significantly related to temperatures, costs and subsidies are mainly trend driven. The effects of precipitation on revenues are statistically insignificant which may, as we noted above, represent the results of measurement error.

Drawing on the temperature coefficients Antoy et al. (2010) calculate average growing season temperatures that maximize revenue (18.62^0C) and value added (18.85^0C), respectively. Figure 4 shows the average growing season temperature developments in selected grape growing regions compared to the calculated value added optimum from 1987 to 2009. These graphs lead to several interesting conclusions.

First, all western European regions display identical temperature patterns over time, with lows in 1987 and 1996, and peaks in 2003; only the levels are different. Since we are interested only in temperature variations, this suggests that temperature data from any weather station in Western Europe may be a good proxy for the respective conditions in any vineyard. In fact, Lecocq and Visser (2006) and Haeger and Storchmann (2006) have shown for Bordeaux and California, respectively, that using temperature data from many local stations does not yield better results than using data from only one station.

Second, the differences across the regions show that adaptation may be significantly more difficult in some regions than others. For instance, further warming in the Rhine and Mosel valleys of Germany will move this region closer to the temperature optimum.[20] In contrast, in Greece, where a large fraction of the grape production is already used for raisins, further warming will leave only a few, if any, options for viticulture.

III. Adaptation Methods

Grapevines have been cultivated for thousands of years and vintners have proven their adaptability to many environmental and economic changes through regional shifts in the areas planted, variation in harvest times, new production technologies and the substitution of cultivars.

Figure 5 depicts growing season temperatures for the longest existing measured data series based on temperature instrumentation. This Manley series for Middle England, begins in 1659 and has been updated to the present (Met Office Hadley Centre, 2012). Storchmann's (2005) analysis of Rhine wine quality suggests that the Manley series serves as a good proxy variable for temperatures in all West European wine growing regions. The 20-year moving average line exhibits an upward trend, which is especially pronounced after approximately 1970.[21]

A. Harvest Dates

One of the oldest documented adaptation methods for grape production has been for farmers to adjust to the vines' phenological stages and completing certain work, such as picking– independent of the calendar date. A good example of this is found in the work of Le Roy Ladurie and Baulant (1981), who report harvest dates for Burgundy from 1659

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[20] Note that the growing season temperatures in Table 3 and Figure 1 are not comparable. While Table 3 refers to Apr-Oct temperatures, Figure 1 refers to Mar-Aug.

[21] Interestingly, the Manley series exhibits an inverse relationship between growing season temperatures and their variance, i.e., warm phases coincide with low vintage-to-vintage volatility.

to 1879. Figure 6 depicts a plot of harvest dates after August 31 and growing season temperatures in Middle England (Manley series). A simple linear regression line shows that warmer temperatures lead to earlier harvest dates and *vice versa*.

B. Northward Movement and Planting Regulations in the European Union

However, climate shifts are not a new phenomenon to European viticulture. Temperature reconstructions based on proxy data such as tree rings suggest that Europe has experienced several long-term climate changes. Figure 7 displays annual temperature deviations from the 1961-1990 average for the time period from the year 1 to 1979 for the Northern Hemisphere (Moberg et al., 2005). Like many other analyses (e.g., Jones and Mann, 2004; Mann et al., 1999, Pfister, 1988), the Moberg data suggest the occurrence of a *Medieval Warm Period* (950 to 1200) followed by a *Little Ice Age* (1600 to 1850). There is evidence that the northern frontier of professional viticulture reached as far north as Northern Germany and the Baltics during the Medieval Warm Period. Waldau (1977) and especially Weber (1980) provide a detailed account of – possibly partly climate induced - shifts that occurred over the last 900 years.

Similarly, increasing temperatures may induce grape growers to move toward the North and South poles or into higher elevations.[22] In addition to being costly for the wine industry itself, this geographic shift may also lead to conservation conflicts in land use and freshwater ecosystems. Hannah et al. (2013) predict considerable conflicts between vineyards and resident wildlife worldwide. Within the U.S., their paper points to areas in the Rocky Mountains and the border area between Washington State and British Columbia that are becoming increasingly desirable for viticulture, which, in turn, may displace animals and native plants.

However, it is unclear how much vineyards will be permitted to shift geographically. While most countries do not restrict new vineyard plantings, the European Union, the

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[22] Temperatures decline by roughly 3.3° Fahrenheit degrees for an altitude increase of 1,000 feet.

world's largest grape producer,[23] requires the possession of planting rights to do so. Since it is illegal to plant vineyards without planting rights, vineyard planting may not be permitted to follow suitable climatic conditions north. As a result, the EU's planting rights regime inhibits the adaptation process: existing grape growing regions in the south may become too warm and suitable land in the north may not be planted.

The regime of planting rights was introduced in 1976, initially as a temporary measure, in order to cap the area under vines and control wine production in the southern European regions where inexpensive bulk wine has been primarily produced (European Commission, 2012). Since planting rights are distributed by country, and the quotas reflect the status quo, monopoly power is granted to the incumbent producers.

In 2007, in order to enhance the competitiveness of the wine producing sector, the European Union decided to abolish the planting rights scheme by 2016. However, and perhaps not surprisingly, considerable opposition has been mobilized against the planned liberalization.[24] As a result, it is unclear whether the planned deregulation will be realized at all. The compromise solution that is currently being discussed retains the existing planting policy for all the current wine growing countries while exempting Belgium, Denmark, Estonia, Finland, Ireland, Latvia, Lithuania, the Netherlands, Poland, the United Kingdom, and Sweden. However, additional plantings within many countries with marginal climates who would be potential beneficiaries of climate change, such as Germany, Austria and the Czech Republic, would be ruled out.

C. New Cultivars and Rootstocks

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[23] In 2011, the European Union accounted for approximately 60% of the worldwide wine production (OIV, 2013).

[24] Interestingly, vintners in some wine growing nations have repeatedly ignored planting rights. In fact, in 2000 the European Union found 120,507 hectares of illegally planted vineyards, an area that exceeds all the vineyard land in Germany and Alsace combined. Most of the illegal plantings were found in Spain (55,088 ha), Italy (52,604 ha) and Greece (12,268 ha). In fact, in Greece, more than 18% of all vineyards were illegally planted. The European Union retroactively legalized almost all of the irregular plantings (Commission of the European Communities, 2007).

As already mentioned earlier, global warming will require the substitution of grape cultivars, moving from the left to the right through the cultivar spectrum in Figure 1. It is apparent that the substitution potential is smaller the more that a wine region is already relying on cultivars on the right end of the Figure, and *vice versa*.

In addition to substitution among existing cultivars, scientists have experimented with new drought resistant rootstock (e.g., Walker and Clingeleffer, 2009) and new, genetically modified grape cultivars (e.g., Webb et al., 2011; Duchêne et al., 2010; Camargo et al., 2008).

Many European wine growing regions and their system of geographic indication (appellations) only permit certain grape varieties for their specific *terroirs*.[25]
For instance, INAO (Institut National d'Origine et de la Qualité), which regulates the Appellation d'Origine Contrôlée (AOC) system in France, defines which grape varieties and winemaking practices are approved for classification in each of France's several hundred geographically defined appellations. It allows, for example, only four grape varieties for the Burgundy appellation (pinot noir, gamay, chardonnay, aligoté) and three for Champagne (pinot noir, pinot meunier and chardonnay). Increasing temperatures will force winemakers to abandon or substantially change many of the appellation-related rules. As a result, the close association between grape variety and location (*terroir*) may have to be redefined.

D. Production Technologies

Webb et al. (2009) report about winemakers' responses during the Australian heat wave in 2009. They learned there are measures that growers can take to mitigate heat damage. Two issues emerged as crucial: water and radiant energy.

Full capacity watering before and during the extreme heat helped to minimize damage. The water needs of high-yield vines were especially high, while vines grafted on drought-resistant rootstocks required less water.

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[25] The French expression *terroir* denotes the specific geography, geology and climate of a location.

While irrigation is common practice in most vineyards in the New World, in most of Europe, natural precipitation is considered the only acceptable source of water for vines. No doubt this is a result, in part at least, of the fact that sufficient rainfall is common in European vineyard areas. Nevertheless, historically, the wine laws of the European Union have, prohibited vineyard irrigation. Thus, adaptation along these lines will take some institutional changes. In fact, in recent years, the irrigation ban has been loosened in Spain; in France, the INAO has been reviewing the issue.

Second, in the Australian heat wave good canopy (the leaf coverage of the grape vine) growth and canopy manipulation helped to protect berries from direct exposure to radiant heat. The same effects can be achieved by changing the row orientation of grape vines from north-south to west-east. In addition, growing a cover crop on the inter-row space mitigated the additional heat reflected from the soil.

IV. Summary and Outlook

This paper provides an overview of the economic literature on viticulture and climate change. Beginning with the early analyses of weather and Bordeaux wine prices by Ashenfelter und collaborators (Ashenfelter, 1986; 1987a; 1987b; 1990; 2010; Ashenfelter, et al., 1995) a growing body of literature has developed. Numerous studies examine the relationship between weather and economic outcomes such as wine prices and quality, prices for vineyard land, or winery revenue and profits for various wine growing regions and cultivars. Depending on current conditions, the evidence shows that rising growing season temperatures can be beneficial or detrimental to viticulture. As a result there will be winners and losers from climate change. In general, while wine growing regions near the northern frontier of professional viticulture (or the southern frontier in the southern hemisphere) will benefit from further warming, regions that are located closer to the equator will face severe problems.

Despite the progress that has been made, the current assessment of the economic impacts of climate change on wine and viticulture suffers from several limitations. First, most analyses rely solely on measures of average temperatures, and this may fail to fully account for the effect of extreme temperatures. Second, many studies consider only partial equilibria and disregard interdependent relationships between crop yield, quality and price. Finally, many analyses also disregard possible farmer adaptations and assume instead a "dumb farmer" scenario. However, grape growers and winemakers have proven their adaptability to changing climatic and economic environments over thousands of year and are likely to do so in the future as well. Disregarding farmer adjustments will thus overestimate the long-term costs of climate change.

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Table 1

Bordeaux Wine Prices and the Weather

	Dependent Variable Logarithm of London Auction Prices for Mature Red Bordeaux Wines		
Independent Variables	(1)	(2)	(3)
Age of vintage	0.0354 (0.0137)	0.0238 (0.00717)	0.0240 (0.00747)
Average temperature over growing season (April-September)		0.616 (0.0952)	0.608 (0.116)
Rain in August-September		-0.00386 (0.00081)	-0.00380 (0.000950)
Rain in the winter preceding the vintage (October-March)		0.001173 (0.000482)	0.00115 (0.000505)
Average temperature in September			0.00765 (0.0565)
R-squared	0.212	0.828	0.828
Root mean squared error	0.575	0.287	0.293

All regressions are of the (logarithm of) the price of different vintages of a portfolio of Bordeaux chateau wines on climate variables, using as data the vintages of 1952–80, excluding the 1954 and 1956 vintages, which are now rarely sold; all regressions contain an intercept, which is not reported. Standard errors are in parentheses. Source: Ashenfelter (2010).

Table 2

Weather and Real per Hectare Profits, Subsidies and Costs of German Wineries

	(1) ln(profits – subsidies)	(2) ln(profits incl. subsidies)	(3 ln(costs)
Temperature Growing	0.309***	0.305***	0.026
Season[a]	(5.17)[5.25]	(4.71)[5.11]	(0.18)[0.19]
Rainfall Winter[b]	-0.0034***	-0.0031***	-0.0003
	(-9.77)[-9.90]	(-3.23)[-8.51]	(-0.29)[-0.29]
Rainfall Growing	-0.0009***	-0.0009***	-0.0001
Season[c]	(-4.62)[-4.68]	(-1.75)[-5.67]	(-0.51)[-0.52]
Trend	-0.074***	-0.072***	-0.029
	(-8.79)[-8.91]	(-8.37)[-7.98]	(-1.40)[-1.42]
Fixed Effects			
Mosel	8.09	8.14	10.33
Rheinhessen	7.55	7.52	10.14
Rheingau	8.28	8.14	10.35
Pfalz	7.79	7.75	9.86
Baden-Württemberg	8.48	8.43	10.18
Franken	8.11	8.10	10.41
R2	0.663	0.644	0.538
F statistic	9.17	11.25	8.26
N	52	52	57

a) February to October, in degree Celsius, b) December to February prior to growing season in ml c) April to October in ml; d) we refer to weather data from the station in Trier (Mosel); significance level of 1% (***), 2% (**), 5% (*), 6.6% (+); Newey-West robust t-values in parentheses; t-values based on year clustered standard errors in brackets. Source: Ashenfelter and Storchmann (2010a).

Table 3

Weather, Revenue, Cost, Subsidies and Value Added in Regions of European Union

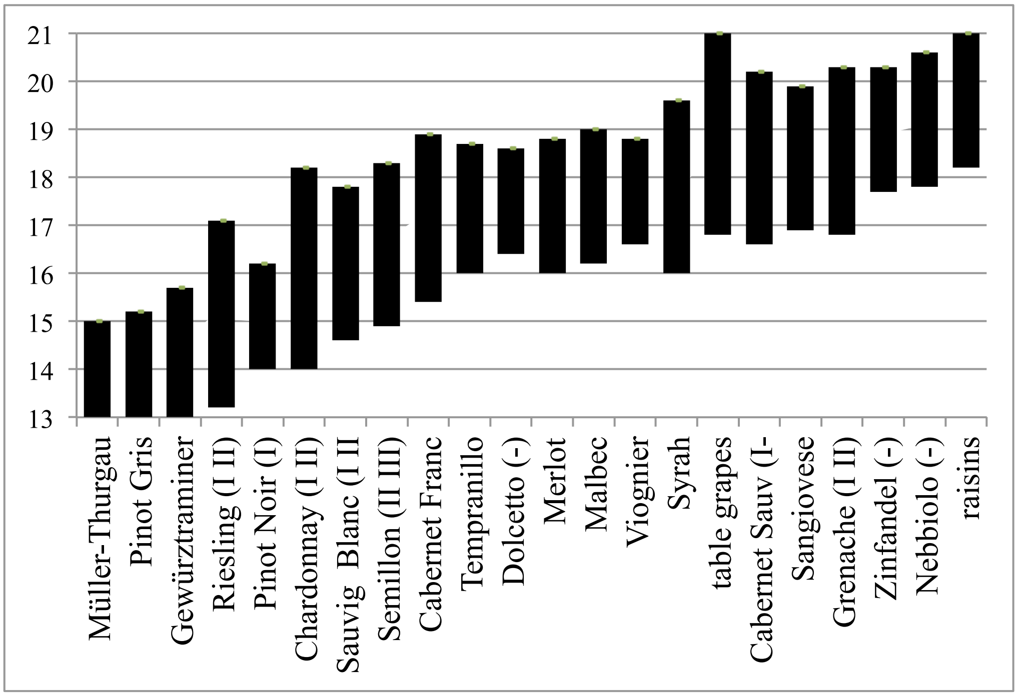
in nominal EUR per hectare

	ln(Revenue)	ln(Cost)	ln(Subsidies)	ln(Value Added)
Temperature Growing Season	0.211***	-0.066	-0.436	0.270**
	(2.59)	(-1.08)	(-0.64)	(2.06)
(Temperature Growing	-0.006***	0.002	0.012	-0.007**
Season)^2	(-2.66)	(1.21)	(0.64)	(-2.12)
Rainfall Winter before	0.0001	0.0001	0.001	0.0002
Growing Season[a)]	(1.34)	(1.07)	(1.23)	(1.19)
Rainfall Growing Season[b)]	-0.000	-0.00001	0.0001	0.00002
	(-0.10)	(-0.29)	(0.08)	(0.17)
Rainfall Harvest	-0.00001	0.0001	0.003*	0.0002
	(-0.15)	(0.38)	(1.76)	(0.35)
Trend	0.017***	0.027***	0.118***	0.016***
	(7.74)	(27.15)	(7.59)	(4.52)
Constant	6.674***	8.514***	7.391	5.535***
	(8.25)	(16.02)	(1.12)	(4.07)
R2	0.942	0.971	0.704	0.895
F(6,18)	13.09***	276.11***	20.59***	4.54***
n	618	618	406	611
$Temp_{opt}$	18.62			18.85

Source: Antoy et al. (2010). All equations with region-fixed effects; a) Mar-Oct, in degree Celsius, b) Dec-Feb prior to growing season in ml c) Mar-Aug in ml; robust t-values based on year-clustered standard errors. Significance level 2%(***), 5%(**), 10%(*).

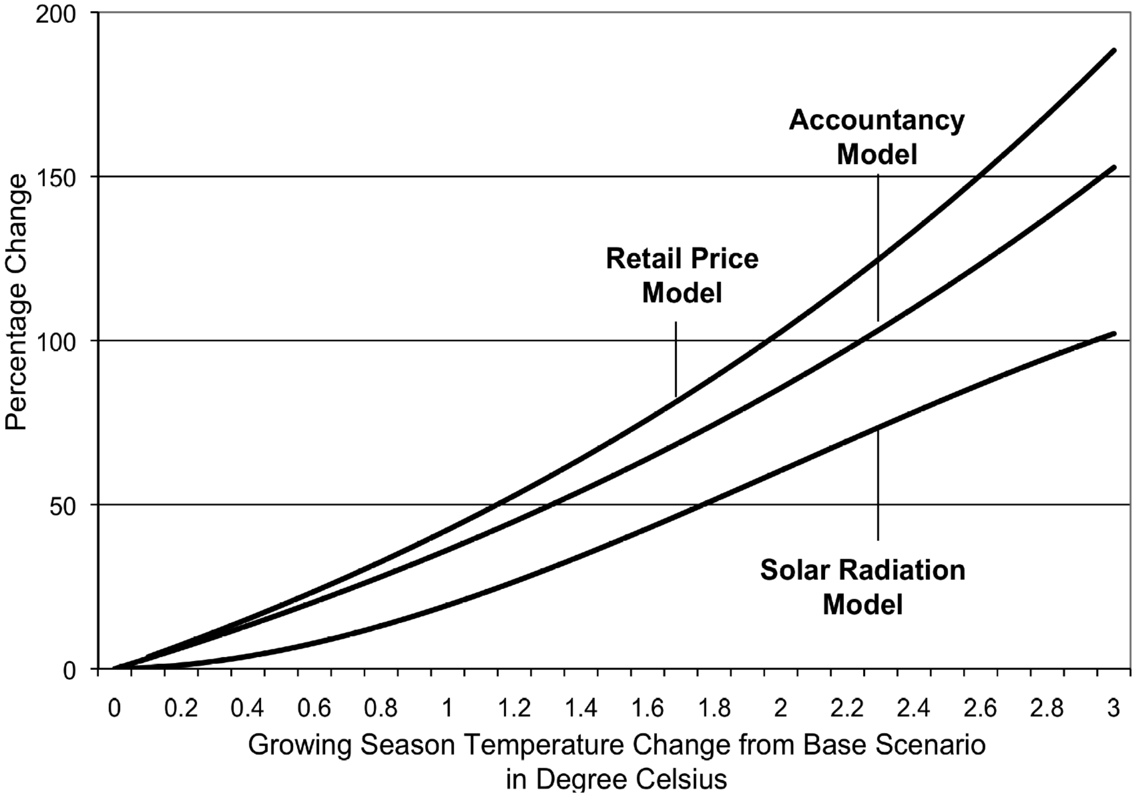
Figure 1

Optimal Growing Season Temperatures
for Selected Grapevine Cultivars
in Degree Celsius



Optimal Growing Season average temperatures for high quality wine production. Northern Hemisphere Apr-Oct, Southern Hemisphere Oct-Apr. Numbers in parentheses are Winkler Regions for fully tested varieties. (-) denotes cultivars with only a limited recommendation. Others have not been fully tested. Source: Jones et al., 2005; Amerine and Winkler, 1944.

Figure 2
Temperature Changes and Percentage Changes in Land Value



Source: Ashenfelter and Storchmann (2010a).

Figure 3

Net Value Added in Selected European Grape Growing Regions in 2009

in 1000 EUR/hectare

Source: Antoy et al., 2010.

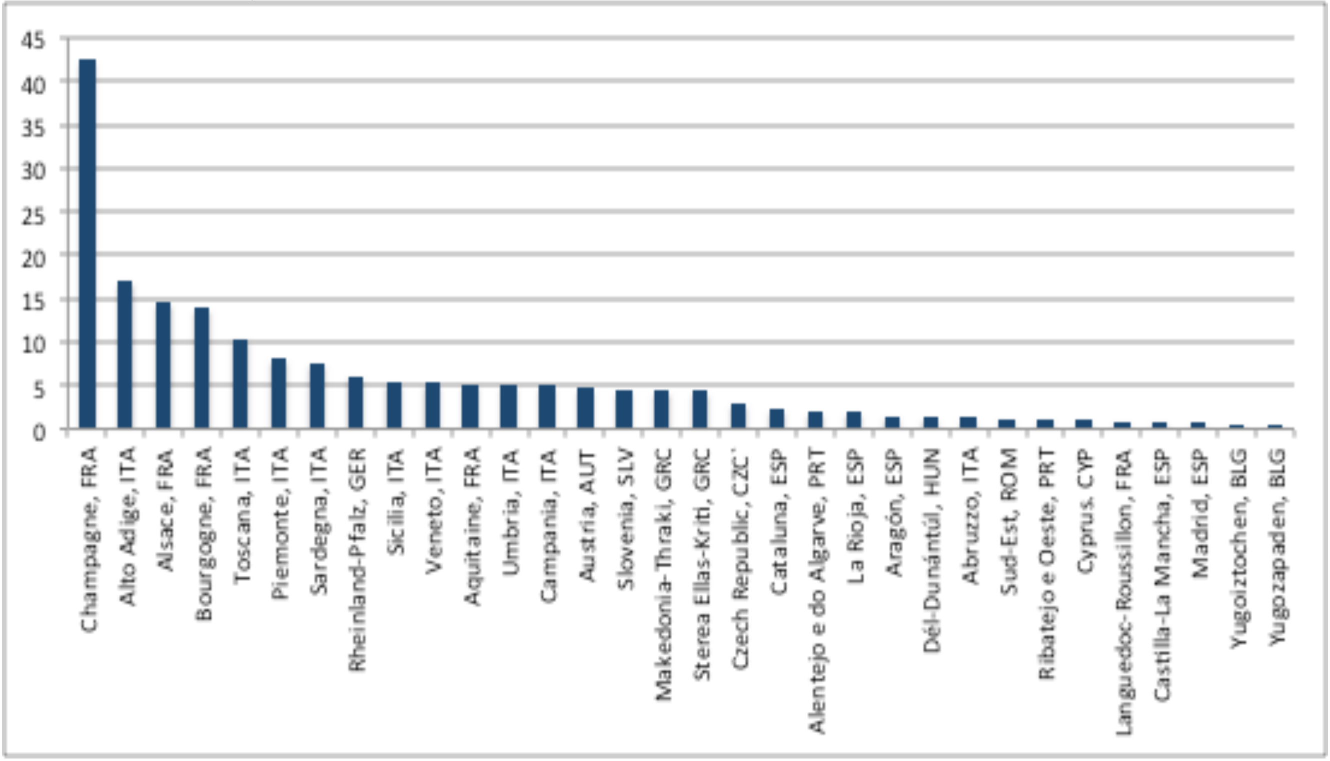


Figure 4

Average Growing Season Temperatures in Selected Wine Regions, 1987-2009

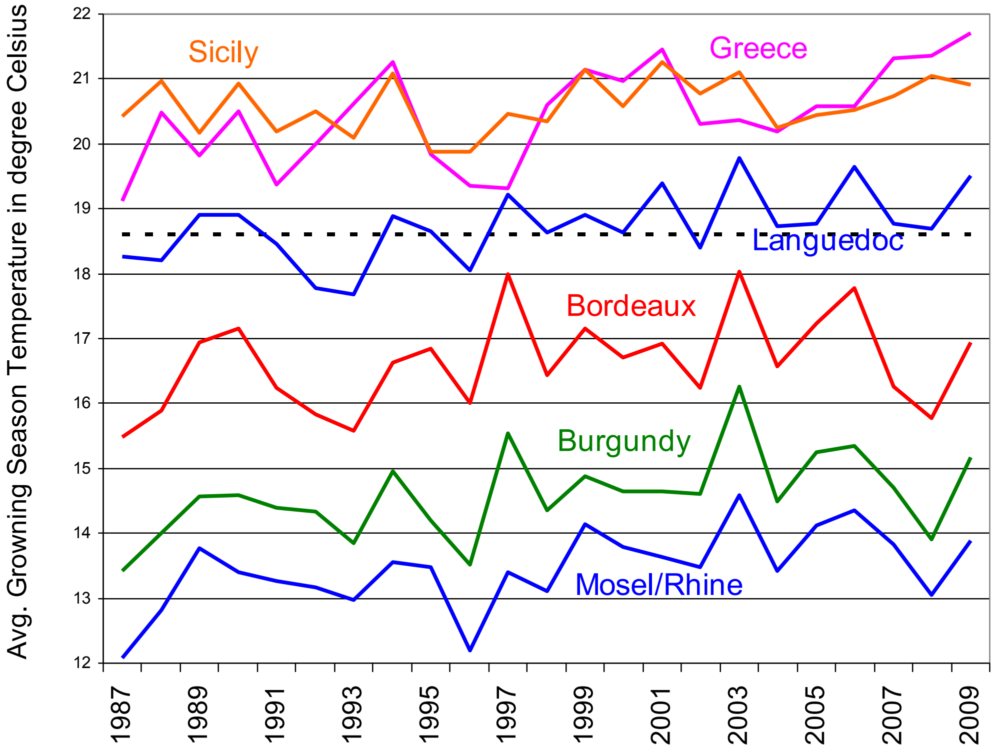
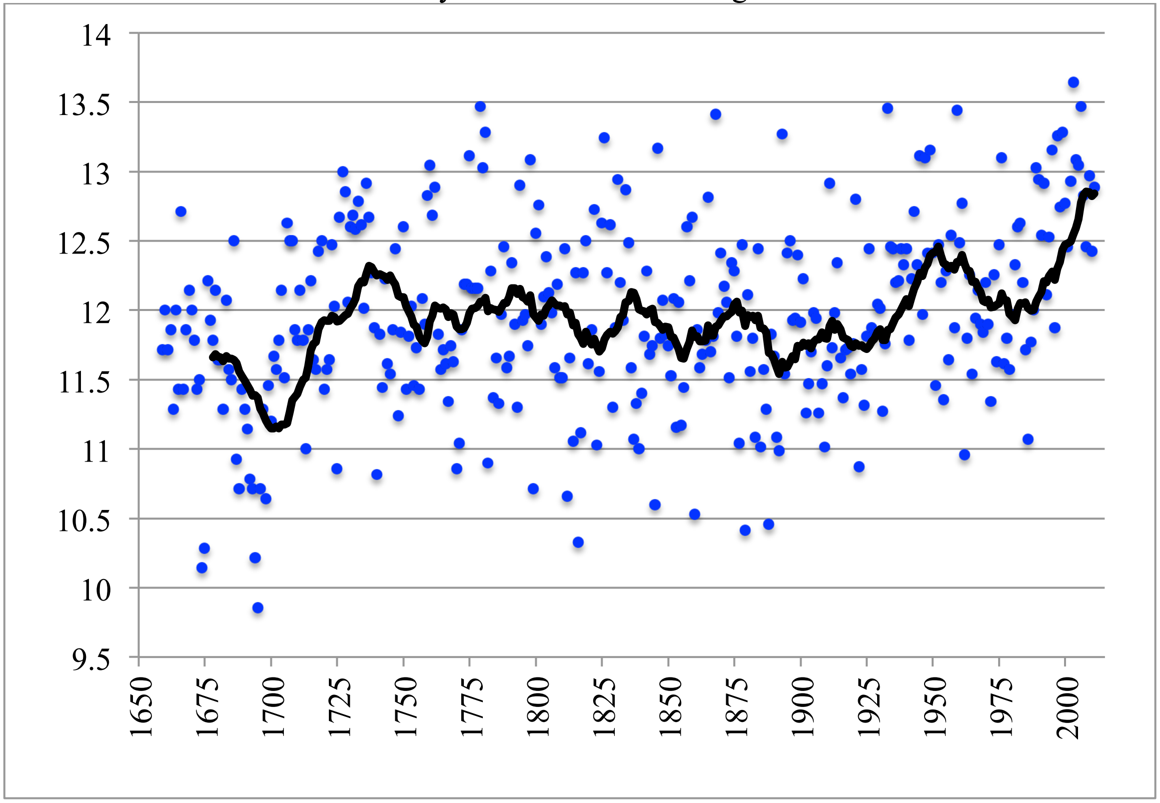


Figure 5

Growing Season Temperatures 1659-2011

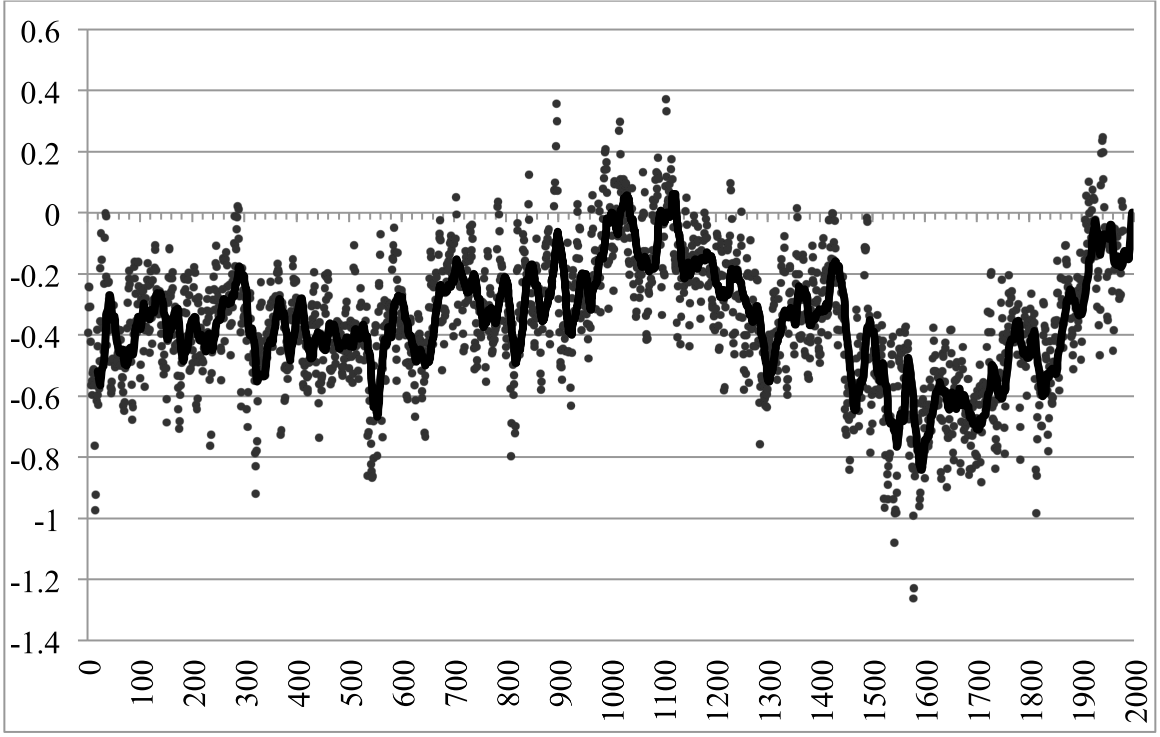
Manley Series for Central England



Average growing sesason temperature, March to August, in degree Celsius. The solid line depicts the 20-year moving average. Source: Met Office Hadley Centre (2012).

Figure 7

2000 Year Northern Hemisphere Temperature Reconstruction
Based on Proxy Data from 1 to 1979
Deviation from 1961-1990 Average in ^{0}C,

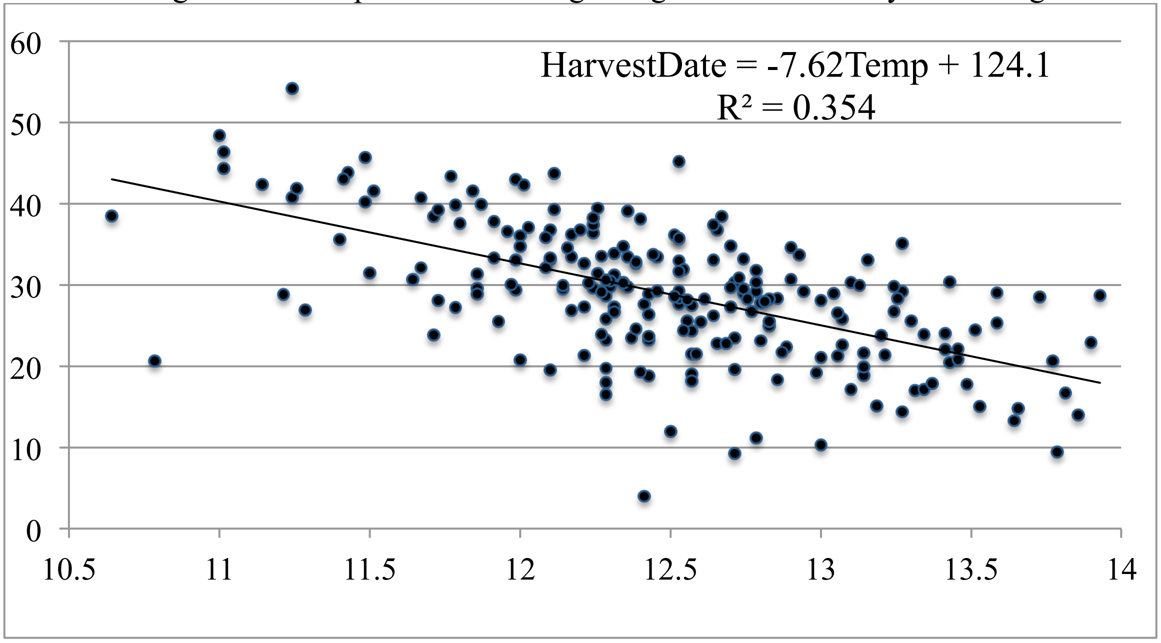


Data range from the year 1 to 1979. The solid line depicts the 20-year moving average. Source: Moberg et al. (2005).

Figure 6

Temperatures and Harvest Dates in Burgundy from 1659 to1879

Growing Season Temperatures and Beginning of Harvest in Days after Aug 31



Source: Harvest Dates were taken from Le Roy Ladurie and Baulant (1981). Temperature data refer to growing season temperatures of the Manley series for Middle England (Met Office Hadley Centre, 2012).