# In vino qualitas: climate change effects on Italian wine production

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**Abstract**

In viticulture, climate conditions prove to be a crucial driver in what regards quality of vintages. Understanding to what extent the predicted variability of these parameters could affect wine production in the future, creates ground for efficient assessment of appropriate mitigation and adaptation measures and guarantees the further sound development of wine industry. Our study analyzes the relationship between meteo-climatic conditions expressed by Huglin Index and precipitation during growing season- and wine ratings of the three of the most representative Italian Wines, namely Amarone, Barolo and Brunello. Resulting coefficients of a panel data regression are used in a dynamic model aimed at forecasting the quality of harvests through to 2050.

**JEL classification**: Q54, Q10.
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## 1 Introduction

Historical evidences suggest that climate changes are part of natural process on our planet. Nevertheless, such effects as desertification, deforestation and changes in atmospheric composition prove that the human role in climate change process is increasing. Following the IPCC, it's easy to understand that future climate changes will depend on two factors: greenhouse gas emissions and response of the climatic system to these emissions (IDDRI, 2009). Particular increase in the level of GHG emissions is related to alterations in Earth's surface that influence the Earth's radiation budget, atmospheric circulation and hydrologic cycle. For this reason it's fundamental to be conscious of the possible impacts of climate changes on agriculture, especially in regard to viticulture.

The aim of our paper is to contribute to the literature of adaptation strategies by evaluating the potential impact of climate change on the evolution of quality of three Italian wine.

As a matter of fact, production of high-quality grapes is subject to significant influence of weather conditions. Generally, the overall quality of grape is linked to a specific geographical/climate niche characterized by certain climatic parameters; hence the climate variability determines vintage-to-vintage quality differences.

In this context the heated climate change debate reveals that anthropogenic emissions have direct and indirect effects on the overall wine production. The direct effects are related to the increase in $CO_2$-concentration (in ppm). Research carried out previously on wine cultivation in Italy by means of Free Air $CO_2$ enrichment system (the method implies rising GHG concentration above +200 ppmv) found a positive correlation between GHG concentration and yield of grapes into wine (+40-45% s.s.), and, besides, some effect on wine quality - in terms of sugar accumulation and acidity. The latter effect keeps the same value for higher level of GHG concentrations (+350 ppmv), with its influence decreasing over time (Bindi et al., 2001).

The indirect effects are related to variability of the factor that affects grapes growth and wine quality (i.a solar radiation, heat accumulation, temperature extremes, precipitation, wind and extreme weather events such as hail) (Jones et al., 2005). Temperatures during the growing season are critical because of the direct impact on the ability of grapes to ripen to an optimum level of sugar, acid and flavour so as to maximize the quality of a specific wine. This influence could be accounted for in three different ways. Firstly, during the flowering and growing seasons, extremes of heat could trigger high grape mortality and enzyme inactivation (Mullins et al., 1992). Secondly, higher diurnal temperature leads to a beneficial synthesis of grape tannins and sugar. Furthermore, long-standing temperature above zero vegetative (10°C) determines anticipation both of vegetative growth and growing season, thus a reduction of yield of grapes into wine (Bindi, Fibbi et al, 2001). Additionally, higher temperature across the growing season will bring forward the grapevine harvest date to a hotter month and thus compress the difference between early and late-harvesting varieties (Anderson et al., 2008).

Our research contributes to the empirical literature in many directions. First of all, we make use of an original dataset, containing precise meteorological information related to three Italian wines (Amarone, Brunello and Barolo) which we combine to construct bioclimatic indexes which can be used effectively to correlate weather changes and wine quality.

Secondly, we project the evolution of wine quality in time (till 2050) by constructing a system dynamics model which simulates grape behaviour and considers IPCC scenarios as inputs of wine quality itself.

The paper is structured as follows: Section 1 contains a literature overview of the relevant existing studies. Section 2 describes data used and the methodology applied in the analysis. Section 3 identifies the econometric model used to find coefficients which are then used in the dynamic model defined in section 4. Section 5 briefly discusses adaptation strategies and section 6 concludes.

## 2 Literature overview

Impacts on wine quality related to weather variables and climate change have been largely investigated. As Jones (2007) suggests, the overall effect implies a more rapid plant growth and out of balance ripening profiles. Each quality is defined by a specific growth period that allows deposition of sugar till a certain level, maintenance of grape acidity and production of the optimum flavour profile for the grapevine in question. The warmer the environment is, the more rapid is the phenological process that the grapevine will go through, resulting in acidity loss and higher sugar ripeness that makes the wine unbalanced. For example, Duchene and Schneider (2005) find a positive correlation between higher alcohol levels and warmer ripening periods and earlier phenology in Alsace for Riesling variety.

Besides, recent studies have shown that in other European regions warming occurred throughout the whole year, increasing during the growing season by 1.7°C on average, with most of it coming at night. Heat accumulation, either measured by Huglin or Winkler Index, increased as well degree-days rising by 250-300 units (°units) (Jones et al, 2005b). As a number of research studies have proven, vintage ratings relating to these regions show increasing trends in overall quality, with less vintage-to-vintage variation. The growing season temperature is an important factor in vintage ratings across many regions, though not uniform across regions and not always linear. Generally, depending on region and wine quality, the warmer growing season temperature translates into a 10-22 percentage points increase of vintage rating. More importantly, there is evidence about the impact of climate change on wine quality that will further be analyzed.

Through a linear regression between wine quality and temperature, Jones et al. (2005) quantify specific temperature anomalies that generate a general quality improvement of Barolo. From 1950 to 1999, the general average growing temperature in the region was 17.8°C, with a standard deviation of monthly temperature throughout the growing season of 4.5°C. General temperature trends prove to be more significant. In the last fifty years warming in the region was on average 1,6°C. Authors estimate that the optimum growing season temperature for Barolo is 18.6°C. This indicates that climate conditions in the region are close to the required. Moreover, variability in predictions suggests that even with optimum growing season temperatures, weather events such as frost or hail are likely to reduce vintage quality. Conversely, high rating for Barolo (100/100 in Sotheby's rating) was achieved during a season cooler than average (-1,1°C) and was probably caused by an inferior variability in the day-to-day temperatures during the season.

In addition, Orlandini et al. (2005) analyze the correlation existing between quality and the bioclimatic index (i.e. Huglin) for Brunello di Montalcino. Results suggest that temperature is directly proportional to the probability of obtaining better quality, as the heat accumulation during the growing season increases. According to the authors, monthly precipitations have negative influence on quality, with a decrease in probability to have better vintage in years defined by high precipitation levels. However, the annual differences between the index and climate average value during the period 1961-1990 suggest that improvement in vintage quality comes from heat accumulation. During the last decade, there has been an increase in the number of years characterized by Winkler Index values above the average. At the same time it was impossible to define any trends for monthly precipitation.

Projections of future climate developments in Italy show that the overall climate change effects should lead to shorter growth intervals together with increases in yield variability (Bindi et. al., 1996). The rate of change projected for the next forty years reveals potential shifts in climate maturity types for many regions at or near a given threshold of ripening potential for variety currently cultivated in that particular region. Referring to Barolo, Jones et al. (2005) suggest an increase in average growing season climate to 18.2°C, including the overall trend in projected warming of 2.4°C by 2049.

Other studies examine climate change at European level applying different modelling approaches, but eventually came up with similar results. Particularly, Kenny and Harrison (1992) perform some early spatial modelling of future climate change impacts on viticulture in the European region and show potential shifts and expansion in the viticulture geography, with part of Southern Europe predicted to become too hot to produce high quality wines and northern regions becoming more viable. Similarly, they estimate an increase from 100 to 600 units for Huglin Index in Europe, which suggests a broad latitudinal shift of varietal suitability in favour of northern regions.

Finally, as Lebon (2002) demonstrates, not only does the overall change in climatic variables affect the characteristics of suitable locations for some varieties, but it also impacts the phenological development implying a reduction in the optimum harvest window for high quality wines. This evidence suggests that heat accumulation, causing overexposure during maturation and especially at night, would disrupt flavour and colour development and ultimately the wine's tipicity. Thus, it will have a certain impact on wine industry, besides the fact that increase of precipitation variability and average growing season temperature, mainly in southern region, will require a more sophisticated and efficient management of water resources.

## 3 Data and Methodology

In order to assess the effects of climate variability on grape quality, appropriate parameters should be chosen that synthetize both wine quality and weather conditions. These parameters must then be incorporated into a linear regression, which allows one to carry out year-to-year comparison of existing relations between wine quality and climate conditions.

1. Quality indicator

Comparison of wines over time is normally carried out on basis of either quality ratings or prices. The relationship between climate variables and wine price is based on the assumption that, ceteris paribus, better climatic conditions will improve the vintage quality leading to higher prices. Quality ratings are easier to obtain and, moreover, serve as a crucial factor affecting the vintage's economic success.

Wine quality assessment is nonetheless subject to biases. Though technology improvement (i.e gas liquid chromatography) makes possible the analysis of chemicals that affect grapes quality, generally wine evaluation is based upon sensorial analysis aimed to assess specific taste buds and olfactory properties. Wines are typically rated by a panel of experts that attempt to quantify flavour, aroma, colour, balance of alcohol and acidity that best represent that variety's wine style.

Recent studies have assessed the way in which experts' ratings incorporate information on weather data. Econometric regressions developed by Corsi and Ashenfelter (2001) on data from Gambero Rosso reveal a decreasing correspondence between predicted and observed ratings along time. This is consistent with the results drawn from previous analysis (Byron and Ashenfelter, 1995), in which the authors clearly demonstrate that "prices in the first years after the vintage over-or-underestimate future prices of mature wines and, since market prices are based on predictions on future wine quality, this means that market operators' predictions in those periods are not accurate" (Corsi and Ashenfelter, ibidem). Undoubtedly, other drivers apart from weather may possibly have important influence on grapevine production, mainly on plant pathologies. Besides, it is possible that experts' opinion do not fully exploit all available information. Nevertheless there is general consensus among authors that wine ratings are able to cover "[...]the same weather factors that have been documented to be determinants of wine quality" (Ashenfelter and Jones, 2000). Furthermore, as numerous rating systems were developed over time, it has become obvious that there exists strong positive correlation among various sources. It indicates that subjective evaluation of quality is a good representation of a vintage (Jones, Corsi et al., 1997)[2].

Quality ratings for this study were drawn from "Vini d'Italia" Gambero Rosso-Slow Food Arcigola, the most influential Italian wine guidebook. It is issued every year, generally provides ratings for wines from individual wineries, as well as general ratings of vintages for the best DOCG wines (as Barolo, Brunello di Montalcino and Amarone). Vintage ratings are given in points from 1 (the lowest) to 5 (the highest) (Corsi and Ashenfelter, 2001).

## 2. Agroclimate indexes

Weather data covering daily precipitation, highest and lowest temperatures were selected according to localization of the most representative wineries for each type of wine and were provided by the Department of Physics of the University of Milan. In particular:

1. Barolo: Azienda Vinicola Cordero di Montezemolo, loc. La Morra, Cuneo, Italy;

2. Brunello di Montalcino: Azienda Agricola Case Basse, Di Soldera Gianfranco, Montalcino, Siena, Italy;

[2]Positive correlations between different ratings could stand that either there is common information not available to the larger public or there is common misperception of actual vintage quality and possibly a self-reinforcing imitation process among experts. Cfr. Corsi et al., *op.cit.*

3. Amarone: Masi Agricola SpA, Gargagnano di Valpolicella, Verona, Italy.

These data were used to construct the bioclimatic index capable to synthesize fundamental characteristics and potential production of a given region. Temperature-based metrics are useful to define both spatial variation in varietal potential growing season climate and ranking grape growing climates. For example, Amerine and Winkler (1944) developed an index for California to order regions into five climate rankings capable of ripening grape varieties. Besides Jones (2005) used average growing season temperatures to identify the climate maturity ripening potential for premium quality wine varieties in cool, intermediate, warm and hot climates. Moreover, thermal indices, such as Huglin and Winkler or pluviometric coefficients, are widely used in winery zoning.

The **Huglin index** (HI) enables classification of regions in terms of the sum of temperatures required for wine production and grape ripening. The value is calculated as the sum of mean and maximum temperatures above +10°C - zero vegetative - from April to September, accounting for a latitude coefficient k. Different grape varieties are therefore classified according to their minimal thermal requirement for grape ripening, from 1200 to 2800. The higher the HI value is, the higher is the probability the grape has longer maturity.

$$HI = \sum_{apr}^{sept} \frac{(t_{average/d} - 10°C) + (t_{max/d} - 10°C)}{2} * K$$

The index accounts only for daily temperatures.

Inclusion of HI in an econometric model produces better estimates than average temperatures, which are normally taken into consideration. Average temperatures do not reflect properly the overall amount of hours in which photosynthesis takes place, which is affected by daily temperature variability.

The **pluviometric coefficient** reflects the sum of monthly precipitations during the growing season (from April to September) expressed in millimetres and is captured by the formula:

$$\sum_{apr}^{sept} mm_d$$

## 4 Econometric model

Econometric approach adopted originally in the present study was based upon panel data analysis taking into account wine fixed effects. We think this methodology adds in robustness of coefficients with respect to Ashenfelter and Corsi (2001)[3] because the possibility of exploiting longitudinal dimension of data reduces omitted variables bias, which is supposed to be cleaned up by fixed effects.

Thus, regressions performed in the study considered pooled data for Barolo, Brunello and Amarone wines in the time period from 1970 to 2004. The dependent variable of the regression is represented with the Gambero Rosso vintage ratings. Values from 1 to 5, which are normally assigned to vintages, were transformed into the scale from 20 to 100. The qualitative independent variables applied in the regression are as follows:

1. Huglin index;

2. Precipitations;

3. 'Wine dummy' variables: the wines are identified with values from 1 to 3 (1=Barolo; 2=Brunello, 3=Amarone di Valpolicella). Basically, the 'wine dummy' variables compare wines 2 and 3 to wine 1.

Results obtained from the regression provide insight on how the temperature factor represented by the Huglin index and precipitations influence wine quality. Table 1 presents the relevant coefficients.

Table 1: Regression coefficients and their significance

| rankinggam~f | Coef. | Std. Err. | t | P>\|t\| | [95% Conf. | Interval] |
|---|---|---|---|---|---|---|
| indicedihu~n | .0095301 | .0130968 | 0.73 | 0.469 | -.016493 | .0355532 |
| precipitaz~i | -.1200765 | .0242759 | -4.95 | 0.000 | -.1683122 | -.0718409 |
| _Ivini_2 | 6.111819 | 6.057466 | 1.01 | 0.316 | -5.924238 | 18.14788 |
| _Ivini_3 | 16.12791 | 8.153424 | 1.98 | 0.051 | -.0727705 | 32.32859 |
| _cons | 87.57229 | 29.62619 | 2.96 | 0.004 | 28.7057 | 146.4389 |

Correlation related to the Huglin Index results positive ($\beta$=0.0095301). Results of the analysis do not reveal nevertheless a statistically relevant dependence of wine quality (P=0.469) on the latter.

There is clear negative correlation ($\beta$=-0.1200765; P=0.00) between wine quality and precipitations, which shows the marginal effect of rainfalls on wine quality. The coefficient proves to be significant at 1% level and therefore, it is robust. Thus, 1 mm increase in the level of precipitations causes the respective improvement of the quality indicator by 0.12 points.

As for the dummies, _Ivini_2 and _Ivini_3 dummy coefficients refer to Brunello and Amarone. They have to be interpreted relatively to the base dummy, which

[3]Coefficient of ordered probit are treated in this paper as a cross-section, while they refer to different time path and should be treated as a panel.

is _Ivini_1 and refers to Barolo. For Amarone di Valpolicella the effect of the explanatory variables (Huglin Index and precipitations) is 16 times greater than that for Barolo. The coefficient is significant at 5% level. For Brunello this magnitude is 6 times greater compared to Barolo. However, the relevant dummy coefficient is insignificant (p-value equal to 0.316). The panel dataset evidenced a higher sensitiveness to climate changes (variations in rainfall and temperatures) of Amarone and Brunello compared to Barolo.

The fixed link among the three wines created excessive sensitivity in the behaviour of the respective coefficients, which subsequently could serve to the detriment of the quality of the constructed Dynamic Model. Since this constrain led to unsatisfactory results, the "panel data set" was dropped so as to unbundle the behaviour of the three wines. Eventually, the coefficients used in the Dynamic Model origin from separate regressions for the three wines, with the quality variable ranging from 1 to 5. Here are the outcomes of the individual econometric analyses:

Table 2: Econometric analysis for Barolo

| Variable | Coefficient | Std. Error | t-Statistic | Prob. |
|---|---|---|---|---|
| C | 4.251073 | 3.787387 | 1.122429 | 0.2733 |
| HUGLIN | 0.000745 | 0.001856 | 0.401308 | 0.6919 |
| PRECIPITAZIONI | -0.006935 | 0.002179 | -3.181924 | 0.0042 |

Table 3: Econometric analysis for Brunello

| Variable | Coefficient | Std. Error | t-Statistic | Prob. |
|---|---|---|---|---|
| C | 4.148462 | 1.843069 | 2.250844 | 0.0314 |
| HUGLIN | 0.001079 | 0.000845 | 1.277012 | 0.2108 |
| PRECIPITAZIONI | -0.007634 | 0.002068 | -3.692460 | 0.0008 |

Table 4: Econometric analysis for Amarone

| Variable | Coefficient | Std. Error | t-Statistic | Prob. |
|---|---|---|---|---|
| C | 3.399145 | 3.026159 | 1.123254 | 0.2697 |
| HUGLIN | 0.001081 | 0.001124 | 0.961967 | 0.3433 |
| PRECIPITAZIONI | -0.004779 | 0.001880 | -2.541412 | 0.0161 |

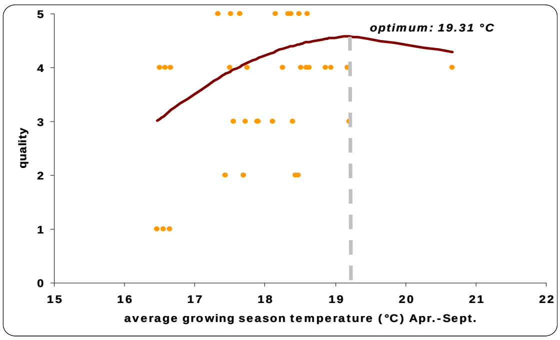
The analysis shows results which are qualitatively similar to the ones obtained with the panel dataset and just provides different coefficients for the Dynamic Model.

Even though there exists positive correlation between Huglin Index and quality of the three wines, one has to bear in mind that the overall quality of grape is linked to the single geographical/climate niches characterized by certain climatic parameters. Due to the possible non-linear correlation between climate and wine ratings, further increase in average growing season temperatures captured by the HI could lead to production of unbalanced wines. To account for this possibility, a quadratic term was introduced into the econometric analysis, following Jones (2005). The below specified formula assumes that wine quality improves with temperature increase, although at decreasing rate:

$$Ranking_{i,t} = c + \beta_1 temp + \beta_2 temp^2 + \varepsilon_{i,t} \qquad (1)$$

To identify the optimum average growing season temperature, partial derivative of equation (1) was taken and set equal to zero.
For Brunello, the results suggest that the predicted optimum growing season temperature is 19.3°C, while it reaches 21.2°C for the Amarone. In the same way, it's possible to detect the minimum average temperature that is recquired to produce Barolo (14.1°C).

Figure 1: Predicted optimum growing season temperature for Brunello

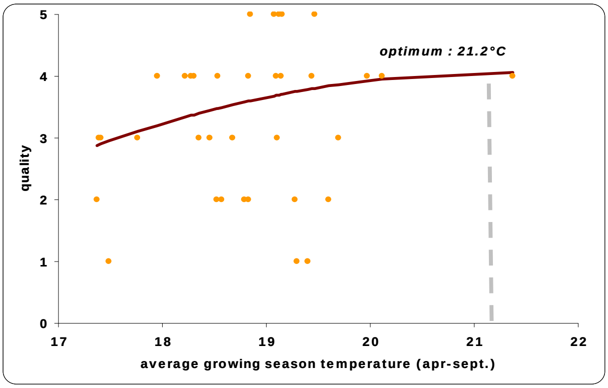



## 5 Dynamic model and future projections

Since the main objective of the present analysis is to identify how possible climate changes might affect the quality of the three wines in question, a dynamic model has been developed to forecast the quality of the harvests through to 2050.

The dynamic model is based on coefficients extrapolated from the econometric analysis and runs simulations that depend on exogenous climate change scenarios.

Figure 2: Predicted optimum growing season temperature for Amarone




Scenarios reported by Giorgi (2010) assume a reduction in rainfalls and an increase in average daily temperatures.

Alas, the scenarios refer to the Mediterranean area in general and clash with the trend of increasing precipitations noticed during the observation period (1970-2004). Since this point is decisive for our investigation, further econometric analysis was carried out to obtain a consistent input climate change trend for the dynamic model. In fact, the model considers rain precipitations and Huglin index (temperatures) as input data and, using the coefficients obtained from econometric analysis, it provides forecasts of the would-be influence of these two factors on quality of the wines. Logical framework of the model is shown in figure 4.

The model is split into three parts - one for each wine - and runs simulations from year 1970 until 2050. It considers historical data till the year 2004 and, subsequently, generates values of Huglin Index and precipitations from trend projections.

Results in figure 5 show an increasing quality over time for all the three wines.

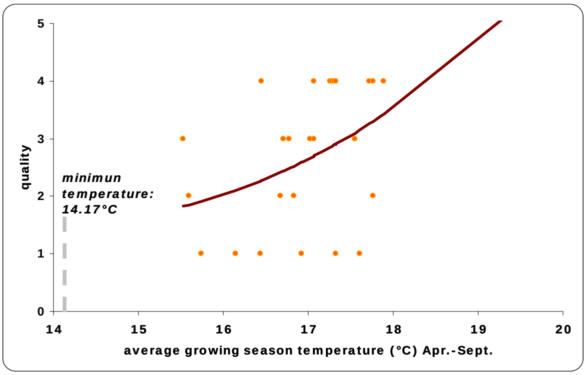
Oscillations are due to the fact that the model uses historical data till 2004 and then simulates projections. This fact explains the linearity of trend after 2004.

Amarone has the highest gradient (in terms of quality improvement/year: Amarone=0.014125; Barolo=0.007909; Brunello=0.006936) because of the highest sensitiveness to the beneficial temperature increases and the lowest sensitiveness to the negative effects of the precipitation increases.

Randomization can be introduced in the control panel of the model.

Basically it is done through randomization of input data projections, as well as

Figure 3: Predicted optimum growing season temperature for Barolo




of the coefficients ($\beta_1$, $\beta_2$). The constant term (c) is randomized as well, since the high standard deviation might influence the accuracy and significance of results. The 'Standard Deviations' are obtained from the 'Standard Errors' computed by Eviews according to the following relation:

$$Std.Deviation = Std.Error * sqrt(n)$$

*where n=number of observations*

With the randomization introduced, precipitation impact dominates due to the high volatility of rainfalls. Results are reported in figures 6 and 7. Oscillations are now spread all over the time horizon of the model.

Another interesting result of the Dynamic Model is the value assumed by the Huglin Index at year 2050, the end point of our time horizon. Trend projections for the three areas show a possible increase of hundreds of points (Barolo: 1875 2497; Brunello: 1945 2763; Amarone: 2291 2984) for the index. This means that Montalcino, Valpolicella and La Morra might become more suitable areas to grow different kinds of grape varieties (cultivars), shifting from a "Superior table wine" target to a "Dessert or high alcoholic content wine" production.

## 6 Climate Change Adaptation Strategies

So as to reduce the uncertainty linked to the future impact of climate change on wine industry, relevant adaptation management strategies should be adopted. Significant research regarding this issue has been carried out in the main viticulture regions in Australia and US California. For Italy the problem also remains acute

Figure 4: Dynamic system logical framework

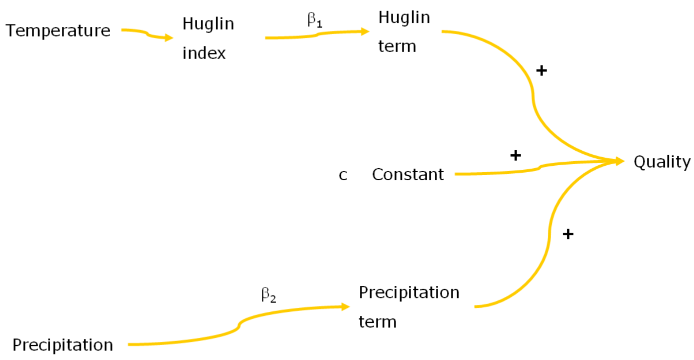
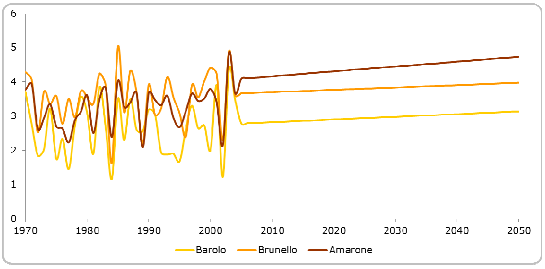



Figure 5: Wine quality trend projections




and climatologists conduct studies aimed at supporting the unique wine making traditions and preventing their demise.

The vine proves extremely sensitive to warming that causes shifts in its phenology to the detriment of final grape quality. In the context of climate change plasticity in the phenology of varieties becomes particularly relevant. It depends mainly on variety itself and production techniques (Anderson et al., 2008).

Experts argue that shifting of vineyards to cooler locations (to lower latitudes and higher altitudes) could be one of the possible adaptation strategies. In general, however, a reduction in areas suitable for growing quality wine grapes is expected (Anderson et al., 2008). Vineyards expansion to cooler areas can be combined with picking of new wine varietals that are more suitable for warmer temperatures and reduced precipitation levels. Grapes can be obtained from cooler areas even outside their current appellations (Gatto et al., 2009)[4]. These strategies are feasible in

[4] *Appellation d'Origine Côntrollée* - laws regulate wine-grape production throughout France,

Figure 6: Wine quality projections with randomization

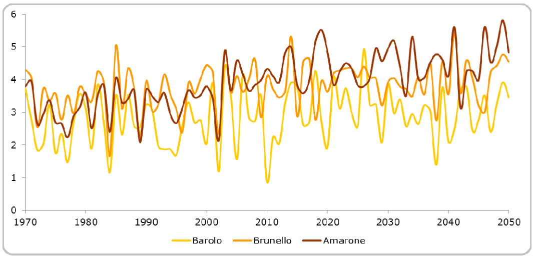



Table 5: Target wine vs. Optimum Huglin Index range

| Target wine | HI |
|---|---|
| Spumanti | 1200-1500 |
| Light table wines | 1300-1500 |
| Wine to distill | 1500-2000 |
| Superior table wines | 1500-2000 |
| Dessert wine or with higher alcol content | 2000-2800 |

long-term and prove to be very costly. It is expensive for growers to shift varietals, as they do not obtain income from the new plants for five to six years (Lobell et al. 2006). Winemakers, in turn, cannot make high quality wine from new grape varieties for the first ten years after new rootstocks are planted (Mason 2007).

In the long run, spatial distribution of viable grape growing areas is hence subject to modification. Some successful examples of such a strategy are represented by champagne grapes planted in England with some respectable vintages harvested (Hertsgaard, 2010). However there are evident limits to this strategy. Importantly, temperature is not the only determinant of a wine's taste. Terroir is a vital aspect - the term refers to the soil of a given region and, moreover, includes the cultural knowledge of the people who grow and process grapes (ibid).

Shift in the timing of key events in the annual cycle of growth and reproduction disrupts the balanced composition of wines by modifying the acidity and alcohol level, which calls for preventive measures. Excess heat causes rapid rise in sugar levels, thus forcing growers to pick grapes sooner and resulting in too alcoholic wine with the detrimented quality of the tannins - wine known as "fruit bombs" (Gatto et al., 2009). After the record summer heat in 2003, wine producers in Alto Adige

parts of Italy and Spain. In Italy it is known as Denominazione di Origine Controllata and imposes restrictive identification of wines. To be certified as a wine of a certain "regione di appartenenza" a certain percentage of grapes used for the wine production must come from that region.

(Italy) obtained wines that had between 14 and 16 percent of alcohol, whereas normally the content is between 12 and 14 (Hertsgaard, 2010). One of the possible ways to counteract these undesired developments can be adoption of techniques for manipulating the grapes aimed at bringing down the sugar and alcohol levels, such as addition of oak chips or oak tannins, during the wine making process (Gatto et al., 2009). There are also some tricks in vineyard management that can be applied to curb rise of alcohol content in grapes. The leaves surrounding the grapes can be allowed to grow bushier, providing more shade (Hertsgaard, 2010). Vines can be replaced with their clones or rootstocks. Research carried out by Carbonneau (1985) shows that grape rootstocks for classical varieties can be made drought-resistant.

Remediation of high alcohol in the winery will require new yeasts that can ferment sugar without creating alcohol. This could be done by genetic modification of yeasts (Thornton, 1985; McBryde et al. 2006). An alternative engineering solution is reverse osmosis procedures to de-alcoholise wine, but this can also take out flavour compounds.

Tartaric acid can be added to compensate for the decline in acidity in berries. Still faster grape maturity implies that grapes will be harvested with higher sugar content. Current trends for red wines in Australia show a one percent increase in alcohol content per decade (Jones et al., 2010).

As far as the ambiguous effects of $CO_2$ concentration are concerned, leaves are more tolerant of high temperatures at elevated $CO_2$ (Barlow, 2010). Still, high $CO_2$ may increase vine canopy size and density, resulting in higher biomass and favourable microclimate for disease proliferation (Manning and Vontiedemann, 1995). The risk of phylloxera spread rises as a result of the increased frequency of emergence of the insect from the soil with warmer winters and warmer night temperatures, and making the spread of the insect more probable. Thus, chemical responses to fight pests and mitigate damages caused to grapes, become increasingly important.

Possible solutions offered by American and Australian experts (Gatto et al., 2009; Jones et al., 2010) could be the use of genetically modified materials - new clones of existing grapes and altered rootstocks that can better accommodate increased pest levels stemming from increasing temperatures. Instead of replacing rootstocks that may be needed to fight particularly difficult new pests or diseases, there is the option to graft the plants of other varieties and clones onto existing rootstock (Gatto et al., 2009).

The study on the future impact of climate change of the wine industry of California (Gatto et al., 2009) suggests a matrix of solutions that hypothesizes combinations between rigid and flexible wine industry and different magnitude of climate change - low and high level, respectively. The rigidity of the wine culture obstacles the use of new clones to manipulate grapes and alter flavours. Varietal shifts are therefore considered to be inappropriate. Importantly, within a rigid wine culture, consumers prefer austere wines and it is hardly possible that they will be willing to shift their tastes.

Disruption of the balanced composition of grapes irreversibly leads to alteration of regional wine styles, and this trend should be reversed. Given the rigidity of production of the premium wines that include the wines in question, namely Barolo, Brunello and Amarone, the winemakers are likely to refuse to use the above mentioned adaptation techniques. Warming effects jeopardize the future of grand wines, since the majority of mitigation techniques available presently are not in line with the centuries-long traditions of wine making. Appellation d'Origine Côntrollée, Denominazione di Origine Controllata and similar laws, which stand in the way of adaptations, will definitely be challenged in the face of increasing temperatures.

Consumers' terroir sentiments should be taken into consideration when designing the potential adaptation strategies. Basically, adaptation responses should be adopted that will enable winemakers to continue to produce austere wines under new climate conditions. It is clear that in long-term applications of scientific knowledge, it will be inevitable to adapt wine production to the changing environment. Shortening the time lags to adoption of adaptive R&D innovations will boost the returns to investment (Anderson et al., 2008).

## 7 Conclusion

The present study, carried on three test-wines (Barolo, Brunello and Amarone) is generally consistent with literature results concerning wine quality.

Our contribution is important in two directions. First of all, we dispose of climatological data, provided by the Department of Physics of University of Milan, which are georeferenced and more precise than data traditionally used for agronomic studies. The availability of these data enables us to construct climate indexes which identify the possible impacts of climate change on wine quality better than max/min temperatures or average precipitations level.

We make use of Huglin Index and of a pluviometric coefficients, carefully described in section 2.

Our empirical analysis is composed of two sections.

An econometric model is run which finds specific coefficients representing the weight of Huglin Index and of pluviometric coefficient in affecting wine quality. Secondly, we use these coefficients as input of a system dynamics model, which simulates evolution of wine quality in the next 40 years.

Our econometric analysis revealed a strong correlation between wine quality and precipitation/temperatures in the harvesting area during the growing season of grapes. The quality of grapes will grow with the rise of temperatures, even if this positive trend cannot be indefinitely sustained.

Introduction of the quadratic term in the regression analysis tests this hypothesis. After a critical point, grape growers and wine makers will inevitably face a reverse trend connected with wine being unbalanced and loosing its original style characteristics.

Precipitation and temperature trends, used in the dynamic model, predict wine quality for the test-wines until 2050. The model shows how the decreasing precipitations and increasing temperatures, projected by IPCC scenarios, are likely to produce a beneficial effect on the three wines in the simulated time horizon.

Besides, the analysis of projected values for Huglin Index to 2050, which we provided together with dynamic simulations, suggests a possible suitability shift from "superior table wine" production to a "dessert/high alcoholic content" grape.

Since wine production techniques are characterised by the presence of evident structural rigidities and since consumers' tastes are affected by long lasting traditions and cultural traits which are persistent and very difficult to modify, the combination of mitigation and adaptation strategies - that range from relocation of vineyards to more suited cooler areas to the use of the genetically modified vine material and yeasts - have been proposed in the last paragraph, which shows the potential relevant consequences of climate change for wine industry, therefore stressing the urgency to design effective public policies.

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