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Climate and the quality of wine: Whites vs. reds☆

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HIGHLIGHTS

- Climatic change can severely affect wine production.
- Substitution between grape varieties can be a viable adaptation strategy.
- We estimate econometric models of wine quality controlling for soil and producer effects.
- We provide reliable evidence on the weather sensitivity of white and red grape varieties.
- Tradeoffs emerge between varieties which winemakers can exploit to face climatic change.

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ABSTRACT

We estimate the effect of weather conditions on wine quality (measured by tasting ratings) using panel data from a geographically homogeneous region in terms of soil and climate, but where both reds and whites are produced. We find that whites react to the weather very differently from reds; in particular, we identify a tradeoff between spring and summer temperatures. Moreover, substantial differences emerge even among individual grape varieties. The results allow for an assessment of the challenges faced by the wine industry in the context of global warming and suggest adaptation strategies based on substitution between grape varieties.

1. Introduction

It is common knowledge that climate has an impact on wine quality. How a specific wine vintage performs in relation to the average quality of that wine variety over time will depend, in part, on the weather conditions to which the vines and grapes were exposed during the growing season and the harvest.[1] The production of fine wines naturally concentrates in regions where an appropriate soil composition is accompanied by a favourable climate, facilitated by the human capital created in decades or even centuries of winemaking tradition. In other words, winemaking is a "local" activity *par excellence*, profoundly rooted in the qualities of the *terroir* and the wisdom of the local actors.

As global warming alters climatic conditions at an unprecedented pace, these foundations are shaken, and the wine industry on which the prosperity of entire communities has rested risks to be put in jeopardy. There are growing concerns that wine production may no longer be viable, at least not at the current quality levels, in some of these areas, while perhaps others which are marginal today will benefit. Progress in winemaking technique and technology will of course provide answers: for example, in Southern Europe the harvesting season has been progressively anticipated, to the point that what traditionally occurred in October is now often taking place in early September (or even at the end of August); yet the ability of winemakers to adapt can find a natural limit if average temperatures should grow too much, or if precipitation should become too scarce and concentrated, as is happening in large part of the temperate regions.

In this sense, statistical models relating wine quality to the weather prevailing during the growing, and then the ripening, season and the harvest can provide estimates of the potential effects of climate change,

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[1] For a descriptive analysis of the relationship between temperatures and precipitation and wine production in Bordeaux over two centuries, see Chevet et al. (2011).

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and suggest adaptation strategies based on substitution between grape varieties (Ashenfelter and Storchmann, 2016). Still, while there is a consensus in the literature on the sign of some effects – for instance, that a hot summer is beneficial for red wines, or harvest rain detrimental – there is little evidence on the differences between varieties, and even between white and red wines. Indeed, most of the literature has so far concentrated on reds, seldom considering white wines. Moreover, there is a lack of comparisons between the sensitivities to weather of the different grapes done under homogeneous conditions (i.e., grown on the same *terroir*).

For the first time in the literature (with the recent exception of Okhunjanov et al., 2024), we estimate a "Bordeaux equation" – regressing wine characteristics on vintage weather – through panel data techniques, controlling for unobserved heterogeneity; again unlike most of the previous literature, our sample – despite being drawn from a small and climatically homogeneous region: the Collio area in Friuli-Venezia Giulia (north-eastern Italy) – includes both whites and reds and a large number of different grape varieties, enabling us to identify the different effects of temperature and rainfall on either.

Most of our results are consistent with agronomic predictions. In general, we quantify the different reaction to climate between whites and reds: which is perhaps the main research result of the paper, although interesting differences emerge within macrocategories as well, particularly among different white varieties. We discuss the results in terms of the magnitude of long-term climate change projections for the Collio region drawn from standard climatological models, assessing the likely consequences on wine quality of the expected changes in rainfall and temperatures in the light of the potential strategic choices and the actions winemakers of the region might undertake to respond to the challenge. Our dataset contains some local grape varieties together with many standard ones, like Pinots (Blanc, Gris, Noir), Merlot, Cabernets (Franc or Sauvignon), Chardonnay and Sauvignon Blanc; therefore, beyond the obvious local specificities, our results are of general interest to international winemakers.

In the following Section 2 we review the relevant literature. Then in Section 3 we describe the dataset in terms of both wines and weather, including climatic projections; and we discuss the expected effects of climate on the different grape varieties. Section 4 is dedicated to the empirical approach: the econometric model specification and the empirical results; a Discussion section follows, highlighting the findings and assessing the robustness and substantial significance of results. Section 5 concludes.

2. Literature review

There is now a long tradition of explaining the properties of wine vintages through statistical models, also known as "Ashenfelter-type" models from the name of their main proponent. Within the larger scope of a paper dedicated to agricultural production in general, Lough et al. (1983, p. 1681) were the first to regress "vintage quality" on the weather conditions for Bordeaux and Champagne, finding that "a warm spring and summer, and dry summer weather [were] conducive to good vintages"; and concluding that global warming would lead to an improvement in wine quality: more so for Bordeaux than for Champagne. Perhaps more famously, Ashenfelter et al. (1995) (see also Byron and Ashenfelter, 1995; Fogarty, 2003; Ashenfelter, 2008, 2010; Outreville, 2018; Corsi and Ashenfelter, 2019) predicted vintage quality based on synthetic weather variables, estimating what came to be known as the "Bordeaux Equation".[2] Rain during the growing season and warm temperatures during the spring and summer, when the grapes ripen, were supposed to improve the quality of the grapes and of the resulting wine; rain before the harvest, on the contrary, would deteriorate the grapes, imbibing them with water and favouring the proliferation of fungi and other pest. Corsi and Ashenfelter (2019) refined the analysis separating temperature in the spring from that of the summer, finding little significance. As we shall see, this distinction will instead be crucial in the present paper.

The wine industry is well aware that climate change may pose opportunities and threats to wine production, because of the influence of temperature, water condition and sun rays during both the growing and the ripening/harvesting season. In Van Leeuwen and Destrac-Irvine (2017)'s words, "plant development, grape ripening and grape composition at ripeness are modified by climate change". In particular, climate change affects "temperature, vine water status and UV-B radiation". "Major adaptations can be reached through modifications in plant material (grapevine varieties, clones and rootstocks), vineyard management techniques (grapevine architecture, canopy management, harvest dates, vineyard floor management, timing of harvest, irrigation) or site selection (altitude, aspect, soil water holding capacity)" (Van Leeuwen and Destrac-Irvine, 2017, Abstract).

Econometric methods have already been employed to illustrate and assess the effect of climate. Hedonic regressions a' la Ashenfelter et al. (1995) have been identified as a potentially useful instrument for assessing the direction, significance and magnitude of the expected effects. Ashenfelter and Storchmann (2016) discuss how Bordeaux-style equations can be used for making predictions regarding the consequences of climate change on the wine industry: if quality is a function of climatic factors, then in principle the consequences of a predictable variation in climate can be predicted as well. From a strategic viewpoint, Ashenfelter (2017) considers the possibility of employing econometric evidence from hedonic models in the selection of vineyard sites: given the prevailing climate and model predictions on the quality of different grapes, it becomes possible to select the variety optimizing the output.

Jones et al. (2005) document the historical adaptation of vine growing over climatic periods, then address the influence of temperature on fine wines of 18 growing regions throughout the world, for a total of 30 variety/region couplets. They discuss the influence of climate based on the specificity of climatic regions, concentrating on temperature in the growing season. In the linear model, they find a negative influence of temperature on quality for some whites (Jones et al., 2005, Table III) which they explain through a nonlinear (quadratic) specification. In the latter (their Table IV) they do not find significant effects of temperatures on white varieties, with the exception of the Rhine Valley and the Loire Valley (sweet whites).

Jones et al. (2005) and Outreville (2018) are, to our knowledge, the only ones to consider reds and whites together. Otherwise, the empirical literature has hitherto focused on fine reds from a single (although sometimes large) region in France (for example Ashenfelter et al., 1995), Australia (Byron and Ashenfelter, 1995; Fogarty, 2003) or Italy (Corsi and Ashenfelter, 2019), overlooking white wines although in 2020 these still account for about 45 percent of world production. Indeed, while e.g. rain during the harvest can be generally expected to be detrimental for grape quality, other variables – especially temperature in the summer – will in principle affect whites and reds in different ways, as reviewed later in the paper. The main objective of the paper is the estimation and comparison of weather effects on the quality of, respectively, white and red varieties. As is usually the case, doing so in an otherwise homogeneous context can be of great help in isolating the effects of interest. In fact, the specification of Jones et al. (2005), because of its broad scope, is of course subject to substantial heterogeneity due to the omission of many potential other determinants of wine quality, either observable or unobservable. More problematic for our theoretical expectations are the findings from Outreville (2018): separate models of vintage ratings versus weather in, respectively, Burgundy and the region of Bordeaux yielding very similar effects of weather on whites vs. reds.

[2] The original Bordeaux Equation is estimated on 1952–1980 vintages of Bordeaux, excluding 1954 and 1956, and reported in Ashenfelter et al. (1995, Table 2) and Ashenfelter (2008, Table 2).

In this paper, we focus on the Collio region in north-eastern Italy which, by contrast to Jones et al. (2005), is compact and climatically homogeneous; and is rich with relatively small firms producing excellent wines out of many different varieties, unlike Burgundy and Bordeaux (Outreville, 2018) where a few grape varieties dominate. Especially well known for the outstanding quality of their whites, Collio wineyards do nevertheless produce a smaller number of fine reds as well. They are therefore an ideal testbed for identifying the different effects of climate on white and red grape varieties in an otherwise homogeneous environment. In fact, we will end up explaining the results of Outreville (2018) in terms of the large variance in the weather sensitivities of white grape varieties.

3. The dataset

The Collio (from the Italian *collina*, "hill") is a small winemaking region located in the North-East of Italy, on the border with Slovenia, within the province of Gorizia and the administrative region of Friuli-Venezia Giulia (see Fig. 1). This narrow corner bordering the river Isonzo is best known historically as a theatre of operations during the Great War, as depicted in Ernest Hemingway's *A Farewell to Arms*. As defined by its controlled designation of origin (henceforth DOC, from the Italian *Denominazione di Origine Controllata*), which ensures the quality and authenticity of the wines produced here, it covers almost 7000 hectares with a vineyard area of approximately 1500 hectares, entirely located on hillsides. Its wine production is a significant contributor to the economy of the province of Gorizia.

The soil is characterized by alternating layers of marl and sandstone, ideal for grape cultivation as they provide good drainage and impart unique mineral qualities to the wines. The climate is influenced by proximity to the Adriatic Sea and the Alps. It is characterized by hot summers and cold winters, with temperatures moderated by the Adriatic Sea, while the Julian Alps provide shelter from harsh weather.

Thanks to the unique combination of soil, climate and grape varieties, the Collio is renowned for producing high-quality white wines characterized by their freshness, complexity, and minerality. These wines often exhibit citrus, stone fruit, and herbal notes, with a distinctive mineral backbone. In turn, red wines from the Collio are typically elegant and structured, with ripe fruit flavours and well-integrated tannins. The DOC "Collio" comprises a total of 19 wine varieties, of which 13 are white and 6 red.

Importantly for our purposes, wine in the Collio is produced from a wide range of grape varieties, as opposed to the relative uniformity one will find in other famous wine regions – like, e.g., the much larger Burgundy where most wines come from Chardonnay grapes (whites) and Pinot Noir (reds), or Bordeaux where red wines are typically blends of Cabernet Sauvignon and Merlot – regions in which the greatest emphasis is on the *terroir*. This also applies to some Italian DOCGs like Brunello di Montalcino or Barolo, and entire regions like Tuscany where red wines are based on Sangiovese. In the Collio, as in much of Italy, wines are identified primarily by grape variety (or specific blend) and the producer.[3]

From the perspective of soil characteristics, despite the obvious variability in microclimates due to differences in altitude, exposure, and related factors, the Collio is a DOC area whose zoning is strictly regulated, ensuring a certain degree of territorial homogeneity across vineyards. According to the regulations, cultivation is only permitted on hillsides, and zoning complies with pedological characteristics: "Pedologically, the soils of the Collio are of flyschoid nature […]. In most of the territory, the marl and sandstone components tend to balance each other, giving rise to flyschoid soils, which are highly beneficial for viticulture".

[3] For a review of international, national and local varieties grown in Italy, see Carbone et al. (2023, Table 3).

Table 1
Dimensions and indices of the dataset.

	Entity	Number	Index
1	Labels	81	
2	Vintages	35	t
3	Producers	43	j
4	Varieties	12	k
5	Wines	191	i
6	White wine vintages	830	
7	Red wine vintages	70	
8	(Total) wine vintages	900	it

Table 2
Description of grape varieties, and wine vintages (i.e., total observations) by variety (panel dataset: i.e., wines with at least 2 observations in time).

	Variety	Red/White	Obs.
CB	Collio (Bianco)	White (blend)	94
CF	Cabernet Franc	Red	16
CH	Chardonnay	White	44
CR	Collio Rosso	Red (blend)	15
CS	Cabernet Sauvignon	Red	–
FR	Friulano (a.k.a. Tocai)	White	140
MA	Malvasia	White	12
ME	Merlot	Red	39
PB	Pinot Blanc	White	81
PG	Pinot Grigio	White (from grey berries)	258
PN	Pinot Noir	Red	2
RC	Riesling del Collio	White	–
RG	Ribolla Gialla	White	22
SB	Sauvignon Blanc	White	177

3.1. Wines

We consider a panel dataset of white and red wines comprising 12 grape *varieties* (including two blends), produced in the Collio region between the years 1987 and 2021 by 43 *producers*. Our individual unit of observation (the "wine") is the intersection of "label" (e.g., "Friulano Collio") and "producer" (e.g. "Livio Felluga"), so that "Friulano Collio (by) Livio Felluga" is one cross-sectional unit of observation: henceforth, a *wine*. Wines are observed repeatedly over time, every year a *vintage*, for a total of 900 observations. The individual observation is then a *wine vintage*, like e.g. "Friulano Collio (by) Livio Felluga, 2000". In the following, wines will be indexed by $i = 1, \dots, n$ and vintages by $t = 1, \dots, T$ (see Table 1).

A given producer does usually sell wines of different varieties, and might also offer more than one product of the same variety, like e.g. "Pinot Bianco" and "Pinot Bianco Riserva". Producers will be indexed by $j = 1, \dots, J$ and varieties by $k = 1, \dots, K$. The panel is unbalanced and contains many units with short time series. In particular, out of 191 units, 54 have 5 or more observations in time, only 37 have 10 or more. The varieties are described in the following Table 2 distinguishing between reds and whites.

Following Outreville (2018) and Corsi and Ashenfelter (2019), wine *quality* is measured here by tasting ratings on a 1–100 scale (effectively starting from 50), sourced from the Wine Spectator database. Like Outreville (2018), we treat the rating like a continuous variable on a cardinal scale.[4]

[4] Corsi and Ashenfelter (2019) consider ratings from three different sources ranging, respectively, 1–5 (Gambero Rosso wine guide), 1–4 (Robert Parker), or 1–12 (Wasserman); they estimate ordered probit models, as is customary with dependent variables with few integer outcomes, interpreted as ordinal. Outreville (2018) observes vintage ratings from the Hachette guide ranging 1–20; given the finer granularity of his measure, he treats the rating

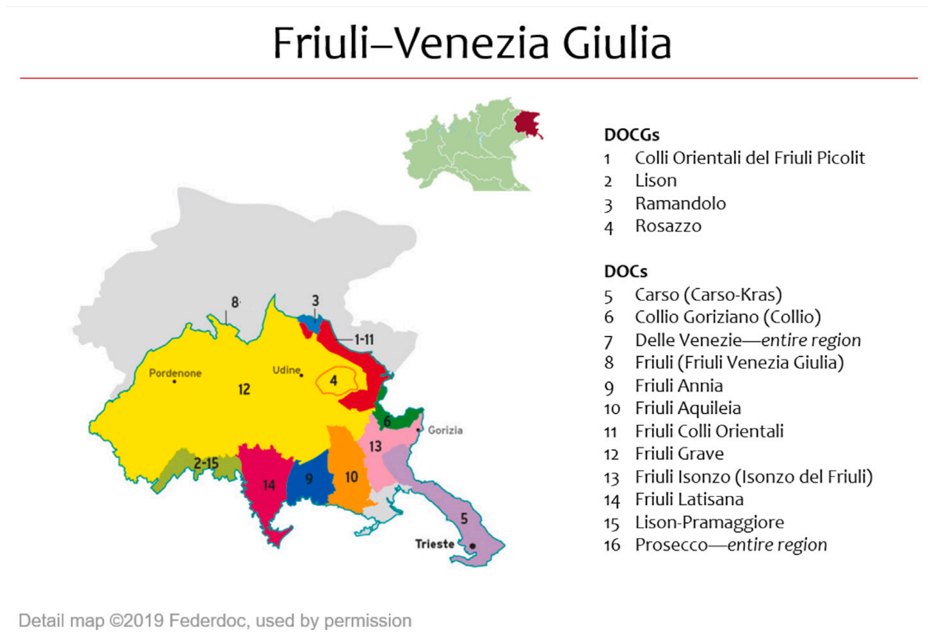

Fig. 1. The *controlled (DOC)* or *controlled and guaranteed (DOCG) designation of origin* regions of Friuli-Venezia Giulia, Italy. The acronym DOC(G) stands for the Italian *denominazione di origine controllata (e garantita)*.

Different measures of wine quality have been employed in the literature, starting with market prices in the seminal article Ashenfelter et al. (1995) which used market prices of Bordeaux wines in auctions observed at a given, common time. This measure is not applicable here, as Collio wines do not have a market complete enough in terms of transaction on vintages of the same label in time; both because of the sheer variety of labels in relation to an overall modest production volume, and also because most of the wines considered here do not stand ageing nearly as well as a Bordeaux red, for which vintages aged 40 and more years are regularly traded – and consumed. By contrast to the French production (and to some Italian reds from, say, Piedmont or Tuscany), ageing is uncommon for Collio wines.

Expert ratings are, in turn, acknowledged to directly impact wine visibility, demand, and price. Therefore, linking vineyard weather conditions to the expected wine rating can support local wineries by turning climate variability into actionable insights, guiding decision-making and strategic planning, and helping winemakers anticipate the market.

Winemaking excellence in the Collio region is relatively recent. Over the sample period, the average rating of Collio wines included in the tasting database, both white and red, evolved from barely Above average quality (80 in the Parker scale) towards Very good (89) (Fig. 2). In a couple of years (2015 and 2016), the reds have crossed into Outstanding territory (90+).

3.2. Climate

We employ the climatic variables proposed in the French context for Bordeaux (Ashenfelter et al., 1995), as later applied in north-western Italy for Barolo and Barbaresco wines (Corsi and Ashenfelter, 2019).

Below we report the definition of the indicators adopted, where months refer to the period preceding the harvest of a given year: WINTRAIN is the cumulative rainfall (mm) in the period from October to March; TEMPSPR the average temperature (°C) of the months between March and July; SUMMRAIN the cumulative rain (mm) in the season from August to September; and SUMMTEMP the average temperature (°C) of the same months considered for the calculation of SUMMRAIN. Their historical evolution prior to and during our working sample is depicted in Fig. 3.

3.2.1. Climate trends and projections

Some specific climatic trends are already apparent from Fig. 3, in particular rising temperatures in the spring and summer, and the increasing variance of winter rainfall. Over the last 40 years, the decadal averages of spring and summer temperatures have risen by respectively 1.2 °C and 1.1 °C. The decadal variance of winter and summer total precipitations has grown substantially as well.

To assess the expected scale of climate change in our region of interest, in line with local climatologists (Gallina and Giorgi, 2018) we considered the simulations from five different CORDEX models (Jacob et al., 2014). The projected temperature increase over the next 30 years is similar across both optimistic scenarios (emissions reduction) and more pessimistic ones ("business as usual"); and considerable, at 1.3 °C for the spring and 0.8 °C for the summer. There is no clear trend in average rainfall, although, as discussed above, the variance of precipitation might increase further.

4. Empirical analysis

4.1. Econometric specification

We specify Ashenfelter's "Bordeaux Equation" as an individual components panel data model. Following Corsi and Ashenfelter (2019), wine quality is explained by the following weather factors: spring temperature ($TEMPSPR$), summer temperature ($SUMMTEMP$), winter rain ($WINTRAIN$) and summer rain ($SUMMRAIN$). In our setting, these are seen as cross-sectionally invariant ("common") factors.

Weather is assumed to affect wine quality, as measured by tasting, in a linear fashion:

$$\begin{aligned} Rating_{it} = {} & \alpha_i + \beta_1 TEMPSPR_t + \beta_2 SUMMTEMP_t + \\ & \beta_3 WINTRAIN_t + \beta_4 SUMMRAIN_t + u_{it} \end{aligned} \tag{1}$$

and every unit i is allowed to have an idiosyncratic intercept, accounting for individual, time-invariant unobserved heterogeneity: *terroir*,

as a continuous variable, estimating standard time series regressions. A fortiori, we follow the latter approach as we draw on ratings in hundreths.

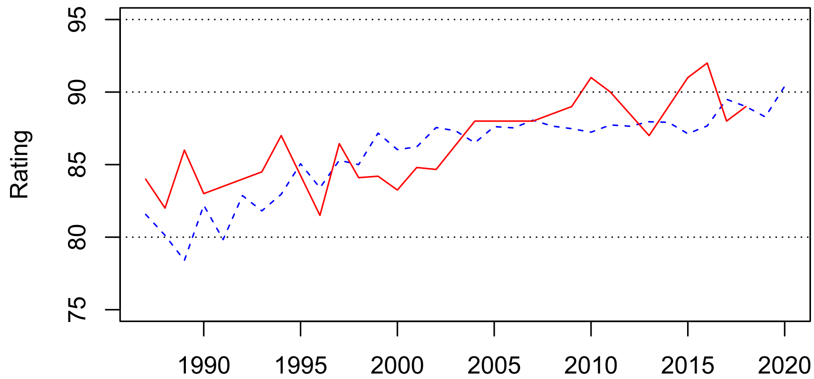

Fig. 2. Average Wine Spectator ratings of Collio wines for White (blue, broken line) vs. Red (red, solid line) varieties; 1985–2021. According to the Parker rating system, 70–79 is Average, 80–89 Above Average to Very Good, 90–95 Outstanding, 96–100 Extraordinary. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

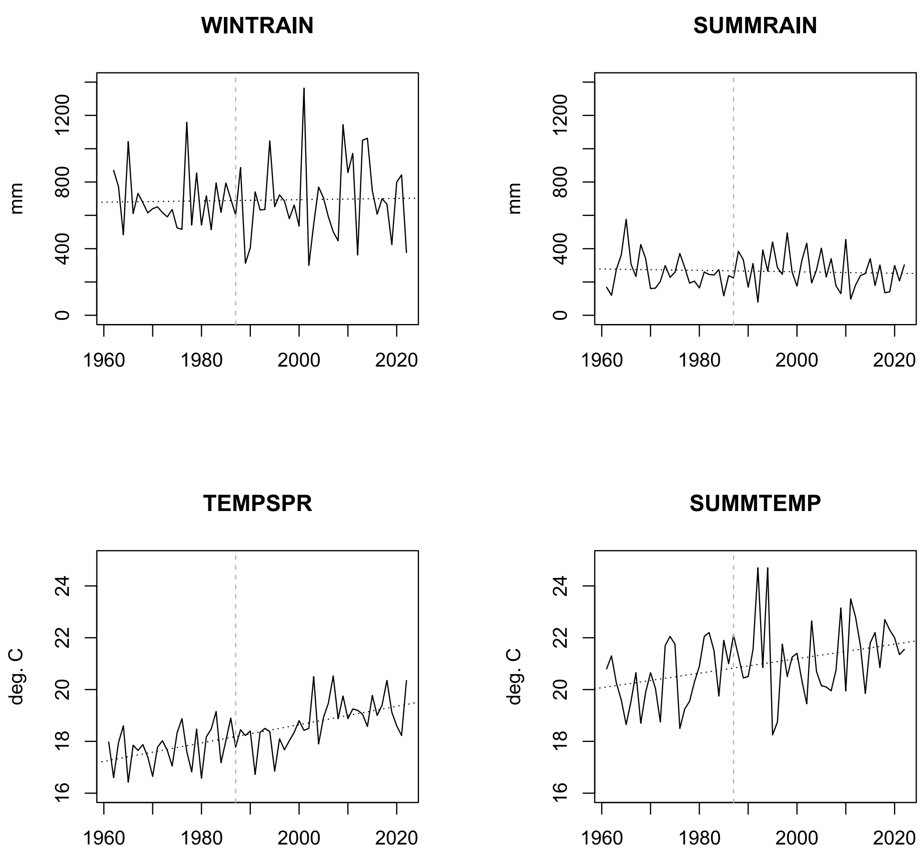

Fig. 3. Left to right, top to bottom: total winter and summer rain (mm, common scale); spring vs. summer average temperatures, °C (common scale); 1961–2022. Dotted lines are trend regressions. The vertical broken line marks the beginning of the wines' sample. Data retrieved from meteorological stations belonging to the regional climatic monitoring network (ARPA-OSMER): 1985–1990, Gorizia (lat: 45.93, lon: 13.60, 86 m asl); 1991–2021, Capriva del Friuli (lat: 45.96, lon: 13.51, 85 m a.s.l.).

position, firm tradition and culture, the quality of the vines or the ability of the winemaker (where i denotes wine, and t denotes vintage: see Section 3.1 above).[5]

The fixed effects (FE) assumption is a researcher's safest bet, allowing for unrestricted correlation between the individual heterogeneity and the regressors by estimating the separate intercept α_i in Eq. (1) for

[5] In line with the econometric literature, we assume time invariance for those characteristics that can be supposed to show "little" variation over the time horizon of our sample. Slow-changing features like culture or technology (let alone soil or vine quality) can then be subsumed into the individual intercept if the time dimension is modest. Below we will also consider common time trends.

each of the wines $i = 1, \dots, n$. The error u_{it} is assumed *i.i.d.* while α_i can be correlated with the regressors. Each combination of producer and label (i.e., each wine) can have its own individual characteristics, potentially correlated with climate. This specification gives the best robustness vs. possible selection effects. As is well known, when estimating Eq. (1) by the usual fixed effects (or "within") method, effects are identified based solely on the deviations of ratings from the time average of each unit.

4.2. Expected effects

In principle, white and red wines can be expected to react differently to climatic conditions as the weather influences tannin, sugar/alcohol and aromas, which in turn have different importance in determining wine quality. Precipitation can, as observed and documented in previous studies (*e.g.* Ashenfelter et al., 1995), be beneficial in the growing season and detrimental if occurring short before the harvest, penetrating the grapes and diluting their contents (fungus development can also be an issue with summer rain). The biggest influence, though, is expected to be that of temperatures during, respectively, the spring and the summer.

Temperature, rain and sunshine influence the formation of substances developing within the grapes which are responsible for the different aromas. Mendez-Costabel et al. (2013) focus on the influence of weather on "green aromas" in grapes and wines. These results hint at whites benefiting from warm springs. In particular, among the varieties we consider, green aromas of this kind are typical of the Sauvignon Blanc. Heat and water stress during the summer can also influence quality, the concentration of aromas and skin phenolics being beneficial for reds but particularly detrimental for whites (Peyrot Des Gachons et al., 2005; Allamy, 2015; Van Leeuwen and Destrac-Irvine, 2017).

In simplified terms: one might expect red wines to benefit from hot, sunny summers, which favour the ripening of the grapes and the development of sugars, flavours, and phenolic compounds, as already documented by Lough et al. (1983), Ashenfelter et al. (1995), Byron and Ashenfelter (1995), Ashenfelter (2010), Corsi and Ashenfelter (2019); while white wines – which rely heavily on harmony in aromas and flavours – would benefit from warm springs for building up aromas, which would in turn be damaged if the subsequent summer is too hot. Hot weather would also reduce the acidity of whites, hence their freshness, balance and resistance to ageing. White varieties with high acidity and rich in phenolics (Chardonnay, to name one) can be expected to be more resilient to summer heat.

Not only can the effect of climate on wine quality be expected to change from red to white wines, but it will also be variety-specific within these two macrocategories. Jones and Storchmann (2001) estimate the influence of climate on the levels of sugar and acid of Bordeaux wines with either dominant shares of Cabernet Sauvignon or of Merlot, finding that the latter are more climate-sensitive. Outreville (2018) estimates and compares Bordeaux equations for wines from Bordeaux and from Burgundy. Interestingly, and for the first time in the literature, he compares local whites and reds, finding very similar results across categories and regions.

Growing regions for different varieties have been classified, on the basis of phenological requirements, according to average temperatures which, as per Jones (2007), "typically define the climate-maturity ripening potential for premium quality wine varieties grown in cool, intermediate, warm, and hot climates": so that some varieties are more appropriate for cooler regions and so on, and each variety falls into an "ideal" temperature bracket, with estimated tolerances of about 0.2–0.6 °C (Jones, 2007, Fig. 1). Thus, *e.g.* Pinot Gris is classified in the cool grouping (13–15 °C), while, say, Sauvignon Blanc falls into intermediate (15–17 °C) and Merlot between intermediate and warm (17–19 °C).

Despite this classification, supposedly "incompatible" grapes like Pinot Gris and Merlot are successfully grown side by side in our study area, producing wines of high and comparable quality. This suggests that combining temperature and rainfall in different seasons may provide a more convincing explanation. The experience of local agronomists provides some priors in this respect.

As regards Pinot Blanc, Sauvignon, Friulano and Pinot Gris: warmer spring temperatures favour vegetative development conditions which predispose the plant to lower yields, therefore lower quantities, but from which wines with greater dry extract are obtained (therefore more concentrated and with greater aromas). Cooler temperatures instead slow down the sugar generation processes and the grape retains greater acidity. One can expect these wines to benefit most from a warm spring, and suffer most from a hot and dry summer.

Chardonnay and Ribolla are known to display greater resistance to water stress in July and August compared to the whites above, and in fact find their maximum expression when grown on the hills in conditions of low humidity and water restriction. Therefore, given their own characteristics and needs in terms of water, a hot and dry summer predisposes them to quality production (incidentally, this is becoming the typical summer pattern in the Collio, with July and August practically always in water stress in recent years).

The expected effects emerging from these considerations (and from the literature, especially Jones and Storchmann, 2001, w.r.t. the Merlot) are summarized in Table 3. In the following, our empirical analysis will confirm most expectations, quantifying the marginal effect of climate changes on the different varieties; albeit with some surprises as regards the magnitude, and sometimes even the direction, of the effects.

4.3. Results

In commenting the estimation results we start from the common model pooling together whites and reds, mainly for the purpose of comparison with the extant literature; then we proceed to separate the assessments for the two berry colour groups; lastly we will focus on individual grape varieties. All significance diagnostics will be based on heteroskedasticity- and autocorrelation-consistent standard errors, clustered by individual unit (Arellano, 1987, henceforth HC).

We first assess whether the effects of climate are different between reds and whites. As observed above, the main expected difference is that the temperature of the summer should benefit reds, not whites. To this end, we estimate separate versions of Eq. (1) for reds and for whites. See the results of common and separate models in Table 4.

The results suggest that Collio whites do, on average, benefit significantly from warm spring temperatures, but suffer both from warm and from rainy summers. Collio reds do, consistently with the previous literature, benefit from a warm summer; unlike some previous results, they are not significantly affected by summer rain; and, somewhat surprisingly, they are negatively affected by warm springs. Moreover, the size of the negative effect on reds is almost double that of the positive effect on whites. In turn, the positive effect of a warm summer on reds is thrice the size of the negative effect on whites. Winter rainfall is insignificant for either whites or reds.

4.3.1. By variety

The coefficients from separate FE models by variety are listed in Table 5. The by-variety results are affected by sample sizes, especially as regards the precision of estimates and hence significance. Of course, it is easier to identify effects drawing on 258 Pinot Grises or 177 Sauvignons than it is for the 16 Cabernet Francs or the 15 Collio Rosso (CS, MA, PN and RC have to be omitted altogether). Readers should therefore interpret results for varieties with very few observations with some caution. All that said, within the two macrocategories of whites (CB, CH, FR, PB, PG, RG, SB) and reds (CF, CR, ME) the coefficient signs and magnitudes are generally consistent. With just one notable exception (RG) and a partial one (CH), white varieties benefit from high TEMPSPR and low SUMMTEMP.

Table 3
A priori expected effects of climate variables on reds, whites and individual varieties — when different from macrocategory. Blends are expected to behave like the relevant macrocategory. Following the previous literature, TEMPSPR and SUMMTEMP are, respectively, the temperatures in the "spring" (March to July) and the "summer" (August to September); WINTRAIN and SUMMRAIN the rainfalls in the "winter" (October to March) and the "summer".

	Variety	TEMPSPR	SUMMTEMP	WINTRAIN	SUMMRAIN
R	*Reds in general*	?	+	+	–
W	*Whites in general*	+	–	+	–
CH	Chardonnay		(+)		
FR	Friulano (a.k.a. Tocai)	++	- -		
ME	Merlot		++		
PB	Pinot Blanc	++	- -		
PG	Pinot Gris	++	- -		
RG	Ribolla Gialla		(+)		
SB	Sauvignon Blanc	+++	- - -		

Table 4
Regression results: separate models for red and white varieties. FE: fixed individual effects. Standard errors clustered by individual unit (HC).

	FE.common	FE.Red	FE.White
TEMPSPR	0.8889***	−1.6157**	0.9750***
	(0.1703)	(0.6490)	(0.1700)
SUMMTEMP	−0.2572**	1.0696***	−0.3731***
	(0.1295)	(0.2659)	(0.1283)
WINTRAIN	−0.0361	−1.4211	0.1351
	(0.3817)	(1.1122)	(0.3921)
SUMMRAIN	−2.8844**	3.8511	−3.6857***
	(1.1906)	(3.0346)	(1.1945)
R^2	0.0650	0.2437	0.0832
Num. obs.	900	70	830

***$p < 0.01$; **$p < 0.05$; *$p < 0.1$.

Even among varieties of the same berry colour, the variance of climate sensitivities is large. As predicted by the sensitivity of green aromas to spring temperature, some whites (Sauvignon and Pinot Blanc) benefit more from warm springs, others less. Curiously enough, the only white obtained from red grapes (Pinot Gris) behaves most "like a white", preferring warm springs and suffering in hot summers. One white variety (Ribolla Gialla) strikingly behaves "like a red", while Chardonnay, despite being one of the varieties benefiting most from warm springs, does not degrade in hot summers (positive and not significant coefficient).

Blends are less informative in terms of estimated effects, probably because winemakers can combine any wines allowed by the DOC protocol without fixed proportions,[6] adjusting compositions in response to the year's climate. Historically, blending grapes and wines was generally the norm (Nandorfy et al., 2023), and mostly a necessity in a viticultural context characterized by mixed plantings and the need to mitigate agronomic and economic risk, enhance phytopatological resistance, smooth qualitative differences across vintages and among varieties. To this day, major wine regions, such as Bordeaux, Champagne, Chianti, Valpolicella, and Porto, still privilege blending as a tool for territorial expression, in contrast to the contemporary monovarietal trend. Since 2020, the Collio consortium has initiated a strategic reflection on the role and the identity of their blends, with some producers developing a new internal mini-disciplinary for a Collio Bianco based on autochthonous varieties only (Friulano and Ribolla Gialla – which, as illustrated in Table 3, show opposite responses to meteorological conditions – and the semi-aromatic Malvasia), conceived as a more representative expression of territorial identity than monovarietal wines.

4.4. Discussion

Our results support the "Bordeaux equation" approach to vintage quality, in the sense that weather variables effectively explain the outcome in accordance to prior expectations grounded in agronomy. Some specific effects are compatible with previous studies, others are predictably different and explained by our models. A synthesis of research findings is presented in Table 6. The reader should always consider the influence of the much different sample sizes on the precision of estimates and hence on the significance of results.

We replicate the finding that red wines "love" hot summers; we fail to find statistical significance for the negative effect of summer rain on reds, but we find it for whites. We document a negative effect of warm springs on reds and, on average, a positive one on whites: both important in magnitude and statistically very significant; we also show the detrimental effect on whites from a hot summer. These latter findings were expected according to agronomy but hitherto undocumented in the empirical literature.

Specific discrepancies with the previous results of Ashenfelter et al. (1995), Byron and Ashenfelter (1995), Fogarty (2003), Ashenfelter (2008, 2010), Outreville (2018), Corsi and Ashenfelter (2019) are encompassed by our separate analysis of red and white grape varieties. In particular, our by-variety results do explain the apparently different findings of Outreville (2018) that reds and whites from Burgundy and from the Bordeaux region behave similarly. In fact, white Burgundy wine is primarily made from Chardonnay grapes, acid and resistant to water starvation (see our discussion above, and the specific results of the CH model). In the Bordeaux region, white wines are typically made from a blend of Sauvignon Blanc, Sémillon and small proportions of Muscadelle. Sémillon has high levels of natural acidity and phenolic compounds; these blends are used to create both dry and sweet white wines, including the famous dessert wine Sauternes. As discussed before, the resulting full-bodied dry whites can well be expected to benefit from a hot summer, unlike some more delicate and aromatic varieties from our sample; not to speak of the sweet wines, which need a long and warm ripening season.

The explanatory power of the models is satisfactory. On average, the weather explains 26 percent of variability for reds, and under 8 percent for whites: which might seem low, but is to be expected considering the large share of the variability accounted for by the interaction of producer and variety (see Table 7 for gross R^2s).[7] Interestingly, the "net" R^2 is higher for red wines. This is likely due to reds being more

[6] The original 1968 regulation for Collio Bianco prescribed the exclusive usage of FR, MV and RG grapes. In 1995, the requirements were relaxed to include any other of the official Collio varieties in any proportion, with the only requirement that aromatic varieties Müller-Thurgau and Traminer cannot exceed 15 per cent combined. In turn, Collio Rosso can be produced with any blend of locally produced grapes.

[7] The R^2 we report for FE estimations is net of the contribution of fixed effects.

Table 5
Regression results: separate models by grape variety, FE. Standard errors clustered by individual unit (HC).

	CB	CF	CH	CR	FR	ME	PB	PG	RG	SB
TEMPSPR	0.49	−1.83	1.10*	−2.41	0.49	−1.88*	1.07**	1.10***	−0.62	1.47***
	(0.39)	(1.57)	(0.54)	(1.66)	(0.39)	(1.07)	(0.42)	(0.28)	(0.95)	(0.31)
SUMMTEMP	−0.36	0.92	0.24	0.38	−0.69***	1.57***	−0.24	−0.42**	1.24**	−0.28
	(0.32)	(0.69)	(0.48)	(0.49)	(0.21)	(0.52)	(0.32)	(0.20)	(0.48)	(0.23)
WINTRAIN	−1.22	−4.19	0.53	3.98	0.71	−1.76	0.51	0.37	6.07**	−0.26
	(0.87)	(4.82)	(1.93)	(3.02)	(1.07)	(1.72)	(1.40)	(0.84)	(2.30)	(0.90)
SUMMRAIN	−5.78	0.13	1.23	8.38	−4.34	2.21	−1.56	−4.11*	10.72	−2.23
	(3.47)	(7.46)	(4.91)	(5.53)	(2.72)	(4.83)	(3.35)	(2.47)	(7.45)	(2.52)
R^2	0.10	0.24	0.15	0.58	0.10	0.34	0.10	0.09	0.59	0.16
Adj. R^2	−0.15	−0.43	−0.35	0.17	−0.25	−0.05	−0.14	−0.11	0.05	−0.07
Num. obs.	94	16	44	15	140	39	81	258	22	177

***$p < 0.01$; **$p < 0.05$; *$p < 0.1$.

Table 6
Summary of model findings (compare with Table 3 above). Significance stars are: '*': 10 percent; '**': 5 percent; '***': 1 percent.

	Variety	TEMPSPR	SUMMTEMP	WINTRAIN	SUMMRAIN	Obs.
R	*Reds in general*	−**	+***	−	+	70
W	*Whites in general*	+***	−***	+	−***	830
CB	Collio (Bianco)	+	−	−	−	94
CF	Cabernet Franc	−	+	−	+	16
CH	Chardonnay	+*	+	+	+	44
CR	Collio Rosso	−	+	+	+	15
FR	Friulano (Tocai)	+	−***	+	−	140
ME	Merlot	−*	+***	−	+	39
PB	Pinot Blanc	+**	−	+	−	81
PG	Pinot Gris	+***	−**	+	−*	258
RG	Ribolla Gialla	−	+**	+**	+	22
SB	Sauvignon Blanc	+***	−	−	−	177

homogeneous (fewer grape varieties). In fact, some white varieties (RG) behave so differently from the rest that omitting them does yield slightly sharper results and marginally higher R^2 (not reported). In by-variety models, the "net" R^2 ranges between 7.5 percent of Pinot Blanc to almost 60 percent of Ribolla Gialla. Weather effects are generally well identified, considering the paucity of observations of some varieties.[8]

4.4.1. Robustness

We perform a number of checks to ensure that our results are not spurious or otherwise driven by specification problems, reporting them in detail in online supplementary materials, and in abridged form here.

Time trends. First, we address the issue of controlling for the time trends that are apparent in the wine ratings. A rising, approximately linear tendency can clearly be observed in the ratings data (see Fig. 2 in the paper), raising the issue of controlling for a deterministic trend in the models. Deterministic components like time trends have been effectively described as "a measure of our ignorance" (Kennedy, 2008), accounting for systematic aspects in the data which we are unable to understand or cannot model explicitly. This is not entirely the case here, where there are two competing explanations for a linear upward evolution of ratings. As Ashenfelter (2017, p. 4) puts it, the key ingredients for winemaking are winemaking technique, winemaker and equipment, and grapes. In other words, the rising time trend might result from a steady improvement of (unobserved) technology, physical and human capital in a region which, as mentioned, has only reached winemaking excellence quite recently. A competing explanation based on observable data would identify a similar growing trend in our temperature variables (see the bottom panels of Fig. 3 in the paper) as determining the improvement of grape quality. Adding a time trend to the models will allow us to discriminate: if the steady improvement in ratings is based on unobservables we expect a time trend to turn out significant, while if it is due to trending regressors then we expect the time trend to be explained out by the former. Of course, there remains the possibility of *separate* time trends for each producer. Still, all producers in our sample live in the same few villages, and belong to one small consortium, where best practices in winemaking and all related vineyard management activities (pruning, training, crop load management, and the management of resources and soil health) are constantly shared. According to the features of the data, we augment our baseline FE specification either with a linear time trend or with a broken trend, setting the breakpoint for the latter in 2005. Trends turn out significant for whites, not significant for reds. The qualitative results from our baseline model are generally upheld, although the effect of spring temperatures on white wines are reduced in magnitude. Trends are significant also for some individual varieties: augmentation here does find a limit in the small size of some samples, but again results are reasonably well upheld.

Weather vs. other common factors. In our models, the weather is assumed to be the only relevant, cross-sectionally invariant common factor affecting wines in a given year. In this setting, we cannot take into consideration any other source of time heterogeneity: one would generally do so by including time dummies, but here they would be perfectly collinear with weather variables. More sophisticated treatments allowing for idiosyncratic factor loadings (Pesaran, 2006) are out of question for the same reasons.

Therefore we proceed to assessing the potential threats from pervasive common factors other than climate, which we cannot include in our analysis and whose effect might be picked up by the common climate variables. To this end, we compare the explanatory power of the climate variables with that of an "empty" two-ways fixed effects specification, finding that the explanatory power of our equation comes

[8] Multicollinearity is not an issue, with the only substantial (negative) correlation between summer temperature and rainfall at −0.63. The former variables are both statistically significant in either model (Whites or Reds). The "rain" variables, which are individually not significant in the Reds model, are also jointly not significant based on a Wald test (χ^2=2.41, p-value: 0.3); this is evidence against any multicollinearity inflating the standard errors.

Table 7
Comparison of explanatory power and Chow test against the nesting two-ways fixed effects model (2FE). Left to right: individual effects and weather controls (w); idem plus time trend (wt) or broken time trend (wbt); individual and time fixed effects (2FE). Leftmost columns: white grapes (W.); rightmost columns: red grapes (R.).

	W.w	W.wt	W.wbt	W.2FE	R.w	R.wt	R.wbt	R.2FE
R2	0.507	0.567	0.575	0.629	0.730	0.734	0.747	0.803
Adj. R2	0.376	0.450	0.459	0.508	0.604	0.600	0.612	0.546
Chow	7.049	3.719	3.377		0.646	0.657	0.567	
p-value	0.000	0.000	0.000		0.827	0.811	0.877	

reasonably close to that of the more general, nesting two-ways fixed effects.

We summarize with a comparison of model fit and restriction testing of the baseline models for whites and reds, and their variants with linear or broken trends, against the encompassing two-ways fixed effects model (2FE). Given that our main specifications, either with or without a time trend, are effectively nested into the two-way FE equation $Rating_{it} = \phi_i + \tau_t + u_{it}$, it is also possible to assess the significance of the difference in fit through a Chow-type test.

We conclude that the baseline "reds" model and the 2FE are statistically equivalent representations of the target variable. By contrast, while the baseline "whites" model provides a reasonably good fit, restriction tests identify the trends as statistically significant. The steady improvement of the average ratings of Collio whites along our sample period is not completely explained by the trending weather variables: unobserved progress in winemaking technology, physical and human capital seems to have had a significant part in it.

4.4.2. Substantive importance

As regards the magnitude of coefficients, and hence the substantive importance of our study, below we try to give an order of magnitude to the expected effects of climate change in the near future based on our estimates. The reader must keep in mind that this is a *ceteris paribus* exercise and cannot be taken as a prediction, because wine making technology is going to adapt as well.

Central scenarios suggest an increase in both TEMPSPR and SUMMTEMP of between 0.6 °C to 2042 and 1 °C to 2052 (no increase until 2032). Rain does not change substantially; although its variance is perhaps more worrying. Therefore one can take one degree as the benchmark change, which makes reading the effect on wine quality immediate. Surprisingly, the most substantial potential change is from red wines, which might lose about 2 rating points on average from warmer springs; but recover part of that (*most* of that, for ME) from hotter summers. Whites will improve about 1 point from warmer spring, lose about half that from high summer temperatures.

All in all, quite counterintuitively, model results suggest that the quality of Collio reds might suffer from global heating, and whites might improve! Although the change would, on average, not be very substantial. Of course here we do not touch the influence of climate change on the produced quantities.

In order to assess the economic significance of a change in ratings, we regressed the price in USD reported in the database, deflated by the US inflation index, on the ratings. On average, an increase of 1/100 in the rating is associated with an increase in price of about 0.5 USD. The effect, nevertheless, is highly nonlinear. A quadratic model yields no effect at a rating of 80, an effect of 0.5 USD at 85, and of over 1 USD at a rating of 90.[9]

[9] One must consider that, despite their excellent quality, Collio wines have traditionally been inexpensive. It is relatively common for category winners, like "Best wine of Friuli-Venezia Giulia", or top-qualifiers in the most prestigious guides (like the "three glasses" of Gambero Rosso), to cost between 20 and 30 USD.

4.4.3. Limitations

The effects of climate change on wine production range much farther than what we address here, and are triggering important changes in the production process. As summers get dryer and precipitation more random and intense, the soil is likely to experience severe water stress, which could in principle be counteracted with irrigation policies — if the regulations did allow for them, and up to the point to which remote water reserves were available at all. Extreme precipitation (including severe hail) in the late summer and early fall has already become frequent in recent decades; together with increased summer heat and the threat of excessive ripening and alcohol formation, this has led to a creeping anticipation of the harvest towards late August from the traditional second half of September. On the other hand, anticipating the harvest shortens the available time for grapes to mature and develop. In this paper we focused on the narrow subject of wine quality, skipping the subject of quantity entirely; the ongoing adjustments of the production technology are of course included in the data we observe and our results. While the outcome of this research can inform potential future strategies on grape variety substitution (in the sense of Ashenfelter, 2017), this is only one part of a much broader picture.

From the point of view of the statistical model, there are also a number of limitations that shall be highlighted.

Omitted factors. The assumption of climatic homogeneity across the Collio region might in principle be too strong, as microclimatic differences related to altitude, slope orientation, and soil type could interact with climatic effects. Microclimates (exposure, etc.) are indeed very important in viticulture and are a source of great variability. Aware of these aspects, we specifically focused on a DOC area, whose zoning is strictly regulated so that there is a certain degree of territorial homogeneity in the vineyards. In particular, most of the vineyards in the region are facing south-west; and all of them are comprised in a narrow altitude range (between 100 and 350 m a.s.l.). Moreover, by the very regulation of the DOC area, cultivation is only permitted on pedologically homogeneous hillsides (see also Section 3). Individual fixed effects will effectively control for any time-invariant source of heterogeneity like the ones mentioned above.

Explanatory power. It can be seen from comparing the gross R^2 in Table 7 with the net R^2 in model tables that individual effects take the largest share of the explanatory power, as often happens with this kind of settings, where the primary interest lies with consistent estimation of the parameters of interest in the face of potentially correlated unobserved heterogeneity. Nevertheless, and perhaps most importantly, the contribution of weather variables is statistically significant and of substantial magnitude: see the discussion of economic significance in the previous Subsection.

Unbalancedness. Lastly, as detailed in Table 6 and relative comment, our panel is highly unbalanced in time: some wines are observed for only a few years, some (few) others for decades. While in principle the econometric techniques here employed are all still appropriate, of course this leads to some weaknesses. This aspect has limited, in particular, the separate econometric analysis of individual varieties, which is presented above as subject to these caveats. Expanding the dataset to neighbouring wine regions (in particular the Colli Orientali in Italy, or the Brda in nearby Slovenia) would allow for a larger sample but, for all the similarities in climate and soil composition, this would bring in more heterogeneity and thus lead to a tradeoff.

Our study region has – as we have argued – convenient characteristics, in that many small producers cultivate different varieties in a small, relatively homogeneous area. The flip side to this is related to the average size of companies in the examined production sector. In general, in Italy and in Friuli-Venezia Giulia, wineries are very small, which potentially makes them subject to mergers, changes in ownership, etc. – an aspect that may have influenced the historical continuity of the data. The production is modest and the diffusion of wines is limited, which makes them less likely to be tasted consistently over time. At the same time, however, it is important to also examine these small producers, both because of the high quality of their products and because common regulations are adopted, with the advantages we have discussed at length in the paper.

Potential extensions. The above limitations of the present study might be overcome by future efforts as follows.[10] While employing the weather variables considered in previous seminal studies was a design choice meant to facilitate the comparison with the extant literature, on the other hand, in order to increase the explanatory power of the models future work might experiment with different variables (like sunshine hours, heatwave days and diurnal temperature range) as well as management-related variables (such as harvest dates or irrigation practices). Moreover, it is worth noting that the linear specification is also a deliberate simplification, chosen for interpretability and comparability with the Ashenfelter tradition, as well as being suggested by sample size. In a data-richer context one could address the potentially relevant issue of nonlinearity (for evidence on the nonlinear phenological effects of temperature, see Sadras and Moran, 2013). Different data collection designs might also allow to employ more systematic controls for technological progress, either through two–ways fixed effects or proxies for innovation and investment, and to include interactions between climatic variables and terroir-related proxies to capture microclimatic heterogeneity. From a methodological viewpoint, hierarchical modelling might provide an efficient alternative to the present fixed effects approach.

5. Conclusions

The research on the influence of climate on fine wine quality has hitherto concentrated on red wines. Following Outreville (2018), we document the different sensitivity of fine white and red wines to weather factors, through an adaptation of the standard model of Ashenfelter et al. (1995) to a panel data context. We measure wine quality through expert tasting ratings from a well-known provider, and relate it to some standard weather variables (winter and summer rain, spring and summer temperature) as defined in Corsi and Ashenfelter (2019). Taking advantage of a detailed dataset regarding a small area where many varieties are grown, we deepen our analysis at the variety level.

We focus on Collio, a small Italian winemaking region which is nevertheless renowned for the quality and variety of its wines, ranking steadily in prominent positions among Italian and international wines in experts' judgments. Best known for its whites, the Collio produces a lower number of excellent reds as well. While for its modest dimension it can be considered subject to a homogeneous climate,[11] we take advantage from the diversity of either red or white grapes that are grown there to assess the different effect of temperature and rainfall on red and white grape/wine varieties in an otherwise homogeneous context.

Unlike the previous literature, we employ panel data methods to account for any time-invariant, unobserved heterogeneity in wine quality, as possibly due to differences in terroir, position, tradition, winemaking experience and any geographic or human factor that can be considered invariant in time over the length of our sample, and potentially correlated with climate.

We estimate separate models for whites, reds and for 10 varieties. Red wines confirm the well-known positive effect of summer temperatures; unlike previous results, they do not seem to benefit from winter rain neither to suffer from a rainy summer. Again unlike previous results, and perhaps more interestingly, we document a negative effect of spring temperatures on red wines: consistent across varieties, very significant and of high magnitude. White wines do generally behave in the opposite way to reds, but for the common insignificance of winter rain. Most whites benefit from a warm spring and suffer from hot summers; varieties relying on green aromas, especially the Sauvignon Blanc but also the Pinots (Blanc and Gris) and the local variety Friulano, are the most delicate w.r.t. summer temperatures. More acid varieties (Chardonnay and the local Ribolla Gialla) are predictably more resilient to summer heat, the latter in particular behaving similarly to the reds. Disaggregating results by variety allows us to encompass some findings from previous literature, understanding and explaining any discrepancies with our results.

As expert ratings are acknowledged to directly impact visibility, demand, and price of wines (Friberg and Grönqvist, 2012; Kaimann et al., 2023; Oczkowski and Doucouliagos, 2015; Spence, 2024), establishing a link between vineyard weather conditions and expected wine rating can support local wineries by turning climate variability into actionable insights. By anticipating how climatic variability may affect the likelihood of high-quality, high-ranking vintages, wineries can make more informed decisions about grape allocation, pricing strategies, and pre-selling campaigns. Additionally, from a marketing perspective, understanding how weather shapes the sensory profile of each vintage might support storytelling on the character and uniqueness of each vintage, enhancing the perceived *vertical* exclusivity (arising from intertemporal heterogeneity, or vintage-to-vintage variability), not only the *horizontal* one (related to differences among producers or labels).

Our results bear on mid- and long-term strategic decisions of winemakers in the face of climatic change, as discussed by Ashenfelter and Storchmann (2016), and despite the mitigating possibilities of technology (see the discussion of irrigation making winter rain irrelevant in Byron and Ashenfelter, 1995, p. 43). As Ashenfelter and Storchmann (2016) put it, "there will be winners and losers"; and production will have to adapt to the new conditions. In the long run, the accumulation of model-based predictions could support strategic planning, such as selecting grape varieties or clones more fit to emerging climate patterns, and identifying vineyard plots more resilient to quality fluctuations. As such, the model not only supports operational efficiency, but also helps safeguard and enhance the long-term reputation of the territory's wines in the current climate change scenario.

Model results show that increases in spring temperature might more than offset the beneficial effect of a warm summer on reds; and that, on the other hand, warmer springs can improve the quality of whites beyond the detrimental effects of a hot summer. In this respect, regions counting on many fine wines of different resilience to climate change seem better positioned to withstand the challenge than regions that produce just one famous excellence.

CRediT authorship contribution statement

Giovanni Millo: Writing – original draft, Software, Methodology, Conceptualization. **Paolo Bogoni:** Writing – review & editing. **Barbara Campisi:** Funding acquisition, Supervision. **Matteo Carzedda:** Writing

[10] We thank an anonymous Reviewer for suggesting these potential extensions.

[11] According to the DOC quality designation, wine must be made from local berries. Compare this, *e.g.*, with the difficulties of defining the climate variables when grapes can be sourced from distant vineyards, as discussed in Byron and Ashenfelter (1995, beginning of Section III).

– review & editing, Investigation, Conceptualization. **Gianluigi Gallenti:** Supervision. **Valentino Riva:** Data curation, Writing – review & editing. **Gaetano Carmeci:** Writing – review & editing, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Due to provider restrictions, the dataset is confidential.

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