Climate cha(lle)nges in global wine production and trade patterns

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Abstract

The global wine trade is interested by significant changes since a few decades, due to new productive scenarios induced by climate change and to (rapidly) evolving trade and policy regimes. We investigate how these changes are altering trade dynamics. Following a gravity-type approach, we find that higher temperatures are beneficial for the terms of trade, and are boosting trade values. As for policy interventions, the impact of technical measures on trade values is heterogeneous across objectives: While technical measures tend to friction trade, the environment-related policies show pro-trade effects.

Keywords: Climate change; Environmental measure; Technical barrier to trade.

JEL codes: F13; F18; Q17; Q18; Q56.

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1. Introduction

The rapid and dynamic evolution in the global trade of wine, documented by Mariani et al. [1] more than ten years ago, has been observed also in the last decade with relevant changes in the relative importance of groups of countries. According to the data from the UN Comtrade, wine imports grew in the period between 1996 and 2008, due to increased consumption in non-producing countries [2], and recovered in 2011 after a reduction in 2009, due to the international economic crisis [3]. In particular, trade between Old World Producers has drastically reduced in favour of a relevant increase in imports from New World Producers, which have gained growing market shares[1] [5, 6].

Changes in trade patterns are likely to be affected both by different types of policy interventions and new productive scenarios due to climate change. Policy interventions are numerous and growing in the wine sector [7]. The average tariff level fluctuated widely over twenty years[2] and non-tariff measures increased exponentially after 2009 to prevent adulterations and frauds [8, 9]. New World Producers tend to implement bilateral measures and Old World Producers in general adopt multilateral measures and tariffs[3] [12]. The use of different types of policy interventions across countries may reflect different adaptation strategies to new productive scenarios due to climate change. Over recent decades, Old World Producers benefited of better growing season temperatures and New World Producers observed climatic regimes more favourable to the production of wine[4] [14, 15]. In this regard, tariffs and multilateral measures may allow Old World Producers to protect domestic production from foreign competition. Vice-versa, bilateral measures may favour market access and strength bilateral partnerships of New World Producers to allocate their growing production. The opening of new regions (benefiting of better climatic regimes) to viticulture and changes in policy interventions would determine new productive scenarios and trade dynamics [16].

Although previous studies reveal that climate change is likely to affect trade (e.g., [17, 18]) with substantial differences across producing regions of wine (e.g., [14, 19]), it seems that the impact of climate change on wine production and trade patterns has not been investigated, nor quantified at global scale. In addition, while the equivalency of tariffs and non-tariff measures has been quantified (e.g., [7]), and the role of specific technical measures has been assessed in previous studies (e.g., [10, 20]), a few studies deepen on the role of environment-related policy interventions and trade dynamics under climate change. The limited empirical literature calls for more investigation: are varying climatic conditions able to shape wine production and trade? Which is the role of environment-related policy interventions in shaping trade patterns? By addressing these research questions, we would understand how climate change and related policy interventions could affect global production and trade of wine.

The aim of the article is two-fold. A preliminary objective is to conceptualise and empirically test how climate change could affect global production and trade of wine. Second, through a gravity-type approach (e.g., [21, 22]), the article explains how bilateral trade reacts to changes in specific determinants of trade (i.e., climatic conditions, policy interventions), net to the effect of country-specific characteristics of importers and exporters.

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[1] Main producing countries of wine are generally classified in Old World producers, such as France, Italy, Spain, with an old tradition in the production of wine and New World Producers, such as Argentina, Australia, Chile, New Zealand, that emerged more recently as great producers of wine [4].

[2] Data are from World Integrated Trade Solution (WITS).

[3] Bilateral NTMs are policy measures regulating trade between a certain country- pair. They differ from multilateral NTMs that are measures implemented by a country on imports from any trade partners [10, 11].

[4] Other than structural changes in climate conditions of main producing regions, also exchange rate changes, wine retailing regulation changes, and the massive growth in China’s demand for wine imports may have contributed to New World production and export growth [13].

The next Section describes data used in the analysis with a detailed focus on the prevailing climate observed in main producing regions of wine of countries under investigation. Section 3 conceptually discusses the relationship between climate change and the production and trade dynamics in the wine sector. Section 4 provides empirical evidence on how climate change and policy interventions affect the wine trade. Concluding reflections are left in Section 5.

2. Data description

The empirical application observes over two decades (from 1996 to 2015[5]) a sample of 14 countries that account for more than two-third of the volume of wine production (70% in 2016, Global Wine Markets, 1860 to 2016 database)[6].

2.1. Climate data

We collected region-specific climate data from different sources and countries from 1961 to 2015[7]. Indeed, the average climate at the national level may be not representative of the climate conditions characterising the main producing regions of wine of that country. This is particularly true for large countries, such as the United States or Australia, where the production of wine is focused on specific viticultural regions. For instance, the average temperature in the main wine producing regions is 3.0 °C higher than the average national temperature in the United States and 4.8 °C lower in Australia. Differences of less than 1 °C are observed in the Old World Producers, exception made for Italy whose average national temperature is 12.1 °C, 1.6 °C lower than the average temperature in some of the main producing regions of wine (table 1).

[5] Thanks to a recent update of trade and climate data, we extend the timeframe of the analysis until 2021 as a sensitivity analysis.
[6] The selected countries are Argentina, Australia, Brazil, Canada, China, France, Germany, Italy, New Zealand, Russian Federation, South Africa, Spain, the United Kingdom, the United States. They ensure representativeness in term of income group (developed and developing countries, according to the 2020 country classification of the United Nations) and geographical location (low-latitude and high-latitude regions), covering different climatic zones (both Northern and Southern Hemisphere). The sample of countries does not include Chile, one of the world's top ten in terms of both wine production and exports [23], because of the lack of climate data at the regional level.
[7] The longer time period used for climate data allows to build climate normal or climatologies (i.e., 30-years averages) of temperature and precipitations: in 1996 (the starting point of the final dataset) climate normal is based on a real 30-years average.

Table 1. Average annual temperature (°C) at the national and regional level, 1996-2015.

Country	Region/State	National	Regional
Italy (avg.)		12.1	13.7
	Piemonte		10.1
	Puglia		15.7
	Sicilia		17.3
	Toscana		13.9
	Veneto		11.4
France (avg.)		11.1	11.6
	Alsace		10.4
	Bordeaux		13.6
	Burgundy		11.0
	Champagne		10.3
	Languedoc-Roussillon		12.7
	Provence		11.2
Spain (avg.)		13.5	13.4
	Andalucia		16.4
	Castilla y Leon		11.7
	Castilla-La Mancha		13.8
	Catalonia		13.6
	Galicia		13.2
	Rioja		11.9
Germany (avg.)		8.9	9.6
	Baden		9.5
	Mosel		9.2
	Pfalz-Rheinhessen		10.1
	Rheingau		9.7
United States (avg.)		7.2	10.2
	California		15.2
	New York		7.8
	Oregon		9.1
	Washington		8.7
Australia (avg.)		21.8	17.0
	New South Wales		18.9
	South Australia		17.1
	Victoria		15.1

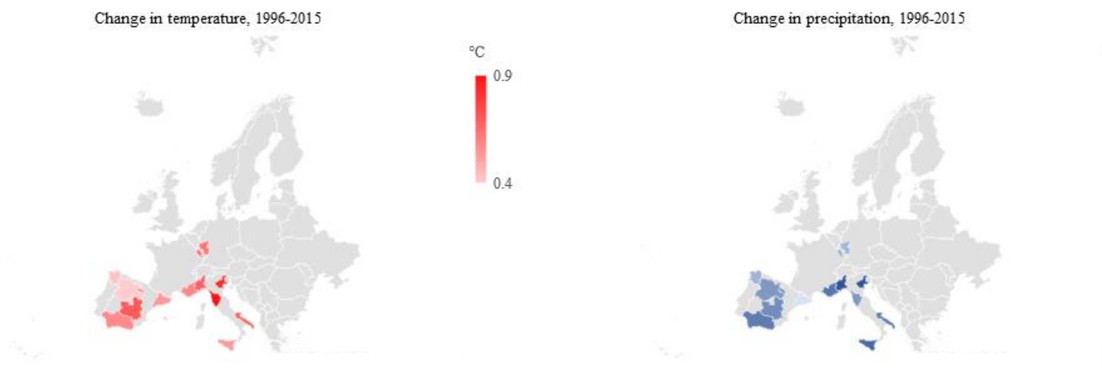
Source: elaboration on data from Climatic Research Unit (CRU) of University of East Anglia, Agri4Cast of the European Commission, National Oceanic and Atmospheric Administration (NOAA) of the National Centers for Environmental Information (NCEI), Bureau of Meteorology of the Australian Government.
Notes: For each country, the first line of table reports the average annual temperature at the national level (under column 'National') and at the regional level (under column 'Regional').

Country-specific climate data are collected for the 14 countries in the sample from the Climatic Research Unit (CRU) of the University of East Anglia[8] [25]. Annual climate normals of temperature and precipitations are built using these historical weather data and serve as baseline

[8] The CRU dataset is a gridded historical dataset derived from observational data, widely accepted as a reference dataset in climate research [24]. It provides quality-controlled temperature and rainfall values from thousands of weather stations worldwide.

climate information. Region-specific[9] climate data are collected from Agri4Cast of the European Commission for countries in the European Union[10] (i.e., Italy, France, Spain, Germany), from the National Oceanic and Atmospheric Administration (NOAA) of the National Centers for Environmental Information (NCEI) for the United States[11], and from the Bureau of Meteorology of the Australian Government for Australia[12]. We collected the mean air temperature (°C) and the mean precipitation (mm/day) for the most famous wine producing regions of Italy (i.e., Piemonte, Veneto, Toscana, Puglia, Sicilia), France (i.e., Alsace, Champagne, Bordeaux, Burgundy, Languedoc-Roussillon, Provence), Spain (i.e., Andalucia, Castilla-La Mancha, Castilla y Leon, Catalonia, Galicia, Rioja), and Germany (i.e., Baden, Mosel, Pfalz-Rheinhessen, Rheingau). Monthly average temperature (in °F) and precipitation (in inches) for the main wine producing States of the Unites States (i.e., California, Oregon, Washington, New York) have been gathered from the US Climate Divisional Database of the NOAA[13]. Monthly historical weather observations, both temperature (in °C) and precipitation (in mm) have been retrieved for the main wine producing region of Australia (i.e., Victoria, New South Wales, South Australia).

Figure 1. Change in climate normals between the period 1996 and 2015 in the most famous wine producing regions of Old World Producers.

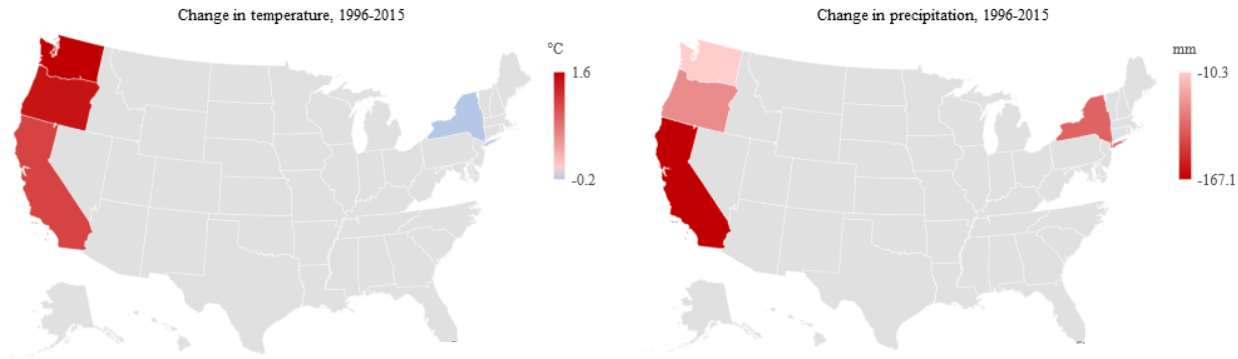


Source: elaboration on data from Agri4Cast of the European Commission.
Notes: Detrimental changes in red (e.g., increase in temperatures/reduction in precipitation), beneficial changes in blue (e.g., reduction in temperatures/increase in precipitation). The most famous wine producing regions of Old World Producers are Piemonte, Veneto, Toscana, Puglia, Sicilia for Italy, Alsace, Champagne, Bordeaux, Burgundy, Languedoc-Roussillon, Provence for France, Andalucia, Castilla-La Mancha, Castilla y Leon, Catalonia, Galicia, Rioja for Spain, Baden, Mosel, Pfalz-Rheinhessen, Rheingau for Germany [23].

[9] Historical (at least 30 years) region-specific climate data are not available for other countries in the sample. Region-specific climate indicators are available, for instance, Anderson and Nelgen [26], but they are collected only for three years (i.e., 2000, 2010, 2016). For this reason this data source is not suitable for our analysis that aims at capturing the impact of long-run changes in climate conditions in the main wine producing regions.
[10] The Datasets of the MARS Crop Yield Forecasting System and Software, developed by Agri4Cast of the European Commission, provides access to daily meteorological observation from weather stations interpolated on a 25x25 km grid. Daily data have been aggregated at the annual level to facilitate the comparison with climate data from the CRU of University of East Anglia and with wine production and trade data.
[11] The NOAA of the NCEI is responsible for preserving, monitoring, assessing, and providing access to climate and historical weather data and information of the United States.
[12] The Bureau of Meteorology of the Australian Government is the national weather, climate and water agency that, through regular forecasts, warnings, monitoring, and advice spanning the Australian region and Antarctic territory, provides one of the most fundamental and widely used services of the Australian Government. Monthly weather data have been aggregated in annual climatologies of temperature and precipitation.
[13] Average temperature and precipitation have been reported to °C and mm respectively and then aggregated annual climatologies of temperature and precipitation.

Italy, France, and Spain are the top three producers of wine worldwide [27]. The climate in the most famous wine producing regions of these countries has a major influence on their leadership.
Wine is produced in all the Italian regions but, historically, the most significant in terms of quality and quantity of production are Toscana (on average 13.9 °C), where the warm and temperate climate of the coastal areas and the increased diurnal temperature variation of the inland areas coexist, Piemonte (on average 10.1 °C), characterised by a temperate climate favoured by the Alps and Apennines, and Veneto (on average 11.4 °C), benefitting of the cooler, alpine-influenced climate of the northeast corner of Italy (table 1). Sicilia and Puglia, characterised by a near-perfect environment for the wine production (i.e., hot Mediterranean climate, persistent sunshine, occasional sea breezes), were traditionally great wine producing regions of Italy, although consumers' preferences shifted towards wine produced in the northern Italian regions since the late 20th Century. Over the period 1996-2015, the average annual temperature and precipitation in the most famous producing regions of Italy registered a limited and homogeneous increase: i.e., between 0.5 and 0.9 °C and between 0.1 and 0.2 mm per day on average (figure 1).
The French climate is very heterogeneous across the main wine producing regions contributing to the great diversity of French wines. The northern region of Champagne is one of the coolest wine-growing regions of the world with an annual average temperature of 10.3 °C (table 1). The eastern regions of Alsace and Burgundy have a continental climate, warm during summers and cold during winters. The maritime climate of the southwest of Bordeaux is mainly due to the proximity to the Atlantic Ocean and the various rivers, which ensure the highest annual regional temperature (on average 13.6 °C, table 1). The south regions of Languedoc-Roussillon and Provence are characterised by a Mediterranean climate. The long-run changes in climate show no differences across regions: since 1996 until 2015, the annual temperatures have grown by 0.55 °C and the annual rainfall levels have increased by 0.15 mm per day on average (figure 1).
In Spain, the greatest wine production occurs in Castilla-La Mancha, but the most famous wines are produced in regions with very heterogeneous climate: the cool Galicia, the Mediterranean Catalonia, the sunny Andalucia, the warm and dry Castilla y Leon and Rioja. The greatest increase in the average annual temperature during 1996-2015 is observed in Castilla-La Mancha (+0.7 °C), whereas the increase in the other regions is between 0.4 and 0.5 °C; the average annual precipitation per day is mostly unchanged (figure 1).
According to the data from the Wine Searcher, the most famous wine producing regions of Germany are Rheingau and Mosel, characterised by a cool, northern continental climate with an average annual temperature of 9.7 °C and 9.2 °C respectively (table 1). Periods of past warming improved the quality of Rheingau wines [28] and of Mosel wines [29]. However new producing regions, such as Baden and Pfalz-Rheinhessen, are emerging favoured by changes in climate trends.

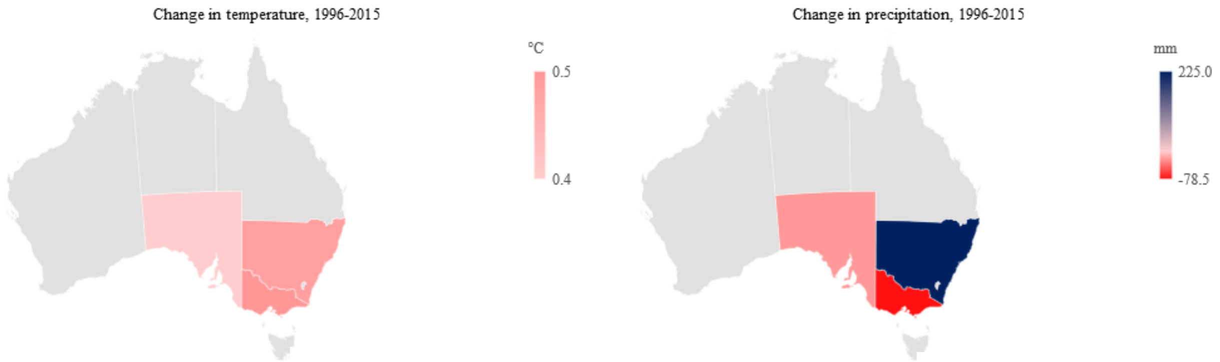
Figure 2. Change in climate normals between the period 1996 and 2015 in the main wine producing States of the United States.



Source: elaboration on data from the National Oceanic and Atmospheric Administration (NOAA) of the National Centers for Environmental Information (NCEI).
Notes: Detrimental changes in red (e.g., increase in temperatures/reduction in precipitation), beneficial changes in blue (e.g., reduction in temperatures/increase in precipitation). The main wine producing States of the United States are California, Oregon, Washington, New York.

According to the data from the National Association of American Wineries and the Wine Searcher, the vast majority of the US wine production occurs in the Pacific Northwest of the United States. Covering 85% of the US wine production, California is the largest and most important wine State, followed by Washington and Oregon that respectively count over 20,000 hectares and 13,500 hectares of planted vineyards. These are amongst the world's youngest and most promising wine States, where pedoclimatic characteristics are determinant for the quantity and quality of wine production [17]. The coastal California wines benefit of the warm and dry climate of northern latitudes and of the proximity to the cool waters of the Pacific Ocean [30], despite during the last two decades California has become 1 °C warmer and drier (-167.1 mm per year) (figure 2). Similar climate conditions occur also in Oregon, where the proximity to the Pacific Ocean ensures warm temperatures and high rainfall levels. Most of the Washington wine production occurs in the eastern part of the State, characterised by a continental climate, where the proximity to the local rivers (e.g., the Columbia) contributes to moderate both summer and winter temperatures (that may drop till -26°C). In Washington, long-run changes in temperatures (+1.6 °C) are stronger than in California (+1.0 °C) or in Oregon (+1.4 °C), but the State has registered a drop of only 10.3 mm per year between 1996 and 2015 (figure 2). Totally different climate conditions characterised New York State, according to the Wine Searcher data the third US wine-producing State in terms of production volumes. Differently from the northwest States, the average annual temperature of New York State has reduced (-0.2 °C) over the last twenty years (figure 2). Most of the wine of New York State is produced in proximity of the coast, rivers, lakes able to reduce the severity of winter temperatures characterising the north-eastern United States. The great water availability allows to face the progressive reduction of annual rainfall levels (-91.0 mm per year) of the last period (figure 2).

Figure 3. Change in climate normals between the period 1996 and 2015 in the main wine producing regions of Australia.



Source: elaboration on data from the Bureau of Meteorology of the Australian Government.
Notes: Detrimental changes in red (e.g., increase in temperatures/reduction in precipitation), beneficial changes in blue (e.g., reduction in temperatures/increase in precipitation). The main wine producing regions of Australia are Victoria, New South Wales, South Australia.

The Australian international competitiveness of the wine sector is firmly established and commensurate with its ideal wine-growing climate [31]. According to the data from Wine Australia and Wine Searcher, about half of the Australian annual wine is produced in South Australia, especially in the south-eastern corner of the State where the presence of two large gulfs and the proximity to the Southern Ocean make the cooler and less arid climate suitable to the wine production. The climate of South Australia has been interested by limited changes during the last two decades (+0.4 °C and -22.2 mm per year, figure 3). A cool, ocean-influenced climate also characterises Victoria the third most productive wine region of Australia, behind South Australia and New South Wales. The New South Wales is characterised by different climate conditions due to its territorial extension: the coastal areas, experiencing mild temperatures and great rainfall (+225.0 mm per year between 1996 and 2015, figure 3), are the most suitable to produce wine.

2.2. Production, trade, and policy data

To estimate the relationship between climate change and wine production, we collected country-specific annual data on the wine production and consumption (in 1000 hl) from the OIV database. We obtained the volume of countries' excess of production (in 1000 hl) as the absolute difference between production and domestic consumption: this variable is a proxy of countries' export capacity. Annual data on bilateral imports of wine (in US$) for each country-pairs in the sample are collected from the UN Comtrade database. Trade data are aggregated at the four-digit level of the Harmonised System classification and use wine of fresh grapes (HS 4-Digit 1996: 2204). Bilateral imports of wine in the sample are 91.33 on average[14]: the United States and Germany are relevant traders (table 2). As expected, the Old World Producers, especially France, Italy and Spain, have the largest volumes of wine production and consequently a higher export capacity. The value of exports is particularly high for France and Italy. The production volumes of Germany (9.30 million hl) are comparable to those of Australia (10.93 million hl), but its export capacity is much higher (10.68 million hl as compared to 6.36 million hl) but less valuable (27.78 million US$ as compared to 95.85 million US$) (table 2).

Table 2. Average wine production and trade data, 1996-2015.

		Production (million hl)	Excess of production (million hl)	Exports (million US$)	Bilateral trade (million US$)
Average		29.45	14.53	13.64	91.33
	Italy	49.20	22.49	226.19	24.74
	France	50.00	19.34	328.97	30.34
	Spain	36.24	23.65	98.76	10.38
	Germany	9.30	10.68	27.78	175.52
	United States	21.05	4.63	39.88	268.26
	Australia	10.93	6.36	95.85	22.94

Source: elaboration on data from OIV.
Notes: Excess of production volumes obtained as the difference between production and domestic consumption. France, Germany, Italy, Spain are Old World Producers, Australia and the United States are New World Producers.

[14] In the sample, we have (structural) zero trade flows (i.e., 0.5% in total exports and 5.6% in bilateral trade of wine). Structural zero trade flows may be associated with data recording issue or may occur when bilateral trade is expected to be low, for instance between distant countries [22]. The dependent variable in the model in equation (1) is the (log) value of exports increased by a very small, arbitrary, value to accommodate zeros and allow for consistent estimates in the presence of a dependent variable assuming null values [32]. The use of the GPML to estimate the model in equation (4) allows to solve the problem of zero trade values in the dependent variable (i.e., the value of wine imports) [33].

To estimate the relationship between trade policy measures and wine trade, we collected tariff data from the World Integrated Trade Solution (WITS) software and non-tariff measures data from the Global Database on Non-Tariff Measures of UNCTAD[15]. In the sample, 40% of trade relationships are regulated by Technical Barriers to Trade (TBT, a type of non-tariff measures) and only three type of TBT deals with environment-related issues (33% of cases). The TBT B14 (i.e., authorisation requirement for TBT reasons) requires that the importer should receive authorisation, permits or approval from a relevant government agency of the destination country, for reasons such the environmental protection. The TBT B15 (i.e., registration requirement for importers for TBT reasons) requires that importers should be registered in order to import certain products: to register, importers may need to comply with certain requirements, documentation and registration fees; it also includes the cases when the registration of establishments producing certain products is required. The TBT B21 (i.e., tolerance limits for residues of or contamination by certain substances) is a measure that establishes a maximum level or tolerance limit of substances, which are used during their production process but are not their intended ingredients. It is worth noting that the TBT B140 is implemented by Australia, Brazil, the United States (8% of cases in the sample), the TBT B150 by Argentina, Brazil, China, Russia, the United States (22% of cases in the sample), the TBT B210 by the United States (7% of cases in the sample).

3. On the relationship between climate change and wine production and trade

The literature on the relationship between climate change and production and trade dynamics is large and varied (e.g., [34]). Previous studies start from the assumption that, for open economies, the impacts of climate change on agriculture in any region is not isolated from the impacts occurring in the rest of the world (e.g., [18, 35]). Given this assumption, adjustments through production within regions and through trade patterns between regions may contribute to smooth consequences of climate change (e.g., [36]). We apply this conceptual framework to the wine sector. Methodologically, previous studies on the linkages between climate change and production and trade patterns are based on equilibrium models. They simulate the effects of adaptive measures to climate change by comparing scenarios without and with climate change (e.g., [37]) or the impacts of climate change without and with trade adjustments (e.g., [38]). Differently, we propose an econometric approach to quantify the effects of climate change on production and trade patterns. In particular, from a theoretical perspective, we combine approaches used in Ricardian trade studies (e.g., [39]) and Ricardian climate studies (e.g., [40, 41]) to understand how climate change, by altering comparative advantage of regions, affects their production and trade capacity, and how regions adapt to climate change by reshaping trade patterns. Methodological details and empirical evidence are detailed in the Appendix B.

The marginal impact of climate on production and trade of wine, reported in table 3, suggests that higher temperatures in the main producing regions of wine tend to favour both the volume of wine production and the value of wine exports. A 1 °C increase (decrease) in regional annual temperature increases (decreases) production volumes by 2.28% (+0.7 million of hectolitres on average) and export values by 4.11 % (+5.6 million USD on average). Greater rainfall levels have neither economically significant impact on the volume of wine production nor statistically significant impact on the value of wine exports.

[15] More details are provided in the Appendix A.

Table 3. Marginal impact of climate and change in countries' wine production and terms of trade.

	Volume of wine production		Value of wine exports	
	Marginal impact (%)	Change in avg. production (mln hl)	Marginal impact (%)	Change in avg. exports (mln US$)
Temperature (+1 °C)	2.28*** [2.05; 2.51]	+0.7	4.11*** [1.88; 6.34]	+5.6
Precipitation (+1 mm)	-0.01** [-0.02; 0.00]	0.0	-0.04 [-0.15; 0.07]	-

Notes: Marginal impacts are obtained applying equation (B.2) on coefficients of variables in level and squared reported in table B.1, evaluated at average temperature (12.6 °C) and precipitation (269 mm); 95% confidence intervals are in brackets. Change in volume of wine production, volume of wine excess of production, value of wine exports considers average volumes and values (see table 2). *** Significant at the 1 percent level. ** Significant at the 5 percent level.

The results complement findings from Macedo et al. [17] who conclude that temperature anomalies (short-run changes in climate) may be detrimental for the wine sector. In particular, they find that the exports of Port wine tend to be frictioned if the importing countries register temperature anomalies: the authors associate this effect to the tendency of consumers to provisionally change consumption habits during hottest periods. This analysis concludes on the long-term impact of climate change on the wine supply: if lower than anomalous, temperature increases tend to favour the volumes of wine production with a consequent positive effect on countries' export capacity and expanded export values. As argued in Gouel and Laborde [38], long-run changes in climate tend to be beneficial for net-exporters of agri-food products.

4. On the effect of climate change and policy interventions on wine trade

4.1. Methodological approach

We adopt a gravity-type approach to investigate the effect of climate change and policy interventions (environment-related trade measures in particular) on the bilateral trade of wine (e.g., [17, 18]). As documented in Costinot and Rodríguez-Clare [21] and Head and Mayer [22], a theoretically founded structural gravity model[16] explains the bilateral trade (X_{ij}) as a function of the value of output in the exporting country i (Y_i), the total expenditure of the importing country j (E_j), the multilateral resistances in both countries[17] (Π_i and P_j) and the determinants of transaction costs between i and j (θ_{ij}):

$$X_{ij} = \frac{Y_i}{\Pi_i}\frac{E_j}{P_j}\theta_{ij} \quad (1)$$

where Y_i is the value of output in i, and E_j is the total expenditure of j, Π_i and P_j are, As defined in Anderson and van Wincoop [42], the multilateral resistances proxy the competitiveness of i and j, θ_{ij} includes proxies and determinants of transaction costs between i and j.

Empirically, the structural form of the gravity model in equation (3) can be expressed as an exponential function:

[16] The subscript t for time varying variables is suppressed for ease of notation.

[17] As defined in Anderson and van Wincoop [42], the multilateral resistances proxy the competitiveness of i and j,

$$X_{ijt} = e^{\{\boldsymbol{\beta}_{it}+\boldsymbol{\beta}_{jt}+\boldsymbol{\beta}_{ij}+\boldsymbol{\theta}_{ijt}\delta\}}\epsilon_{ijt} \tag{2}$$

where the term X_{ijt} collects the value of bilateral trade at time *t* and ϵ_{ijt} is the error term. We use a three-way structure of fixed effects to control for unobserved country- and pair-specific heterogeneity [43]. The exporter-time and importer-time fixed effects, $\boldsymbol{\beta}_{it}$ and $\boldsymbol{\beta}_{jt}$, control for multilateral resistances and countries' output shares and total expenditure at time *t*. The time-varying country-specific fixed effects allow to capture the unobservable heterogeneity characterising the exports and importers over time [32]. Country-pair fixed effects, $\boldsymbol{\beta}_{ij}$, control for bilateral time-invariant determinants of trade, such as geographic distance, common language, contiguity, and do not impede the estimation of time-varying bilateral determinants of trade [44]. Following Macedo et al. [17] and Bozzola et al. [18], the determinants of transaction costs between *i* and *j* at time *t*, $\boldsymbol{\theta}_{ijt}$, include variables proxying climate change (i.e., temperature and precipitation normals[18] in the exporting countries) and policy interventions[19] (i.e., bilateral tariff levels and dummies that control for the presence of multilateral technical barriers to trade[20]); δ is the corresponding vector of regression coefficients. A set of dummies control if an importer set a technical measure on imports from its trading partner in a specific year. Since $\boldsymbol{\theta}_{ijt}$ also includes variables with the importer-time dimensions only (i.e., climate variables and multilateral technical barriers to trade), collinearity problems may arise with the vector of importer-time fixed effects. To solve this concern, we replace the importer-time fixed effects with importer fixed effects and time fixed effects.

The model (2) is estimated through the Gamma Pseudo Maximum Likelihood (GPML) estimator that is robust to heteroskedastic errors and allows to deal with zero trade flows [33]. Following Yotov et al. [32], the trade volume effects are calculated in percentage terms as follows: $TVE = \left(e^{\hat{\delta}} - 1\right) * 100$, where $\hat{\delta}$ is the estimate of the structural gravity coefficient on the indicator variable of interest.

4.2. Empirical evidence

The gravity estimates are in table 4. Climatic conditions of trading partners are positively correlated with their level of bilateral exports. Consistent with the evidence from the preliminary analysis in Section 3, the effect temperature is much higher than the impact of precipitation. This is in line with empirical evidence on the trade-climate nexus (e.g., [18]). The results also support findings of Adams et al. [46], who project a 90% increase in the wine sector of California by 2100 with increasing temperatures (+ 3 °C), and of Jones et al. [14], who show how increasing temperatures have benefited wines from Germany and France but not from the South Australia. Similarly, Nemani et al. [47] suggest that climate change has been beneficial for the wine sector in coastal California.

The effect of TBT on imports of wine is, in most of cases, not detectable. The result is not surprising considering the well-documented dual effect of non-tariff measures on trade (e.g., [48]). Non-tariff measures may be both catalysts and barriers to trade and these contrasting effects may offset each other in the overall picture: this occurs for trade of agri-food products but also in the wine sector [9, 49]. The direction of the effect is likely to depend on the policy objective of each measure [50, 51]. Indeed, the results of the specification 'Environmental TBT', where the effect of climate-related TBT is separated from the effect of all other TBT, shows that TBT tend to hinder

[18] Traditionally used in climate literature (e.g., [40, 41]), the term climate normal, a synonymous of climatologies, refer to long time averages (usually 30-years) in climate variables (e.g., temperatures and precipitations) in a given location.

[19] The use of country-pair fixed effects allows us to account for the unobservable linkages between the endogenous trade policy covariates and the error term, solving for the problem of endogeneity of trade policy variables [45].

[20] Technical barriers to trade are introduced as a general category, as specific measure pursuing a particular policy objective (i.e., the protection of the environment), as specific instrument regulating a particular aspect of trade related to environmental issues (e.g., authorisation requirement).

trade, but not if their aim is the protection of the environment (specification ii). The results confirm findings of Dal Bianco et al. [7] who argue that "*technical barriers are considerable frictions to exports*": they disentangle the effect of TBT related to 'food containers', found to be non-prohibitive, and related to 'human health', 'conformity assessment' and 'labelling', assessed as trade barriers; however, TBT aiming at protecting the environment is out of the scope of their analysis. In support of the trade-enhancing effect of environment-related TBT, Will [52] argue that WTO Member States may choose to address environmental concerns with any level of protection and type of measure, but they are required to avoid discrimination if the environmental TBT are suspected to restrict WTO free trade.

Table 4. Effects of climate change and policy interventions on bilateral wine imports.

Variables	Specification (i)	Specification (ii)	Specification (iii)	Specification (iv)	Specification (v)
Temperature	0.785***	0.737***	0.203	0.666***	0.752***
	(0.199)	(0.207)	(0.284)	(0.127)	(0.209)
Precipitation	0.004***	0.004***	0.006***	0.005***	0.004***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
TBT	0.185	-0.416***	-0.116	0.212	0.200
	(0.206)	(0.057)	(0.128)	(0.209)	(0.219)
Environmental TBT		0.686***			
		(0.213)			
TBT B14			0.508***		
			(0.167)		
TBT B15				0.125	
				(0.086)	
TBT B21					-0.311
					(0.268)

Notes: Gamma Pseudo Maximum Likelihood (GPML) estimation of the structural gravity model. The dependent variable is the value of bilateral imports (in level). The TBT-related explanatory variables are modelled as dummy variables. B14 and B15 consist, respectively, in authorisation requirement and in registration requirement for importers for TBT reasons (including environmental protection); B21 are tolerance limits for residues of or contamination by certain substances. All specifications include a constant, importer, time, exporter-time, and country-pair fixed effects, tariff levels. Robust standard errors are in parentheses. Observations are 494. *** Significant at the 1 percent level.

The effect of the TBT B21 is not detected. Similarly, Macedo et al. [17] find no significant effects of measures setting tolerance limits for residues and restricted use of substances on trade of Port wine. They find no effect also of import authorisation/licensing related to TBT, but their analysis stops at the intermediate level of aggregation (i.e., TBT B1). Their result may thus signal heterogeneity in the effects of measures at a more disaggregated level, as revealed by results in table 4: i.e., positive effect of authorisation requirement for importers for TBT reasons (TBT B14) and null effect of registration requirement for importers for TBT reasons (TBT B15). The objective of this measure is to fulfil the needs of domestic market, to get the taxes and charges fully, to control the illegal importation by permitting the wine importation in limited amount [53]. Although the steps to obtain the permission of importation for wine may require paperwork (time-consuming) and registration fees (negligible direct costs), the measure does not impose relevant indirect costs (e.g., changes of product characteristics and attributes or of production processes) such as in the case of the TBT B21 (i.e., reduce or avoid the presence of residues in the final product). A measure that provides specific importers with authorisation to import would advantage them over their competitors devoid of the import authorisation [54].

5. Concluding remarks

The evolution in grapes productivity, due to changes in climate conditions, shape countries' specialisations and their comparative advantage (e.g., [18]). We investigate how wine trade has evolved in lieu of the long-run changes in climate.

Higher temperatures in the main wine producing regions are beneficial for countries' levels of production, and favour exports (both in terms of volumes and values). Put differently, climate change alters the terms of trade. Consistent with findings from the lietrature (e.g., [36, 38]), the results confirmed that the impacts of climate change on grapevines yields within and between regions propagate throughout the wine supply chain, and that the production and trade patterns adjust accordingly. Indeed, climate change alters comparative advantage of regions and, thus, affects their production and trade capacity that adapt to the changed climate conditions [34].

We also controlled for the role of trade regulations. We show that technical measures have differentiated impacts, depending on the objectives of the measures. While technical measures tend to friction trade of wine (e.g., [7, 17]), the environment-related TBT tend to be pro-trade.

The results of this research flag the relevance of the interrelations between the wine sector and climate change. As argued in the OIV guidelines for sustainable vitiviniculture, climate has a key role in the activities in the vine and wine sector and the "*protection, and preservation of these natural assets [solar energy, climate, water, soils] through environmentally sustainable practices are imperative for the long-term viability of vitivinicultural activities*"[21]. Policymakers should put more efforts in promoting strategies to achieve environmental, economic, and social sustainability of the grape production and processing systems on a global scale. The containment of risks to the environment should be a priority. This is in line with the objectives set during the OIV General Assembly held on Paris, 30th July 2004: i.e., "*minimize environmental impacts linked to viticulture and the transformation process, […] promote sustainable vitiviniculture from an environmental, ecological and economic standpoint*"[22]. As demonstrated by the results of our analysis, the achievement of these objectives cannot disregard the evaluation of the global production system and the adaptation of proposed strategies to the characteristics of the main producing regions.

On an international scale and considering the role of interactions between countries, potential mitigation strategies may be the adoption of environmental-friendly measures regulating trade of wine at the global level. They have proved to be economically sustainable for the implementing countries: compared to the limited compliance costs countries have to face (e.g., negligible direct costs to obtain the permission to importation of wine), the gain in monetary terms is much higher. In addition, the ultimate objective of these policy measures (i.e., the protection of the environment) makes them a win-win, socially desirable strategy. However, the research pointed out that much work should be done to harmonise standards on the maximum residue limits for the vine and wine sector, which may still constitute a friction to the free trade of wine. The debate is vivid also at the OIV, where some decisions on the issue have already been officially adopted and some other positions have been registered during various occasions[23]. For instance, the guidelines for the application of the maximum residue limits related to wine products and wine have been introduced as expected results in the OIV Strategic Plan 2012-2014.

[21] OIV Resolution CST 1/2008, "OIV guidelines for sustainable vitiviniculture: production, processing and packaging of products", available at www.oiv.int.
[22] OIV Resolution CST 1/2004, "development of sustainable vitiviniculture", available at www.oiv.int.
[23] For more details see www.oiv.int.

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A. Details on policy data

To estimate the relationship between trade policy measures and wine trade, we collected tariff data from the World Integrated Trade Solution (WITS) software. Annual tariff data are country-pair specific and available at the four-digit level of the Harmonised System classification for wine of fresh grapes (HS 4-Digit 1996: 2204). The main information collected is the simple tariff average (Sum of duties/Number of duties, in percentage), which measures the average level of nominal tariff protection. Tariff averages are provided for the Most Favoured Nation (MFN) applied rates, that is the normal, non-discriminatory, tariff charged on imports of a good (wine of fresh grapes in this case).

The Global Database on Non-Tariff Measures from UNCTAD provides data on non-tariff measures (NTMs). The database contains all NTMs aggregated at the HS 6-digit level and specific for country-pairs. According to the international classification of UNCTAD [53], technical barriers to trade (TBT) are technical NTMs implemented by a country against all its trading partners (multilateral NTMs). The UNCTAD database provides the number of TBT at three levels of aggregation: (i) chapter includes indiscriminately any TBT implemented by a country for product category under investigation; (ii) the intermediate level of aggregation; (iii) the highest level of detail involves specific types of TBT. The UNCTAD database also provides the date of entry into force of specific TBT and the date in which they expired (or will expire): this allows to track the validity of each TBT. The table A.1 lists all the TBT regulating trade of wine between countries in the sample according to the objective of each measure. Measures refers both to technical regulations, laying down characteristics of wine (under chapters B1, B2, B3, B6, B7) and related production processed and methods (under chapter B4), and to procedures for assessment of conformity with technical regulations and standards (under chapter B8), excluding measures covered by the Sanitary and Phytosanitary (SPS) Agreement.

Table A.1. Technical Barriers to Trade (TBT) regulating trade of wine between countries in the sample.

Chapter	Title	Description
B1	**Prohibitions/restrictions of imports for objectives set out in the TBT agreement**	**Such prohibitions/restrictions may be established for reasons related, *inter alia*, to national security requirements; the prevention of deceptive practices; protection of human health or safety, animal or plant life or health, or the environment.**
B14	Authorisation requirement for TBT reasons	Requirement that the importer should receive authorisation, permits or approval from a relevant government agency of the destination country, for reasons such as national security, environment protection, etc.
B15	Registration requirement for importers for TBT reasons	Requirement that importers should be registered in order to import certain products. To register, importers may need to comply with certain requirements, documentation, and registration fees. It also includes the cases when the registration of establishments producing certain products is required.
B2	**Tolerance limits for residues and restricted use of substances**	**Restrictions on the tolerance limits on residues or use of certain substances contained in the final products.**
B21	Tolerance limits for residues of or contamination by certain	A measure that establishes a maximum level or tolerance limit of substances, which are used during their production process but are not their intended ingredients.

	substances	
B3	**Labelling, marking, and packaging requirements**	
B31	Labelling requirements	Measures regulating the kind, colour, and size of printing on packages and labels and defining the information that should be provided to the consumer. Labelling is any written, electronic, or graphic communication on the packaging or on a separate but associated label, or on the product itself. It may include requirements on the official language to be used as well as technical information on the product, such as voltage, components, instruction on use, safety, and security advice.
B32	Marking requirements	Measures defining the information for transport and customs that the transport/distribution packaging of goods should carry.
B33	Packaging requirements	Measures regulating the mode in which goods must be or cannot be packed and defining the packaging materials to be used.
B4	**Production or post-production requirements**	
B41	TBT regulations on production processes	Requirement on production processes not classified under SPS. It also excludes those specific measures on tolerance limits for residues and restricted use of substances (or its subcategories).
B42	TBT regulations on transport and storage	Requirements on certain conditions under which products should be stored and/or transported.
B6	**Product identity requirement**	**Conditions to be satisfied in order to identify a product with a certain denomination (including biological or organic labels).**
B7	**Product-quality or -performance requirement**	**Conditions to be satisfied in terms of performance (e.g., durability, hardness) or quality (e.g., content of defined ingredients).**
B8	**Conformity assessment related to TBT**	**Requirement for verification that a given TBT requirement has been met. This could be achieved by one or combined forms of inspection and approval procedure, including procedures for sampling, testing and inspection; evaluation, verification, and assurance of conformity; accreditation and approval.**
B81	Product registration requirement	Product registration requirement in the importing country.
B82	Testing requirement	A requirement for products to be tested against a given regulation, such as performance level – includes sampling requirement.
B83	Certification requirement	Certification of conformity with a given regulation: required by the importing country but may be issued in the exporting or the importing country.
B84	Inspection requirement	Requirement for product inspection in the importing country – may be performed by public or private entities. It is similar to testing but does not include laboratory testing.
B85	Traceability information requirements	Disclosure requirement of information that allows following a product through the stages of production, processing, and

		distribution.
B851	Origin of materials and parts	Disclosure of information on the origin of materials and parts used in the final product.
B859	Traceability requirements, n.e.s.	
B89	Conformity assessment related to TBT, n.e.s.	
B9	**TBT measures, n.e.s.**	

Source: Elaboration on UNCTAD [53].
Notes: n.e.s. stand for not elsewhere specified.

In the sample[24], only the United States implement tolerance limits for residues of or contamination by certain substances (TBT B21) on imports of wine. Given the multilateral nature of TBT measures, the tolerance limits apply indiscriminately to any partner exporting wine to the United States. According to data from the BCGlobal Pesticide MRL Database, in the United States tolerances are established for the combined residues of the insecticide cyantraniliprole[25], including its metabolites and degradates, in or on wine grapes[26] (i.e., 2 ppm), for emamectin including its metabolites and degradates[27] (i.e., 0.03 ppm), for fluazinam including its metabolites and degradates[28] (i.e., 3 ppm), for residues of a metiram including its metabolites and degradates[29] (i.e., 5 ppm), for the combined residues of the fungicide vinclozolin[30] and its metabolites containing the 3,5-dichloroaniline moiety (i.e., 6 ppm).

[24] Countries in the sample are Australia, France, Germany, Italy, Spain, the United States for which climate data at the regional level are available.

[25] 3-bromo-1-(3-chloro-2-pyridinyl)-N-[4-cyano-2-methyl-6-[((methylamino)carbonyl]phenyl]-1Hpyrazole-5-carboxamide.

[26] Compliance with the tolerance levels is to be determined by measuring only cyantraniliprole in or on wine grapes.

[27] Compliance with the tolerance levels is to be determined by measuring only the sum of emamectin (a mixture of a minimum of 90% 4'-epi-methylamino-4'-deoxyavermectin B1a and maximum of 10% 4'-epi-methylamino-4'-deoxyavermectin B1b) and its metabolites 8,9-isomer of the B 1a and B1b component of the parent (8,9-ZMA), or 4'-deoxy-4'-epi-amino-avermectin B1a and 4'-deoxy-4'-epi-amino-avermectin B1b; 4'-deoxy-4'-epi-amino avermectin B1a (AB 1a); 4'-deoxy-4'-epi-(N-formyl-N-methyl)amino-avermectin (MFB 1a); and 4'-deoxy-4'-epi-(N-formyl)amino-avermectin B 1a (FAB 1a), calculated as the stoichiometric equivalent of emamectin.

[28] Compliance with these tolerance levels is to be determined by measuring only fluazinam and its metabolite AMGT (3-[[4-amino-3-[[3-chloro-5-(trifluoromethyl)-2-pyridinyl]amino]-2-nitro-6-(trifluoromethyl) phenyl]thio]-2-(beta-D-glucopyranosyloxy) propionic acid).

[29] A mixture of 5.2 parts by weight of ammoniates of [ethylenebis (dithiocarbamato)] zinc with 1 part by weight ethylenebis [dithiocarbamic acid] bimolecular and trimolecular cyclic anhydrosulfides and disulfides. Compliance with the tolerance levels is to be determined by measuring only those metiram residues convertible to and expressed in terms of the degradate carbon disulfide.

[30] 3-(3,5-dichlorophenyl)-5-ethenyl-5-methyl-2,4-oxazolidinedione.

B. Empirical evidence on the relationship between climate change and wine production and trade

We use an approach based on Ricardian studies (e.g., [39-41]) to estimate the relationship between long-run climate and production and trade dynamics in the wine sector. We estimate how much climate explains observed cross-sectional variation of the wine supply[31], using the following log-linear specification:

$$Y_{it} = \boldsymbol{\beta}_m + \boldsymbol{\beta}_t + \boldsymbol{C}_{\boldsymbol{rt}}\gamma + u_{it} \tag{B.1}$$

The term Y_{it} indicates the wine supply of country i at time *t*. We estimate different specifications using as dependent variable, alternatively, the volume of countries' wine production and the value of countries' wine exports (i.e., a proxy of the value of excess of production). The term $\boldsymbol{C}_{rt}$ includes region-specific (r) climate normals[32] of temperature (T) and precipitation (P) and their squares; γ is the corresponding vector of regression coefficients. The terms $\boldsymbol{\beta}_m$ and $\boldsymbol{\beta}_t$ are macro-region and time fixed effects. They control, respectively, for exogenous unobserved factors at the macro-region level [55] and for exogenous technological progress [56]. u_{it} is the error term.

Consistent with the climate literature (e.g., [57]), we compute the marginal impact of climate normals as follows:

$$\frac{\partial \hat{Y}}{\partial T} \cdot \frac{1}{\hat{Y}} = (\gamma_T + 2\gamma_{T^2}\bar{T}) * 100 \quad \text{and} \quad \frac{\partial \hat{Y}}{\partial P} \cdot \frac{1}{\hat{Y}} = (\gamma_P + 2\gamma_{P^2}\bar{P}) * 100 \tag{B.2}$$

where γ_T, γ_{T^2}, γ_P, γ_{P^2} are coefficients estimated for long-run mean temperature and precipitation and their squares from equation (1), whereas $\bar{T}$ and $\bar{P}$ are the average value of temperature and precipitation normal of the sample.

The estimation results of the model in equation (B.1), reported in table B.1, show the relationship between wine productive and trade dynamics and long-run trends in climate in the main producing regions of wine in selected countries (i.e., Australia, France, Germany, Italy, Spain, the United States)[33]. While the effect of higher annual temperatures is observable both in production and trade patterns, greater annual precipitations tend to affect only the volume of wine production. The negative coefficient of precipitation and the positive coefficient of its squared term indicate that the volume of wine production would benefit only from rainfall levels larger than a certain threshold. After this threshold, a marginal increase in the precipitation normals would increase the production volumes.

[31] We rely on the pooled Ordinary Least Square (OLS) estimate of equation (1).

[32] Traditionally used in climate literature (e.g., [57]), the term climate normal, a synonymous of climatologies, refer to long time averages (usually 30-years) in climate variables (e.g., temperatures and precipitations) in a given location. Climate normals are built using the prevailing climate in the regions (*r*) that produce wine.

[33] The wine producing regions of Old World Producers are Piemonte, Veneto, Toscana, Puglia, Sicilia for Italy, Alsace, Champagne, Bordeaux, Burgundy, Languedoc-Roussillon, Provence for France, Andalucia, Castilla-La Mancha, Castilla y Leon, Catalonia, Galicia, Rioja for Spain, Baden, Mosel, Pfalz-Rheinhessen, Rheingau for Germany. The wine producing regions of New World Producers are California, Oregon, Washington, New York for the United States, Victoria, New South Wales, South Australia for Australia.

Table B.1. Effects of climate on countries' wine production and terms of trade.

Variables	Volume of wine production	Value of wine exports
Temperature	3.39645***	7.53360***
	(0.11702)	(1.27413)
Temperature-squared	-0.04421***	-0.13586
	(0.00865)	(0.08676)
Precipitation	-0.02142***	-0.07093
	(0.00803)	(0.08422)
Precipitation-squared	0.00002***	0.00005
	(0.00001)	(0.00005)
R-squared	0.923	0.189

Notes: Pooled OLS estimates of the model in equation (3). The dependent variables are in log. Regional annual temperature is in degrees Celsius and regional annual precipitation is in units of mm per year. The specification includes a constant term, time and macro-region fixed effects, countries' latitude and longitude. Robust standard errors are in parentheses. Observations are 1,473 in the first specification, 1,465 in the second specification (due to a few missing values in the exports from Australia). The sample of countries includes Australia, France, Germany, Italy, Spain, the United States.
*** Significant at the 1 percent level.

As a sensitivity analysis, we extend the timeframe until 2021, the last year available for climate data, to better capture the changes in the global wine trade over the past decade. The cross-sectional climate model is run on different time periods (table B.2). The results of the models estimated over the period 1996-2015 (column 1) and considering both the more recent time period (i.e., 2016-2021, column 2) and the whole period (i.e., 1996-2021, column 3) are comparable. The significant positive effect of temperatures found with outdated data (1996-2015) is confirmed when we incorporate more recent data (1996-2021) to capture the evolution of the global wine trade in the last decade.

Table B.2. Effects of climate on countries' value of wine exports.

	(1)	(2)	(3)
VARIABLES	1996-2015	2016-2021	1996-2021
Temperature	7.347***	7.547	2.650***
	(1.206)	(7.538)	(0.713)
Temperature-squared	-0.125	-0.248	-0.083**
	(0.082)	(0.315)	(0.040)
Precipitation	-0.047	-0.096	-0.009
	(0.080)	(0.199)	(0.007)
Precipitation-squared	0.00004	0.0001	0.00001*
	(0.0001)	(0.0001)	(0.00001)
R-squared	0.196	0.219	0.166

Notes: Pooled OLS estimates of the Ricardian model. The dependent variable is the logarithm of export values of wine. Regional annual temperature is in degrees Celsius and regional annual precipitation is in units of mm per year. The specification includes a constant term, time and macro-region fixed effects, countries' latitude and longitude. Robust standard errors are in parentheses. Observations are 1,552 in column (1), 465 in column (2), 2,017 in column (3). The sample of countries includes Australia, France, Germany, Italy, Spain, the United States.

*** Significant at the 1 percent level.

In order to investigate the relationship between climate change and wine supply, we estimate different specifications of the equation (B.1) using as dependent variable, alternatively, the volume of countries' wine production, volume of countries' excess of production (obtained as the difference between production and domestic consumption), value of countries' wine exports (i.e., a proxy of the value of excess of production).
The results of the pooled Ordinary Least Square (OLS) estimates are reported in table B.3. Higher temperatures in the main wine producing regions have a beneficial impact (up to a certain threshold) not only on countries' production levels of wine, but also on their excess of production volumes (net to the effect of domestic consumption) and values (i.e., countries' exports). The relationship between temperature normals and productive dynamics in the wine sector (both volumes of production and of excess of production) tends to be nonlinear. The effect of precipitation on the excess of wine production and on wine exports is not detected.

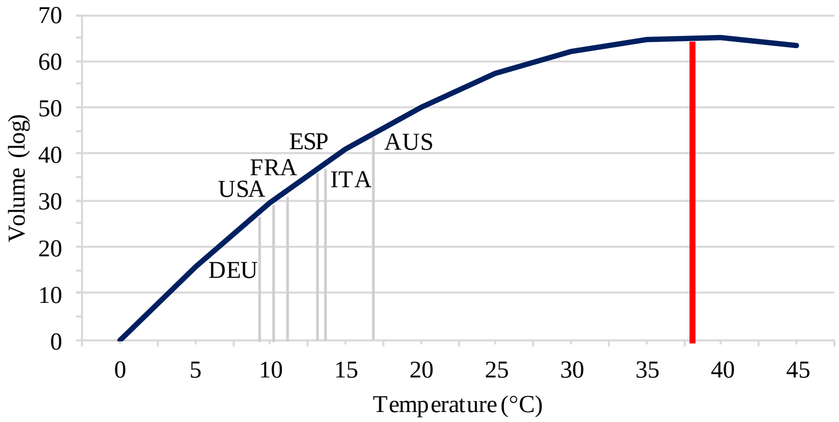
Table B.3. Effects of climate on countries' wine production and terms of trade.

Variables	Volume of wine production	Volume of wine excess of production	Value of wine exports
Temperature	3.39645***	1.69023***	7.53360***
	(0.11702)	(0.21296)	(1.27413)
Temperature-squared	-0.04421***	-0.10721***	-0.13586
	(0.00865)	(0.01515)	(0.08676)
Precipitation	-0.02142***	0.00336	-0.07093
	(0.00803)	(0.01068)	(0.08422)
Precipitation-squared	0.00002***	-0.00001	0.00005
	(0.00001)	(0.00001)	(0.00005)
R-squared	0.923	0.793	0.189

Notes: Pooled OLS estimates of the model in equation (1). The dependent variables are in log. Regional annual temperature is in degrees Celsius and regional annual precipitation is in units of mm per year. The specification includes a constant term, time and macro-region fixed effects, countries' latitude and longitude. Robust standard errors are in parentheses. Observations are 1,473 in the first and second specifications, 1,465 in the third specification (due to a few missing values in the exports from Australia). The sample of countries includes Australia, France, Germany, Italy, Spain, the United States.
*** Significant at the 1 percent level.

The results are robust: higher temperatures in the main wine producing regions have a beneficial impact (up to a certain threshold) not only on countries' production levels of wine, but also on their excess of production volumes (net to the effect of domestic consumption) and values (i.e., countries' exports).
Also, the relationship between temperature normals and productive dynamics in the wine sector tends to be nonlinear (i.e., positive first-degree and negative second-degree terms for temperatures). The figure B.1 shows the concave response of the volume of production to temperature normal: it increases at a declining rate up to 38.5 °C, after which it decreases.

Figure B.4. Effects of temperature normals on the volume of wine production, turning point, and positioning of producing countries.



Notes: The dependent variable is the volume of wine production (in log). Regional annual temperature is in degrees Celsius. The turning point is 38.5 °C. Acronyms are Australia (AUS), France (FRA), Germany (DEU), Italy (ITA), Spain (ESP), the United States (USA).

The average regional temperatures of the countries in the sample are lower than the turning point (figure B.1): all else being equal, the production of wine both in Old World Producers (France, Germany, Italy, Spain) and New World Producers (Australia, the United States) would benefit from a marginal increase in temperature normal in the main producing regions. The benefits would be greater for countries characterised by lower average temperatures, such as Germany or the United States, than for warmer countries, such as Australia were the wine production is focused on regions of Victoria, New South Wales, and South Australia.

It is reasonable to assume that trends of temperature observed in the main producing regions of wine should be responsible of the impact of climate on the production of wine. To test the external validity of this hypothesis, we estimate the last specification of the model (using the value of countries' wine exports as dependent variable) controlling for temperature normals at the country level. The results are shown in table B.4.

Table B.4. Effects of temperature normals on countries' wine exports: comparing the impact of national and regional climate.

Variables	Selected (Regional climate)	Selected (National climate)	All (National climate)
Temperature	7.534***	-4.061	0.091***
	(1.274)	(2.166)	(0.024)
Temperature squared	-0.136	0.019	-0.001
	(0.087)	(0.077)	(0.001)
Observations	1,465	1,465	2,851
R-squared	0.189	0.204	0.422

Notes: Pooled OLS estimates of the model in equation (1). The dependent variable is the log value of wine exports. Regional and national annual temperature is in degrees Celsius. The specification includes a constant term, time and macro-region fixed effects, precipitation and its quare. Robust standard errors are in parentheses. The sample of selected countries includes Australia, France,

Germany, Italy, Spain, the United States; the sample of all countries additionally includes Argentina, Bazil, Canada, China, New Zealand, Russia, South Africa, the United Kingdom.
*** Significant at the 1 percent level.

Consistent with results based on regional climate, we find a positive (although non-linear) effect of higher national annual temperatures in the expanded sample. As hypothesised, the impact of climate change on the value of wine exports is mainly due to trends of temperatures observed in the main wine producing regions rather than on average in the country. This is particularly true for large countries characterised by climate conditions heterogeneous across different regions. For instance, the average temperature in the main wine producing regions is 8 °C warmer than the average national temperature in the United States, about 3 °C in Spain, and less than 1 °C in Germany (see table 1). Within the same country, long-run changes in climate may be beneficial for some wine regions and detrimental for others [29, 58, 59]: these differences may offset each other considering the average climate at the national level.

C. Sensitivity analyses on the effect of climate change and policy interventions on wine trade

Consistent with the gravity theory (e.g., [22]), the value of output in the exporter i should be equal to the total expenditure on i's outputs in all trading partners j ($Y_i = \sum_J X_{ij} \ \forall j$)[34]. The output share of *i* may depend on its climate conditions. To test the robustness of the gravity model, we introduce in the gravity equation the prediction of countries' output shares ($\hat{Y}_{it}$), both in volume and values, as a proxy of countries' excess of production due to long-run changes in climate. The prediction of countries' output shares derives from the estimation of the model in equation (B.1).

The table C.1 reports the estimates of three different specifications: the baseline specification aims at capturing the effect of TBT on the value of wine imports (specification i), further specifications control for the effect of the excess of wine production, both in volume (specification ii) and in value (specification iii) predicted from the estimation of the model in equation (B.1) using regional climate variables. The larger the excess of production volumes due to long-run changes in climate, the lower the value of wine imports. The climate-induced changes in the productive dynamics in the main producing regions may alter comparative advantages of countries with consequences on the terms of trade [34].

Table C.5. Effects of TBT and excess of production for climate reasons on bilateral wine imports.

Variables	Specification i	Specification ii	Specification iii
TBT	0.254	0.013	0.238
	(0.205)	(0.179)	(0.203)
Excess of production (volume)		-0.743***	
		(0.237)	
Excess of production (value)			0.038
			(0.040)

Notes: Gamma Pseudo Maximum Likelihood (GPML) estimation of the structural gravity model. The dependent variable is the value of bilateral imports (in level). The TBT-related explanatory variable is modelled as dummy variables. All specifications include a constant, importer, time, exporter-time, and country-pair fixed effects, tariff levels. The excess of production (both in volume and value) predicted from the estimation of the model in equation (B.1) using regional climate variables. Robust standard errors are in parentheses. Observations are 494.
*** Significant at the 1 percent level.

To test the robustness of the relationship between environment-related trade policies and wine trade, we estimate the specifications (ii) and (iii) of the table C.1 controlling for the impact of environment-related TBT. The results are reported in tables C.2-C.5.

[34] It is worth noting that the value of output in exporter *i* should be equal to the sum of domestic internal consumption and the total expenditure on *i*'s outputs in all trading partners to account for both domestic and international demand and ensure a balanced supply-demand relationship.

Table C.6. Effects of environment-related TBT and excess of production for climate reasons on bilateral wine imports.

Variables	Specification i	Specification ii	Specification iii
TBT	-0.382***	-0.402***	-0.426***
	(0.079)	(0.073)	(0.062)
Environmental TBT	0.723***	0.522***	0.744***
	(0.215)	(0.176)	(0.212)
Excess of production (volume)		-0.606***	
		(0.190)	
Excess of production (value)			0.060
			(0.038)

Notes: Gamma Pseudo Maximum Likelihood (GPML) estimation of the structural gravity model. The dependent variable is the value of bilateral imports (in level). The TBT-related explanatory variables are modelled as dummy variables. All specifications include a constant, importer, time, exporter-time, and country-pair fixed effects, tariff levels. The excess of production (both in volume and value) predicted from the estimation of the model in equation (B.1) using regional climate variables. Robust standard errors are in parentheses. Observations are 494.
*** Significant at the 1 percent level.

Table C.7. Effects of authorisation requirement for TBT reasons on bilateral wine imports.

Variables	Specification i	Specification ii	Specification iii
TBT	0.100	-0.393***	0.100
	(0.159)	(0.098)	(0.158)
TBT B14	0.176***	0.358***	0.176***
	(0.056)	(0.097)	(0.065)
Excess of production (volume)		-0.982***	
		(0.239)	
Excess of production (value)			-0.001
			(0.045)

Notes: Gamma Pseudo Maximum Likelihood (GPML) estimation of the structural gravity. The dependent variable is the value of bilateral imports (in level). The TBT-related explanatory variables are modelled as dummy variables. B14 consists in authorisation requirement for importers for TBT reasons (including environmental protection). All specifications include a constant, importer, time, exporter-time, and country-pair fixed effects, tariff levels. The excess of production (both in volume and value) predicted from the estimation of the model in equation (B.1) using regional climate variables. Robust standard errors are in parentheses. Observations are 494.
*** Significant at the 1 percent level.

Table C.8. Effects of registration requirement for TBT reasons on bilateral wine imports.

Variables	Specification i	Specification ii	Specification iii
TBT	0.257	-0.144	0.235
	(0.206)	(0.150)	(0.204)
TBT B15	-0.038	0.387***	-0.086
	(0.088)	(0.103)	(0.066)
Excess of production (volume)		-1.141***	
		(0.229)	
Excess of production (value)			0.058**
			(0.026)

Notes: Gamma Pseudo Maximum Likelihood (GPML) estimation of the structural gravity model. The dependent variable is the value of bilateral imports (in level). The TBT-related explanatory variables are modelled as dummy variables. B15 consists in registration requirement for importers for TBT reasons (including environmental protection). All specifications include a constant, importer, time, exporter-time, and country-pair fixed effects, tariff levels. The excess of production (both in volume and value) predicted from the estimation of the model in equation (B.1) using regional climate variables. Robust standard errors are in parentheses. Observations are 494.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.

Table C.9. Effects of tolerance limits on bilateral wine imports.

Variables	Specification i	Specification ii	Specification iii
TBT	0.272	0.016	0.257
	(0.213)	(0.190)	(0.213)
TBT B21	-0.470*	-0.042	-0.451
	(0.267)	(0.187)	(0.278)
Excess of production (volume)		-0.739***	
		(0.225)	
Excess of production (value)			0.032
			(0.044)

Notes: Gamma Pseudo Maximum Likelihood (GPML) estimation of the structural gravity model. The dependent variable is the value of bilateral imports (in level). The TBT-related explanatory variables are modelled as dummy variables. B21 are tolerance limits for residues of or contamination by certain substances. All specifications include a constant, importer, time, exporter-time, and country-pair fixed effects, tariff levels. The excess of production (both in volume and value) predicted from the estimation of the model in equation (B.1). Robust standard errors are in parentheses. Observations are 494.
*** Significant at the 1 percent level.
* Significant at the 10 percent level.

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