Adaptation strategies of winegrowers to climate change: Comparison of Languedoc Roussillon (France) and Tuscany (Italy) wine regions

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Abstract

The relationship between wine products and the concepts of quality, identity, place, typicality and terroir is rooted in a deep socio-cultural and agricultural connection. Today, that bond, once considered incontrovertible, is increasingly at risk of weakening or fading due to the impacts of Climate Change. In light of this, our study aims to explore wine growers' perceptions of these effects and examine the adaptation strategies, both planned and already implemented, chosen by winegrowers. The phenomenon was investigated at both national and regional levels in two of the world's most significant wine-producing countries, namely France and Italy, focusing specifically on producers in the Languedoc-Roussillon and Tuscany wine regions. Data were collected through semi-structured interviews with twenty-three wine producers, revealing a high level of awareness regarding the severe climatic impacts, with coping strategies varying by region. However, these adaptive approaches often conflict with the rigid product specifications of the designations of origin, which have remained largely unchanged over time, showing limited flexibility in response to an evolving climate, society and market. In this context, the study underscores the urgent need for dynamic regulatory frameworks to support the adaptation efforts and measures developed by European wine producers.

Keywords*: Wine, Climate change, Typicality, Identity, Quality, Terroir, Strategies, Languedoc-Roussillon, Tuscany, Policies and regulatory framework.*

1. Introduction

The wine industry holds significant cultural, economic, and social relevance, particularly in Europe, where many countries have long-standing winegrowing traditions. Furthermore, given the strong connection between wine and the concepts of place, identity, and *terroir*, wine production has adjusted over the centuries to each unique socio-economic and climatic scenario, resulting in wine products deeply tied to specific sites, capable of conveying their territorial uniqueness, thus contributing to the economy and cultural heritage at local, regional and

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national levels. Additionally, in many old-world wine countries, the well-known expertise and knowledge regarding the interaction between the environment and the cultivated variety have often shifted from tradition to legislation.

Yet, there is a major, long-term menace to the traditional bond between wine and place: climate change, the outcome of natural and anthropogenic forces, is making decades of wine-making know-how obsolete. In such a context, the looming climate crisis, accentuated more and more by rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events, impacts grape yields, quality, and the identity profiles of the resulting wines, thus threatening the economic, social and environmental sustainability of the world vitivinicultural sector. As a result, climate change is inevitably giving rise to new challenges. Scholars have already observed shifts in viticultural suitability, which are likely to reshape the geographical distribution of many wine-growing regions worldwide, with shattering effects on product specifications. Although these impacts will have heterogeneous effects, with some areas potentially benefiting from this evolution, the need for timely, appropriate and cost-effective adaptation strategies remains urgent. To successfully mitigate risks, adaptation measures and policies must be carefully planned and tailored to local conditions and needs and, given the perennial nature of grapevines, must account for both the short and long-term impacts of climate change.

In this context, winegrowers are becoming increasingly aware of these threats. Proactive and well-timed strategies to mitigate negative impacts can, in turn, provide significant competitive advantages.

However, although the importance of adopting proactive measures to tackle climate change is now clear, very little information exists on winegrowers' perceptions and adaptations to this global-scale issue. Previous studies have sought to address, albeit partially, similar questions. Some researchers (Neethling *et al*., 2020), for instance, have undertaken a global analysis, comparing up to 18 wine-producing countries to gain a broad understanding of winegrowers' perceptions and adaptations to a changing climate, both from a global and regional perspective. Other scholars (Battaglini *et al*., 2009), conversely, have focused their attention on a comparative study between three major wine-producing countries, namely Italy, France, and Germany. Furthermore, some researchers (Alonso & Martin, 2011) have conducted national-level investigations while others (Neethling *et al*., 2017) have chosen to compare two wine-growing areas within a given subregion.

In line with the studies to date, our research will employ both a national and regional scale approach to investigate this phenomenon in two of the most influential wine-producing countries in the world, namely Italy and France, with a particular focus on wine producers from Tuscany and Languedoc-Roussillon wine regions. The present study aims to investigate the level of awareness among winegrowers regarding the impending effects of climate change and explore the strategies they are adopting or planning to face this threat. The uniqueness of our study lies in the desire to take a closer look at the concepts of identity, typicality, and *terroir* of wine to understand how and to what extent these, according to the interviewees, have been impacted by climate change. Understanding the priorities and challenges of wine producers is essential for implementing targeted actions at local and national scales, highlighting the need for tailored strategies to enhance climate resilience in vitivinicultural systems. Data was collected through semi-structured interviews with a total of twenty-three wine producers.

2. The vitivinicultural sector in an ever-changing climatic context

Weather and, over the long term, climate play a pivotal role in the global production landscape, influencing not only yield, but also the canopy microclimate, vine growth, vine physiology, and berry composition, which collectively define wine characteristics and typicity. The effects of atmospheric conditions on grapevines can be analyzed across two different temporal scales. In the long term, climate – defined as the statistical distribution of atmospheric variables over

decades in a given location – determines the bioclimatic potential and viticultural suitability of a given region. Macroclimatic conditions, in particular, influence the spatial distribution of grapevine varieties and the geography of wine production, whereas mesoclimatic and microclimatic factors create unique terroir units that contribute to the diversity and distinctiveness of wines (Santos *et al*., 2020).

In the short term, weather has a significant impact on grapevine development. It regulates the entire growth cycle by providing heat, water, and sunlight, both in terms of intensity and duration. These variables ultimately affect yield, biomass production, berry composition, and the wine's structure and flavour profile. As highlighted by Van Leeuwen and Darriet (2016), vineyards thrive across a wide range of climates. However, the main wine-producing areas are predominantly located between the 35th and 50th parallels in the Northern Hemisphere and the 30th and 45th parallels in the Southern Hemisphere. Moreover, as stated in the aforementioned review by Santos *et al*. (2020), "changes in viticultural suitability over the last decades, for viticulture in general or the use of specific varieties, have already been reported for many wine regions. These shifts may reshape the geographical distribution of wine regions, while wine typicity may also be threatened in most cases" (Santos *et al*., 2020).

In addition, as forecasted by Hannah *et al*. (2013), wine production suitability is expected to decline in traditional regions such as Bordeaux, the Rhône Valley, and Tuscany while expanding into more northerly regions in North America and Europe. Existing suitability will likely persist in smaller areas within current wine-producing regions, particularly at higher elevations and along coastal zones (Hannah *et al*., 2013). Furthermore, regions at higher latitudes and elevations currently unsuitable for viticulture are projected to become viable for wine production soon. A recent study by Sgubin *et al*. (2023) confirms that these predictions are gradually becoming a reality. Year by year, shifts in wine production patterns are increasingly evident, with new regions emerging as appropriate for viticulture, particularly at higher latitudes and elevations. According to Sgubin *et al*. (2023), by 2040, new emerging wine regions will represent around 35% of the total suitable area in Europe. In general, however, the development of new wine regions balances the decline in traditional areas, leading to a greater overall extent of suitable wine-growing regions across Europe compared to the recent past: "At the end of the century, depending on the emission scenario, the total suitable regions for wine production are 33% to 45% greater than in the recent past" (Sgubin *et al*., 2023).

2.1. *Major Impacts of Climate Change on Modern Viticulture and Wine Quality*

With rising global temperatures, wine-growing regions are witnessing shifts in weather patterns, affecting grape ripening levels, harvest dates, and the overall balance between sugars, acidity, and tannins in the berry. These significant changes lead to modifications in the wines' flavour profiles, alcohol content and, no less importantly, ageing potential, resulting in far-reaching socio-economic and commercial consequences. Furthermore, extreme weather events, namely droughts, heatstrokes, heavy rainfall or late frosts undermine vine health and conventional vineyard management practices. However, as previously mentioned, certain regions may benefit from climate change, potentially widening the area suitable for vine cultivation. In this framework, understanding and adapting to these outcomes is crucial for preserving the recognized attributes of uniqueness and high quality chased by wine consumers.

2.1.1. *The role of temperature and the Impact of Increasing Temperatures on Vine Development, Fruit Composition and Wine Quality*

Of all atmospheric elements, temperature is a key driver of grapevine growth and phenological development. According to Parker *et al*. (2011), the relation between temperature and vine phenology is so tight that the latter can be predicted only by relying on temperature-based models. Van Leeuwen and Darriet (2016) highlight that "an increase in temperature, which is one of the major consequences of climate change, triggers an advance in phenology". In favour of that, fur-

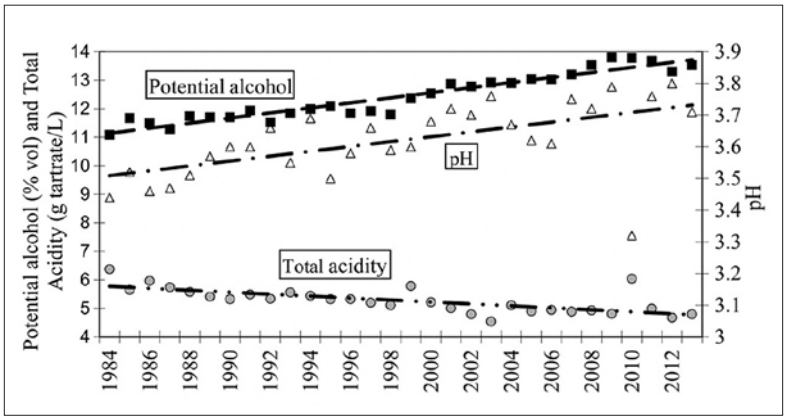

Figure 1 - Potential Alcohol Levels, Total Acidity and pH of Grape Juice Just Prior to Harvest in Languedoc from 1984 to 2013.

Source: Dubernet laboratory, 11100 Montredon-Corbières.

ther studies have provided evidence that, since the 1980s, harvest dates in many wine-growing regions have experienced a significant advance. That is the case, for instance, of Saint-Émilion, a commune of the Gironde department in Nouvelle-Aquitaine, in Southwestern France, where harvest dates have been brought forward by roughly two weeks (ONERC).

As a consequence, climate warming and advanced phenology have significantly altered grape composition over the last 30 years. Data from the Dubernet laboratory in France shows (Figure 1) increases in potential alcohol levels by over 2%, decreases in total acidity by 1 g/L of tartrate, and rises in pH by 0.2 units of grape juices before harvest in the Languedoc wine region from 1984 to 2013. These changes are likely to be influenced, in addition to higher temperatures, by increased CO2 levels (which recorded a 15% increase over the reference period), enhanced radiation, and improved viticultural techniques (Van Leeuwen and Darriet, 2016).

Temperature-based models predict that by mid-century (2020-2050), flowering in Bordeaux will be advanced by 15 days and 30 days by the end of the century (2070-2100) (Van Leeuwen and Darriet, 2016). Ripeness levels, instead, will be advanced by 25 and 45 days, respectively, potentially shifting harvest to early September or mid-August, which may not be suitable window periods for high-quality *terroir* wine production. Even though predicting future grape composition under changing climate conditions is challenging, it is possible to expect that the trend of higher sugar levels leading to increased alcohol content in wines will continue. While higher alcohol levels can enhance wine quality, they can also degrade it if too high.

Regarding acidity, pH is a critical factor. Higher pH levels make wines taste rounder and sweeter, a change most consumers prefer. However, high pH can reduce freshness and stability, increasing susceptibility to spoilage by *Brettanomyces bruxellensis*, thus requiring more sulfur dioxide (SO_2) for stabilization (Lonvaud-Funel *et al*., 2010).

2.1.2. *Increasing Water Deficits and Radiation Impacts*

Climate change has led to increasingly drier vintages over time. This trend is not necessarily linked to reduced rainfall but is more likely driven by higher evapotranspiration rates resulting from rising temperatures. In addition to temperature, soil water content and solar radiation significantly impact vine development, fruit composition and wine quality. Vine water status is influenced by many factors, such as soil texture, stone percentage, rooting depth, rainfall, evapotranspiration (ET0) and leaf area. Water deficits can reduce photosynthesis (Hsiao, 1973), hinder shoot growth (Lebon *et al*., 2006) and decrease berry size (Van Leeuwen and Seguin, 1994) while increasing tannin and anthocyanin content in grapes (Van Leeuwen and Seguin, 1994). High water deficits are particularly beneficial for red wine production as they promote early shoot growth cessation, reduce berry size, and enhance skin phenolics (Van Leeuwen *et al*., 2009). How-

ever, excessive water stress can damage leaves, block grape ripening, and negatively affect yield and quality, particularly in drier regions or soils with low water-holding capacity.

As previously mentioned, climate change's impact on wine aromas and precursors varies, with water stress reducing some compounds while moderate deficits increase others. For example, according to a study from the early 2000s (Peyrot des Gachons *et al*., 2005), the berry content in volatile thiol is reduced by water stress but increased by moderate water deficit. Instead, Koundouras *et al*. (2006) reported increased norisoprenoid C13 levels in grapes under water deficit conditions. Light intensity, on the other hand, boosts vine photosynthesis until a certain point, beyond which it stabilizes. In addition, high light levels increase grape skin anthocyanins, although high temperatures can have an inhibitory effect on these compounds (Spayd *et al*., 2002).

Over the past decades, UV-B radiation (280-320 nm) has increased by about 1-2% per decade, up to 8% at higher altitudes (Van Leeuwen and Darriet, 2016). This increase enhances the synthesis of colour, flavonols, and tannins in red grapes (Martinez-Lüscher *et al*., 2022) but can cause off-flavours in white grapes (Schultz, 2008). Increased radiation can also lead to sunburn events on grapes, particularly before the véraison phase. Thus, while beneficial for red wine production due to increased skin phenolics, higher UV-B levels can harm white wine quality, causing atypical ageing. Although our investigation mainly focused on temperature, soil water content and solar radiation, it is worth acknowledging that other climatic and pedological variables affect wine quality. Factors such as humidity, wind, soil texture and structure, topography, etc. interact complexly to influence vine growth and grape development. We have not delved into these additional variables for time and space constraints, but future studies could benefit from a more comprehensive analysis that includes these factors to provide a holistic understanding of the impacts of climate change on viticulture.

2.1.3. *Main effects of extreme climatic events*

Extreme weather events, such as heatwaves, extreme precipitation, bushfires, droughts, hailstorms, and windstorms, are becoming increasingly common in the well-known ever-changing climatic context. The frequency of these extreme climatic events will likely increase in the upcoming years, with varying outcomes for wine quality, identity, and typicality depending on the affected producing region and the extent of the climatic impact. Hailstorms, for instance, which tend to occur mainly during spring and summer, can damage vines at sensitive phenological stages, like flowering and ripening, with huge impacts on final production quantity and quality levels. On the other hand, heatwaves, often combined with droughts can lead, among other issues related to grape quality, to a decline in soil structure and an increase in salinity, particularly in coastal areas and when saline water is employed to irrigate.

However, among the most concerning phenomena of recent years is the increase in episodes of intense rainfall. That is particularly problematic in areas with steep terrain, where it can trigger surface water runoff and significant soil erosion and degradation, posing a serious threat to vineyard stability. Addressing these emerging issues is crucial to fostering effective adaptation strategies that preserve the resilience of local wine production. Implementing sustainable water resource management practices, supported by innovative technologies like high-resolution monitoring and targeted irrigation techniques, offers a viable path to adapt to the dual challenges of excessive rainfall and water scarcity in the major wine-producing regions and countries (Straffelini *et al*., 2023).

2.2. *Climate Change adaptation strategies*

To address the challenges posed by climate change, the winemaking industry must implement effective adaptation measures. This requires developing strategies tailored to specific regional and local contexts, especially in areas expected to face severe impacts in the upcoming years. On the one hand, winegrowers are increasingly recognizing risks and needs, while, on the other hand, it is nonetheless up to stakeholders and policymakers to take conducive action measures. However, as underlined in a

Table 1 - Climate Change Adaptation Strategies: short- and long-term perspective approach

	Short-term perspective	*Long-term perspective*
CC adaptation strategies	Canopy management	Modifying vine training system
	Harvest date management	Genetic material selection
	Water management	Preserving genetic diversity
	Pest and disease management	Vineyard relocation
	Sustainable soil management	Sustainable soil management

Source: Authors.

recent review, "the overall approach should always be the adoption of a combination of local solutions to cope with a global problem" (Santos *et al*., 2020).

Vitivinicultural adaptation strategies combine short-term and long-term measures to ensure the resilience and sustainability of vineyards (Table 1). In the short term, crop cultural measures are essential for mitigating the effects of increased temperatures and variable weather conditions. Canopy management (such as selectively removing leaves or altering their geometry) helps minimize water consumption and loss, reducing vine water stress. Anti-transpirant substances, like kaolin or shade nets, further help minimize water loss while protecting grapes from sunburn. Early harvesting is another effective response to rising temperatures, allowing grapes to retain the desired acidity and sugar balance before over-ripening (Santos *et al*., 2020). Water management plays a critical role in regions increasingly prone to drought. Advanced irrigation techniques, such as regulated deficit irrigation or partial root-zone drying, enhance water-use efficiency, while drip irrigation systems deliver precise amounts of water to the vines. The integration of smart irrigation systems with soil moisture sensors ensures the rational use of resources, preventing overuse. At the same time, pest and disease management becomes more challenging as rising temperatures alter pest dynamics. Enhanced monitoring systems and the use of natural compounds or biocontrol measures provide sustainable solutions, ensuring vine protection without over-reliance on chemical pesticides.

Sustainable soil management supports these efforts by improving the health and water retention of vineyard soils. Practices such as composting winery residues enrich organic matter, enhancing soil fertility and structure. Cover crops, including legumes and grasses, prevent erosion, improve biodiversity, and aid in water infiltration, although their competition with vines must be carefully managed to avoid adverse effects on vine growth (Santos *et al*., 2020). In the long term, structural changes to vineyard systems are necessary to adapt to the ongoing climatic shifts. One of the key measures is modifying vine training systems, such as adopting minimal pruning or adjusting canopy height and row orientation. These practices optimize light capture, delay ripening and reduce heat stress in favour of the vines. Selecting grape varieties and rootstocks better suited to warmer conditions can be considered another crucial adaptation strategy (Santos *et al*., 2020). Heat- and drought-tolerant varieties like Cabernet Sauvignon, Syrah, and Tempranillo are increasingly planted, while drought-resistant rootstocks enhance the resilience of vines in water-scarce regions. At the same time, preserving the genetic diversity of indigenous grape varieties remains vital for maintaining terroir identity and providing options for future adaptability (Santos *et al*., 2020).

In some cases, vineyard relocation becomes inevitable. Planting vines at higher altitudes or in regions previously unsuitable for viticulture, such as northern latitudes, offers new opportunities as warming trends make these areas more favourable for wine production. By integrating these measures, viticulture can address both the short- and long-term challenges of climate change. These efforts ensure the production of high-quality wines while safeguarding the economic viability and cultural heritage of vineyards in an era of profound environmental transformation (Santos *et al*., 2020).

3. Methodology

3.1. *Context of the study and comparison between the two investigated regions*

The Tuscany region, renowned for its picturesque landscapes and historical vineyards, presents a distinctive profile in the realm of Italian wine production. The region boasts a total vineyard area of 61,000 hectares (ISMEA). This expansive viticultural landscape supports a diverse range of grape varieties and wine styles, contributing significantly to Italy's viticultural heritage. In terms of wine production, Tuscany holds a notable position nationally. According to Unione Italiana Vini (2023), Tuscany ranked 7th in wine and must production in 2021, with 2,049,909 hectoliters (hl). Within this region, PDO (Protected Designation of Origin) wines play a pivotal role, showcasing the region's commitment to quality and tradition. In 2021, PDO wine production in Tuscany amounted to 1,418,486 hl, complemented by an additional 556,538 hl of IGP (Indication of Geographic Origin) wine production. The region's PDO offerings are anchored by prominent appellations such as Chianti DOCG and Chianti Classico DOCG, which rank 7th and 10th, respectively, among Italy's top PDOs by bottled volume.

Tuscany demonstrates a strong presence in organic viticulture. With an organic vineyard area of 25.2 thousand hectares (kha), representing 42% of its total vineyard area, Tuscany secures the 2nd position nationally in terms of organic viticultural dedication (Unione Italiana Vini). This commitment translates into significant organic wine production, accounting for 15% of Italy's total national output in 2021. Notably, 22% of Tuscany's total wine production is certified organic, illustrating a robust embrace of sustainable practices within the region (Unione Italiana Vini). In conclusion, Tuscany emerges as a dynamic force in Italy's wine sector, blending traditional craftsmanship with modern sustainability initiatives. Its expansive vineyard area, diverse wine production portfolio, and strong organic commitment underscore its pivotal role in shaping the landscape of Italian wine production.

On the other hand, Occitanie stands as a cornerstone of France's agricultural economy, with viticulture playing a focal role. The wine sector constitutes 22% of the region's total agricultural income averaged over the period from 2019 to 2021 (Invest in Occitanie). In terms of vineyard area, Occitania boasts a substantial production base with 250,391 thousand hectares under cultivation as of 2021, making it the largest viticultural region in France. The majority of vineyards are distributed across key departments such as Hérault (31%), Aude (25%), Gard (21%), Pyrénées-Orientales (9%), and Gers (8%) (DRAAF). With a total output of about 13 million hectolitres, the region is renowned for its extensive wine production capabilities, encompassing five main production areas: Languedoc, Roussillon, Pays d'Oc, significant portions of the Southwest, and part of the Rhone Valley (Gard). This vibrant viticultural landscape supports over 13,900 thousand winemakers and accounts for an impressive 43% of French red and rosé wine production. Moreover, approximately one-third of the regional wine production is exported, highlighting Occitania's influence on the global wine market (Invest in Occitanie). In terms of geographical indications (GI), Occitania boasts 51 PDO (Protected Designation of Origin) and 36 PGI (Protected Geographical Indication) wines, leading France in producing quality-labelled wines.

Organic viticulture is a significant aspect of Occitania's agricultural landscape, as it is the leading organic wine-producing region in France. It encompasses 35% of France's organic vineyards, reflecting a strong commitment to sustainable agricultural practices. The region hosts 13,823 thousand organic and in-conversion farms (Interbio Occitanie), comprising a quarter of all French organic farms, covering more than 63,051 hectares certified organic or in conversion, which constitutes 20% of the regional Utilized Agricultural Area (Invest in Occitanie). Therefore, Occitania emerges as a powerhouse in French viticulture and organic agriculture, combining rich traditions with innovative practices. Its vast vineyard area, diverse wine production, and leadership in organic farming underscore its pivotal role in shaping the French agricultural sector.

Figure 2 - Languedoc-Roussillon map.

Source: Alamy (Image ID CRH2WW).

Figure 3 - Tuscany map.

Source: Alamy (Image ID CRH2WW).

Figure 2 and Figure 3 depict the geographical location of the two investigated regions, offering a clear view of their spatial context at a national level. Table 2, on the other hand, presents a comparative analysis of the areas based on several quantitative variables.

3.2. *Sample companies' selection*

In the selection process of the companies that are the object of the study, the primary aim was to create a sample as diverse and heterogeneous as possible. This approach aims at ensuring a comprehensive representation of the company dynamics within the Languedoc-Roussillon and Tuscany wine regions. To achieve this goal, we carefully considered the geographical distribution within the region, seeking to include firms located in different areas. Furthermore, we paid particular attention to the company characteristics that may contribute to the diversity of the sample, like the firm's nature (family-owned wineries or cooperatives), the role played by the respondent, the number of employees, the type

Table 2 - A comparison of Tuscany and Occitanie wine regions.

Region	*Variable*	*Value*
Tuscany	Vineyard area (ha)	61.000
	Organic vineyard area (ha)	25.200
	Wine production (hl)	2.049.909
	PDO wine production (hl)	1.418.486
	IGP wine production (hl)	556.538
	N. of producers	12.700
Languedoc-Roussillon	Vineyard area (ha)	185.000
	Organic vineyard area (ha)	35.000
	Wine production (hl)	9.000.000
	PDO wine production (hl)	3.700.000
	IGP wine production (hl)	3.000.000
	N. of producers	13.900

Source: Authors.

Table 3 - Firms profiling.

Firms profiling	*Languedoc-Roussillon*	*Tuscany*
N. of firms sampled	11	12
Average surface (ha)	366	208
Average production (bottles/year)	1.200,000	879.833,33
N. of organic certified firms	7/11 (64%)	8/12 (67%)
Governance model		
Family-run	6/11 (55%)	7/12 (58%)
Private company	2/11 (18%)	3/12 (25%)
Cooperative	3/11 (27%)	2/12 (17%)

Table 4 - Characteristics of the Interviews.

Characteristics	*Languedoc-Roussillon*	*Tuscany*
Number	11	12
Respondent Profiles	Owners (6), General Director (3), R&D Manager (1), Technical Supervisor (1)	Owners (5), Oenologist (1), Vineyard Manager (5), Sales Manager (1)
Average Duration	35 minutes	40 minutes
Period	October 2023	February 2024
Topics covered	Farm profiles, climate change effects, adaptation strategies adopted, future projections.	Farm profiles, climate change effects, adaptation strategies adopted, future projections.

Source: Authors.

of wine produced, appellations of origin, viticultural and oenological practices adopted, and other relevant factors.

This careful selection aims to ensure that the research is representative of the complexity of the Languedoc-Roussillon and Tuscany wine sectors and to examine, as thoroughly as possible, the differences and similarities between different wineries. In this way, we aimed to obtain a comprehensive overview of producers' perceptions of the effects of climate change on the quality, identity and *typicality* of the wines produced, as well as of the already implemented or planned adaptation strategies that could help respond to this crisis. The following tables summarize the sampled companies' profiling (Table 3) and the respondents' characteristics (Table 4).

3.3. *Contact method*

French wineries identification was achievable thanks to the "Sud de France" web page (Link: https://sud-de-france.com/les-adherents/), notably in the "Les adherents" section, Tuscan companies, on the other hand, were identified through the websites of the main denominations of origin. To maximize the response rate, we reached a large number of companies. Overall, fifty companies were contacted via e-mail for the Languedoc-Roussillon wine region, while seventy were contacted for Tuscany, given the lower response rate. As a result, companies that did not have e-mail addresses or company websites were not included in the sample). After about a week, considering the weak response rate, we reached them by phone. It is relevant to underline that the interviews were carried out in France during the post-harvest period (October 2023) and during the pruning phase in Italy (February 2024), two of the busiest periods of the year for wineries. That negatively affected the response rate. Fortunately, we reached the predefined number of sample companies in both areas.

3.4. *Data collection and analysis*

To structure the interviews, we adopted an approach based on three main questions:

1. *Over the past 20 years, what have been the most noticeable effects of Climate Change on your company?*
2. *Which viticultural, oenological, or marketing strategies have been implemented on a corporate level to address the challenges arising from climate evolution?*
3. *Do you foresee worsening impacts of climate change in the following decade? Which strategies are you considering to manage this threat in the future?*

The previous questions were the starting point for a more in-depth conversation with the respondents, during which they were asked quick, transversal questions aimed at better understanding company dynamics. These questions focused, for instance, on topics ranging from sustainability certifications adopted (*Has the company implemented any environmental labels? If so, which one and when?*) to the observed climate change impacts on the identity and typicality of wines (*What is your perception of the effects of climate change on wine identity and typicality?*).

As for general information about the firm, we initially retrieved such data from the respective company websites, and if necessary, the respondents were asked for clarifications and confirmations directly. Interviews were conducted in French and Italian, mainly by telephone or video calls via the *Teams* platform, due to time constraints and the participants' numerous work commitments. It is important to note that this method, which cannot be compared to face-to-face interaction, may have affected the quality of interaction with respondents. Nevertheless, we gathered all the information necessary for our research. On average, the interviews lasted 35 minutes. The collected data were then organized by question in an Excel spreadsheet and analysed. Data collection also involved consulting several secondary sources, including nineteen reports (each averaging approximately 30 pages in length) and two press articles.

4. Results

4.1. *Climate Change Effects: a comparative analysis*

Table 5 highlights the most noticeable effects of climate change in the areas under study over the past 20 years. In Languedoc-Roussillon, the most mentioned climatic impact is the increase in alcohol levels, reported by 9 firms out of 11, followed by earlier grape maturity (7 out of 11) and a reduction in yield (6 out of 11). In particular, concerning yield reduction, one of the French producers stated: "Although our average production has consistently been around 1,200 hectoliters, over the past two years, we have observed a decline of approximately 700 hectoliters, with production levels not exceeding 500 hectoliters".

In the Tuscany region, instead, the main effect is yield reduction, reported by 11 wineries out of 12. Additionally, higher alcohol levels and lower acidity levels were each reported in 9 out of 12 cases, followed by earlier maturity of grapes (5 firms out of 12). In this regard, for instance, an Italian producer highlighted "In the past, it was challenging to achieve even 13 degrees of alcohol, whereas today, alcohol levels ranging from 15 to 17 degrees are easily attainable". Thus, these findings underline how climate change is having a significant impact on these regions' vitivinicultural sector, with relevant outcomes affecting both the quantitative and qualitative aspects of wine production.

Table 6 examines, instead, the winegrowers' perception of the effects of climate change on wine identity and *typicality*. In the French region, the identity and *typicality* of wines seem to have largely remained unchanged, as reported by 8 firms out of 11. However, no positive impacts have been reported, while negative effects were noted in 3 out of 11 cases. In this regard, one of the latter observed, for instance, "A loss of acidity and a fatter mouthfeel".

On the contrary, in the Italian wine region, the identity and *typicality* of wines remained unaffected in 10 out of 12 cases. Interestingly, there were positive impacts in 2 wineries, one of which stated that "What has changed is the starting matrix: the wines have more and more concentrated

Table 5 - The most noticeable effects of Climate Change in the last 20 years.

The most noticeable effects of Climate Change in the last 20 years			
	1°	2°	3°
Languedoc-Roussillon	Higher alcohol levels (9/11)	Early maturity (7/11)	Yield reduction (6/11)
Tuscany	Yield reduction (11/12)	Higher alcohol levels Lower acidity levels (9/12)	Early maturity (5/12)

Source: Authors.

Table 6 - Impacts on wine identity and typicality.

Identity and Typicality profile of wines			
	Not impacted	*Positively impacted (+)*	*Negatively impacted (-)*
Languedoc-Roussillon	(8/11)	(0/11)	(3/11)
Tuscany	(10/12)	(2/12)	(0/12)

Source: Authors.

phenols and significant structures, which even allow a period of ageing in barrels". The other one pointed out, instead, that "Paradoxically, increasing sugar content of grapes and, thus, the higher alcohol content of wines has greatly helped our firm in producing wines characterised by a good structure. Today, however, the challenge is to avoid excessive colour concentration and loss of freshness in the wines." In the sample of Tuscan firms, no negative outcomes were reported. These findings suggest that, although climate change has affected the sensory profiles of these regions' wines, the extent and nature of the impact differ significantly between Languedoc-Roussillon and Tuscany, reflecting the territorial and climatic heterogeneity of the two surveyed areas.

4.2. *Adaptation strategies*

Table 7 outlines the major climate change adaptation strategies already implemented by Languedoc-Roussillon and Tuscany wineries, highlighting key differences. In Languedoc-Roussillon, for instance, the most cited agronomic strategy is harvest dates adjusting (reported by 7 wineries out of 11) while irrigation systems, varietal selection, and night/morning harvests have been cited by 4 firms out of 11 each. In the cellar, two French winegrowers adopt cold working with temperature control as an adaptation strategy to face climate change impacts. Commercial strategies, on the other hand, are less common, with only one company targeting specific niche market segments, consisting of consumers who better appreciate the new qualitative profile of the company's products.

In contrast, the Tuscany region shows a wider and more mixed approach. The leading agronomic strategies include canopy management (8 firms out of 12), followed by adjusting harvest dates, increasing soil organic matter (SOM), and use of biostimulants and/or kaolin (6 firms out of 12). Tuscany's most prominent oenological strategy is maceration techniques (8 out of 12), followed by cold working with temperature control (6 out of 12). Concerning commercial/marketing strategies, Italian firms emphasize the communication of the implemented strategies (5 out of 12) along with targeting niche markets and conveying the resilience of the cultivated grape varieties (2 out of 12 each).

Finally, table 8 outlines potential future adaptation strategies for the wine regions of Languedoc-Roussillon and Tuscany. In Languedoc-Roussillon, possible future agronomic approaches include the employment of resistant and/or new varieties (cited by 8 respondents out of 11) and site selection (mentioned by 4 firms out of 11). Concerning the

Table 7 - Major adaptation strategies already implemented.

Major adaptation strategies already implemented			
	Agronomic	*Oenological*	*Commercial/Marketing*
Languedoc-Roussillon	Harvest date adjustment (7/11) Irrigation system Varietal selection Night/morning harvest (4/11)	Cold working (T control) (2/11) Gravity winery (2/11)	Targeting specific niche segment in the market (1/11)
Tuscany	Canopy management (8/12) Harvest date adjustment Increasing SOM in the soil Use of biostimulants products / Kaolin (6/12) Permanent inter-row grassing Softer soil tillage Delaying winter pruning (4/12)	Maceration techniques (8/12) Cold working (T control) (6/12) Partial dealcoholisation of wines (2/12)	Communication of the implemented strategies (5/12) Targeting specific niche segment in the market Communicating CC impacts and issues Emphasizing the resilience of varieties (2/12)

Source: Authors.

Table 8 - Potential future adaptation strategies.

Potential future adaptation strategies			
	Agronomic	*Oenological*	*Company strategies*
Languedoc-Roussillon	Resistant and/or new varieties (8/11) Site selection (not only at higher altitudes) (4/11)	Carbonic maceration (1/11)	Production diversification (4/11)
Tuscany	Site selection (not only at higher altitudes) (4/12) Rootstock selection (3/12)	Partial dealcoholisation of wines (2/12)	Production diversification (1/12)

Source: Authors.

oenological domain, carbonic maceration is considered by 1 out of 11 respondents. Finally, the companies' strategies will mainly focus on production diversification, as mentioned by 4 wineries out of 11. In Tuscany, agronomic strategies will mainly rely on site selection (mentioned by 4 out of 12 respondents) and rootstock selection strategies (cited by 3 out of 12 respondents). Oenological approaches will likely include, for 2 wineries out of 12, the partial dealcoholisation of wines. As for Languedoc-Roussillon wine producers, production diversification may be one of the future company strategies to face climate change. However, in the Italian region, this approach was mentioned only 1 out of 12 times.

5. Discussion

Our comparative analysis of two of the world's most significant wine regions has addressed the core questions of our research. Firstly, we aimed to explore the perceptions of French and Italian winegrowers—specifically in the Languedoc-Roussillon and Tuscany regions—regarding the effects of climate change on wine quality, identity, and typicality. Secondly, we sought to identify the strategies that wineries have implemented and are considering for future adoption to mitigate and adapt to these climatic impacts.

The previous results denote a significant level of awareness among winegrowers regarding the impending impacts, addressing our research objectives effectively. In this regard, findings reveal that both regions are significantly aware of the effects. Wineries in Languedoc-Roussillon and Tuscany recognize the severe climatic impacts, particularly citing increased summer droughts, late spring frosts, and extreme temperature phenomena. Both regions have stressed impactful effects on wine quality, such as earlier grape maturity and increases in alcohol levels, highlighting their understanding of the potential evolution that wine sensory profiles could undertake as a consequence of climate change without the implementation of proper adaptation strategies.

The second objective was to determine if the identity and typicality of wines have already been impacted by climate change. The findings suggest that while climate change has affected the sensory profiles of wines, the extent and nature of the impact vary between the regions. In Languedoc-Roussillon, most wineries reported that the identity and typicality of their wines have largely remained unchanged, although some noted negative effects. One of the French interviewees for instance, stated that "although the overall identity profile of our products is still recognizable, in recent years wines have acquired a more Mediterranean sensory profile, despite the higher altitude and cooler climate of our terroir compared to the rest of the region". Furthermore, another respondent underlined that "Climate Change has led to the loss of the typical green character of some late-ripening varieties, which in the past used to fail to reach full ripeness. Overall, despite the implemented strategies, more mature profiles have been observed".

Conversely, in Tuscany, the identity and typicality of wines have not been impacted in the majority of cases, with some wineries even reporting positive effects. This indicates a clear regional difference in the perception and impact of climate change on wine identity and typicality. Subsequently, we attempted to identify which strategies have been employed or are likely to be adopted by the producers to face this threat in the future. As we have been able to observe, adaptation strategies vary between regions, reflecting their specific conditions and challenges. In the Languedoc-Roussillon wine region, for instance, wineries focus mainly on adjusting harvest dates and varietal selection, indicating a proactive approach to agronomic changes.

In Tuscany, canopy management and maceration techniques are predominant, showcasing an emphasis both on oenological and agronomic adaptation. Both regions are considering adopting future strategies too, that is to say employing resistant and new varieties and rootstocks, careful site selection, and diversifying production. These results not only underscore producers' commitment to preserving the identity and typicality of wine amidst changing climatic conditions but also highlight the severity of the climatic situation, particularly in the south of France, where some firms have even emphasized the need to diversify their production beyond traditional wine categories. Among the alternatives considered are de-alcoholized wines and olive oil.

The results obtained from our research are partially in line with the national-scale study conducted by Battaglini *et al*. (2008), which focused on three different countries, namely Germany, Italy, and France. Even in that study, the producers reported changing climatic conditions. Regarding Italy, one of the most evident impacts observed at that time affected the harvested quantities. However, unlike our study, most respondents (65%) highlighted impacts on wine quality, which were positive in 55% of cases. Additionally, a noteworthy aspect is the mention of the greater incidence of pests and diseases: "Perceived impacts on pests and diseases were

reported in 56% of the responses. Most of this group (80%) also reported increasing threats." In our study, this issue was not among the most frequently mentioned effects.

Finally, concerning adaptation strategies, while the study by Battaglini *et al*. (2008) highlighted a limited inclination among French producers at the time to employ new grapevine varieties to adapt to climate change, our research, based on a different sample of producers, revealed a contrasting trend, with 72% of respondents considering this option. Conversely, only a minority of the Italian sample in our study, as well as in the study by Battaglini *et al*., expressed willingness to address the climate issue by employing new genetic material.

The global and regional-scale study by Neethling *et al*. (2017), on the other hand, highlights different situations depending on the context and scale of reference. Focusing exclusively on the two countries analyzed in our study as well, the scholars observed that, in line with our findings, almost all French and Italian producers (84% and 88%, respectively) reported undergoing climate changes. Regarding the most frequent climatic events, "increasing hailstorms" were most commonly cited in Italy, while in France, "increasing frost events" were also mentioned alongside hailstorms. While "increasing hailstorms" did not emerge as one of the main effects of climate change in our study, "frost events" were cited by 58% of respondents from the Tuscany region.

Lastly, regarding climate change adaptation strategies, the study by Neethling *et al*. (2017) highlights that in both France and Italy, the primary adaptation strategies mainly concern "soil management practices." Both French and Italian producers mentioned these strategies in our study too, although the latter appeared more interested in agronomic strategies for facing climate change. In this context, with both French and Italian producers stating their willingness to relocate their vineyards to higher altitudes or new areas, plant new and resistant varieties and install irrigation systems for their vineyards, we must, however, consider the pivotal role played by wine appellations of origin and the rigidity of their respective product specifications and overall regulatory framework. It is clear, to date, how challenging it is to take regulatory action to find climate change adaptation solutions that are both effective and adaptable to multiple countries, territories and production contexts but, at the same time, it is even more evident how the status quo option will be, in most cases, disadvantageous. At a time when climatic regions are shifting and, with them, wine identity profiles, why should the regulatory-political context not do likewise?

In this regard, the joint promotion of an adaptation system will likely reduce the direct and indirect impacts of climate change on the agricultural sector, namely food availability, income distribution and growth. Additionally, as stated by El-Nasser & Ibrahim (2024), "climate change can cause imbalances between demand and supply sides through increasing prices of food, which influence the demand side by decreasing incomes and the supply side by decreasing productivity."

To address the escalating challenges posed by climate change in the agricultural sector in Mediterranean countries, governments, policymakers, and stakeholders must take urgent and decisive action. Delaying such efforts could result in irreversible damage and catastrophic costs. Accordingly, Mediterranean governments need to prioritize investments in rural development to enhance food availability and foster economic opportunities that bolster food access. Additionally, they should develop and implement national adaptation strategies that are specifically tailored to the unique circumstances of each country and regional context. A robust and inclusive legal framework should be established to facilitate stronger collaboration among stakeholders – both governmental and non-governmental – at national and international levels. This framework should also focus on raising awareness of climate change impacts and devising effective mitigation strategies. Lastly, Mediterranean nations must allocate greater resources toward environmentally sustainable technologies aimed at reducing greenhouse gas emissions, alongside supporting research initiatives and providing continuous training for those involved in facing climate

change (El-Nasser & Ibrahim, 2024). Climate change, as a worldwide challenge, implies a comprehensive and shared strategy capable of bringing nations together to align priorities, pool resources, and drive meaningful action toward a sustainable and resilient global agri-food system.

6. Conclusions

The distinct wine styles and typicity associated with particular regions, as recognized by consumers, are deeply tied to local *terroirs*, accentuating the wine industry's overall susceptibility to climate change. Challenges to viticultural suitability have been noted in various winemaking areas worldwide, and the wine industry has begun to observe shifts at multiple levels. In this regard, our research highlighted the wine industry's urgent need to adapt to the growing challenges arising from the climatic evolution, using data collected through semi-structured interviews with twenty-three wine companies. With a focus on two of the world's most esteemed wine regions, namely Languedoc-Roussillon, in France, and Tuscany, in Italy, we gathered valuable insights into the perceptions and adaptive strategies of winegrowers facing this looming global-scale threat. The diversity and heterogeneity of the responses obtained reflect the regions' unique priorities and challenges and the peculiar climatic, geographical, and socio-economic conditions of each investigated territory.

Furthermore, the investigated regions' will to consider future strategies for the years to come underlines the strong producers' commitment to preserving the identity and typicality of wine amidst changing climatic conditions. This commitment to innovation and sustainability is vital for maintaining these regions' cultural and economic heritage. What should not be overlooked, however, is the necessity and concern expressed by some producers in planting new varieties, that could better suit the changing climate, or diversifying their production to safeguard financial sustainability. If the former decision could inevitably upset the vitivinicultural and cultural heritage mentioned above, as well as wine typicality, the latter could lead to a gradual decline of wine growing in the most affected areas. This critical scenario, highlighted in particular in the southern region of France, stresses, once again, the severity of the climatic situation.

In this context, alongside the winegrowers' autonomous adaptations, there is the need for a firm stance by stakeholders and decision-makers. The strong relation between PDO wines and the specific conditions, geographical boundaries and production practices defined during the application process determines, in fact, the products' vulnerability to any changes in climatic, environmental, or economic conditions. Hence, in order to allow winegrowers to keep producing high-quality wines, far-reaching changes will be extremely necessary. All this will inevitably imply reshaping the geographical boundaries of the current and well-known designations of origin and require tailored strategies at both technical, organisational and institutional levels.

In conclusion, although this research provided important insights by documenting the perspectives and proactive measures implemented by Italian and French winegrowers, several limitations must be acknowledged. Firstly, the diverse pedoclimatic and socio-economic features of the two investigated regions have likely influenced the final results. Secondly, the interviews were conducted at different times for the two areas under study, potentially impacting the answers given by respondents. Lastly, interviewing multiple people holding diverse positions within each firm would have provided a more comprehensive understanding of the corporate vision. Therefore, future research should address these limitations to enhance the robustness of the findings.

The results underscore the importance of "territorializing" adaptation strategies by accounting for the specific characteristics of the sectors under study. This analysis points to two main directions for future research. First, comparative studies could focus on other major wine-growing regions, both within the same countries and at the international level. Second, examining differences between the adaptation strategies of winegrowers and those of other farmers may yield valuable insights. These approaches can potentially inform innovative

approaches, including diversification, the valorization of by-products, and the implementation of territorial policies. Furthermore, this research highlights the need to consider institutional actors in the analysis of producers' adaptation strategies. The role of public authorities and producer organizations is particularly critical in facilitating the dissemination and refinement of adaptation strategies among worldwide wine producers.

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