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CLIMATE CHANGE ADAPTATION STRATEGIES OF WINE COMPANIES IN TUSCANY

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CLIMATE CHANGE ADAPTATION STRATEGIES OF WINE COMPANIES IN TUSCANY

Abstract

Climate change presents critical challenges to the global wine industry, with Tuscany– a region famed for its high-quality wines – facing pronounced risks from rising temperatures and shifting weather patterns, which could even make most of the area unsuitable for viticulture. This thesis examines the adaptation strategies employed by wine companies in Tuscany to address these challenges and ensure the sustainability of their operations. Using a qualitative research approach, the study is based on semi-structured interviews with entrepreneurs, managers, and agronomists from a diverse range of wine enterprises throughout the region.

The findings reveal that Tuscan wine companies, in contrast to the stereotype of a sector reluctant to change, are aware of the problems posed by climate change and are already implementing a variety of adaptation strategies, including changes to vineyard management practices and adjustments to harvesting schedules. Participants highlighted the growing role of innovative technologies, such as precision viticulture tools and advanced climate monitoring systems, for both data collection and sustainable adaptation. These technologies enable producers to optimize water use, monitor soil health, and predict climatic impacts, significantly enhancing their resilience to climate variability. However, producers underscored the pressing need for greater institutional and financial support to address the escalating costs and complexities of climate adaptation. Limited access to funding and insufficient technical guidance were identified as significant barriers to effective implementation, especially for small-size companies, that, differently from the sample interviewed for the thesis, constitute the majority of wine producers in the region.

The research concludes by offering targeted recommendations to reinforce general sustainability and strengthen the adaptive capacity of the Tuscan wine industry through enhanced support mechanisms, technological integration, and proactive climate strategies tailored to the unique challenges of the region.

Keywords: Sustainability, Wine, Climate Change, Adaptation, Business Strategy

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Introduction

The cultivation of grapevine (*Vitis vinifera)* has played a fundamental role in human civilization for thousands of years. Because of its ecological plasticity, grapevine is cultivated in all five inhabited continents, evolving alongside human race (Iatisin et al., 2018). The origins of winemaking can be traced back over 8,000 years in the South Caucasian region, spreading through the Mediterranean Sea and becoming deeply embedded in trade, religion, and culture across Europe. The Romans revolutionized viticulture, standardizing cultivation and fermentation methods, improving storage solutions, and commercializing wine production on an unprecedented scale. Roman viticultural expertise shaped many of today's prominent wine regions, laying the foundation for the industry as we know it (Ashenfelter & Storchmann, 2014). The global wine market has grown into a multi-billion-dollar industry, valued at approximately US$302.02 billion in 2017 (Jamali et al., 2020). Wine production remains highly concentrated in regions with optimal climatic conditions, primarily in mid-latitude zones. However, climate change is now threatening this balance. The industry has often been described as a "barometer" of climate change due to the high sensitivity of grape yields, quality, and wine characteristics to environmental fluctuations (Galbreath & Tisch, 2022). Increasing temperatures, shifting precipitation patterns, and extreme weather events are forcing wine producers worldwide to rethink their cultivation strategies and adopt sustainable adaptation measures.

Italy, one of the world's foremost wine-producing nations, has a viticultural tradition dating back over two millennia. The Etruscans were among the first in the Italian peninsula to cultivate vines systematically, and their knowledge was further developed under Roman rule. During the Middle Ages and Renaissance, monastic orders and noble families played a crucial role in refining winemaking techniques, leading to the development of distinctive regional wine styles. Today, Italian wine is globally recognized for its quality and diversity, with the country frequently ranking among the top wine exporters in the world. Wine production remains a cornerstone of the Italian economy, forming an integral part of the agricultural sector despite its relatively small direct contribution to GDP (Accetturo & Alpino, 2022; Dalla Marta et al., 2010).

However, like many other wine-producing nations, Italy is facing increasing challenges due to climate change. The narrow climatic ranges required for optimal grape cultivation make Italian viticulture highly vulnerable to both short-term weather variability and long-term shifts in temperature and precipitation patterns (Jones & Webb, 2010). Extreme weather events such as heatwaves, droughts, hailstorms, and floods are becoming more frequent, posing risks to both

yield and quality (Fraga, 2020). The impact of these changes is particularly pronounced in regions that rely on traditional, non-irrigated viticulture, which is the case for many of Italy's premium wine appellations. The economic ramifications of climate change on Italian viticulture are significant, with studies estimating that an increase of 0.93°C in temperature by 2050 could result in GDP losses ranging between 0.12% and 0.16%, increasing to as much as 0.2% with a rise of 1.2°C (Carraro & Sgobbi, 2008).

Tuscany is one of the most prestigious wine-producing regions in the world, renowned for its iconic wines such as Chianti, Brunello di Montalcino, and Vino Nobile di Montepulciano. The region's viticultural success has been built on centuries of accumulated knowledge and tradition, optimized for a relatively stable climate. Tuscan vineyards are characterized by their hillside locations, well-draining soils, and reliance on natural weather patterns rather than irrigation. The high quality of Tuscan wines is largely attributed to these environmental and agricultural factors, as well as the meticulous care taken in vineyard management, including manual pruning, thinning, and harvesting (Allen & Lueck, 2019).

However, Tuscany's wine industry is particularly vulnerable to the effects of climate change. Rising temperatures are altering the ripening cycles of grapes, affecting acidity levels, tannin structure, and overall wine profiles. Extreme weather events, such as prolonged droughts and unexpected frost, are threatening both the quantity and quality of production. These challenges are forcing Tuscan winemakers to reconsider traditional cultivation methods and implement adaptive strategies to maintain wine excellence and economic stability (Spano et al., 2020).

The unpredictability of climate patterns has heightened concerns over sustainability within the wine industry. While many Tuscan wineries have begun experimenting with adaptation measures – such as altering harvest timings, adjusting canopy management, and exploring drought-resistant grape varieties – many strategies remain in the planning stage rather than fully implemented (IPCC, 2023). Despite the growing body of research on climate adaptation in agriculture, there remains a gap in understanding how specific agribusinesses, such as wineries, are addressing these challenges (Galbreath, 2015).

Unlike annual crops, where planting decisions can be adjusted each season, grapevines are perennial plants with a productive lifespan exceeding 25 years. This makes adaptation a long-term commitment requiring careful planning and investment (Ashenfelter & Storchmann, 2016). The transition to more climate-resilient practices in Tuscany requires not only changes at the vineyard level but also shifts in supply chain logistics, marketing strategies, and regulatory frameworks. Sustainability in the wine industry extends beyond environmental

concerns to include economic and social dimensions, such as fair labor practices, responsible water usage, and biodiversity conservation.

This thesis explores sustainable strategies for climate change adaptation among wine companies in Tuscany. By analyzing current challenges, business responses, and policy implications, this research aims to contribute to a deeper understanding of how the wine industry can integrate climate resilience into its operations. The findings will highlight key adaptation strategies, assess their feasibility and effectiveness, and provide recommendations for both industry stakeholders and policymakers. Given the significant economic, social, and environmental stakes involved, an effective adaptation framework for Tuscan wineries may serve as a model for other wine-producing regions worldwide. Ultimately, this study seeks to bridge the gap between theoretical research and practical applications, offering actionable insights for a more resilient and sustainable wine industry. In fact, while much of the research has focused on the impact materiality of climate change, the financial materiality aspect has taken on more importance (Flores, 2018; Galbreath et al., 2020).

The research is structured in the following way: the first chapter presents the global wine industry, starting from its historical roots to understand how production evolved to this day, both in an international context and with a focus on the Italian industry. The second chapter analyzes the academic and institutional literature on sustainability, climate change and adaptation to lay the foundation of the on-field research. The third chapter explains the choice of the research area and the methods used for the company interviews and the qualitative analysis of the data. The fourth chapter presents the results of the analysis and the discussion of them to generate a model of climate change adaptation strategies used by Tuscan wine companies.

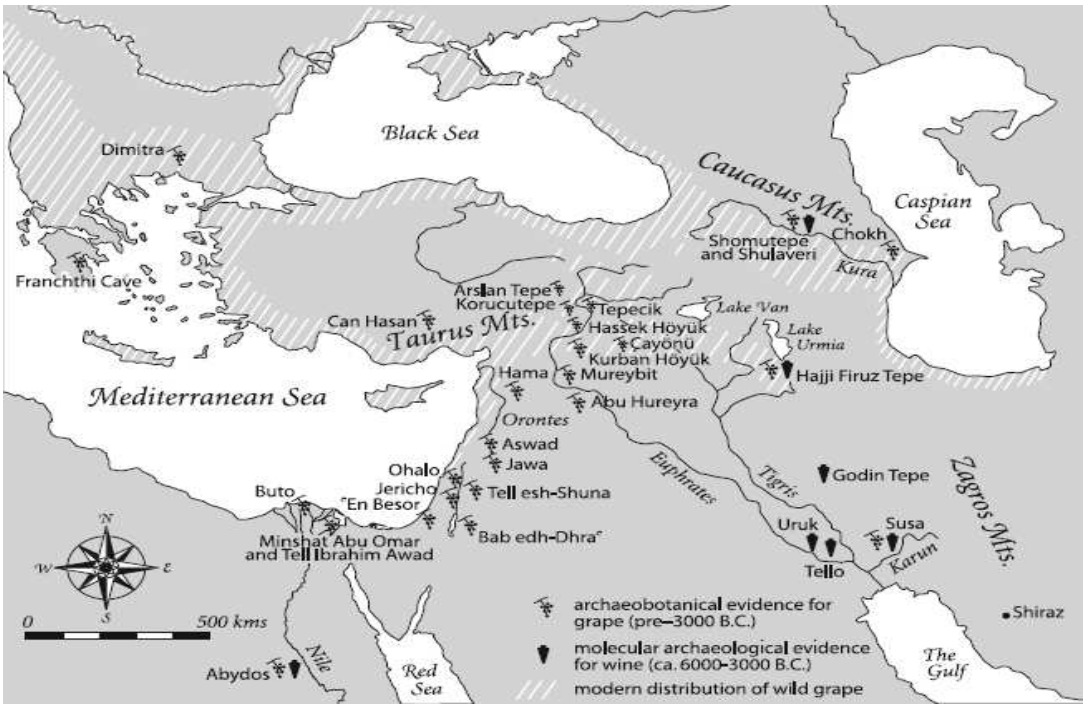
1. Wine Industry: History, Globalization and Italy

The wine industry has deep historical roots, tracing back thousands of years and evolving into a globally significant sector. This chapter aims to analyze the industry from three different perspectives: historical, global and national. In the first section, the analysis will delve into the evolution of the wine industry, outlining its cultural and economic importance throughout civilizations, from its ancient origins to its present-day role as a global economic force. The second section examines the global dynamics of the wine trade, pushed by the forces of globalization that have revolutionized the international markets with the emergence of the New World, and introduces the main trends that are shaping the future wine landscape. Finally, the third section takes a closer look at Italy, one of the world's leading wine producing country, analyzing the unique structural features the Italian wine industry and how they were generated.

1.1 Brief History of Wine

The first encounter between humans and the Eurasian grapevine, in its wild subspecies (*Vitis vinifera sylvestris*), occurred around 60,000 to 100,000 years ago during the Paleolithic period, in the area of modern Lebanon (Li et al., 2018). Given that wild grapes contain all the elements needed for fermentation (the appropriate concentration of sugar, water, acid, and yeast), it is highly probable that the first wine was made unintentionally through accidental fermentation of grapes in a container (Estreicher, 2017). Evidence of the production of fermented juice containing grapes was found in Jiahu, near the Yellow River in China, dating back to 7,000 BCE; but the oldest pure grape wine traces were discovered in pottery jars from 6,000-5,800 BCE in Georgia (P. McGovern et al., 2017). From the South Caucasian area, vine cultivation spread throughout the Middle East, becoming a central production for the Mesopotamian, Egyptian, and Phoenician civilizations (Fig. 1). Emerging trade routes through the Mediterranean Sea allowed wine production to reach Crete; consequently, the Greeks exported viticulture throughout their empire, including southern Italy. Here, winemaking became so central that the area was referred to as *Oenotria*: land of wine (Phillips, 2002).

Figure 1. Map of ancient wine expansion.



Notes: The distribution of modern wild grapevine (Vitis vinifera sylvestris) is shown by hatching; isolated occurrences of wild grape also occur in Turkmenistan, Uzbekistan, and Tajikistan, off the east map. The grape cluster symbol indicates wild and domesticated grape remains recovered from representative sites primarily dating from ca. 8000-3000 BCE. The jar symbol marks wine jar types for the period of ca. 6000 to 3000 BCE, which have been chemically confirmed. *Source:* adapted from P. E. McGovern (2019).

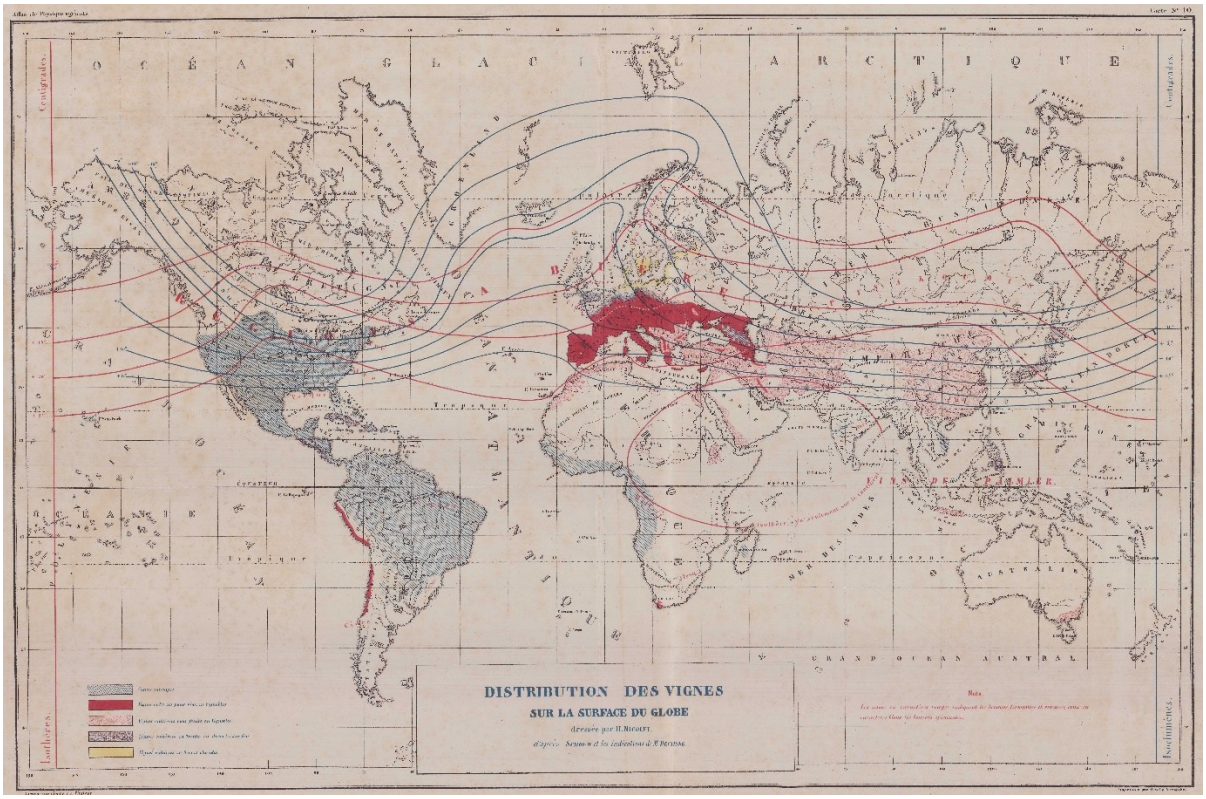
At the same time, the Etruscan population, coming from Asia Minor, had settled in central Italy, bringing viticulture with it (Bordoni, 2017). The Romans, building on their Greek and Etruscan heritage, were able to transform winemaking into a commercial activity that expanded at the same rate as the empire territory, especially in Gaul (Estreicher, 2006). In Greek and Roman societies, wine undergoes a process of democratization, and consumption becomes widespread even in the lower classes (Phillips, 2002).

After the fall of the Roman Empire (476 CE), religious orders were the main contributors of the diffusion of viticulture and wine drinking: monasteries controlled vast lands in all of Europe, and wine, in addition to being central for liturgy and personal consumption, represented the best way of taxing the peasants as a product that could be easily converted in money (Estreicher, 2006; Phillips, 2002). A warmer climate (the so-called 'Little Optimum' period roughly from 900 to 1300 CE) was the other main factor influencing the diffusion of viticulture in the Middle Ages, making cultivation possible in southern England and coastal areas of the Baltic Sea (Jones et al., 2005). Although these areas are now unsuitable for grape growing, the still famous French and Italian wine regions started to be objects of geographical indications during the Renaissance: two documents dated 1398 and 1404 contain the first recorded association of

Chianti and wine (Rosemary, 2005), long before Pepys' mention of the first modern brand name wine in 1663 (Estreicher, 2006).

During the sixteenth century, the wine market continued its growth, with the Dutch becoming protagonists of the global wine trade thanks to the access to colonies and their position between France and England. But the most significant expansion of demand is registered inside Europe itself: on the lower-class side, wine is used as part of the wages of workers in many enterprises, from the Royal Navy to the Venetian Arsenal; on the upper-class side, wine tourism in Italy and France is recorded in the diaries of notable Englishmen. This development is fueled in the following century by innovation in glass bottles and cork stoppers, which made possible the birth of sparkling wines (Phillips, 2002). Viticulture spread in the New World countries (Fig. 2), operated by English and Spanish colonizers, continued in the eighteenth century, until reaching Australia in 1788 (Anderson & Pinilla, 2018a; Estreicher, 2006). Some years earlier, in 1716, the Grand Duke of Tuscany, Cosimo III de' Medici, published a decree for the protection of high-quality wine production areas in Chianti (Pult Quaglia, 2007), a measure considered the very first production regulation and the forerunner of current designations of origin (Bordoni, 2017).

Figure 2. Distribution de vignes sur la surface du globe, from the Atlas du Physique agricole (18-).



Notes: This map shows the spread of vines, with colors differentiating between areas with wild vines (blue), vineyards for wine (red), vineyards for grapes (pink), vines in trellis (purple) and vines in hothouses (yellow). *Source:* retrieved from Smith (2023).

The Napoleonic wars and the French domination of Europe at the start of the nineteenth century imposed a major change in the winemaking landscape: many estates, including vineyards, controlled for centuries by the Church, were confiscated by the imperial government and sold to secular owners. For most of the century, production increased thanks to expansion of land under viticulture and productivity improvements, including optimized winemaking techniques based on the discoveries of scientists like Lavoisier and Pasteur (Phillips, 2002). Then several terrible vine diseases, such as powdery mildew, phylloxera, and downy mildew, arrived in Europe through American trade exchanges and led to the destruction or serious damage of almost all vineyards (Estreicher, 2006). These diseases also reached and affected Italian producers; nevertheless, toward the end of the century, wine weighed 6% of all Italian exports (Ciuffoletti, 2007). Some wine producing regions (Tuscany, Piedmont, Sicily) acquired high international prestige, even if most of the wine produced at the time was for internal consumption and predominantly of poor quality (Vaquero Piñeiro et al., 2022b).

After natural disasters, international wine trade was also affected by the two World Wars, which occurred simultaneously with the rise of anti-alcohol movements, economic depression, and trade protectionism (Estreicher, 2006). Only in France, where wine was considered a patriotic beverage and a medicine, there was a fundamental development on wine and quality regulation. In 1935 the first comprehensive legislation on AOC (*Appellation d'Origine Contrôlée*) was adopted, linking the geographical origin and the intrinsic quality of wine (Phillips, 2002)– almost thirty years later, in 1963, the DOC (*Denominazioni di Origine Controllata*) classification system was born in Italy, followed in the 1970s by the DOCG (*Denominazione di Origine Controllata e Garantita*) certification (Bordoni, 2017). In the aftermath of WWII, wine producing countries experienced decades of prosperity and stability, which, in conjunction with agricultural developments, generated a production and quality increase. The latter was also caused by a change in consumer taste (and wallet capacity) and the birth of modern marketing, which provided many opportunities for product differentiation (Phillips, 2002). From this point of view, the focus of the Old World countries on quality and *terroir*[1] was also a consequence of the competition from the New World countries such as the Unites States and Australia (see next section). More recently, the globalization impulse helped the emergence of new wine producing countries, which are categorized as the New New World (Alonso Ugaglia et al.,

[1] "Vitivinicultural *terroir* is a concept which refers to an area in which collective knowledge of the interactions between the identifiable physical and biological environment and applied vitivinicultural practices develops, providing distinctive characteristics for the products originating from this area. *Terroir* includes specific soil, topography, climate, landscape characteristics and biodiversity features." (OIV, 2010)

2019) (Li et al. (2018) proposed calling this group of producers the Ancient World because China and the Black Sea countries are where wine was first produced in history).

1.2 Global Wine Industry: Structural Evolution and Trends

In 2023, global wine production saw a 10% decrease from the previous year, with a total output of 237 mhl, the lowest since 1961 (OIV, 2024). This negative record is significantly due to the impact of extreme climatic conditions, and in Europe, where the major producers are located, also due to the end of subsidies to wine distillation in 2011 (Del Rey & Loose, 2023). However, low production could bring equilibrium to the world market characterized by declining global consumption (-2.6% from 2022) and high stocks in many regions of the world (OIV, 2023). At the same time, international wine trade is growing in volume and even more in value (OIV, 2024). The ratio of total world wine consumption and traded wine has been consistently growing in recent decades, up to around 46% in 2022; that is, almost every second bottle of wine is consumed in a country other than the one in which it was produced (Del Rey & Loose, 2023). These trends are a consequence of the globalization dynamics that have invested the wine sector in the last fifty years.

1.2.1 Wine Globalization

At the start of the first globalization wave, towards the end of the nineteenth century, global wine production and consumption were concentrated in a very small number of European countries, with the top five accounting for 81% of the world total. Because wine being a perishable product and in the absence of adequate conservation methods, international trade was nearly nonexistent: the share of global wine production that was exported was no higher in 1960 than a century earlier, at around 5% (Anderson & Pinilla, 2018b). It was only in the 1970s that Italy and then France started to export increasing amounts of wine. Spain came much later because of its late entry to the EU in 1986 (Del Rey & Loose, 2023). Thanks to the contribution of the ‘traditional triad’, which countries were also the biggest producers and consumers, in 1990 this share had reached 15%. However, by the year 2000 exported production had reached 25% of global production and more than 30% in 2010, climbing to 40% by 2012 (Anderson & Pinilla, 2018b; Mariani et al., 2012).

The explosion of wine trade has several causes: diffusion of wine consumption in emerging areas (Cusmano et al., 2011); new patterns of investment and ownership combined with governmental policies to push wine production and export in New World countries (Inglis, 2021); integration of global markets (Mariani et al., 2012).

The globalization of wine consumption was characterized by the increase in consumption in Northern Europe and North America (where the traditional large importers (United Kingdom, USA and Germany are located), which has for many years compensated the decline in wine consumption in the traditional producer triad (Del Rey & Loose, 2023). The widespread change on the demand side was also qualitative and quantitative: the advent of supermarkets, where inexperienced consumers can buy inexpensive wine, has substantially modified the role of the consumer in the industry, leading to a second historical democratization of wine consumption (Cusmano et al., 2011). More recently, global consumption is starting to decline even with increasing demand in Asian countries, previously only marginally involved in wine imports (Mariani et al., 2012). Despite this process of diffusion, Europe still represented about half of global consumption in 2011 and 48% in 2023 (OIV, 2024; Regnerová & Hes, 2016).

Before 1970s, the output of New World countries production, started by colonial settlers and based on imported root stock, was typically bulk wine of variable quality, posing no real threat to the European hegemony in the international market (Mariani et al., 2012). Innovation in product and process, spurred by consistent investments and research efforts, has played a prominent role in the emergence of New World producers in the international market (Giuliani et al., 2011). The power shift on the wine market from the Old World to the New World will be analyzed more deeply later; for now, we can visualize it from the comparison of shares in production, exports, and imports. The 'traditional triad' continues to have the biggest share of production, reaching a combined 48.2% in 2023, but New World countries are keeping up with them, especially the USA, whose share was just one percentage point below Spain in 2023 (Fig. 3). In 1995, the same three countries accounted for 80% of total exports in volume, just over 66% in 2017. These exports are largely directed to three major consumer countries: the United States, the United Kingdom, and Germany, which concentrated 80% of imports in volume in 1995, a share declining to 54% in 2017. Looking at these numbers, it is clear that there is a trend of decrease in the degree of concentration of the international wine trade, even though Europe still retains its preeminent position (Alonso Ugaglia et al., 2019).

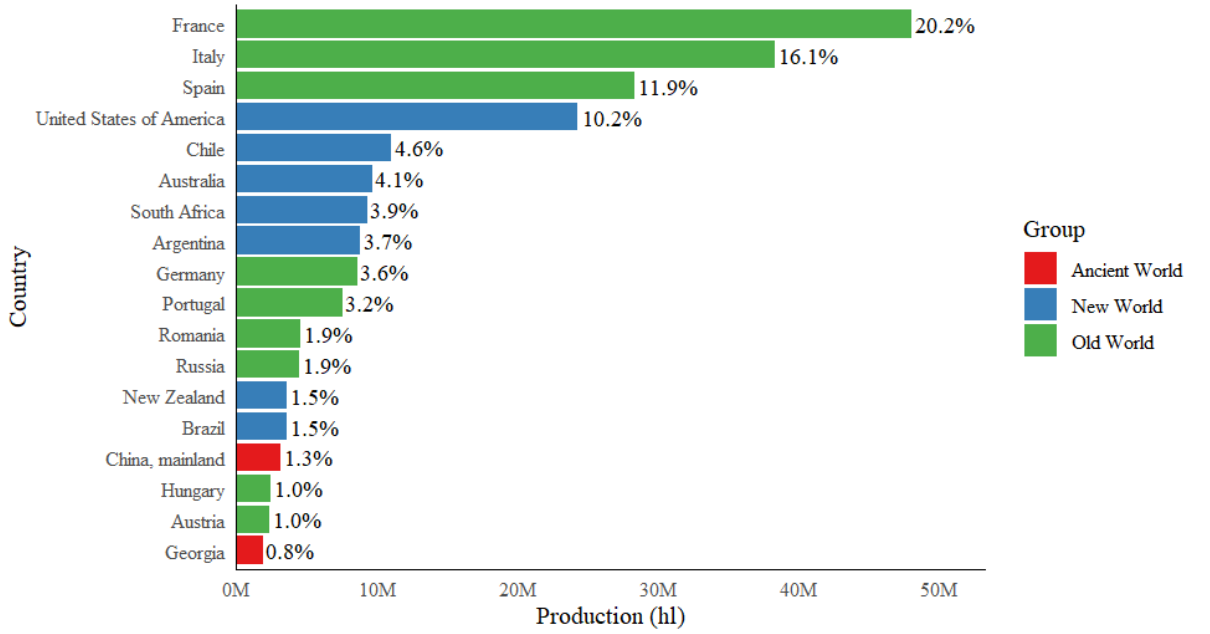
The first move toward market integration after WWII was the development of the intergovernmental organization that has now become the EU. One of the main policy instruments was, from the start, the Common Agricultural Policy, put in place for the first time in 1962 with the creation of Common Market Organization for each agricultural product, including wine[2] (Corsinovi & Gaeta, 2019). Later, in the 1990s the creation of the WTO

[2] From 2007, a single CMO has incorporated all the agricultural products under one regulation (Corsinovi & Gaeta, 2019).

generated broad liberalization: in the wine sector, the TRIPS agreements left a gap in quality protection that penalized the EU's PDO/PGI system – EU tried to react to that with the 2008 CAP, which contained soft wine laws (Corsinovi & Gaeta, 2019; López, 2019). In the wine sector specifically, two international organizations play a major role: the International Organisation of Vine and Wine (OIV) and the World Wine Trade Group (WWTG). The first has a European nature, but achieved a stronger global influence, despite the absence of the USA; its main activity is harmonization through the establishment of standards and the development and approval of new practices. The WWTG, born in the United States, exists to facilitate trade through mutual acceptance and recognition of standards, and to develop international trading agreements. It also provides a strong link to the Asia-Pacific region due to well-developed relationships (López, 2019).

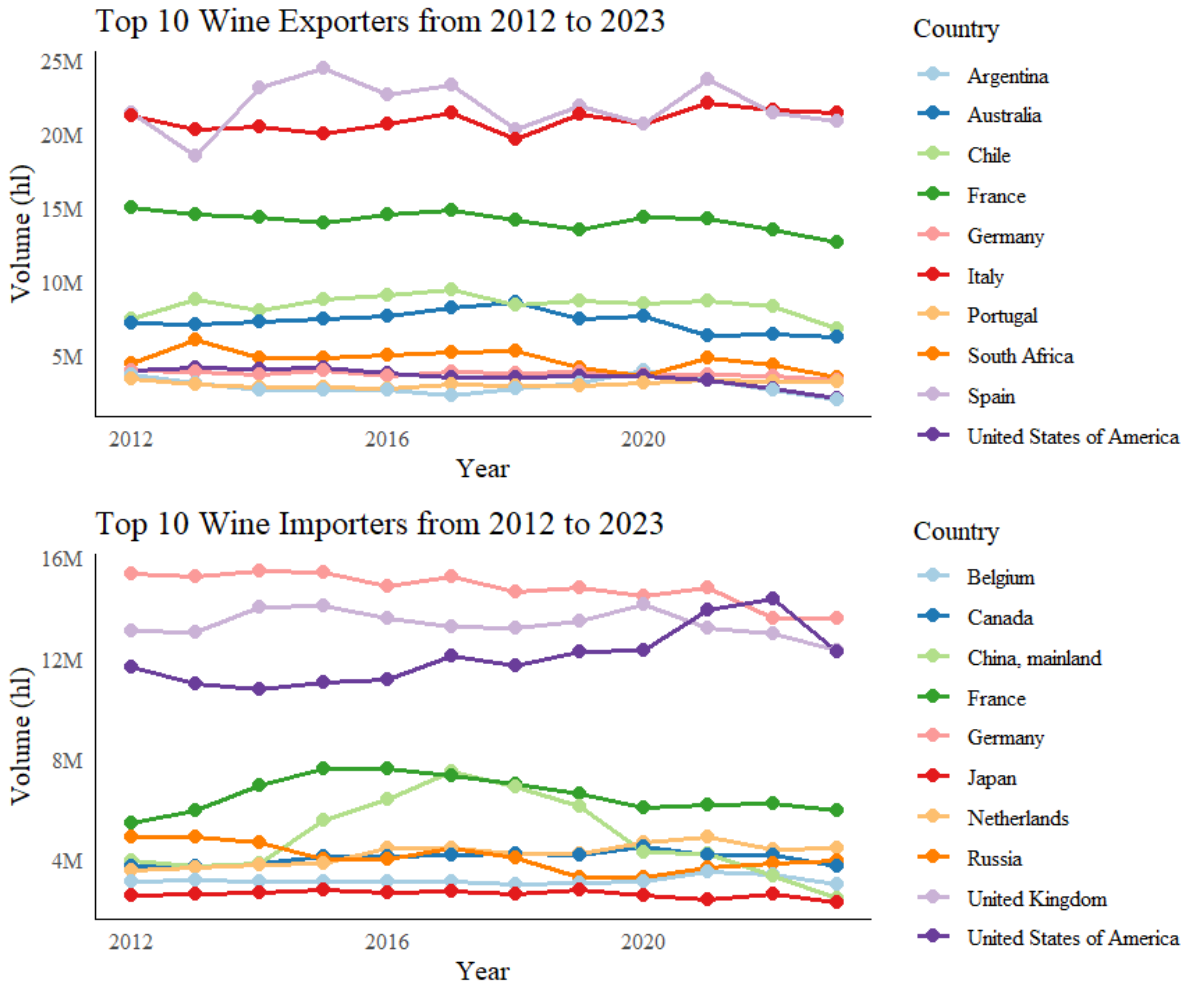
Since 2011, the global wine trade has grown in volume at a very limited compound annual rate of 0.4%. This is a very low rate compared to 4.3% annual growth in the first 11 years of the century. Both exports and imports in the respective top ten countries have seen an almost static trend from 2012 to 2023 (Fig. 4). Although the wine trade in volume terms is constant, it is growing sharply in value terms. Average prices increased from €2.32/l in 2011 to €3.59/l in 2022 at an annual growth rate of 4.1%. world exports increased by €7 billion between 2000 and 2010 and doubled (€14.3 billion) between 2011 and 2022 (Del Rey & Loose, 2023).

Figure 3. Volume of wine produced per country in 2023.



Notes: Countries are grouped into Old World, New World and Ancient World (see paragraph 1.1). Percentage shares of global production are shown for each country.
Source: personal elaboration based on OIV data.

Figure 4. Volume of wine exported and imported by the top ten respective countries from 2012 to 2023.



Source: personal elaboration based on OIV data.

1.2.2 New World versus Old World

These shifts have been analyzed in the literature through the lens of the Old World and New World dichotomy. There are many differences in the wine industry structure and organizational model of the firms between the two groups (Fig.5), which explain the competition dynamics seen in the last decades (Mariani et al., 2012).

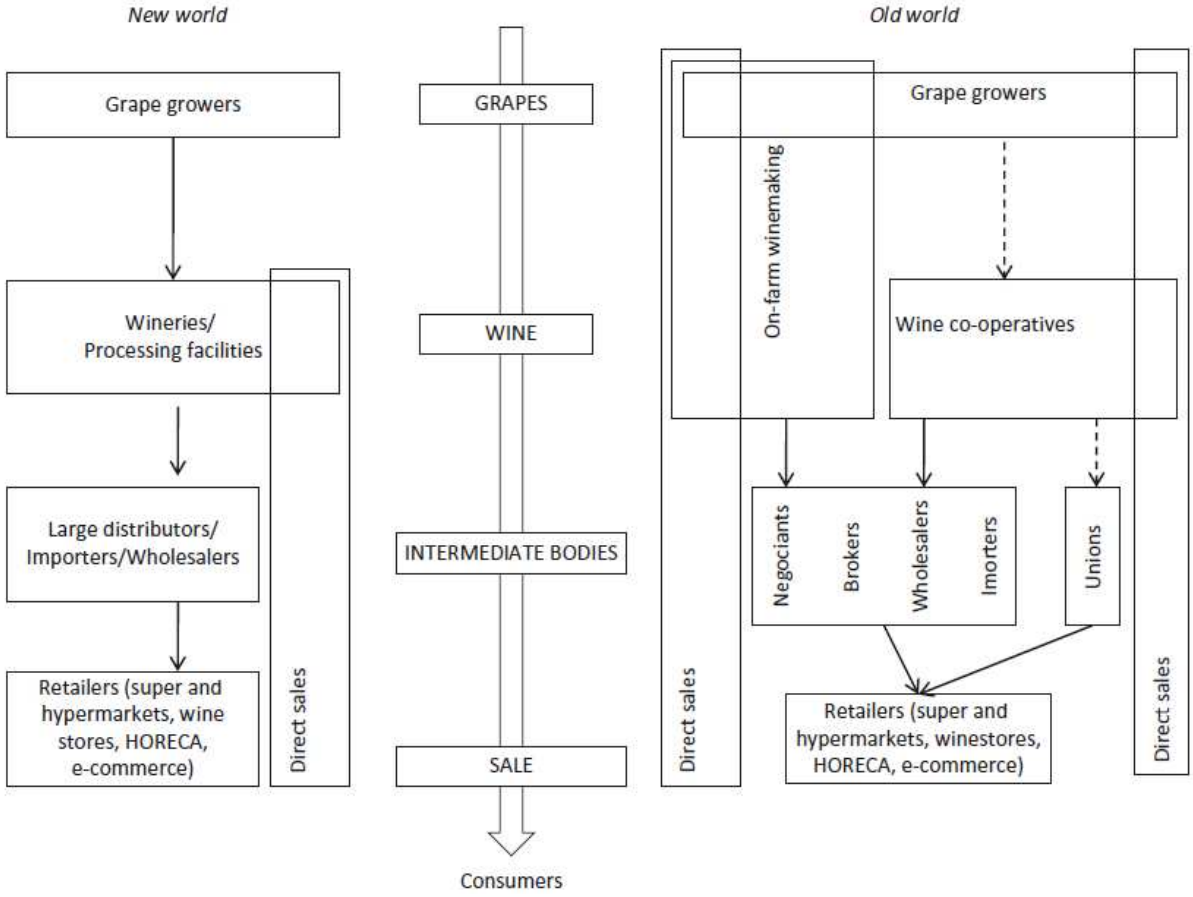
The Old World wines are characterized by long-established and relatively unchanging methods and locations of wine production. Certain varieties have been selected and refined over many years to find the ones that best fit certain regions (Van Leeuwen et al., 2019). Similarly, the methods of growing grapes and making wine have developed slowly and have been perfected by generations of small-scale, locally-based producers (Menna & Walsh, 2019). These farms can also be the ones processing, distributing, and/or selling the wine directly to the consumer (Alonso Ugaglia, 2019). Tight government regulation, based on subsidies to production and protection of domestic markets, created a long multilevel value chain, with service providers in

many of the links lacking either the scale or the expertise to operate efficiently (Corsinovi & Gaeta, 2019; Menna & Walsh, 2019). The Old World relies more on family estates producing grapes and wines with powerful intermediate bodies to sell wine on the market (Alonso Ugaglia, 2019). As a result of the fragmented approach of wine production and classification systems in various regions of the old world, countries were unable to support branding (Corsinovi & Gaeta, 2019). The precise definition for some wine regions does not allow a fast response to changing tastes of customers, which in turn reduces competitiveness on the world market (Regnerová & Hes, 2016).

New World wines are places where varieties are not limited to certain places and winemakers are free to trial modern oenological techniques. Most winemakers process and sell wine, but do not produce grapes, even if some of them now integrate grape growing to control the supply part of production. The large New World winemakers control the entire value chain, extracting margins at every level and retaining bargaining power with increasingly concentrated retailers (Menna & Walsh, 2019). They naturally have become multinational, using not just their production expertise but also their knowledge of market niches globally to deliver to those markets at the lowest cost from anywhere in the world. Therefore, they are well suited to sell in the supermarket retailing system (more on that in the next section), which is why it was New World firms that initially dominated the burgeoning sales of commercial premium wine in Britain, Ireland and other wine importing countries of Northwest Europe during the current globalization wave (Anderson & Pinilla, 2018b). With their market orientation, New World countries are overall better positioned to capitalize on the opportunities created through industry globalization and its driving forces (Menna & Walsh, 2019).

Lately, the process of convergence in the wine market is making the broad juxtaposition between the two categories obsolete. National and transnational mergers, acquisitions, and strategic alliances have intensified, not only to satisfy the requirements of supermarket channels but also for quality concerns, diversification strategies and innovation (Cusmano et al., 2011). Wine merchant companies started the concentration process in the Old World producing countries (Alonso Ugaglia, 2019). The wine policy changed to a policy that aims to stimulate quality production and competitiveness of the wine sector on the international scene. A concrete forward step in international competitiveness was made through quality policies that increased and fortified, with production of PDO and PGI wine, the characteristics of the personality of the EU quality wine on the world market. (Corsinovi & Gaeta, 2019).

Figure 5. Simplified representation of wine supply chain structure for Old and New world countries.



Note: The dashed arrows reflect the potential financial contract to buy fresh grapes between producers and co-operatives or between co-operatives and commercial unions depending of the law status of the co-operative. *Source:* retrieved from Alonso Ugaglia (2019).

However, path dependency differences are not eliminated: consolidation is higher in the New World, fragmentation remains strong in the Old World where atomization of the wine supply is the norm[3], and the fear that increasing globalization of the wine trade would result in homogenization of the world's wines has not materialized. (Alonso Ugaglia, 2019; Anderson & Pinilla, 2018b; Cusmano et al., 2011). Winemakers' income has great variability, related to differences in the size of the farms, the productivity and the costs of the labor force. Winemakers who bottle and sell their wines must also bear the cost of vinification and commercialization. Price also plays an important role in the differentiation of the income levels of wine producers. The appellation regimes dominating the Old World constraint yields to preserve quantity and quality of wines on the market, while yields are not limited in the New World. It means that the production costs are higher in the Old than in the New World, in relation to the quantity produced per ha. (Alonso Ugaglia et al., 2019). The latter's larger firms

[3] In 2017, the four largest firms in terms of domestic sales in Europe were in the 10 to 20 percent range whereas in the New World they were in the 50 to 80 percent range (Anderson & Pinilla, 2018b).

can exploit huge economies of scale in viticulture, oenology, and wine marketing. Focusing on aggressive branding, New World producers have changed established patterns of perception, thus altering the reputation and media recognition of wine regions traditionally associated with low-quality segments and low status in international markets (Cusmano et al., 2011). Wine differentiation is based on explicit declaration of grape variety rather than disguised by deliberate obfuscation through inordinately complex 'place of origin' labeling (Anderson & Pinilla, 2018b). This strategy has forced adaptations in the organization of production and in the marketing strategies of Old World producers emphasizing the concept of *terroir*, thus maintaining a producer-driven approach and increasingly targeting market niches dominated by highly sophisticated consumers, who are attracted by small independent producers and local wine varieties. (Cusmano et al., 2011; Menna & Walsh, 2019).

1.2.3 Main Wine Trends

The consolidation of distribution channels has had a major effect on competition in the wine market, making it increasingly difficult for smaller producers (which characterize the Old World) to get their wines on the shelves. Wholesalers and supermarkets prefer to stock only the top-selling brands, at the expense of small or new labels. As we saw before, supermarkets completely revolutionized the role of the consumer: wine quality, once derived only by the geographical origin of the product, is now based on the perception of the consumer (Cusmano et al., 2011). That is why the three megatrends that drive customer preferences (health, convenience and indulgence/premiumization), provide explanations for the latest demand-side trends in wine consumption, such as increase in the international trade in sparkling wine, which is lighter and refreshing, as well as wine for consumption in bag-in-box (BiB) packaging (recorded as bulk wine[4] in the official statistics (Mariani et al., 2012).

With the convergence between the New World and the Old World, which should also drive to a convergence between WWTG and OIV, new dichotomies are becoming visible (López, 2019). Looking at the wine trade, we see an increase in import values due to higher average prices and a decrease in import volumes, which seem to favor the performance of exporters well placed in both the high-quality and low-cost ends of the market. On the consumer side, a period of increasing polarization between premium and super-premium wines for traditional drinkers and newcomers increasingly looking at wine as a sort of elegant refreshment can be hypothesized (Del Rey & Loose, 2023).

[4] The increasing importance of bulk wine is also partly driven by new organization schemes in the wine supply chain, seeking cost reductions and a higher level of environmental sustainability (Mariani et al., 2012).

After the growth of wine trade within a club limited to a few developed countries, a second phase of emergence has seen the New World countries take over. The leaders of the Old World are competing with the outsiders of the New World, mainly in terms of price competitiveness. A third phase of emergence is at work. It mainly concerns China, whose vineyard is one of the largest in the world (Alonso Ugaglia et al., 2019).

1.3 Wine and Viticulture in Italy

In the previous sections, we have seen some elements of the historical and international importance of Italy in the wine sector. Wine was important for the society and the economy of the Italian peninsula in ancient times; it continues to guarantee relevant incomes to Italian winemakers and state, and it progressively enlarges its positive effects to other economic sectors (Vaquero Piñeiro et al., 2022b). From the low-quality production aimed at local consumption at the end of nineteenth century, Italian wine has become synonym of premium quality (cf. Section 1.1).

1.3.1 Italian Wine Sector Evolution

The great transformation of the Italian wine sector occurred in the post-WWII period. Thanks to market and production trends and strong national and European policies, the sector changed radically: from unspecialized to specialized winegrowing; from domestic-oriented to largely export-oriented production; from an almost undifferentiated low value production to a production characterized by quality at different levels; from a large, low level domestic consumption to much lower but articulated consumption (Corsi et al., 2018; Pomarici et al., 2021). This process started with a radical decrease of nonspecialized intercropped vineyards (-75% between 1950 and 1960), while the specialized grape area rose by 20%. As a result, yields increased (+130% between 1950 and 1980), while the number of farms growing grapes decreased dramatically (Pomarici et al., 2021). Wine production in volume rose by 33% from the 1950s to 1980s: wine was increasingly produced in rationally organized wineries, in which cooperatives began to play an important role (more in the next section). There were 148 cooperatives in 1950, producing 3% of total production, a share that had increased to 18% by 1970, produced by 690 cooperatives (Corsi et al., 2018). Born as an expedient by which the state intervened in the wine sector, cooperatives helped to solve historical problems of Italian agriculture, such as fragmentation and poor coordination of farms, but also acted as a transmission belt between political power and the interests that revolved around wine (Vaquero Piñeiro et al., 2022a). Between 1985 and 2000, the trend reversed: production decreased by 23%, mainly due to the fall in vine area following some changes to European policy which

strengthened the prohibition on new plantings (Pomarici et al., 2021; Vaquero Piñeiro et al., 2022a). The number of grape growers halved, but several grape growers started processing and bottling their wine, particularly in the premium wine segment. The cooperative sector was consolidated through mergers and acquisitions, and by producing both premium and basic wines. Wine exports, which have already become a strength of the Italian industry, are now being driven by the improving quality of Italian wines, as shown by the increasing share of appellation and geographical indication wines and by the dynamics of the international market (cf. Section 1.2.1). Even in a period characterized by the rapid emergence of New World producers, Italy's share of global exports remained constant in both volume and value terms (respectively, from 32.1% in 1985 to 30.2% in 2000, and from 18.7% to 18.6% in the same years) (Pomarici et al., 2021). In the period 2000-2011, its market share in value increased by 2% and the loss of market share in volume was limited to 3.6%. These changes are explained by the dynamics of vineyard surface area: in the second half of the 2000s grape growing area saw a reduction of 7% as the effect of the increase of vineyards for the production of PDO wines (+40%) and the decrease of vineyards for other wines (-31%). This is also why Italy has gained market share in both value and volume for bottled and sparkling wines but has suffered a significant loss of market share for bulk wine (Mariani et al., 2012). Although the negative trend in production continued, exports continued to grow in volume (+11.3% from 2000 to 2018) and especially in value (+ 187% in the same period), demonstrating the strong positioning of Italian exports among wines of higher quality and higher price (Pomarici et al., 2021; Vaquero Piñeiro et al., 2022a). Compared to other major producers such as Spain, Italy showed a more stable value increase with weaker sensitivity to economic crises (Del Rey & Loose, 2023). In geographical terms, positive results, in both value and volume, were achieved with almost all categories of importing countries (large importers, small traditional importers and Eastern Europe) (Mariani et al., 2012; Vaquero Piñeiro et al., 2022a). The Italian strategy is probably the most balanced between high-volume production with a good added value, as attested, for example, by the international success of Prosecco, and the more exclusive productions from Tuscany and Piedmont (Alonso Ugaglia, 2019).

This decades-long transformation has made Italy a leader in the wine market, carefully responding to the qualitative and quantitative evolution of wine consumption and distribution. Its remarkable available production capacity allows the Italian wine sector to cover all price segments (Pomarici et al., 2021) Even in a year of historically low production, due to heavy rainfall fostering downy mildew, floods and hails, Italy has produced 16% of global wine production, equivalent to 38.3 mhl, ranking as the second wine producing country globally

(OIV, 2024). In terms of quality, DOC/DOCG production is 20.3 mhl in 2023, accounting for 52,3 % of total (inumeridelvino.it, 2024). Italy also has the fourth largest vineyard surface area, which has been growing since 2016. While domestic consumption volume is 5.8% below the 5-year average, attested at 21.8 mhl, Italy is the largest wine exporter in volume (21.4 mhl), exporting 56% of its production, and second after France in value with €7.74 billion (OIV, 2024). Of this volume, 74% is made of DOC/DOCG wines that, instead, contribute to 89% of export value. As a confirmation of the importance of wine in the Italian economy, wine exports represent 12,1% of total agricultural exports (Sarnari, 2024).

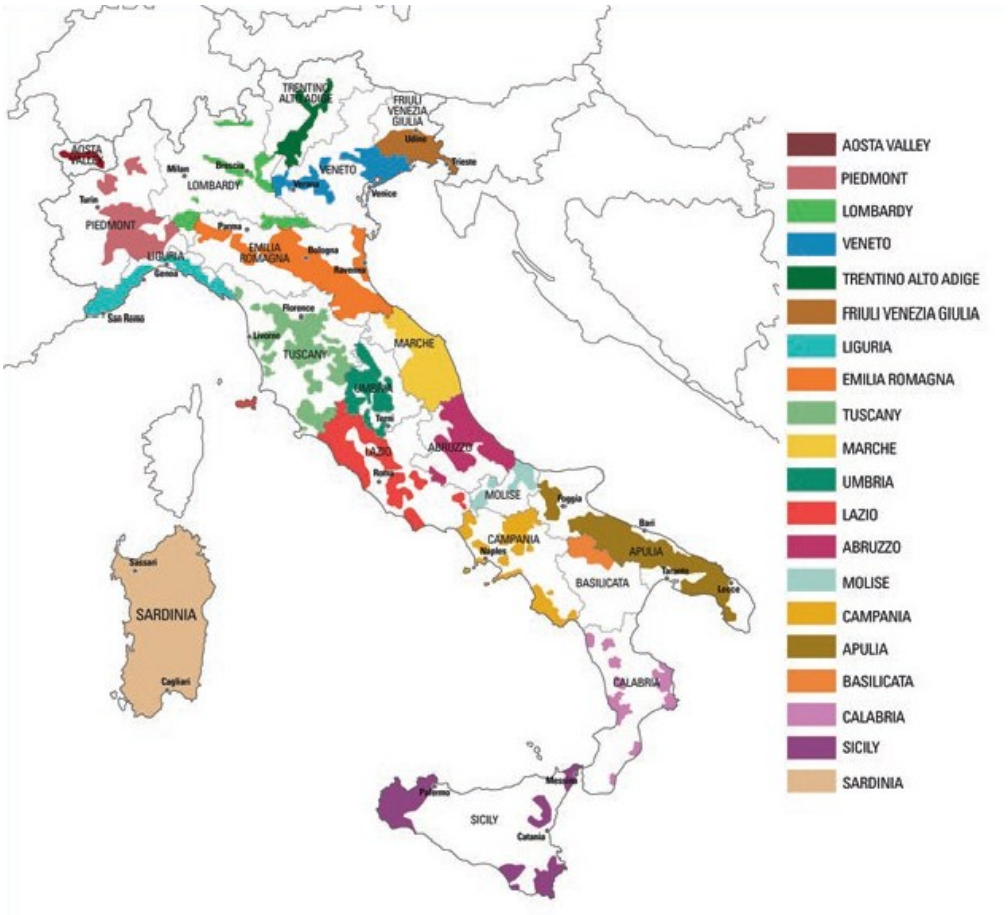
The Italian wine sector enjoys fair profitability, comparable to the overall manufacturing sector. On average, almost all large companies are experiencing positive results, while the variability of the performance of smaller agricultural companies is influenced by geographical location and yearly harvest size. However, grape and wine production is constantly one of the most profitable agricultural activities due to the substantial balance between supply and demand in the intermediate markets (Pomarici et al., 2021). In 2023, the sector obtained revenues of €13.84 billion (10% of total agricultural revenues) and counted 240,699 wine farms, 30,000 wine-making companies and 1,833 industrial companies, employing 21,562 people (Sarnari, 2024). According to Area Studi Mediobanca (2023), it is possible to identify three main trends of Italian wine companies: premiumization, visible from the value of the PDO wine reaching €11.3 billion (56% of the total value of Italian PDO production) (Sarnari, 2024); sustainability, approximated by the growth in the production of biologic and vegan wines (we will analyze this topic more deeply in later sections); wine tourism, embraced in some form of related activity (farm and cellar visits, hospitality, food service), by 82.5% of Italian wine companies and with growing interest shown by consumers (Pomarici et al., 2021).

1.3.2 Unique Features of the Italian Wine Industry

The first peculiarity has been known for centuries: the catalog about the Kingdom of Italy drafted for the Paris exhibition of 1862 put in evidence the presence of vineyards in every part of the Italian peninsula, from the Alpine valleys to the plains up to the heart of the Mediterranean on the island of Pantelleria (Fig.6). This obviously implied (and continues to imply) a great variety of grapes and forms of cultivation depending on the heterogeneity of the location of the vineyards (Federico & Martinelli, 2018; Vaquero Piñeiro et al., 2022b). The enormous diversification of Italian wine supply based on the specific features of the local area, varieties, physical and climatic or cultural characteristics, is the reason for the focus on terroir, which encompasses all these elements (Pomarici et al., 2021). In a context of diversified

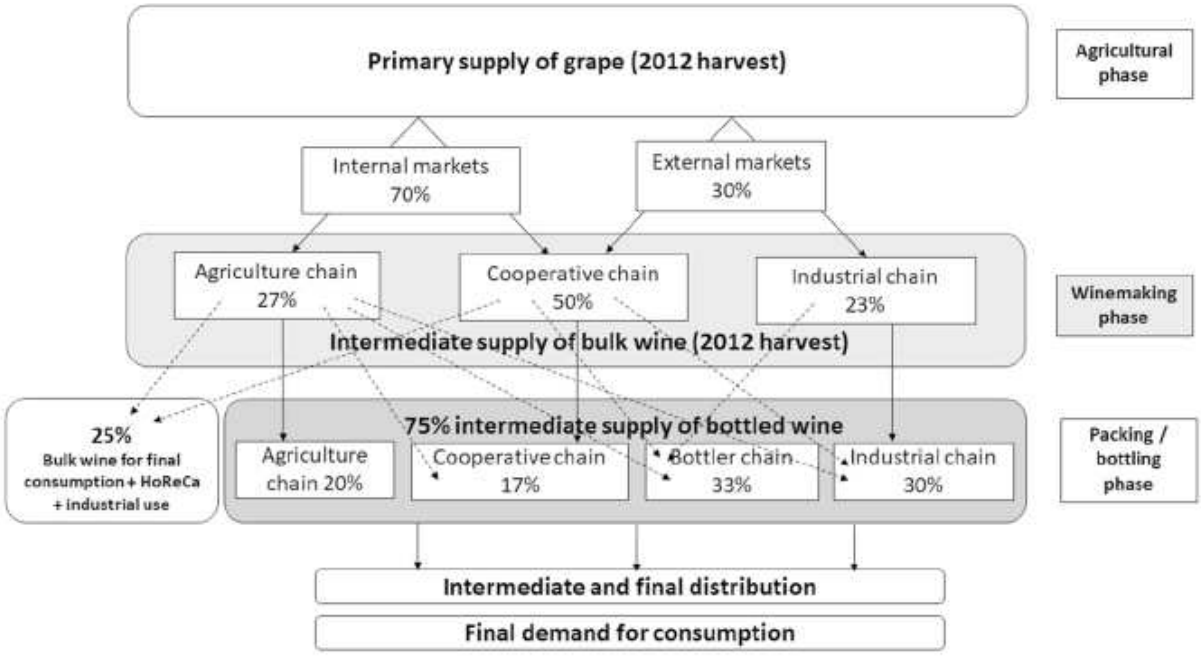
demand, with increasing sophistication and curiosity from consumers, the diversity of Italian wines, fueled by the rich variety of vines and the endowments of wine culture and specialization of traditional regions, now appears to be an 'Old World style' strategic asset (Cusmano et al., 2011). Logically, the differences are great depending on the area. A large proportion of wine-growing farms are located in the South (36%), while the North-East (21%), the Center (19%), the Islands (15%), and the North-West (9%) are less populated. However, in terms of vine-bearing area, the share of the South is much smaller (25%), and the share of the North-East (27%) and of the Islands (20%) is much larger. The differences are more striking in terms of quality, since the South only accounts for 19% of farms producing only PDO wines, while the North-East has the largest share of such farms (41%) (Corsi et al., 2019).

Figure 6. Map of Italian winegrowing areas in 2021.



Source: retrieved from Vaquero Piñeiro et al. (2022b).

Figure 7. Value chain structure of the Italian wine industry (volume shares).



Source: retrieved from Pomarici et al. (2021).

A second relevant aspect of the Italian wine industry is its peculiar structure (Fig.7), based on a complex network characterized by a radical concentration of flows (Corsi et al., 2019). The grapes originate in a huge number of farms but are crushed by a much smaller number of winemaking technical units, and bottled wine is delivered to the market by a small number of bottling wineries or pure bottlers (see previous section for the on the number of companies). These farms are largely made up of small- and medium-sized enterprises that are deeply rooted in their territory and have a long-standing family origin (Broccardo & Zicari, 2020; Cusmano et al., 2011). The presence of such a large number of grape growers is a distinctive feature of the wine supply chain in Italy compared to other countries, particularly New World producers. The dispersion of overall production is high among small farms, while the few larger farms and companies (with capacity > 10,000 hl, nearly 1000 companies) concentrate around 80% of Italian wines. This segment includes few large limited companies, mainly under family control, industrial operators and cooperative wineries which, despite their limited number (518 in 2019), play a very important role, as they produce about half of Italian wines. Therefore, the Italian wine industry is polarized between many very small units that represent a small share of production, and the few large companies that cover most of it (Pomarici et al., 2021). In fact, the first four companies cover 14% of the total market (Sarnari, 2024). While consolidation is not as widespread as in other wine producing countries, this picture is beginning to change. Cantine Riunite & CIV, a cooperative, is in 2022 still the biggest wine company for revenues,

but the podium is now completed by Argea, a limited company born in 2022 from a private equity acquisition, and Italian Wine Brands, the first Italian wine company listed on a stock exchange[5], very different from the traditional familiar private companies (Area Studi Mediobanca, 2023). The role of cooperatives is crucial to understand the intermediate grape market and procurement arrangements in Italian winemaking. About half of total Italian grape production is crushed by cooperatives that are a large part of the most important wine firms operating on the final market (Pomarici et al., 2021). The intermediate grape market consists of two channels: 'external' market (with respect to the agricultural phase), represented by grape sales from grape growers to winemaking industries or cooperative wineries of which they are not members; 'internal' market, represented by self-processed grapes within the producing farms and by deliveries to cooperative wineries by their members. In the former case, grape sales take place according to prices defined by private supply contracts or interprofessional agreements or by spot sales on the grape market (Pomarici et al., 2021). The spot market involves a minor share of total grapes; however, the share of the spot market is larger for grapes for generic wines or for some large-volume PDO/PGI wines. In some cases, collective agreements are signed between wine grower associations and industrial winemakers, setting prices and other conditions (Corsi et al., 2019). Through the other channel, a return is achieved in terms of a processing price, strongly linked to the wine price and to the efficiency of the winemaking operator (Pomarici et al., 2021). Since Italian law imposes strong constraints on the destination of profits of cooperatives, in practice profits are distributed to members as higher prices for the grapes that they deliver. Members (generally bound to provide their total production to the cooperative), therefore, receive a first price as an advance. When cooperative accounts are closed, profits are distributed as an additional price. Therefore, the real price that the cooperative members receive depends on the general wine market and the efficiency of the cooperative rather than the grape market. The same is true for grape growers that are also on-farm winemakers (Corsi et al., 2019). Geographically, the highest incidence of the internal market is reached in Central Italy (80% of processed grapes) due to the weight of the farmers' enterprises in winemaking and in the North-East (almost 74%), due to the considerable weight of cooperation. The incidence of external markets is substantially higher in the North–West (around 39%) and in the South (approximately 41%) due to the prevalent presence in both areas of industrial winemakers, linked to the type of wine produced locally and the different types of grape. The incidence of agriculture in winemaking increases in relation to PGI and PDO wines.

[5] Informations about Argea and Italian Wine Brands have been retrieved from their respective websites (Argea, n.d.; Italian Wine Brands, n.d.).

Overall, the Italian wine sector is largely organized on localized production systems characterized by a very high endowment of local social capital, which allows individual producers to interact between them and with the local context and, in particular, with the knowledge and production experience established therein (Pomarici et al., 2021).

Finally, the third characteristic of the Italian wine sector is the importance of public-private partnerships in the history of its success. The basic drivers of the success of Italian wine in the world were the increasing competition and the continuous renewal of the productive and retailing systems: these elements strongly depended (and continue to depend) on the integration of the public and private projects and on the related availability of financing for investments in innovation. Besides the establishment, at the European level, of the CAP, national laws and public investments strongly supported winemakers, regulated the competition in the wine sector, and favored the diffusion of the oenological education (Vaquero Piñeiro et al., 2022b). After a massive frost in 1956, a disruptive vine renewal program was implemented. In many terroirs, this replacement improved the development of grape varieties and encouraged the end of promiscuous cultivation with a general improvement in grape quality and an increase in yields. In addition, viticulturists received investment subsidies, and more attention was paid to entrepreneurial and technical education for winemakers (Vaquero Piñeiro et al., 2022a). The structural change was also supported through the European (1962) and national (1963) legislation on appellations that propelled the upgrading of Italian wine quality (Pomarici et al., 2021). From 2008, the EU law for quality wine consists of two types of classification: (1) Protected Denomination of Origin (PDO) regarding quality wines produced in a specified region and (2) Protected Geographical Indication (PGI) regarding quality wines with geographical indication. PDO and PGI refer to the geographical names and qualifiers corresponding to the regions of production, used to designate the wines referred to in the regulations, whose characteristics depend on the natural conditions, correlated to their viticulture characteristics (Corsinovi & Gaeta, 2019). The new laws allowed each member state to keep its historical denominations, so in Italy PDO wines are still divided in DOC and DOCG, while PGI are called IGT. Up until March 2024, Italy is home to 515 wines with designation of origin, divided in 77 DOCG, 330 DOC and 118 IGT (Federdoc, 2024).

Despite Italy being a 'traditional' producer, since the 1960s remarkable innovation processes have been developed in the wine sector, sustained by close cooperation between producers, research institutions and input supply companies. As a result, more than 70% of wine technologies in wineries around the world are Italian. The combination of a system of public support, stemming from the European Union, and the innovative application of this policy in

Italy appears to be a key driver of the modernization of the different phases of the wine supply chain that contributes to the positioning of Italy as a major global producer, favoring the reputation and recognition of national production all over the world (Pomarici et al., 2021).

2. Sustainability and Adaptation in the Wine Industry

The wine industry influences the physical environment within which it operates and at the same time its future viability is inextricably linked to environmental impacts and conditions (Christ & Burritt, 2013). This principle is referred to as the 'double materiality' perspective, in which the risks to and the impacts of the undertaking each represent one materiality perspective: since 2024, European companies have to disclose information from both perspectives in their reporting (Directive 2022/2464/EU).

While climate change is inevitably concentrating the focus on the natural environment, it is now agreed to interpret sustainability not only as an environmental concern, but also as a social and economic one: rather than limiting the approach merely to an environmental dimension, proper consideration of the ecological, economic, and social dimensions of sustainability can lead to a change in the unsustainable modes of production and consumption, thus contributing to protecting and managing natural resources and enhancing a bioeconomic and circular approach to development (Sardone et al., 2023).

In this chapter, we are going to understand this general approach to sustainability, then deepening the analysis of climate change adaptation frameworks to finally understand how climate change can impact wine production and how winemakers can contrast it.

2.1 Overview on Sustainability

2.1.1 Sustainability Definition and Policy

Sustainability is a wide-ranging concept that has been the subject of increasing interest over the last four decades, a period in which definitions of sustainability proliferated. In terms of agriculture, the United Nations Food and Agriculture Organization (FAO) has adopted, since 1989, a concept of 'sustainable agriculture and rural development' based on environmental conservation, economic viability, and social acceptance, aligned with the three pillars of the Brundtland Report[6] (FAO, 1997). In the wine sector, the formal recognition of the topic of sustainability, as reported by Mastroberardino et al. (2020), began in 2004, when OIV gave the first definition of sustainable development applied to vitiviniculture: "a global strategy on the scale of the grape production and processing systems, incorporating at the same time the economic sustainability of structures and territories, producing quality products, considering

[6] This document is the foundation of sustainability efforts at international level and contains the first and most famous general definition of sustainable development: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (World Commission on Environment and Development, 1987, p.37).

requirements of precision in sustainable viticulture, risks to the environment, products safety and consumer health and valuing of heritage, historical, cultural, ecological and aesthetic aspects".

From these first definitions, the concept of sustainability has been introduced into the vocabulary of policy makers. At the EU level, sustainability is one of the main policy objectives, particularly in the CAP. In recent years, starting with the 2013 CAP reform for the 2014-2020 programming period, sustainability objectives have been formally recognized with the identification of three main goals defined as guidelines for European action in agriculture: viable food production, sustainable management of natural resources, and climate action, and, last, balanced territorial development. The proposals launched in 2018 identify an increasingly developed set of goals for CAP interventions resulting in the identification of nine specific objectives, with a clear major importance assigned to the needs related to environmental protection and climate change mitigation. The centrality assigned to these topics found continuity in the European Green Deal at the end of 2019, with the declared objective of pursuing a higher level of climate and environmental ambition (Pomarici & Sardone, 2020). Two years later, the Regulation 2021/2115/EU, which provides rules for Member States' CAP Strategic Plans to be implemented in the 2021-2027 programming period, lays out as general objectives: "(a) to foster a smart, competitive, resilient and diversified agricultural sector ensuring long-term food security (economic dimension); (b) to support and strengthen environmental protection, including biodiversity, and climate action and to contribute to achieving the environmental and climate-related objectives of the Union, including its commitments under the Paris Agreement (environmental dimension); (c) to strengthen the socioeconomic fabric of rural areas (social dimension)". Sustainability objectives are pursued from a financial perspective through basic and complementary income support payments, which have less stringent requirements; the European Commission also encourages the creation of specific eco-schemes which are aimed at supporting farms active in environmental and climate actions, including, among others, climate change adaptation. Although wine is not included in the sectors eligible for coupled income support[7], the wine sector has a dedicated section in the regulation: the first objectives posed regard sustainability and climate change actions, and the regulation also indicates the types of intervention suggested to member states; some of them overlap with the main adaptation actions recommended by the scientific literature

[7] Payment of income support, under the CAP provisions, is defined coupled if it is linked exclusively to the production of specific agricultural products. This type of support has been progressively removed, to avoid overproduction and risks of market distortions (European Commission, n.d.).

or already implemented by wine companies (see Section 2.4). The calculation of direct payments for areas under vines considers that vineyards, being permanent crops, are automatically allowed to receive the additional payments for agricultural practices beneficial to the climate and environment (green payment). (Pomarici & Sardone, 2020). The justification for support is tied to objectives of public interest, in particular environmental ones. Farmers are recognized for producing positive externalities, the so-called 'ecosystem services', which must be adequately remunerated, as they are essential for the entire community. Furthermore, the transition toward sustainable production techniques, which are recognized as having social value due to their lower environmental impact, entails costs and investments that cannot be entirely borne by small farmers (who constitute the majority of the Italian wine sector, cf. Section 1.3), whose economic resources are generally limited (IRPET, 2023a). At the national level, within the Italian plan for implementing the CAP (Ministero delle Politiche Agricole Alimentari e Forestali, 2023), a specific section is dedicated to the wine sector. The outlined interventions focus mainly on agricultural profitability and sector competitiveness (economic dimension of sustainability), while environmental sustainability is addressed in terms of biodiversity conservation and, with reference to climate change, reduction of emissions through mitigation measures.

2.1.2 Sustainability in the Wine Sector

The concern of consumers about environmental and social issues of products and organizations is pushing companies to recognize their moral and legal obligations toward society (Pizzol et al., 2021). So, more and more firms are integrating sustainability, which is becoming a key source of innovation and profitability, into their business activities (Broccardo & Zicari, 2020). In the wine sector, since the first definition of sustainability from OIV (see previous section), the concept has become widespread among consumers (Mastroberardino et al., 2020): customers are sensitive to the concept of sustainable winemaking, and there is a trend for wines that have been produced using sustainable practices in customer choices (Flores, 2018). This shift was confirmed by the 2019 Global S.O.L.A. (Sustainable, Organic, Lower-Alcohol, Alternative Wines) report, which found a growing sense of responsibility by consumers (Moggi et al., 2020), and the 2020 ProWein report, stating that wine trade companies expected a positive increase in consumer demand for environmentally friendly wine (Loose & Nelgen, 2020). Besides, the customer tends to conclude that wine quality is improved by sustainable practices, with label information associated with sustainability becoming determinant drivers of purchasing choices, even if customers do not have a clear idea of what it means in practice

(Dans et al., 2023; Flores, 2018). In addition, the results indicate a willingness to pay higher prices for the products identified with sustainability (Flores, 2018).

The growing interest from consumers for sustainable products and the pressures from governments and environmental groups are among the institutional drivers to sustainability (Pizzol et al., 2021). Producers can identify concrete advantages in adopting sustainable practices, mainly in the environmental dimension, resulting in quality improvements, awarded by higher consumer WTP, and economic efficiency, which generates an important return on sustainability investments (Flores, 2018); in this case, wine companies use sustainability as a product differentiation lever rather than an ethical choice (Corbo et al., 2014). However, many empirical studies have shown internal motivation as the main driver to adopt sustainability practices (Flores, 2018): given that the sector is mainly made up of small-medium companies, the personal values of managers, the personal motivations of entrepreneurs, and the environmental attitudes of employees are crucial in the implementation of sustainable strategies (Corbo et al., 2014). Entrepreneurs' awareness about their role in society and the impacts of their activities on the territory, intended as a combination of environmental, social and cultural resources, is increasing in all industries, as confirmed by the rise of Corporate Social Responsibility (CSR) functions in various organizations (Pizzol et al., 2021). The specificity of the wine sector derives from a sort of instinct for preserving the environment, caused by the concern of winemakers in maintaining the productivity of the land for the present business and for the future generations of producers (Corbo et al., 2014).

Due to these changes from both producers and consumers, sustainable production has become a relevant issue for the global wine industry (Schäufele & Hamm, 2017). In Italy, the movement for sustainability in the wine sector has emerged later with respect to other countries; nevertheless, Italy now has a primary role in Europe for what concerns sustainable viticulture (Merli et al., 2018): the amount of academic literature dedicated to sustainability in the Italian wine sector is increasing, sustainability is a dominant element for international wine conferences held in Italy, and a wide range of sustainability programs launched in recent years by private producers and consortiums (Corbo et al., 2014). Merli et al. (2018) report the existence of at least 15 sustainability programs, with an emphasis on environmental sustainability indicators, greenhouse gas emissions, and the use of Life Cycle Assessment (LCA) methodology. This wave of sustainability, while signaling concern about this issue in viticulture, can have negative consequences: farmers and producers cannot easily compare the benefits and costs of so many different sustainability programs; at the same time, consumers

are affected by the lack of clarity and/or understanding of sustainable wine certifications[8], which often miss an adequate explanation (Corbo et al., 2014).

2.1.3 Sustainable Practices and Programs

The literature reports several sustainability practices in all three dimensions; for the scope of this research and for agricultural activities such as viticulture, the environmental dimension has a major role. Some aspects of environmental sustainability are common for all agricultural products: soil management, water management, wastewater, biodiversity, solid waste management, energy use, air quality, agrochemical use, workers and community protection (Corbo et al., 2014). Mariani and Vastola, following the OIV guidelines, add some specific viticultural practices, in particular site selection and variety selection. Other practices, mainly carbon accounting and transportation efficiency, focus on climate change mitigation, while promoting awareness and research through education and partnerships is considered a strategic supporting action to improve overall sector sustainability (Corbo et al., 2014; Mariani & Vastola, 2015).

Among non-conventional production practices, using methods and materials that minimize the negative environmental impact of agricultural production, the two main standards are organic and biodynamic (Mariani & Vastola, 2015). A wine can be defined as 'Organic' when it is produced according to the Regulation 203/2012/EU, that is: (in the vineyard) produced from 'organic' grapes; (in the cellar) produced using only products and processes authorized by the above Regulation (Corbo et al., 2014). In general, organic vineyards are managed without the use of synthetic-type fertilizers and plant protection substances, and the use of genetically modified organisms is prohibited. Instead, biodynamic agriculture is founded on anthroposophic principles[9] and a complex system of herbal sprays and composting techniques, known as 'preparations', is used (Mariani & Vastola, 2015). Scholars and policy makers agree on considering sustainability applied to viticulture and winemaking as something different from organic or biodynamic production, given the broader and more holistic value placed on the former (Pomarici & Sardone, 2020). In fact, both the FAO and OIV concepts of sustainability do not treat organic or biodynamic production as a synonym of sustainability (Flores, 2018).

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[8] Since consumers cannot verify the production method of the purchased product even after consumption, sustainability cues are credence attributes. The expectations generated by sustainability certifications have an effect on consumers' perceived quality and sensory experiences, becoming new attributes for wine purchase decisions and WTP (Schäufele & Hamm, 2017).

[9] Biodynamic is more a belief than a cultivation technique: the biodynamic grower applies the anthroposophy theory, which states that the human being is in the middle between the earth and cosmos rhythms, bridging a gap between spiritual and material world. Still, the use of the biodynamic method generally addresses to a better environmental sustainability of the agricultural activity (Castellini et al., 2017).

However, according to IRPET (2020), academic literature underscores the positive role that organic agriculture can play in improving environmental sustainability. This is clearly explained by the International Federation of Organic Agriculture Movements (IFOAM): "Organic agriculture, based on the principles of health, ecology, fairness, and care, has a great potential to contribute to many of these (sustainable development, author's note) goals, directly or indirectly. There is sufficient evidence of positive impacts on a wide range of important issues including consumer health, soil health, water, biodiversity, climate change, environmental pollution, animal welfare, and improved livelihoods of producers." (IFOAM, 2017, p. 2).

Alongside organic and biodynamic production, and sometimes in combination with them, many winemakers certify their product as 'natural wine'. In Europe, these producers are united under the VinNatur consortium. At present, there is no official or legal definition for 'natural wine'; however, there are many unofficial codes of practices released by several associations of natural wine producers, promoting a wine that is produced with the lowest possible number of human interventions in the vineyard and in the cellar (Corbo et al., 2014).

Another complementary type of sustainable practice programs are certified environmental management standards, with the most widespread being ISO 14001. Such systems are mainly used by larger wineries with the scale to suit and absorb their costs, while most wineries (i.e., family-owned or small-scale) often lack the financial resources needed to implement them (De Steur et al., 2019; Mariani & Vastola, 2015).

Lastly, throughout the many different sustainability programs launched in Italy, Sardone et al report as the most diffused are V.I.V.A. and Equalitas.

V.I.V.A. is a public certification established in 2011 by the Ministry of Environment, in cooperation with the University Cattolica del Sacro Cuore and the University of Torino. The scheme provides guidelines and performance measurement indicators related to the environment (air, water, vineyard, and territory) and socio-economic aspects. Participation in the scheme is communicated with a label and a QR code that allow consumers to identify the score for the single wine bottle and for the entire organization (Sardone et al., 2023).

Equalitas is a private certification, established in 2015 thanks to the initiative of Unione Italiana Vini, Federdoc, and other organizations. The scheme addresses the needs of the entire supply chain and includes two additional sustainability pillars: socio-environmental and communication. Equalitas is characterized by a gradual approach to sustainability goals, and the results achieved are monitored by an annual Sustainability Report. Certification can be obtained by a single producer or by a territory and refers to three different dimensions: the

organization standard, the product standard, and the territory, when it involves at least 60% of a specific PDO/ PGI (Sardone et al., 2023).

2.2 Climate Change and Adaptation

As the detrimental role of human activity on the global climate has been acknowledged, political, social, and business actors need to direct their efforts towards researching alternative patterns of production and consumption to mitigate climate change, in order to affect the rate and magnitude of change, while, at the same time, researching possible ways to adapt to climate change impacts on social and business activities. Although some uncertainty exists about the impacts of this change (e.g., exact nature, timing, location, and magnitude), empirical scientific evidence clearly indicates the increasing likelihood and severity of extreme events and natural disasters, such as droughts, flooding, hurricanes, extreme and unpredictable weather patterns (Gasbarro et al., 2019).

2.2.1 Climate Change in the Mediterranean Area

Human activities have led to an unprecedented global warming (EEA, 2024). Numerous studies have provided evidence for systematic changes in climate, showing increasing temperature trends, accompanied by alterations of other climatic parameters and significant changes in extreme events (Tomasi et al., 2011). The global temperature, for different Representative Concentration Pathways (RCP)[10], is expected to rise between 1°C in the moderate scenario (RCP2.6) and 5°C in the severe scenario (RCP8.5) over this century (Fraga, 2020). Europe, since the 1980s, has seen a rate of warming about twice the global rate (EEA, 2024). The present climatic trend and future climate simulations indicate the Mediterranean basin as a potential hotspot (Bartolini et al., 2021; Ministero dell'Ambiente e della Sicurezza Energetica, 2023b; Moriondo et al., 2013). The Mediterranean area is certainly one of the most vulnerable[11] regions in the world, for its population density, for the concentration of economic activities in coastal zones, and for its climatic borderline equilibrium (Carraro & Sgobbi, 2008). While the past increase in temperature in the Mediterranean basin was similar to the hemispheric change, there is evidence of significant warming trends in both the minimum and maximum summer extremes with a decline in the frequency of cold nights (Tomasi et al., 2011). In addition, in the last

[10] "RCPs quantify future greenhouse gas concentrations and the radiative forcing (additional energy taken up by the Earth system), due to increases in climate change pollution." (Copernicus Climate Change Service, 2021)

[11] Vulnerability is an integrated measure of the expected magnitude of adverse effects to a system caused by a given level of certain external stressors. This definition includes an external dimension, which is represented by the exposure of a system to climate variations, as well as an internal dimension, which comprises its sensitivity and its adaptive capacity (Füssel & Klein, 2006).

decades the hydrological cycle has intensified, with positive trends in both heavy precipitation events and the number of consecutive dry days, and extreme events increased (Bartolini et al., 2021).

In Italy, the period 1981-2010 registered an increase of 1,1°C in annual average temperature compared to the period 1971-2000 (Spano et al., 2020). Precipitations showed a decreasing trend in overall amounts, combined with an increasing intensity of precipitation events (Spano et al., 2020; Tomasi et al., 2011). These trends are confirmed at smaller scales: a study from Pavan et al. (2019), analyzing precipitations in Nort-Central Italy from 1951 to 2015, while reporting a non-significant decreasing linear trend in overall precipitation, found out a significant decrease in summer precipitation, linked with an increase in the length of dry spells and with signals of increased intense precipitation events; Tomasi et al. (2011) showed clear climatic changes in the Veneto region, consisting in significant temperature increase since 1980 and precipitation decrease since 1995.

Future projections delineate an even worse climate situation, especially in Europe, with progressively warmer and drier conditions (Moriondo et al., 2013). The continent is also facing stronger climate hazards, including heatwaves, prolonged droughts, fluvial and coastal floods (EEA, 2024). In particular, the Mediterranean area will experience an increase in average temperature at a rate between 20% and 100% faster than the global rise, accompanied by a strong decrease in precipitations, leading to a significant increase in heatwaves (Accetturo & Alpino, 2022; Carraro & Sgobbi, 2008). These impacts are going to affect sensitive regional and local economies dependent on tourism, agriculture, fisheries, and forestry (EEA, 2024). Potential impacts in Italy do not differ much from the rest of the Mediterranean area, with an expected increase in average temperature up to 2°C in the period 2021-2050 (compared to the period 1981-2010), a decrease in annual average precipitation and a generalized increase in frequency of extreme events (Accetturo & Alpino, 2022; Ministero dell'Ambiente e della Sicurezza Energetica, 2023b; Spano et al., 2020). But the gravity of the economic, social and environmental impacts is likely to be more severe than in other European areas, due to the preexisting vulnerability[12] to natural risks of the Italian territory, characterized by complex climate and orography, that will be amplified by climate change (Bartolini et al., 2021; Ministero dell'Ambiente e della Sicurezza Energetica, 2023a). In particular, the Center and South Italy will face a higher increase in temperature, especially during spring and summer, in all of the RCP scenarios (Spano et al., 2020).

[12] The DARA Climate Vulnerability Monitor puts Italy in the severe vulnerability category for desertification and in the high vulnerability group for drought and water resources (DARA & Climate Vulnerable Forum, 2012).

Some of the effects of climate change started to become evident in recent years, when many long-time climate records were broken. On the global scale, 2023 was the warmest year on record over more than 100.000 years, with the average temperature between February 2023 and January 2024 exceeding preindustrial levels by 1,5°C (EEA, 2024). 2023 was also the second warmest year in Europe and in Italy, but, in the latter, the warmest regarding average minimum temperatures, and with many other anomalies regarding extreme indicators: the third lowest number of frost days and the third highest number of tropical days and nights (SNPA, 2024). Looking at precipitations, 2023 was within the normal variability in terms of amount, but the spatial and temporal distribution of precipitations was very inhomogeneous (SNPA, 2024).

Many authors and institutions have tried to quantify the economic impacts of climate change. The European Commission in 2021 calculated present annual average losses of €12 billion, while estimating that exposing the current EU economy to global warming of 3°C above preindustrial levels would result in an annual loss of at least €170 billion (Regulation 2021/2115/EU). The problem with these estimates is that they tend to underestimate the real costs of future climate change, especially when they account for autonomous adaptations of the economic system, because they do not consider a lot of non-market impacts with potentially important economic repercussions (Carraro & Sgobbi, 2008). Climate change impacts have a predominantly redistributive nature, causing some sectors and regions to be more affected than others: in the primary sector, even if characterized by an intrinsic adaptive capacity, negative impacts will predominate, with lower harvestable yields, higher yield variability, and a reduction in the areas suitable for traditional crops. (Carraro & Sgobbi, 2008; Ministero dell'Ambiente e della Sicurezza Energetica, 2023a; Moriondo et al., 2011). Crop production is already facing substantial climate risks in Europe as a whole, with the expectation of increased yield variability as a result of extreme weather events and pests and diseases facilitated by climate change (EEA, 2019). Climate risk levels are even more critical in southern Europe (EEA, 2024). In this region, particular attention should be devoted to assessing the impact of climate change on valuable crops such as wine grapes, which are going to suffer the worst losses in territorial suitability (Moriondo et al., 2011; Spano et al., 2020). The specific regional situation is determined by the frequency of droughts, hydrological conditions, and the status of irrigation infrastructure where available; if crop yields are reduced under climate change, efforts to maintain overall production levels can further increase pressures on biodiversity, water resources, soil, and ecosystems (EEA, 2024). Italian agriculture is one of the most vulnerable to climate change at the European level, so an improvement in the adaptive capacity will be

needed to reduce impacts but also to capture positive opportunities (Ministero dell'Ambiente e della Sicurezza Energetica, 2023a).

2.2.2 Climate Change Response

The two fundamental response options to the risks posed by anthropogenic climate change are mitigation of climate change and adaptation to climate change: mitigation refers to limiting climate change through reducing the emissions of greenhouse gases and enhancing their sink, to the point of trying to reverse it; adaptation primarily aims at moderating the adverse effects of unavoidable climate change or taking advantage of any opportunities presented by it (Füssel & Klein, 2006; Galbreath, 2015). Mitigation has traditionally received much more attention than adaptation in the climate change community, both from a scientific and a policy perspective. This focus has three important reasons: first, mitigation improvements produce positive externalities in all climate-sensitive systems; second, reducing greenhouse gas emissions applies the polluter-pays principle; lastly, emission reductions are relatively easy to monitor quantitatively, whereas is incredibly difficult to measure the effectiveness of adaptative actions (Füssel & Klein, 2006). But mitigation should not be the only lever of action, in fact, even if the world's greenhouse gases emissions stabilized today, we would still observe a global average temperature increase, with all associated impacts (Boutang et al., 2020; Carraro & Sgobbi, 2008). Other than the necessity to adapt to already unavoidable changes, there are three main arguments that justify a focus on adaptation: first, most adaptation measures have almost immediate benefits, while mitigation effects take decades to realize; second, adaptations can be implemented on a local or regional scale such that their efficacy is less dependent on the actions of others, whereas mitigation of climate change requires international cooperation; third, most adaptations to climate change also reduce the risks associated with current climate variability, which is a significant hazard in many world regions (Füssel & Klein, 2006).

From a climate risk perspective, mitigation can reduce climate-related hazards, while adaptation and sustainable development reduce exposure and vulnerability to these hazards. Vulnerability is connected to resilience, defined as the capacity of a system to cope with a hazardous event maintaining its essential function, identity, and structure. Therefore, vulnerability and resilience represent two sides of the same coin: a system vulnerable to climate change will have low resilience, and vice versa (ISPRA; Lee et al., 2023). However, vulnerability drivers do not systematically predict resilience, as the latter concept is not only determined by preexisting conditions to the crisis (risk), but also by the post-catastrophe situation (Boutang et al., 2020).

So, adaptation of the system is important to reduce vulnerability and increase resilience (Gasbarro et al., 2019).

Adaptation and sustainable development are also interlinked: adaptation facilitates sustainability, which is hindered by impacts and risks from climate change; sustainable development facilitates adaptation by expanding the resources and capacity available to manage climate risks. Policymakers should focus on closing adaptation gaps, which are the differences between implemented adaptation and a socially set goal of climate change impacts on natural resources and sustainable development (IPCC, 2023).

2.2.3 Policy Shift to Adaptation

The emphasis is thus gradually shifting from mitigation only to mitigation and adaptation, from whether adaptation is needed to how to adapt (Carraro & Sgobbi, 2008; IPCC, 2023). While appropriate adaptation responses are often related to specific risks and vulnerabilities in local contexts, action in one sector or locality can have negative spillovers in another, suggesting the need to design and implement adaptation policies through coordination processes across multiple sectors and tiers of government (Russel et al., 2020). Proactive adaptation planning is fundamental to capitalize on potential benefits of climate change and minimize climate risks (Ministero dell'Ambiente e della Sicurezza Energetica, 2023b). This process is often composed of five general stages: (a) awareness, (b) assessment, (c) planning, (d) implementation, and (e) monitoring and evaluation (IPCC, 2023). It is a lengthy process because climate risks are characterized by long policy horizons, due to the difficulty of implementation and long-term considerations about lock-ins (EEA, 2024). This means that there is an urgency for government, nongovernment and private sector actors to start ambitious adaptation processes that, according to some estimates, could halve the global climate risk under all warming scenarios (IPCC, 2023; UNEP, 2024).

The first intergovernmental documents on climate change, from the 1992 United Nations Framework Convention on Climate Change to the 1997 Kyoto Protocol, focus more on mitigation than adaptation (Ministero dell'Ambiente e della Sicurezza Energetica, 2023b). The 2015 Paris Agreement is the first to set a global adaptation goal, prescribing efforts from Member Countries regarding adaptation planning processes (IPCC, 2023; Ministero dell'Ambiente e della Sicurezza Energetica, 2023a). However, the European Union started introducing adaptation in the equation from 2007 and approved the first Climate Change Adaptation Strategy in 2013, with three main objectives: to promote action by Member States, to provide tools for policy decisions informed by scientific research results, and to support the

adaptation of strategic infrastructure through the European Union's direct funding programs (Ministero dell'Ambiente e della Sicurezza Energetica, 2023b; Spano et al., 2020). The Strategy was updated in 2021, with four priorities: smarter adaptation (improve the quality and quantity of data and tools), systemic and integrated adaptation (macro-fiscal level, local level, nature-based solutions), faster adaptation, more global coordination in adaptation (Ministero dell'Ambiente e della Sicurezza Energetica, 2023a). Various EU financial programs are available to support local resilience, such as European Structural and Investment Funds, the Recovery and Resilience Facility and the LIFE Programme, which has a subprogram, LIFE CLIMA, focusing on mitigation and adaptation actions, with €0,95 billion available for the period 2021-2027 (Communication (2021)82, final; Ministero dell'Ambiente e della Sicurezza Energetica, 2023a).

Another important policy instrument for adaptation is the Common Agricultural Policy. In fact, as noted by UNEP (2024), the agricultural sector plays an important role in adaptation considerations. One of the 10 objectives based on which the CAP for the planning period 2021-2027 is based is the contribution to mitigation and adaptation to climate change (Ministero dell'Ambiente e della Sicurezza Energetica, 2023a). Four entry points are available for implementing adaptation measures at farm level: enhanced conditionality, eco-schemes, rural development interventions, and sectoral interventions for specific productions (including vineyards) (EEA, 2019).

As a result of increased attention to and investment in adaptation planning over the past two decades, 171 countries now have at least one national adaptation planning instrument in place (UNEP, 2024). Crucially, the impacts of climate change on adaptation activities have so far been relatively modest in Europe. This indicates that the acute need for action has still been generally moderate with the exception for some regions/locations; however, recent studies indicate an increasing willingness to coordinate not only adaptation principles, but also concrete actions (Russel et al., 2020). Italy was a relative latecomer to nationally coordinated climate change adaptation policies: in fact, Italy's National Adaptation Strategy was adopted in June 2015, in response to the EU's adaptation policy (Russel et al., 2020). Fast forward to the EEA (2022) report, Italy emerges as one of the most active European countries on adaptation, with more than 5000 adaptation actions identified in the Covenant of Mayors (where Italy also has the highest number of signatories) of which 400 have already been implemented, 2982 are ongoing and 2082 are not started yet. The private sector is included in sector-specific projects. With the National Adaptation Plan (PNACC) approved in 2023, the process will advance even faster, with many Italian regions completing their Regional Adaptation Strategies/Plans. In fact,

in the EEA (2023) report, Italy is in the first half of European countries that reported substantial achievements in terms of climate-related assessments.

Institutional effort in climate change adaptation must be coordinated and supported by the private sector. Although historically public organizations have been responsible for dealing with disasters, some studies highlight the importance of the private sectors for improving community resilience: firms can activate society to adopt anticipatory measures to deal with the physical impacts of climate change and be precious partners in post-climate events relief and disaster recovery (Gasbarro et al., 2019). So, business adaptation to climate change plays a very important role in supporting sustainable development and the green economy, but, as we will also see in the case studies, the number of variables that influence business adaptation makes the issue very complex.

2.3 Wine Production and Climate Change

Viticulture thrives under specific climatic conditions, with Mediterranean climates - characterized by warm, dry summers and cool, wet winters - being particularly suitable (Hannah et al., 2013). Grapevines produce high-quality fruit at economically sustainable levels when grown in these ideal climates (Tomasi et al., 2011). Climate thresholds for optimal grapevine growth are best represented by average growing season temperatures of 12–13°C at the lower end and 22–24°C at the upper end (Schultz & Jones, 2010). Most of the major wine growing regions are situated between the 35th and 50th parallels in the Northern Hemisphere and the 30th and 45th parallels in the Southern Hemisphere (Galbreath, 2016). Outside these zones, particularly in tropical or subtropical regions, producing high-quality wine is virtually impossible (van Leeuwen & Darriet, 2016).

However, the establishment and management of vineyards have significant ecological consequences. Vineyard development often involves the removal of native vegetation and other practices that result in long-lasting degradation of habitat quality. As a result, vineyard expansion into biodiverse regions can lead to substantial habitat loss, and the methods used to manage vineyards have major implications for conservation and freshwater resources (Hannah et al., 2013).

Climate change adds another layer of complexity to the relationship between viticulture and biodiversity. Rising temperatures and shifting precipitation patterns are expected to move the boundaries of biogeographical regions northward and uphill, altering vegetation patterns, and triggering major shifts in forests and farmland (Communication (2021)82, Final). In response, viticulture may expand into previously unsuitable regions, threatening native habitats and

biodiversity in these areas (Hannah et al., 2013). The fragmented nature of many ecosystems exacerbates this challenge, as trees and crops often cannot keep pace with rapid climate shifts (Communication (2021)82, Final).

To address these challenges, innovative solutions are urgently needed. Farmers must adopt strategies to reduce climate risks, such as utilizing genetic diversity and sustainable plant genetic resources. These adaptations, informed by the latest scientific advances, could help crops adjust to new conditions without causing additional environmental harm (Communication (2021)82, Final). At the same time, sustainable viticulture practices must align with global goals which emphasize the importance of balancing agricultural development with the need to conserve biodiversity and ensure that ecosystems can adapt naturally to changing conditions (Hannah et al., 2013).

2.3.1 Grape Growing Process and Climate Vulnerability

The sensitivity of viticulture to climate has made changes in wine production a valuable proxy for understanding past climate variations (Hannah et al., 2013). In fact, climate has a strong influence on grapevine growth, development, production, and quality (Fraga, 2020). The relationship of grapevine phenology[13] with climate has been confirmed by numerous studies and is the most important among environmental factors, such as soil and grapevine variety (Di Lena et al., 2019; Tomasi et al., 2011; van Leeuwen & Darriet, 2016).

Grapevines are characterized by a distinct annual growth cycle beginning with bud break (in the Northern Hemisphere, during March/April), continuing with bloom (May/June), berry growth and *véraison* (change in the color of the grape, marks the start of ripening) (July/August), maturation (September/October), and culminating in leaf fall in autumn followed by winter dormancy (Ashenfelter & Storchmann, 2016; Pomarici & Seccia, 2016). All of these phases are dependent on climate: budbreak timing and its consistency have been tied to adequate winter chilling requirement followed by warm and frost-free springs; bloom events appear to be most strongly correlated with maximum temperature levels in the preceding month; growing season radiation exposure and temperatures, which should be warn but not too much, are more important for *véraison* and harvest, with fluctuations between daytime and nighttime temperatures enabling the development of flavor compounds (Ashenfelter & Storchmann, 2016; Galbreath, 2016; Tomasi et al., 2011).

[13] Phenology is the study of the relationships between climate and the timing of periodic natural phenomena such as bird migration, insect growth stages, and plant flowering (Tomasi et al., 2011).

Phenology is the most important attribute involved in the final yield assessment and consequently in the adaptation of crops to the changing environment. Both the timing of phenological stages and the relative duration of the pre- and post-flowering phases (vegetative and reproductive phases, respectively) are, in fact, critical determinants of yield (Moriondo & Bindi, 2007). In a given wine producing region, climatic conditions vary from one year to another, inducing the 'vintage effect', which describes year-to-year variations in yield, quality, and typicity (van Leeuwen & Darriet, 2016). The main effect of climate change is the acceleration in the achievement of the main phenological phases and the length of the growing season, advancing phenological stages, which further influences final grape quality and yield (Di Lena et al., 2019; Moriondo & Bindi, 2007) .

The length of the growing season is in turn determined by many atmospheric factors, such as temperature, rainfall, solar radiation, heat accumulation, wind, weather variability and extreme weather events (heatwaves, hail, frost, and floods) (Fraga, 2020; Jones et al., 2005). Among these elements, temperature and moisture regimes, which are also the primary elements of terroir, play a key role in delimiting regions suitable for grape growing (Hannah et al., 2013; Jones et al., 2005). In the rest of this section, we are going to focus on the importance of temperature, rainfall, and radiation. Historically, growers have chosen plant materials (variety, clone, and rootstock) and viticultural practices based on these elements, which will also guide future adaptation to changing climatic conditions (van Leeuwen & Darriet, 2016).

The phenology of grapevine development is a predominantly temperature-driven process: the relationship is so strong that vine phenology can be predicted by models that are based only on temperature (Moriondo et al., 2011; van Leeuwen & Darriet, 2016). Warmer temperatures, advancing grapevine phenological stages and shortening grapevine growth cycles, are usually related to lower yields, due to reduced times for biomass accumulation (Moriondo et al., 2011). Temperatures during the growing season can affect grape quality and viability in at least three ways. First, prolonged temperatures above 10°C initiate spring vegetative growth and thus determine the start of the growing season (Jones et al., 2005). Second, during flowering and throughout the growth of the berries, prolonged high temperatures can cause premature *véraison*, grape mortality, enzyme inactivation, and partial or total failure of flavor ripening; at the same time, also frost events at bud break are dangerous, causing shoot loss and lower yield (Ashenfelter & Storchmann, 2016; Moriondo & Bindi, 2007; Pomarici & Seccia, 2016). Third, during the maturation stage, a high diurnal temperature range leads to the beneficial synthesis of grape tannins, sugars, and flavors (Jones et al., 2005; Pomarici & Seccia, 2016). In general, high temperatures increase grape sugar accumulation and reduce grape acidity (Jones & Webb,

2010; van Leeuwen & Darriet, 2016). This determines the style, balance, and potential alcohol of the wine (Ashenfelter & Storchmann, 2016).

Ideal balance in grape composition at ripeness with respect to sugar/acid ratio, color, and aromas, is obtained when grape ripening occurs under moderate temperatures: excessive cool climatic conditions during ripening can result in green and acidic wines; high temperatures between *véraison* and harvest can result in unbalanced fruit composition, but also sunburn, negating flavor and productivity (Galbreath, 2016; Lamonaca et al., 2021; Van Leeuwen et al., 2019). Complicating matters is the fact that there are many different kinds of wine grapes, which are even more particular about where and under which conditions they will best grow, so hotter temperatures can also restrict the types of varieties that grow well, forcing decisions around plantings, row orientations, and location choices (Galbreath, 2016; Galbreath et al., 2020).

We have seen that increasing temperature causes an advance in phenology, so harvest dates are advanced too, even if less than the advance of phenology: this means that grapes show a higher potential alcohol level, due to an increase in sugar accumulation and a lower acidic content (van Leeuwen & Darriet, 2016). A study from Di Lena et al. (2019) on Montepulciano d'Abruzzo vines confirmed this trend, leading to two main consequences: on the positive side, earlier harvest date creates an advantage for vines, because it is associated with a more favorable post-harvest period; on the negative side, this trend can impair wine quality, because the alcohol level will be too elevated and higher pH could cause yeast thriving during aging or even after bottling (van Leeuwen & Darriet, 2016).

In summary, higher temperatures during the growing season should strongly affect grapevine growth, expecting to lead to earlier phenological events. Furthermore, high temperatures during maturation are likely to negatively affect wine quality and yields. Moreover, extreme heat and water stress, under future climates, may threaten grapevine productivity (Fraga, 2020). With changes in temperatures and humidity, due to milder winters, microclimatic conditions will also be altered, and grape growers will face an increase in the threatening presence of insects and insect-borne diseases as their temperature limits shift poleward (Galbreath, 2016; Pomarici & Seccia, 2016).

The water balance of the vine is mainly determined by supply-side factors: local precipitation, atmospheric humidity and temperature, and the soil water-holding capacity. On the demand side, there is evapotranspiration, the combined loss of water evaporating from the soil and transpiring (i.e. evaporating from leaves) from the plant (Ashenfelter & Storchmann, 2016). The overall quantity of annual rainfall and its distribution in the growing and non-growing

seasons is crucial when the vines are not irrigated, as is the case in almost all of Europe (Ashenfelter & Storchmann, 2016). In general, abundant rainfall during the winter and early vegetative stage is beneficial, while more stable precipitations are desirable from flowering to ripening (Lamonaca et al., 2021). Within existing production areas, where temperature conditions are generally favorable for grape cultivation, water shortage is the most dominant environmental limitation, given that water availability is one of the main drivers of quality and yield (Galbreath et al., 2020; Van Leeuwen et al., 2004; Wagner et al., 2023). Modifications of rainfall distribution patterns are difficult to predict, and the impact of these changes is strictly linked with temperature increase: in the case of earlier harvest dates, the most intense period of water stress will occur after it (Galbreath et al., 2020). At the same time, higher temperatures will increase evapotranspiration, destabilizing the water balance by means of a deficit in most wine growing regions (Wagner et al., 2023). Water deficits are a direct cause of reduced yield, due to the smaller size of the berry and the reduced fertility of the bud. Nonetheless, quality impacts can vary: in red wine production, a moderate water deficit enhances quality, because, as leaf pores (stomata) close incrementally, in order to conserve water, photosynthesis decreases and the content of grape tannin increases; moreover, reduced humidity could decrease the likelihood of fungal diseases (Ashenfelter & Storchmann, 2016; van Leeuwen & Darriet, 2016). But severe water stress can damage the plant, leading to leaf necrosis and stuck grape ripening (van Leeuwen & Darriet, 2016). This phenomenon is concerning because it opens up the possibility of a shift in regional suitability and consequently the loss of varietal identity (Wagner et al., 2023).

In a warming climate, water use may increase as vineyard managers attempt to cool grapes on the vine to reduce quality loss from heat stress and to reduce drought stress (Hannah et al., 2013). However, even irrigated vines can experience transpirational restrictions under hot and dry atmospheric conditions, or low relative humidity (Ashenfelter & Storchmann, 2016).

Regarding the last factor, contradictory results have been published on the impact of radiation on grape phenolics, because it is difficult to separate the effect of light from that of temperature. According to van Leeuwen & Darriet (2016), an increase in radiation can cause sunburn on grapes, particularly in the *prevéraison* phase. An increase in UV-B radiation might be favorable for red wine production due to increased skin phenolics, but it can impair the quality of white wine and induce atypical aging.

2.3.2 Climate Change Impacts on Viticulture

Viticulture is facing the growing implications of climate change, as multiple regions are subjected to increasing temperatures, altered precipitation patterns, prolonged drought periods, and higher variability in meteorological attributes. We have already outlined in the previous section how the grape growing process can be impacted by expected climate changes, such as significant increases in temperature, changes in precipitation patterns, and the rate of occurrence of extreme weather events is also increasing (Fraga, 2020).

However, climate change affects wine-producing regions nonuniformly. Vineyards in regions characterized by a warm climate, high levels of evapotranspiration, and low water availability are becoming increasingly dependent on irrigation. In contrast, more temperate regions may benefit from the temperature rise as wine quality is expected to improve. These shifts are uncertain and unstable and strongly affect the wine market (Ohana-Levi & Netzer, 2023). In fact, at high latitudes, wine growing is limited by the scarcity of solar radiation, low temperatures in spring, and high precipitation levels during summer, factors that can injure the vine (Ministero dell'Ambiente e della Sicurezza Energetica, 2018; van Leeuwen & Darriet, 2016).

With the new conditions that climate change is expected to bring, areas currently suitable for grapevine could become unsuitable and vice versa, with an increase in the number of good vintages in cold climate areas, determining a geographical shift toward the poles of grape growing regions in both hemispheres (Ashenfelter & Storchmann, 2016; EEA, 2019; Hannah et al., 2013; Moriondo et al., 2013; Pizzol et al., 2021; Tomasi et al., 2011). As previously seen (Section 1.1), this type of shift has been occurring for millennia, due to the inherent climate sensitivity of grapevines, but never so rapidly as in the case of human-made climate change (Moriondo et al., 2013). Only the projected higher frequency of extreme events could undermine a geographical expansion that has already been observed in northern European countries such as Denmark, Finland and Sweden, where several grapevine cultivars have been growing for 20 years (EEA, 2019; Spano et al., 2020). The wine industry will be impacted by these changes in at least three ways: first, spatial changes in grapevine viability are going to generate new productive and competitive scenarios, affecting the actual dominance of Mediterranean regions (Jones & Webb, 2010; Lamonaca et al., 2021); second, the potential ecological footprint of viticulture, defined as the intersection of viticultural suitability and natural habitats, is projected to increase as suitability expands into uncontaminated montane areas (Hannah et al., 2013); finally, in areas negatively impacted, adaptation will become a prerequisite for survival (Di Lena et al., 2019). Furthermore, the role of mitigation will be

emphasized, because winegrowing regions are characterized by an optimal thermal limit, so any action to slow the temperature rise above this limit can be relevant for the survival of grapevines in some regions (Di Lena et al., 2019).

Warming temperatures, at the farm level, will have an impact on both grapevine yield and quality. The main impact is represented by a shorter duration of the growing season, with the acceleration of phenological phases (Jones & Webb, 2010; Ministero dell'Ambiente e della Sicurezza Energetica, 2018; Moriondo et al., 2011; Pomarici et al., 2021; Pomarici & Seccia, 2016; Schultz & Jones, 2010; Spano et al., 2020). This trend is already relevant in Europe, where maturation has been recorded 6-25 days earlier in numerous cultivars and locations (Alikadic et al., 2019; Di Lena et al., 2019; Tomasi et al., 2011). Although in cooler areas wine grape quality and yield will benefit from warmer temperatures, for Southern European countries, which are already at their thermal optimum for grape growing, the decreasing length of the phenological cycle may lead to yield losses, only partially compensated for by the positive effect of increasing CO2 concentration (Ashenfelter & Storchmann, 2016; EEA, 2019; Jones et al., 2005; Ministero dell'Ambiente e della Sicurezza Energetica, 2018). Wine quality, which has been favored until now by increasing temperature, will also suffer from the projected temperature growth that is going to move many varieties out of their ideal ripening window (Accetturo & Alpino, 2022; Jones et al., 2005; Van Leeuwen et al., 2019). This evolution, which generally leads to a higher sugar content and thus a higher potential alcohol content, will mean changes in the winemaking process, which will require the addition of tartaric acid to address acidity imbalances and new yeasts capable of fermenting sugar without creating alcohol (Galbreath, 2016; Pomarici & Seccia, 2016). Climate change is also expected to increase the frequency of extreme events, often centered at the time of sensitive grape growth stages, increasing the yield and quality loss risk due to two different main trends: increasing late spring frosts, hailstorms, and precipitations at the bud-burst, altering grape development; longer dry spells and heatwaves during *véraison* and grape ripening, causing failure in berry color and flavor development (Accetturo & Alpino, 2022; Moriondo & Bindi, 2007). Consequently, drought conditions will determine a negative soil water balance in vineyards and general water shortages; in other words, water stress for grapes, demanding irrigation, will be in contrast to increasingly scarce water resources, generating great damage to freshwater ecosystems (EEA, 2019; Hannah et al., 2013; Moriondo & Bindi, 2007; Pizzol et al., 2021; Van Leeuwen et al., 2019). Under the new climate regimes, the pressure from pests and diseases on grapevines is likely to increase, even if some pathogens, such as oidium, could be limited by rising temperatures (Ashenfelter & Storchmann, 2016; EEA, 2019; Ministero dell'Ambiente e della

Sicurezza Energetica, 2018). However, a report from IRPET (2024) indicates that in 2023 changing climatic conditions created the perfect environment for the insurgence of parasites and diseases, compromising yield for wine producers, especially organic ones, in southern Europe.

Both the impact on yield and quality will constitute a substantial economic problem in the wine industry. In fact, while revenues from agricultural production are generally largely driven by yield, for wine grape growing the quality potential of grapes is dominant, as wine prices can vary by a factor of 1000 while yields vary by a factor of 10 (Van Leeuwen et al., 2019). Assessment of the economic impacts of climate change on viticulture suffers from several limitations. First, most climatic analyses rely solely on measures of average temperatures, failing to account for the effect of extreme events (Ashenfelter & Storchmann, 2014). The second hurdle regards the accuracy of projections about physical impacts of climate change, in particular at regional and local levels (Carraro & Sgobbi, 2008). This is important because, as we have seen previously, different regions can be impacted in different ways as a consequence of the combination of changes in yield, quality, prices, and adaptation costs (Pomarici & Seccia, 2016). This is part of the third problem with economic evaluation of climate change impacts, given that oftentimes the interdependent relationship between crop yield, quality and price is not included in partial equilibria analyses, which also tend to assume a 'dumb farmer' scenario with no adaptation. (Ashenfelter & Storchmann, 2014). Finally, it is intrinsically problematic to translate climate change impacts into monetary values because they affect environmental goods and services not traded in the market, such as biodiversity and landscape beauty (Carraro & Sgobbi, 2008); even more problematic is keeping track of negative externalities on the society and the general labor market. In regions where grapevine cultivation is part of the agricultural, economic and cultural heritage and identity, socioeconomic impacts can be severe, and redistribution of the viticulture climate in new countries could profoundly influence the economic relevance of the sector and world supply (Pomarici & Seccia, 2016).

Despite these complications, some studies have tried the evaluation exercise. According to EEA (2019), two thirds of the losses in farmland value from climate change would be concentrated in Italy, ranging from €58 billion to €120 billion by 2100 (34-60% value decrease) according to climate scenarios compared to the present climate. At the same time, Ashenfelter & Storchmann (2010) estimated that in the Mosel Valley, an increase in temperature of 3°C would more than double the value of this vineyard area, while an increase of 1°C would raise revenue by approximately 30%. Furthermore, industry experts see climate change and hotter summers as a driver of consumers preferring lighter and fresher wines, which would become harder to

produce under the new projected conditions (Del Rey & Loose, 2023). So, the quality of wine in good years will not be guaranteed, and the demand for wine in poor years will not be met, resulting in greater economic risk for growers, causing them to adapt their viticultural and enological practices (Moriondo et al., 2011).

2.4 Adaptation in the wine sector

Although grapevines, relative to other crops, are well adapted to stress conditions, climate change may pose a major threat to winemakers in general. But grape growers and winemakers have proven their adaptability to changing climatic and economic environments over thousands of years (Ashenfelter & Storchmann, 2014). One of the oldest documented adaptation methods for grape production has been for farmers to adjust to the phenological stages of the vines and complete certain work independently of the calendar date (Ashenfelter & Storchmann, 2016). On the other hand, while they are likely to adapt in the future as well, adjustments to changing climate can be slower for perennial crops like vines, so it is imperative for growers and stakeholders to become aware of this problem in order to timely implement these measures, because, absent some adaptation, a climate change will affect the prices and quantities of wine produced, and thus the profit from existing plantings (Ashenfelter & Storchmann, 2014). In this context, the vast grapevine genetic diversity becomes a valuable resource and can be used as a powerful adaptation measure, allowing for the continuation of production of high-quality wines under future climates. Additionally, there are vast resources available for growers in terms of changing some of the current management practices, which may prove beneficial when adapting to climate change (Fraga, 2020). In this section, following the duality between long-term drastic changes and short-term management, adaptive practices will be categorized into two groups: transformational adaptation, including all the adaptation methods that fundamentally change the production process; progressive adaptation, including practices moderating the effects of climate change in the current production system of the company.

2.4.1 Transformational Adaptation

The choice of plant material (rootstock[14] and grape variety) is a powerful way to adapt because it encompasses solutions for almost every climate risk factor, while being environmentally friendly. However, the clear drawback is represented by the large investment needed for this type of adaptation in the case of a perennial crop (Van Leeuwen et al., 2019). On the positive

[14] "Rootstocks are specialized stock material to which grape cultivars with desirable fruit properties are grafted; the shoot portion of the two grafting partners is termed the scion, whereas the rootstock provides the root system to the fused combination of genotypes." (Keller, 2010, p. 16)

side, once planted, new rootstocks do not increase production costs, even better they can reduce them (van Leeuwen & Darriet, 2016). That is the case of drought resistant rootstocks, which permit to sustain yield and avoid quality losses from excessive water stress and temperature (Van Leeuwen et al., 2019; Wagner et al., 2023). Plant material choice can also be a helpful tool to delay vine phenology, with the use of rootstocks that induce a longer growing cycle (Van Leeuwen et al., 2019). Clonal variety choice can be used in the same way: many late-ripening or resilient varieties are already available and planted even in traditional regions; moreover the research has obtained varieties with a very high percentage of *Vitis vinifera* genes (approximately 99%), so offering a similar wine quality, but with factors of disease resistance and adaptability to environmental stresses (Galbreath, 2015; Galbreath et al., 2020; Pomarici & Vecchio, 2019; van Leeuwen & Darriet, 2016; Wagner et al., 2023). Investment in new varieties may be important for the industry and for the conservation of water resources and habitats, that instead could be endangered by other solutions, such as moving vineyards to cooler areas, namely higher latitudes and altitudes, which carry with them high environmental, social and economic costs (Alikadic et al., 2019; Hannah et al., 2013; Moriondo & Bindi, 2007; Van Leeuwen et al., 2019; Wagner et al., 2023).

While in New World wine-growing regions these adaptations are easier to implement, they are limited in European countries by institutional factors (Ashenfelter & Storchmann, 2016; van Leeuwen & Darriet, 2016). In fact, grapevines in Europe are regulated strictly by appellation regimes, prescribing the varieties which must be used and imposing narrow geographical delimitations to producers in the production specification codes (Ashenfelter & Storchmann, 2016; Ministero dell'Ambiente e della Sicurezza Energetica, 2018). Moreover, EU regulations furtherly restrict the expansion of vineyards through the planting rights regime: introduced in 1976 to cap the area under vines and control the production of inexpensive bulk wine, they now constitute an obstacle to adaptation which could put at disadvantage the traditional producing countries compared to the New World (Ashenfelter & Storchmann, 2016). Climate change could determine radical modifications of PDO and PGI specifications, which in some cases even prohibit irrigation, and could steer the discussion over planting rights in favor of the abolitionists (Ashenfelter & Storchmann, 2016; Ministero dell'Ambiente e della Sicurezza Energetica, 2018). Changes could also become inevitable in the marketing model of both Old and New World: terroir and geographic indication marketing for European countries may be obsolete in a scenario of cultivar or location shift; New World winegrowing regions could need to widen variety range, which itself could be intended as an adaptation tool, and stop producing

preeminently well-known international varieties (Ashenfelter & Storchmann, 2016; Hannah et al., 2013; Van Leeuwen et al., 2019; Wagner et al., 2023).

Vineyard restructuring could provide some other adaptation solutions. First, producers could introduce training systems with high drought resistance; the most efficient is the *gobelet*[15] (Fig. 8), which drastically reduces vine water use but makes harvesting by machine more difficult (van Leeuwen & Darriet, 2016; Wagner et al., 2023). Second, producers can operate on row spacing and orientation to protect berries from direct exposure to radiant heat and decrease water needs (Ashenfelter & Storchmann, 2016; Galbreath, 2015; Galbreath et al., 2020; Hannah et al., 2013; Hayman et al., 2012; Pomarici & Seccia, 2016; Van Leeuwen et al., 2019). Finally, cover crops in interrow spacing can produce favorable effects for heat protection, but require careful management to avoid excessive water competition (Ashenfelter & Storchmann, 2016; Hayes et al., 2021).

Figure 8. Gobelet *vines in Cyprus.*

Source: retrieved from Tischelmayer (n.d.).

2.4.2 Progressive Adaptation

Many other adaptation practices available to grape growers require smaller investment in technological innovations or the introduction of best practices in the vineyard and in the cellar. These smaller changes will be fundamental to face inevitable differences in wine quality caused

[15] "It is a special form of head training. The vines are trained in the classic form without any support (wires) or tied up to single stakes to create a cup-like shape (*gobelet* = cup or goblet) or by creeping along the ground." (https://glossario.wein.plus/gobelet-2)

by climate change in the short-term horizon, especially for premium-quality winemakers (Pomarici & Seccia, 2016).

In the vineyard, farmers need to address the problem of excessive heat and water stress through canopy management. Irrigation could become a necessity in areas particularly affected by droughts, but should be employed judiciously due to its economic, environmental and social costs. However, advanced techniques such as regulated deficit irrigation (RDI), partial root-zone drying (PRD) and 'fertigation', which consists in the delivery of water-soluble nutrients through irrigation, are able to minimize environmental footprint while retaining grape quality (Hayes et al., 2021; Pomarici & Seccia, 2016; van Leeuwen & Darriet, 2016; Wagner et al., 2023). To ensure robust canopy growth, which naturally shade grape bunches, delayed pruning should be employed, along with reduced hedging, selective leaf pulling, trunk height modifications through specific trellis systems (Galbreath, 2015; Galbreath et al., 2020; Hannah et al., 2013; Hayes et al., 2021; Hayman et al., 2012; Pomarici & Seccia, 2016; van Leeuwen & Darriet, 2016; Wagner et al., 2023). These practices enable better control of the bunch zone microclimate, protecting grapes from direct heat, radiation exposure and water deficits; these objectives can also be achieved using artificial shading with UV-B filtering nets, screens, windbreaks and anti-transpirants such as kaolin sprays (Galbreath et al., 2020; Hayes et al., 2021; Hayman et al., 2012; Van Leeuwen et al., 2019; van Leeuwen & Darriet, 2016). To enhance soil structure and texture, increasing moisture and fertility, pruning residues can be left in the field contributing to organic matter, also reducing the reflection of radiant heat produced by bare soils (Galbreath et al., 2020; Hayman et al., 2012; Novello, 2018).

In the cellar, it is possible to employ production methods to reduce grape content imbalances that could impair wine quality and style and to ensure consistent products. There are many options to counteract the excessive sugar concentration caused by climate change: using technologies like reverse osmosis or spinning cone, adopting yeast strains that metabolize less sugar into ethanol, adding tartaric, malic or citric acid blends to reestablish the correct acidity balance, even adding water in the countries where it is permitted; new cellar hygiene practices, such as the use of antimicrobials and antioxidants, could further help, as well as new blending techniques to offset vintage variability (Ashenfelter & Storchmann, 2016; Pomarici & Seccia, 2016).

Furthermore, Agriculture 4.0 and precision agriculture[16] provide many technological tools useful for adaptation purposes. Advanced technologies like Plant Cell Density (PCD) imaging and Digital Elevation Modeling (DEM) enhance water management in vineyards. PCD images, derived from the ratio of infrared to red reflectance, identify areas with varying water needs, guiding the placement and operation of subsurface drip irrigation lines. DEM helps to map water movement, identify optimal locations for drainage systems, and predict the impacts of salinity and frost. These tools enable growers to manage environmental stressors and protect vineyard health, and to reduce the environmental footprint to the point of contributing to climate change mitigation. However, the shift to Agriculture 4.0 introduces new and complex routines, so it will be easier to adopt for farmers with developed absorptive capacity (Galbreath, 2016; Galbreath et al., 2020; IRPET, 2023a).

In the long run, combining short-term practices and transformational adaptation will be the best way to support long-term resilience to climate change and sustainable use of resources in viticulture (Hannah et al., 2013; Pomarici & Seccia, 2016). In most cases, investment and implementation of adaptation practices, even if they have a bad reputation as in the case of irrigation, may prove to be a no-regret choice also from an economic point of view, because they could contrast instabilities in the wine market and in the already fragile balance sheets of small wine companies (Hayes et al., 2021; IRPET, 2024; Ohana-Levi & Netzer, 2023).

[16] Those methods aim to optimize resource use, particularly water, fertilizers, and pesticides, through data-driven approaches. Precision agriculture employs sensors on machinery to collect bio-physical and bio-chemical data on factors such as soil conditions, pathogens, and weather. These data can be processed and combined with georeferencing systems to produce detailed maps that identify soil stress, pathogen infestations, nutrient levels, and potential crop growth outcomes, enabling targeted interventions (IRPET, 2023a).

3. Methodological Approach

3.1 Region Choice

To select a region for the study, the analysis concentrated on the economic and environmental vulnerability of the main wine producing Italian regions. Although all these regions and their wine sector will be impacted by climate change, Tuscany emerged as a good selection due to the importance of the sector and some specific vulnerabilities.

3.1.1 Economic Assessment

Wine in Tuscany has a historical and cultural relevance that goes beyond economic considerations. From the Etruscan civilization, that laid the basis for making Etruria the cellar of the Roman Empire under Aureliano, through the Medicean age, when the first regulations of wine quality and production were introduced, to the two World Wars, after which production shifted from low to high quality, wine has played an important role in the culture, economy, and landscape of Tuscany for centuries (Accademia dei Georgofili & Accademia italiana della vite e del vino, 2007; Vaquero Piñeiro et al., 2022c).

This evolution has made Tuscany in 2023 the sixth producing region in volume, with almost 2 mhl, but third in export value, amounting to €1.2 billion (15% of national export value). From this difference emerges the focus on quality production, confirmed by the number of wines with denomination of origin: 58, divided into 11 DOCG, 41 DOC, and 6 IGT, making Tuscany second in this special ranking, after Piedmont, and covering 96.4% of the vineyard area (Federdoc, 2024; ISMEA, 2022). Unique identity and attention to quality are also demonstrated by the diffusion of organic agriculture, 35.8% of total production (IRPET, 2020). The same is true for organic viticulture, which jumped by 217% between 2010 and 2020, compared to a national increase of 127%, covering more than 19000 hectares (32% of the regional vineyard area and 17% of Italy's organic vineyard area) (ISMEA, 2022). For all these reasons, according to Camerano et al. (2020), Tuscany is recognized by consumers as by far the most attractive region in terms of enotouristic offer.

The data show the competitiveness of Tuscany compared to much larger comparable regions, such as Piedmont and Veneto. This was made possible by the market orientation developed in the last decades; therefore, the share of viticulture value in total Tuscan agricultural production has been around 13% in 2010 and remained similar ten years later (Camerano et al., 2020; IRPET, 2023b; Moriondo et al., 2011). The importance of the sector in the overall Tuscan economy, in expectation of strong climate change impacts, can be seen as a weakness, which,

in combination with the peculiar structure of Tuscan sector, is a recipe for economic disaster. In fact, the prevalence of small companies, cultivating an average of less than 5 ha, not coordinated under cooperative forms, that account for only 18% of the total production, make Tuscan wine companies more vulnerable than their competitors in comparable regions (IRPET, 2023a; ISMEA, 2022). A simulation by IRPET (2024) calculated that the shock in regional production in 2023 (-26%), in the majority attributed to impacts of climate change, would generate an increase in the population of vulnerable viticultural companies (defined as companies with negative gross operating margin) between 14% and 18%. Even with an optimistic estimate, given that some costs could be underestimated, Tuscany shows a particularly negative trend that could be exacerbated by stronger impacts and lack of adaptation.

3.1.2 Climate Change Vulnerability

Wine makers have already faced costly losses due to climate conditions and extreme weather in recent years. For example, 2017 was the worst season in 50 years for Tuscan wine producers, who lost 31% of production as a consequence of water stress induced by high temperatures and droughts; in that occasion, the north-eastern Italian regions suffered less impacts thanks to higher levels of innovation and flexibility in the management of wine companies (IRPET, 2019). Then 2022 was the hottest year since 1955, closely followed by 2023 (Consorzio LaMMA, 2024). In terms of temperature, each month recorded a higher anomaly, except for April, when vines are more exposed to late frosts and hail. In terms of precipitations, the average anomaly was not significant, but they were concentrated in just a handful of months (sometimes even days), causing floods and landslides in many locations within the region. In terms of extreme weather, summer 2023 recorded 3 heatwaves (with two of them being the third and fourth longest since 1955), 25 tropical nights and many hotter days than expected, all events way above the average for the period 1991-2020 (IRPET, 2024; SNPA, 2024). This is a confirmation of the more general trends of climate change, such as the increasing annual number of dry days and longer dry spells highlighted by Bartolini et al. (2021). The seasonal coincidence of most extreme anomalies with the grape growing season exponentially increases the risk for wine producers: in Tuscany, adverse conditions throughout 2023 have cut the real value of production more than double the national average (IRPET, 2024).

Future projections imply an even worse scenario for the Tuscan wine sector, because climate change could cause a profound shift of viticulture suitability from actual production areas, which may generate a drop of 85% in wine production by 2050 (Galbreath, 2016; Hannah et al., 2013). According to Moriondo & Bindi (2007), an increase in temperature of 4°C would

shift premium varieties towards higher elevations (400-800 m above sea level). In areas suitable for best quality wines, worsening vintage quality will move the equilibrium toward the substitution of present varieties with those typical of southern Mediterranean areas, producing generally low quality and high alcohol content wines. The production of premium quality wines will be restricted to higher hilly areas that at the moment are not viable for grapevines. This shift would deeply affect the regional wine industry: the Tuscan wine economy, based on export of premium quality wines, will have to reduce this type of production in favor of lower quality varieties that may not meet local and international market demand; moreover, moving production higher would increase production costs, further decreasing the income of companies already affected by lower yield and vintage quality (Moriondo et al., 2011).

These scenarios could at least be improved by timely adaptation, which we will see if it is happening in the next chapter, but this requires a sustainability base of the industry and solid institutional support; however, Tuscany seems to be lacking in both categories. In the Sustainability Wine Index, proposed by Sardone et al. (2023), the region ranks near the Italian average in all three dimensions, with slightly better results for environmental sustainability, but consistently lower than comparable regions such as Piedmont or Veneto. From the institutional point of view, Pietta et al. (2022), in their analysis of regional adaptation policies, report that Tuscany has not provided an adaptation strategy or plan, but only approved a document on climate change without focusing specifically on adaptation nor single industries.

3.2 Relevance and Aim of the Study

We have seen that climate change will inevitably transform the wine industry with a speed and depth more powerful than any other supply or demand factor, especially in a region where wine is a big part of the history, culture, landscape and economy as in the case of Tuscany. Therefore, the objective of this research is to analyze if and how wine companies in the region are reacting to the current impacts of new climatic conditions and are adapting to the forecasted consequences of climate change.

The relevance of this subject can be found in the Sixth Assessment Report by the Intergovernmental Panel on Climate Change (Ara Begum et al., 2022), where it is recognized the existence of an adaptation deficit, defined as inadequate or insufficient adaptation to current conditions. Adaptation efforts have increased significantly in the last decade, but assessing their effectiveness and adequacy is challenging also due to the lack of relative literature, so research in this area can improve the understanding of climate change and provide new adaptation solutions. In particular, given that most of current studies focus on climate change policy,

governance or theoretical basis for adaptation practices, a focus on business adaptation strategies is missing. This is fundamental because adaptation is always to the here and now, so different companies in different industries will have different adaptation strategies (Galbreath, 2014; Russel et al., 2020). Moreover, managers are the final recipients of policy and, at the same time, the ones who have to concretely choose and realize adaptation options. For these reasons, this research aims to assess climate change adaptation strategies currently activated or planned by wine companies operating in Tuscany.

First, we need to understand how natural environment and climate change are perceived by those companies. Following the attention-based view of the firm[17], the natural environment can be considered a primary stakeholder; companies' decision-makers who think of nature as a primary stakeholder usually have a direct learning and understanding of opportunities and threats provided by nature and how these can affect the strategic landscape of the firms in relationship with the other stakeholders (Haigh & Griffiths, 2009). We will use attention to and proactivity in environmental sustainability as a proxy to check whether Tuscany wine companies consider the natural environment as a primary stakeholder. In the same way, we will check if managers of these companies consider climate change as having legitimacy, power, urgency, and proximity, which are the characteristics of a primary stakeholder (Galbreath, 2014; Galbreath et al., 2020).

Then, this study is going to verify if some common assumptions contained in adaptation literature, that could be true in the past, hold true in this specific sector and area. For instance, many analyses of economic effects caused by climate change do not consider spontaneous adaptation (differently from the literature, we will call this approach 'myopic farmer' scenario), and past reports on the subject affirm that, despite the expected benefits in terms of loss avoidance, adaptation measures are not implemented widely (Ashenfelter & Storchmann, 2016; Gasbarro et al., 2019). In the case of disproving these assumptions, it will be necessary to examine how companies evaluate the economic viability and returns of adaptation and which time horizon is chosen for the evaluation, given that the worst effects of climate change could be over 50 years away (Galbreath, 2015; Pomarici & Seccia, 2016).

Collaboration and communication with other companies, institutions and the final market constitute another relevant point to investigate. Innovation is a fundamental factor in the development of new adaptive technologies or practices and could be easier to achieve through

[17] "An attention-based theory views firms as systems of structurally distributed attention in which the cognition and action of individuals are not predictable from the knowledge of individual characteristics but are derived from the specific organizational context and situations that individual decision-makers find themselves in." (Ocasio, 1997, p. 189)

coordinated efforts of companies, research institutions such as universities, and governmental bodies. However, innovative adaptation efforts come at a cost, so these organizations must embrace the challenging process of addressing and communicating climate change to the public (European Commission, 2021). In our study, we will test the propension of wine companies in Tuscany to collaborate and create networks but also listen to their needs in terms of financial or other types of support to overcome climate change adaptation challenges.

3.3 Research Methods

To answer the main research questions posed in this thesis, aimed at analyzing whether and how Tuscan wine companies are implementing adaptation strategies to contrast the impacts of climate change, a qualitative approach was chosen. To obtain primary data, the case study methodology was chosen, because it can fit this topic particularly well: from the words of decision makers, it is possible to deeply understand the motives of business strategies and the nuances of perception of a complex and novel subject such as adaptation to climate change. Moreover, it is an often used method in the existing exploratory studies about this specific topic (Galbreath, 2011, 2014, 2016; Gasbarro et al., 2019; Moggi et al., 2020; Pierli et al., 2023). The resulting data was then interpreted through a qualitative analysis based on the Gioia Methodology (more on that in Section 4.2) (Gioia et al., 2013).

To ensure credibility, dependability and confirmability of the results, the research was developed following the steps detailed by Bell et al. (2019):

1. General research questions. Drawing on previous literature about the wine industry, sustainability, climate change, and adaptation (see Chapters 1 and 2), we found a research gap in current climate change adaptation practices in the wine industry and developed the general aims detailed in the previous section.
2. Selecting relevant site and subjects. The area of interest was chosen among Italian regions based on an analysis of the economic importance and vulnerability to climate change of the local wine industry (see Section 3.1). After the selection of Tuscany, we used the AIDA database to find a comprehensive list of wine companies operating in the region. As suggested by experienced researchers, to ensure a higher response rate, we checked their interest in environmental sustainability by inspecting websites and news about the companies. Over fifty companies were contacted by email: only five showed interest in participating in the research (a response rate in line with other studies), but two of the respondents did not have time to organize the interview. Therefore, to get a more significant

number, we used snowballing[18] and personal contacts to find three other companies willing to participate, for a total of six.

3. Collection of relevant data. Qualitative data was collected through semi-structured interviews with managers, agronomists and entrepreneurs from the participating companies. The semi-structured interview with open-ended questions represents a powerful tool in qualitative research because it allows the researcher to acquire in-depth information from interviewees, guiding the conversation but leaving room for flexibility and adjustments (Ruslin et al., 2022). For these reasons, it is the most widely employed method for qualitative data collection (Kallio et al., 2016). The interview guide (see Appendix I) was formulated following the process suggested by Kallio et al. (2016), with main themes and follow-up questions in line with the research aims and inspired by the literature review. The protocol was divided into four main sections: after introducing the objectives of the interview and the methods with which it would have been carried out, the participants were asked some general demographic information about the companies and themselves, followed by questions about the environmental sustainability profile of the company; the second section tackled the impacts of climate change, asking whether the company suffered losses from them and which climate-related risks were considered most dangerous; the following section investigated adaptation practices and strategies implemented or planned by the company; finally, participants were asked about the challenges and economic implications of climate change adaptation, how they are evaluated and also giving space to the needs of the respondent company in terms of institutional support. Four of the six interviews were conducted on site at the company location, while the remaining two took place online through videoconference platforms (specifically, Zoom Meetings and Microsoft Teams). The interviews were carried out between October 2024 and December 2024 and lasted around 40 minutes. In-person meetings were recorded via a digital recorder and online meetings using available tools embedded in the software used; all participants gave their expressed oral consent to recording and usage of collected data. The recordings were then transcribed verbatim and double checked to ensure the correctness and orthography of the conversations.
4. Interpretation of data. A thematic analysis of the content of the interviews was conducted, to find similarities and differences between the concepts expressed by the participants.

[18] "Snowball sampling is a sampling technique in which the researcher samples initially a small group of people relevant to the research questions, and these sampled participants propose other participants who have had the experience or characteristics relevant to the research." (Bell et al., 2019, p. 396)

Specific qualitative coding or analysis software were not used in the process due to their excessive cost compared to the amount of data. Using the Gioia Methodology, open coding was used to find first-order informant-centric concepts from the raw interview data.

5. Conceptual and theoretical work. Through an inductive approach, we integrated almost 300 first-order codes into 13 second-order themes and repeated the process to reach 5 aggregate categories. This data structure was analyzed to build a grounded theory of the implementation of adaptation practices in the Tuscan wine sector.
6. Writing up findings/conclusions. The themes emerged from the research were analyzed for correspondence in the theory and the thesis was sent to interviewed participants for feedback to guarantee its reliability. The conclusions were evaluated by taking into account the intrinsic limitations of the methodology applied and accompanied by suggestions on how knowledge of the topic can be improved by future research.

4. Discussion of Results

4.1 Profiles of Participating Companies

4.1.1 Col D'Orcia

Col d'Orcia is an historic estate located in the southwestern part of the Brunello di Montalcino region, overlooking the Orcia river. The winery was established in 1890 by the Franceschi family, and was acquired in 1973 by the Cinzano family, which expanded the vineyard area and grew production significantly. For this thesis, we interviewed the actual owner, who acquired the company in 1991. The company covers 540 hectares of land, all located on the Sant'Angelo hill, of which 150 hectares are dedicated to grape growing, 200 are made up of forests and Mediterranean scrubland while the rest is composed of olive groves, arable land and farm-like activities, such as vegetable gardens, orchards and free-range poultry breeding. Thanks to this variety, the company, while being mainly dedicated to wine production, especially Brunello di Montalcino DOCG and Rosso di Montalcino DOC, provides a differentiated range of products, such as extra-virgin olive oil, pasta and honey, and agritouristic services. Since both Brunello and Rosso di Montalcino denominations require the exclusive use of Sangiovese grapes, this is the only variety cultivated in Col d'Orcia vineyards; from these grapes, about 700,000 wine bottles are produced per year (around 5,250 hectolitres).

4.1.2 Cantine Dei

Maria Caterina Dei is a sole proprietorship, named after the owner, which was founded in 1964 by her grandfather. Located in the Montepulciano territory, the company covers a total area of 80 hectares: 60 of them are dedicated to vineyards (almost double the area reported by Rosemary (2005) twenty years ago), 3.5 to olive groves, the same area to tree cultivation for wood and the rest is represented by fallow lands, forest and scrub. Cantine Dei wines are all under a denomination of origin, consisting of Vino Nobile di Montepulciano DOCG, Rosso di Montepulciano DOC, Vin Santo di Montepulciano DOC and IGT Toscana for less typical wines, such as their rosé, white and Super Tuscan[19] wines. For this reason, the predominant variety is Sangiovese, but Dei vineyards also present other red varieties, like Cabernet, Merlot, Petit Verdot and Canaiolo, and white grapes of Chardonnay, Malvasia and Grechetto varieties. As reported by the company's production manager, overseeing both the fields and the winery,

[19] The term 'Super Tuscan' was coined by prestigious Tuscan wine makers in the 1970s to distinguish their high-quality wines, produced from non-traditional varieties prohibited under denomination regimes, from inexpensive and low-quality table wine (Corsinovi & Gaeta, 2015).

Cantine Dei wine production is approximately 250,000 bottles per year (around 1,875 hectolitres).

4.1.3 Matrignano

Matrignano is a small estate of 22 hectares located near Arezzo. Founded in 1962 by Alessandro Baroni, it has been managed since 2017 by his granddaughter and her partner, with the help of her parents. They brought a new production approach to the company, with the idea of bringing bottles to the market other than selling bulk. The peculiarity of the 7 hectares of company's vineyards is that half of the vines were planted at the end of the '60s and are mixed vineyards of 80% Sangiovese and 20% other Italian varieties (Canaiolo, Colorino, San Colombana, Trebbiano, Malvasia), while the newer plantings, dating back to the start of the millennium, are made up of Sangiovese vines with a few rows of Merlot and Trebbiano. These vines generate an annual yield of 30-50 quintals per hectare, which is split into two types of productions: part of this is bottled and sold under company label as IGT Toscana (around 10,000 bottles yearly, meaning 75 hectoliters); the rest is sold as bulk wine to other wineries, getting downgraded from Chianti dei Colli Aretini DOCG to common wine once bottled. Given the small size of the company in terms of size and workforce, the interviewee covers a general administration and PR role, but does not abstain from the fieldwork when possible.

4.1.4 Ruffino

Ruffino is one of the oldest and most celebrated wineries in the world (Rosemary, 2005). With a historical base in Chianti, it was founded in 1877 by the Ruffino cousins, who later passed it down to the Folonari family, until it became part in 2010 of the international beverage group Constellation Brands. Other than the headquarters in Pontassieve, Ruffino can be found in eight sites, with six estates in Tuscany and two, acquired in 2019, in Veneto. These possessions sum up to a total area of 1,200 hectares, half of which are dedicated to viticulture and the other half is allocated to bottling, cellars, hospitality, and various other facilities, including forests, lakes, springs and olive groves. The diffused Tuscan presence translates to the production of most of the main denomination wines (Chianti Classico DOCG, Bolgheri DOC, Morellino di Scansano DOCG and many others), accompanied by famous Super Tuscan wines and whites under the IGT Toscana denomination. As always, in the Tuscan vineyards the company cultivates mainly Sangiovese grapes, with a marginal growing of Merlot, Cabernet Franc, Cabernet Sauvignon and Colorino varieties. Overall production reaches 20 million bottles a year (around 150 thousand hectoliters), which are sold to just under 90 different countries; this shows the international character of Ruffino business, where exports account for 90% of both sales

revenue and volume. The huge size of the firm relative to the typical wine company has enabled Ruffino to introduce in 2022, among the 249 employees, a specific role dedicated to sustainability: the Corporate Social Responsibility Manager, which is a transversal role, reporting directly to the Operation and the CEO. The peculiar position in the organizational chart makes the current CSR Manager, who took part in the interview, in charge of delineating a pervasive sustainability strategy, able to put sustainability at the first place in all of the firm's activities.

4.1.5 Tenute di Fraternita

Tenute di Fraternita is a public-owned company: the sole proprietor is Fraternita dei Laici and the board of directors is appointed by the Arezzo municipality. For this reason, the portfolio of agricultural products is very diverse, ranging from wine grapes, which still represent the most important production, to olives, cereals and so on. The company covers an area of about 1200 hectares, of which forest takes up the largest part with 500 hectares (bees are brought there during flowering to produce honey); of the area dedicated to crops, the majority is made up of arable land for cereals, legumes and oilseeds, while olive groves, apple trees and vineyards occupy the rest of the surface. Specifically, the company owns around 45 hectares of vineyards, dislocated across the municipalities of Castiglion Fibocchi, Civitella in Val di Chiana and Arezzo and producing up to 4000 quintals of grapes. The main variety is Sangiovese, followed by Merlot, Cabernet, Petit Verdot, Colorino, Syrah, Canaiolo for reds and Chardonnay, Trebbiano, Malvasia, Grechetto, Vermentino for whites. This amount pf grapes results in 2000 to 2,700 hectoliters of wine which is partly marketed wholesale to large bottlers and partly bottled internally (70,000 to 80,000 bottles per year) and destined to export markets both inside and outside Europe. Most of the red wines are certified Chianti DOCG, but the company produces also IGT Toscana reds and whites. For our research, we interviewed the agronomist of Tenute di Fraternita, who illustrated the strategies to bear with climate change impacts in a company with so many different crops.

4.1.6 Tenuta di Trinoro

Tenuta di Trinoro is the oldest of the three estates owned by the Vini Franchetti company. The founder, Andrea Franchetti, after a formation period in Bordeaux, decided to buy this estate located in Sarteano, at the extreme south of the Val d'Orcia area, in the '80s. This territory did not have viticultural tradition, but Franchetti recovered the hectares with most fitness for viticulture from the scrub and started to plant vines in the '90s. He found soil types very similar to the ones in Bordeaux, which enabled him to plant varieties mostly found there, such as

Cabernet, Merlot, Cabernet Sauvignon and Petit Verdot. Not only the varieties, but also vineyard techniques and training systems were imported from Bordeaux, which is also the reason why Trinoro wines, while being produced inside the Orcia DOC area, do not have this denomination of origin, but are produced only as IGT. However, Trinoro, together with other Super Tuscan producers, gained a reputation and a resulting price demonstrating the irrelevance of denominations for true high-quality wines (Rosemary, 2005). Production volume is approximately 110,000 bottles a year (around 875 hectoliters), made from 23 hectares of vineyards situated in the valley between Mount Cetona and Mount Amiata. At the interview participated the enologist overseeing Tenuta di Trinoro and Passopisciaro (the Sicilian estate of Vini Franchetti), together with the internal agronomist managing Tenuta di Trinoro vineyards.

4.1.7 Summary

Table 1. Main general information on participating companies.

Company	Type	Product Portfolio	Location	Vineyard area (ha)	Wine production (bottles)	Employees (2023)	Revenues in € (2023)
Col d'Orcia	Ltd.	Wine, Olive oil, Honey, Pasta, Beer	Montalcino	150	700,000	61	7,289,711
Cantine Dei	Sole proprietorship	Wine, Olive oil	Montepulciano	60	250,000	N/A	N/A
Matrignano	Simple partnership	Wine, Olive oil	Arezzo	7	10,000	N/A	N/A
Ruffino	Ltd.	Wine, Olive oil	Tuscany, Veneto	600	20,000,000	249	97,581,000
Tenute di Fraternita	Ltd.	Wine, Olive oil, Honey, Vinegar, Apples, Cereals, Legumes	Arezzo	45	70,000-80,000	9	658,642
Tenuta di Trinoro (Vini Franchetti)	Ltd.	Wine	Val d'Orcia	23	110,000	52	4,985,574

Source: financial data are taken from AIDA Database, the rest from the interviews or companies' websites.

From Table 1 the difference in size between the sample companies clearly emerges. The distribution does not correspond with the population of wine companies operating in Tuscany, which is mainly composed of micro- and small-size producers. But we were able to gather data from each size category: Matrignano represents small-size producers; Tenute di Fraternita, Cantine Dei and Tenuta di Trinoro belong to the medium-size category; Col d'Orcia can be considered a big-size wine company; finally, Ruffino is the third biggest wine company operating in Tuscany in terms of revenues.

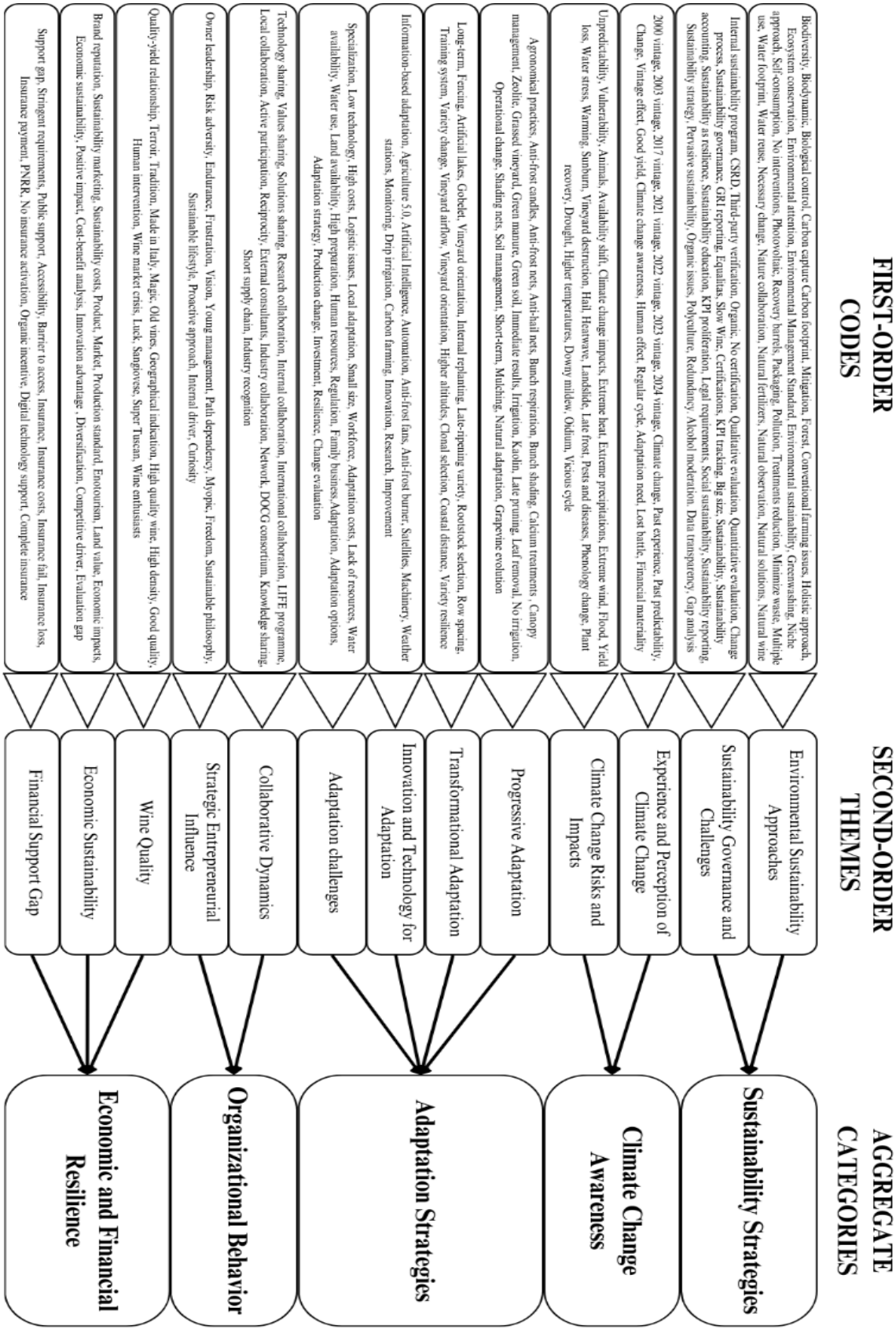
4.2 Data Structure

This study adopts a qualitative, inductive approach based on grounded theory to explore how wine companies in Tuscany adapt to climate change (Corbin & Strauss, 2014). Given the complexity and context-specific nature of adaptation strategies, a grounded theory approach is particularly suitable, as it allows theoretical insights to emerge directly from empirical data rather than being imposed by existing frameworks. Climate change adaptation in viticulture is a dynamic, multifaceted phenomenon influenced by environmental, economic, and regulatory factors, making it well-suited to an exploratory, data-driven methodology. Grounded theory provides a systematic yet flexible framework for analyzing qualitative data, ensuring that findings remain closely linked to the experiences and perspectives of industry practitioners. Through an iterative process of data collection, coding, and constant comparison, this method enables the identification of patterns and strategies that may not yet be fully articulated in existing literature. This is particularly important in the context of wine production, where adaptation strategies are influenced by local environmental conditions, traditional practices, and business considerations, all of which require an in-depth, contextualized understanding.

To ensure analytical rigor, we employ the Gioia methodology, which structures qualitative data into distinct coding stages (Gioia et al., 2013; Magnani & Gioia, 2023). This process begins with 1st-order codes, capturing the voices of industry informants, followed by the development of 2nd-order themes, which reflect researcher-driven conceptual patterns. These themes are further distilled into aggregate dimensions, providing a structured theoretical understanding of climate adaptation in the Tuscan wine industry. By applying this approach to the interview data, we identified nearly 300 first-order codes, which were then grouped into 13 themes and consolidated into 5 aggregate dimensions.

This structured process ensures theoretical transparency and traceability, making the study's findings both empirically grounded and theoretically robust. The combination of grounded theory and the Gioia methodology is particularly effective for this research because it allows for: 1) a deep understanding of industry-specific adaptation strategies, rather than relying on pre-existing theoretical models; 2) the development of a theory that reflects real-world practices, offering practical insights for wine producers, policymakers, and sustainability experts.

Figure 9. Data structure using Gioia method.



Source: personal elaboration.

4.3 Sustainability Strategies

4.3.1 Environmental Sustainability Approaches

The attention to sustainability emerges from the words of all the companies interviewed. This result confirms what has been reported in academic literature, where winegrowers have often been shown to be ahead in sustainable practices, particularly when compared to other food processors (Golicic, 2022; Pullman et al., 2010). In Tuscany, a report from (IRPET, 2023a) has highlighted how it is precisely this sector, together with the olive sector - whose companies sometimes overlap, as is also the case in the majority of our sample - that leads investments in sustainability.

At the same time, the vision regarding sustainability appears to be very narrow, mainly focused on the environmental aspect. This vision is also reflected in the literature and is probably motivated by the Natural Resource Dependency Theory, according to which if a company depends on natural resources, its actions will reflect this dependence (Broccardo & Zicari, 2020; Galbreath & Tisch, 2022; Mariani & Vastola, 2015; Moggi et al., 2020). In other words, wineries are forced to relate to nature in their daily operations, so they easily develop an instinct to conserve natural resources. For this reason, with the exception of Tenuta di Trinoro, all the companies have implemented environmental sustainability practices, starting with the conversion to organic production, which however is not automatically considered synonymous with sustainability, contrary to what Mariani & Vastola (2015) claims. Another practice that these companies have in common is improving energy efficiency, with investment in photovoltaic systems, often for self-consumption. In general, there is an explicit intention to introduce vineyard management methods based on reducing treatments and waste: a particular case is that of Matrignano, producers of natural wine with a non-interventionist philosophy, whose concept of sustainability is as follows:

> *«I would love to, the goal of this company is: it doesn't matter if I make wine or papayas, the important thing is to be able to work in nature in a way... with the least possible impact, in which you are truly in collaboration with your surroundings.»*

This approach aims to safeguard the natural ecosystem in which the vineyard is inserted, and is echoed, albeit with different practices, by the maintenance of biodiversity in the soils of Col d'Orcia, which follows a holistic environmental approach aimed at the biological control of the vineyard, especially for the protection of plant health. This is linked to the mitigation of climate change, which in larger companies, such as Col d'Orcia, Tenute di Fraternita and Ruffino, is also achieved by offsetting carbon dioxide emissions through CO2 capture by the company-

owned woodlands. All of them pay attention to the use of water resources, which is even more important in the current context of climate change. In general, the need for continuous improvement of the environmental sustainability profile is recognized, an awareness that reflects the results of other studies on the subject in the wine sector (Golicic, 2022; Moggi et al., 2020; Pullman et al., 2010).

Some researchers have tried to categorize wine producers based on their relationship with environmental sustainability. Using the groups described by De Steur et al. (2019), who divided these producers into 'high sustainability' and 'low sustainability' clusters, it is possible to include five of the six companies interviewed in the high sustainability cluster because they are characterized by a higher number of sustainability practices and more optimistic evaluation of them. The model by Santini et al. (2013) identifies four categories of wineries: 'laggards', who would never adopt sustainability practices; 'opportunists', who adopt few practices but tend to heavily highlight them; 'unexploiters', who adopt sustainability practices without informing stakeholders of the decision; 'devoted' wineries, who have a strong orientation toward sustainability and emphasize it in their communication. From the interviews, the same five companies fall somewhere between 'devoted' and 'unexploiters', with a strong orientation toward environmental sustainability that, however, is not clearly communicated to the final consumer, perhaps also due to the specific market that each company addresses. In any case, as expected, all companies have shown that they consider the natural environment to be a primary stakeholder, with whom they can communicate and collaborate according to its needs. Even Tenuta di Trinoro, despite lacking formal sustainability certifications or practices, expressed a strong connection between workers and nature, as well as careful consideration of the sustainability of their choices, for example the choice of practices that reduce pollution, as we will see in more detail later.

4.3.2 Sustainability Governance and Challenges

We have seen that organic is the main form of sustainability certification for the companies interviewed, regardless of their size. This is despite the significant difficulties involved in converting to organic, both in terms of higher production costs and greater vulnerability to climatic risks (Golicic, 2022; IRPET, 2020; Wagner et al., 2023). Organic practices are sometimes accompanied by biodynamic or natural ones, demonstrating the consideration of organic as a starting point for sustainability. In terms of environmental sustainability, Ruffino has introduced the ISO 14001 Environmental Management Standard (EMS), which can only be followed by companies with greater availability due to its high costs (De Steur et al., 2019).

The same is true in terms of general sustainability, for which the company has an internal sustainability program called Ruffino Cares and uses the GRI[20] methodology to publish sustainability reports despite the large number of key performance indicators to be tracked. This is also possible thanks to a corporate governance structure with a managerial role dedicated exclusively to sustainability; in fact, Galbreath et al. (2020) state that governance mechanisms are fundamental for the effectiveness of sustainability strategies. And they will become even more important with the introduction of the European Union's Corporate Sustainability Reporting Directive, which, according to Ruffino's CSR manager, will lead to a proliferation of KPIs up to twice as many as those required by the GRI standard.

The economic and governance obstacle largely explains why companies in the wine sector in Italy have so far shown a low rate of adoption of sustainability programs, although their number has increased sharply in recent years (Flores, 2018; Moggi et al., 2020; Pizzol et al., 2021). However, the majority of the sample interviewed is still undergoing a process of change due to the introduction of the Equalitas sustainability standard. In this case too, companies are faced with bureaucratic, economic and organizational challenges: Tenute di Fraternita, which, like Cantine Dei and Col d'Orcia, has undertaken the process for Equalitas certification, explains the difficulty in fulfilling the hundreds of points required by the certification at an environmental and social level, compensated however by greater ease of access to markets more sensitive to the issue, such as Canada and Northern Europe.

From the point of view of social sustainability, a noteworthy initiative is Ruffino's participation in the international program Wine in Moderation as an Ambassador Company, for the promotion of responsible drinking. On the other hand, there is a lack of social sustainability practices carried out by the other companies, which will certainly dedicate more attention to this aspect with the transition to Equalitas certification.

In general, the empirical rule that large companies in the sector are more sustainable is confirmed, mainly thanks to the greater availability of resources to invest in projects and innovation (Moggi et al). Other obstacles remain external to the companies, such as the low awareness of sustainability among Italian wine consumers, which sometimes leads to confusion and mistrust towards companies that claim to be sustainable (Golicic, 2022; Mastroberardino et al., 2020). Finally, bureaucratic barriers and excessive administrative burdens are still a hindrance to sustainability, especially for smaller companies (IRPET, 2019).

[20] It is a standard overseen by the non-profit organization Global Reporting Initiative, created with the aim of harmonizing sustainability reporting methodologies on a global level (Global Reporting Initiative, n.d.).

4.4 Climate Change Awareness

4.4.1 Experience and Perception of Climate Change

Climate change has been a recognized reality in the wine sector for years: a study by Battaglini et al. (2009) shows that already in the first decade of the 21st century the majority of wine producers had noticed changes in the climate compared to the past. Such awareness derives from the specific activity of winegrowers, for whom climate impacts all business operations, from the vineyard to marketing (Battaglini et al., 2009); this allows them to have direct experience of climate change, which, according to Gasbarro et al. (2019), is a fundamental factor in motivating companies to undertake adaptation actions.

In the interviews, the same high degree of awareness of climate change is found. The interviewees who have been working in the vineyards for the longest time, namely the respondents from Col d'Orcia and Tenute di Fraternita, indicate the early 2000s as a turning point, in particular 2003, when they observed extreme heat phenomena for the first time. Since then, companies have reported an increase in years characterized by extreme weather events, which have gone from being the exception to the rule. If before the operations in the vineyard followed a basically predictable cycle, now even good years see an anticipation of the phenological phases of the vine. And there seem to be fewer and fewer good vintages, given that since 2017, described by Tenuta di Trinoro as a vintage full of extreme climatic events, almost every year the Tuscan producers consulted have experienced problems related to climate change. Precisely because of this acceleration, companies see the fight against climate change as a lost battle, so the impacts generated by the company (impact materiality) are now negligible, while the impact of climate change on the company (financial materiality) is becoming increasingly important. The vision of the sample object of this research is not dissimilar to what Loose (2024) discovered, whereby 45% of respondents to the ProWein Business Report 2023 survey considered climate change to be one of the major threats to the wine industry. The only option to counter this threat, according to the producers interviewed, is the necessary adoption of climate change adaptation practices.

4.4.2 Climate Change Risks and Impacts

Ruffino summarized the main impacts of climate change as follows:

> *«Now, what's really happening? We have the heat that is more constant, basically; this causes things to germinate earlier. But the heat is not always constant, on the contrary it alternates with sudden frosts, even late frosts, much later than they were twenty years ago, that is to say*

there is an absurd difference between twenty, thirty years ago and today. There are many more heat waves, and they last much longer. There is rain, from the point of view of rainfall, but it varies a lot, that is, there are some years of drought, but it doesn't vary that much; the problem is that the way this water arrives varies: it arrives after dry periods with so-called "water bombs", so you get a month's worth of rain in 2 or 3 hours or in one day and then it stops raining. What happens? The drier the soil is, the less water it absorbs, it's like a dog chasing its own tail. Then, when this water bomb arrives, the soil can't retain it well, and phenomena of erosion and washouts are created, so the vineyard can collapse, in short, it's a bit of a problem. Or, you have periods of drought: until thirty years ago, we never needed to irrigate. Irrigation in the vineyard was not necessary, period. It was a fairly resistant plant that had its own peaceful cycle.»

From this picture, which is also confirmed in the other interviews, it can be deduced that the most insurmountable problem does not derive from individual climatic risks, but from their combination. Another example, reported by Tenute di Fraternita and Matrignano, concerns the presence of parasites and diseases, facilitated by heavy rainfall, which at the same time prevents the implementation of defense treatments in the vineyard, making the impacts more serious; the case of hail is different, as it inevitably leads to the partial or complete destruction of the plant. Even more specific events are attributed to climate change, such as the increased presence of ungulates in the cultivated hectares of Matrignano and the gusts of extreme wind that have broken off the branches of centuries-old olive trees belonging to Col d'Orcia.

Many producers see the effects of climate change more on yields than on grape quality, since from a qualitative point of view it is human intervention, for example during the harvest phase, that makes the difference, as Col d'Orcia explains. On the other hand, the loss of production following extreme weather events is clearly visible, also given the sometimes catastrophic extent: in 2023, following heavy rainfall and consequent attacks of downy mildew, Matrignano managed to obtain only 10% of its usual wine production, a situation similar to that experienced in the vineyards of Cantine Dei. In the same year, Ruffino's production at one of their various estates was completely wiped out due to a fungus. However, not everyone agrees on the clear difference between quantitative and qualitative impacts: for Tenuta di Trinoro, adverse climatic events destabilize the balance of the grapevine, inevitably altering the quality of the wine. Compared to the impacts perceived by Italian producers in the research by Battaglini et al. (2009), it is clear that any type of positive impact on quality or quantity has been lost.

Direct impacts lead to a series of indirect problems for companies (Galbreath & Tisch, 2022). One of these is the constant unpredictability that has replaced the vintage effect and makes

planning almost impossible. Here too, adaptation is a necessary response to try to reduce vulnerability to unpredictable climatic events.
In general, as for the natural environment, climate change is considered a primary stakeholder in the strategic decisions of Tuscan wineries.

4.5 Adaptation Strategies

4.5.1 Progressive Adaptation

The main approach taken by companies to react to the urgency with which climate change is manifesting itself is that of short-term adaptation practices, since they can be implemented quickly and give immediate results. From this point of view, the results are in line with academic literature, both in terms of the fact that producers are trying to respond to the risks of climate change, and in terms of how they are doing it, that is, primarily with water management and canopy management techniques (Galbreath, 2016; Galbreath et al., 2020; Pomarici & Seccia, 2016). In fact, all the interviewees spoke about canopy management practices in the vineyard, such as modifying pruning techniques (including late pruning), changing the vine training system and applying treatments to the leaves or bunches. The latter refer to the application of calcium by Col d'Orcia or the covering of bunches and leaves with kaolin in the case of Tenute di Fraternita. All these interventions are mainly aimed at counteracting the excess heat and radiation that damage the development of the plant, thanks to an increase in bunch shading and respiration.
As far as water management is concerned, the main form of adaptation is irrigation. We have seen previously (see Section 2.4) how this solution tends to be opposed in Old World viticulture, since until a few years ago it was not necessary for this production. Now, even the most reluctant companies are forced to recognize the need, at least in the future. Other companies have already introduced drip irrigation systems: these tend to be companies with more resources, such as Ruffino (which also practices fertigation) and Col d'Orcia, or companies less tied to local traditions such as Tenuta di Trinoro.
Soil management practices also play a fundamental role in progressive adaptation, counteracting both heat and radiation-related problems and the consequent water stress. Among the most common solutions we find the use of green manure, mulching and maintaining the greenery in the vineyard soil. A lesser-used practice, employed only by Col d'Orcia and Tenute di Fraternita, is the addition of zeolite to the soil, as explained during the interview with Col d'Orcia:

«Zeolite is a volcanic rock, a particular type of rock with a chemical structure that gives it special hydroponic properties, so that zeolite accumulates humidity at the cooler winter temperatures and then releases it again at the high summer temperatures.»

One last technique used by Tenuta di Trinoro is to cover the vineyard with shading nets, which have also proven useful for protection from late frosts and for reducing hail damage. In the future, this multiplicity of purposes could also be discovered in other techniques, making adaptation more efficient.

4.5.2 Transformational Adaptation

The other category of adaptation strategies concerns long-term practices that require significant transformations of production methods and of the vineyards themselves. These are mainly two types of practices: the choice of plant material and the modification of the structure and position of the vineyard. Although the solutions belonging to the first group, mainly the replacement of the rootstock and the variety with types more resistant to climate change, are one of the best adaptation tools in terms of environmental and economic sustainability, as well as being widespread in other wine regions, they are rarely adopted in the Tuscan context (Galbreath et al., 2020; Pomarici & Seccia, 2016; van Leeuwen & Darriet, 2016). In addition to the time factor linked to the long lifespan of grapevine plants, there are several reasons why these solutions are rarely applied: for Tenute di Fraternita, replacing Sangiovese would mean distorting the nature of Tuscan wine and it would only be possible to do so in small quantities; in the Matrignano vineyards, on the other hand, they have observed that the oldest plants are those with the greatest resilience; Tenuta di Trinoro has chosen to focus on the already prevalent variety, Cabernet Franc, because it has noticed that it is well suited to the increase in temperatures. There are also those who have made changes, such as Cantine Dei, but for purely commercial reasons, not related to sustainability or climate change. As for the vineyards themselves, Col d'Orcia has added a few small *gobelet* vineyards and restructured others by changing row orientation, as other companies plan to do in the future. Other interventions planned by the interviewees concern increasing the space between the rows, to make the vineyard more ventilated and allow the plant to breathe better. If we talk about investing in new land with better expected climatic conditions, we find two insurmountable limits for many companies: one is the lack of available hectares in areas within a denomination, as explained by Col d'Orcia; the other is, of course, the heavy financial investment required by such a strategy. In fact, once again it is the more structured companies that have acquired new land, with Tenuta di Trinoro that has expanded its production area up towards Mount Amiata, slope

permitting, and Ruffino that has moved into the Bolgheri area, closer to the sea, where it has found more tolerable climatic conditions than those currently encountered in other traditional wine-growing areas of Tuscany.

4.5.3 Innovation and Technology for Adaptation

One of the most recent IRPET (2023a) reports reveals that the propensity of Tuscan agricultural entrepreneurship to innovative investments is growing but still low. The same result is also obtained from the interviews in this research, in which only two companies show an innovative and technological character. Ruffino uses agriculture 5.0 practices to obtain data on climate change and its impacts in order to improve and make adaptive solutions more sustainable: using satellites, they analyze meteorological information by means of artificial intelligence systems that generate forecasts on the water and nutritional needs of the plants to be supplied by fertigation, while 5.0 machinery studies and maps the vineyard in order to improve the efficiency of treatments. Tenuta di Trinoro, on the other hand, has replaced the expensive, polluting, dangerous and inefficient anti-frost candles with automated fans, combined with a burner, which are activated when necessary to move and heat the cold air.

Borrowing from Füssel & Klein (2006) categories, these companies are among the 'smart farmers', who use available information on expected climate conditions to adjust to them proactively. The other companies, on the other hand, tend to adjust management practices in reaction to persistent climate changes only, belonging to the 'typical farmers' group. This does not mean that their adaptation is not information-based: almost all the participants have weather stations to monitor the weather and pests. It is possible that this is again a question of different sizes. Naturally, greater opportunities to invest in technological innovation, even by smaller companies, could greatly strengthen efforts to adapt to climate change (Bednar-Friedl et al., 2022).

4.5.4 Adaptation Challenges

Adaptation, although seen as necessary and already introduced in the strategies of the companies interviewed, is hindered by three types of barriers, which in part are similar to those identified for sustainability strategies.

1) Organizational limits. The unpredictability of the climate and the high variability of extreme events in their form and combinations, forces companies to try to anticipate all possibilities without being actually able to do so. Ruffino explains it well:

> *«And the real problem, look, is this: you can't just have... it's not anymore like, "ok, it's not raining, I'll water, and that's my plan A, period". No, I need plan A, B, C, it might not rain, it*

might freeze, it might rain too much. It's not like you can say, oh well, I have a dry season and a rainy season. No, maybe I have a bit of a dry season, a bit of a rainy season, a bit of season... Unfortunately, you now have to have 800 plans; and that's the problem of adaptation, something that our grandparents didn't have to do from an agricultural point of view. Then, of course, there was the ill-fated year, but it was just one, you didn't have 28,000 of them.»

Furthermore, dealing with adaptation requires very advanced skills within the company, in order to increase its absorptive capacity (Galbreath et al., 2020). Therefore, unprecedented levels of preparation, continuous education and specialization are required from agricultural entrepreneurs and human resources. Finally, there are strictly logistical problems, where adaptation practices make agricultural operations even more complex: one example is the use of shading nets that, once placed on the vineyard, prevent further treatments, or the shortage of agricultural workers during the period in which late pruning is carried out.

2) Economic limitations. According to Galbreath et al. (2020), company size in the wine sector is positively associated with adaptation practices. The present research seems to confirm this statement and the underlying reason is plainly the greater availability of economic resources. In fact, as with sustainability, adaptation is expensive and poorly remunerated by the market. We know that Italian and Tuscan farms tend to be micro-enterprises under family management (IRPET, 2023a; Sellers & Alampi-Sottini, 2016). This characteristic of the sector forces companies to favor reactive adaptation solutions for short-term survival, which could develop into maladaptation practices if climatic conditions worsen (Bednar-Friedl et al., 2022).

3) Limits of sustainability. Certain forms of adaptation could directly conflict with sustainability objectives. For example, the need for irrigation in crops that were previously exempt from it means a greater expenditure of water resources, resources whose scarcity is expected to increase. Ruffino has responded to this issue by creating artificial basins, which have the dual function of collecting rainwater and mitigating the extent of damage resulting from extreme rainfall. All the other companies that don't have the possibility of building lakes will have to find other ways to keep their water footprint under control while managing to avoid water stress for their plants. Another potential problem concerns the availability shift of areas suitable for viticulture, which seems destined to lead to expansion into new areas. In this case, adaptation strategies should try to anticipate the direct and indirect impacts on the ecosystems and communities of these places (Hannah et al., 2013).

4.6 Organizational Behavior

4.6.1 Collaborative Dynamics

Cooperation is important for the circulation of information, thus compensating for any information asymmetries, reducing transaction costs and favoring the spread of innovation. Furthermore, in contexts of scarce resources and high fragmentation, cooperation can favor vertical and horizontal integration and stable configurations of supply organization can increase the added value of production, with positive spillover effects both in terms of competitiveness and reduction of environmental impact. Companies specializing in permanent crops tend to be more inclined to collaborate, an attitude also found in the sample of companies interviewed in this research (IRPET, 2023a).

The dynamics of collaboration can involve various players outside the company, mainly grouped into government and research institutions, other wineries and external consultants.

The collaboration with the first group of organizations is mainly aimed at research in the activities of the participating companies: Col d'Orcia has been maintaining a grassy vineyard for thirty-five years as part of a research project with the University of Florence, while it has collaborated with the National Research Council (CNR) for the use of zeolite as an adaptation practice; Tenute di Fraternita collaborated with the Arezzo municipality's waste management company to use sustainable compost made from the city's organic waste in the vineyard; Ruffino took part in various environmental projects under the aegis of the European Union's LIFE programme. Collaborations for research purposes are necessary for sustainability and adaptation, because they allow the transformation of technical knowledge born from science into business practice (Pomarici & Seccia, 2016). Another way to interact with institutions is also implemented by Ruffino, who collaborates with local authorities on social sustainability initiatives, such as when they supplied equipment to the authorities when a neighboring town was hit by a flood.

Another common factor is the collaboration with other local companies, which can have commercial purposes, as in the case of Tenuta di Fraternita, or be aimed at sharing solutions, as is the case concerning the constant exchanges with other producers maintained by Matrignano, or sharing tools and data within a network of local companies, as is the case with the weather stations provided by Cantine Dei to the Consorzio del Vino Nobile di Montepulciano DOCG. Even partnerships that started out as purely commercial can, over time, become a powerful tool for sharing sustainability and adaptation practices (Moggi et al., 2020).

Finally, we have collaborative dynamics expressed in the collaboration with external agronomic consultants, on whom Cantine Dei and Tenuta di Trinoro rely, able to spread best practices of sustainability and vineyard adaptation to multiple companies. This can greatly speed up the process of adaptation in the sector, as demonstrated by the crucial contribution of SPEVIS[21] (where the agronomist of Cantine Dei comes from) in the rapid process of organic conversion of Tuscany vineyards (Chaminade & Randelli, 2020).
The most interesting and positive aspect is the open attitude to sharing knowledge and information expressed by all the interviewees, with a vision described as follows by Col d'Orcia:

> *«In reality, what one contributes sooner or later, maybe even in not so clear or direct ways, comes back.»*

Not only colleagues, but also academic literature agree with them: the involvement of external stakeholders and the free sharing of information are fundamental aspects in the development, in the timeliness of adaptation decisions and in the improvement of the company's sustainability (Battaglini et al., 2009; Golicic, 2022).

4.6.2 Strategic Entrepreneurial Influence

In the literature on sustainability and adaptation in the wine sector, internal factors are considered to be more important than external factors (De Steur et al., 2019; Flores, 2018; Mariani & Vastola, 2015). In fact, in this sector, leadership theory, which suggests that the actions of firms can be at least partly predicted by the attitudes of their leaders, can explain much of the organizational behavior of firms, because the leadership roles tend to be covered by the owner as CEO and a couple of other managers, often relatives of the owners or functional experts (Galbreath & Tisch, 2022). Owners provide their entrepreneurial beliefs, which can become a key lever to enhance or arrest sustainability processes (Moggi et al., 2020).
Leadership theory seems to perfectly apply in some of the cases presented by our interviewees. Case in point is the influence of the founder's initial vision on current decisions at Tenuta di Trinoro: the company has no certification of any kind, including organic and denominations of origin, as the owner did not want his products to be categorized. This case also shows how important the leader's vision is in long-term consequences, such as the choice of grapevine variety:

[21] "SPEVIS (Experimental Station for Viticulture Spevis) is a private institution that studies the most effective ecological solutions in viticulture. The project was created in cooperation with wine producers and scientific consultation with prestigious research institutes." (SPEVIS, n.d.)

«We don't change, but because someone saw further, with a longer range previously.»

The values and ideas of the owner are even more important in a small company like Matrignano. Here, the owner's philosophy of non-interventionist environmental sustainability is fully reflected in her strategic choices, even when they slow down the adoption of adaptative and innovative practices.

Although founded on the same basis of deep respect for nature, the vision of the owner of Col d'Orcia goes in the totally opposite direction. The opening of his company to sharing, innovation and research (see Section 4.6.1) is based on a sense of curiosity of its owner that leads to the observation of the behavior of the plant in order to take the necessary measures, especially in terms of adaptation.

«We need to have the scientific research spirit that they had in the mid-nineteenth century, when Darwin postulated the theory of evolution - by now it's no longer a theory, it's recognized as a reality - and we really need to observe the behavior of the plant, the behavior of nature in relation to these phenomena and act accordingly.»

4.7 Economic and Financial Resilience

4.7.1 Wine Quality

The dominant business model in the wine industry consists of producing high quality wines that warrant premium pricing (Pullman et al., 2010). This is even more true for a traditional region like Tuscany, where producers emphasize the terroir to generate consumer appeal. Generally, wine quality is seen to be enhanced through conscientious environmental stewardship, but for Italian wine it is still reputation the determining factor in market demand (Pullman et al., 2010; Winfree et al., 2018). All this leads many Tuscan producers, especially in a moment of market downturn, to try to enhance the value of their products by referring to the wine-making tradition of the territory: this is why Cantine Dei is increasing the production quota of Sangiovese. Another important element in defining the quality of Tuscan wine, at least in the eyes of the customer, is the designation of origin; it is no coincidence that most of the participating companies produce mainly or entirely wines with protected designation of origin/geographical indication. Col d'Orcia defines the elements prescribed by the Brunello di Montalcino DOCG regulations (100% Sangiovese, Montalcino microclimate, oak barrels) as a “magic formula” that explains the extraordinary success of this wine. But quality remains central even for those who don't use geographical indications to signal it, as is the case for the expensive Super Tuscans from Tenuta di Trinoro.

Anyway, the focus on quality can have positive repercussions on environmental sustainability, since the relationship between quality and yield is inversely proportional. This favors vineyards that consume fewer resources and have characteristics that allow them to better withstand the impacts of climate change. At the same time, rising costs to preserve the heritage and the regional character based on terroir and competition with new producing areas may represent the endgame for many small-size Tuscan wine companies (Pomarici & Seccia, 2016).

4.7.2 Economic Sustainability

Economic sustainability is the key to overcoming the challenges posed by climate change. However, this aspect of sustainability is often formally neglected by companies, sometimes because it is not understood, sometimes because the unpredictability of climate change is such that it does not allow the company to carry out structured economic planning. As with social sustainability, producers who are obtaining Equalitas certification will be forced in some way to make economic sustainability an integral part of their strategy.

Even if not explicitly stated, economic sustainability must be present to guarantee the survival of a company in the market. The very structure of the Tuscan wine sector makes the economic sustainability of many companies precarious: in fact, the profitability of winegrowers is very low, with as many as 40% of companies operating at a loss (IRPET, 2022). This data is obviously not reflected in our sample, but it is still important to understand the representativeness of companies like Matrignano, when they talk about frustration linked to constant production uncertainty and the future option of stopping or changing production. Indeed, diversification is an increasingly widespread strategy in the sector and can translate into changes in production for Tenute di Fraternita, expansion into other areas for Ruffino or the development of wine tourism, mentioned by Col d'Orcia but already practiced by the majority of companies.

The costs and benefits of sustainability and adaptation strategies play an increasingly important role in companies' economic considerations. While the increase in expenses due to investments in these fields is clear, their benefits are difficult to measure quantitatively. The uncertainty factor returns: without the counterfactual, companies struggle to assess the short-term economic return of adaptation practices, as they would not be able to know the impacts of climate change on production.

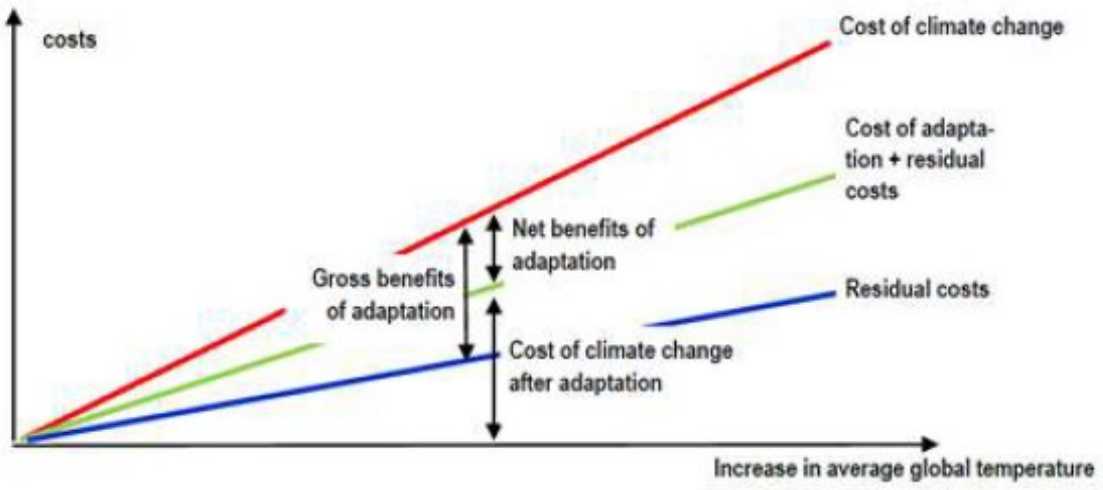
In order to try to reduce vulnerability to these economic risks, the classic choice is insurance policies. On this issue, the behavior of the companies interviewed differs considerably, ranging from taking out comprehensive insurance to deciding not to cover themselves. But the

assessment is quite unambiguous: insurance is not an economically viable solution. There are many reasons for this: the increase in premiums linked to the increased vulnerability of the sector; the mechanism for covering individual extreme weather events, which involves high deductibles and, above all, does not consider losses due to a combination of factors; the calculation of the value of the company based on the value of the land, whereby the highest quality grapes from companies such as Tenuta di Trinoro, which do not adhere to any designation regulations, are assigned the value of common wine. These are all mechanisms that need to be revised before they are exacerbated by the expected worsening impacts of climate change.

Despite the numerous difficulties, the companies interviewed generally consider the economic impact of sustainability and adaptation practices to be positive, which is why they continue to make investments. This result is in line with other studies, as well as with the models of the relationship between costs and benefits of climate change (Fig. 10) (Broccardo & Zicari, 2020; IRPET, 2023a; Pullman et al., 2010).

What could help improve the economic sustainability profile is the adoption of strategies to enhance and promote sustainability, perhaps even with bold brand repositioning, that show and educate consumers on the relevance of the practices implemented to try and capture a premium price in a future scenario of greater attention to the issue from the demand side (Golicic, 2022; IRPET, 2023a; Mariani & Vastola, 2015; Pullman et al., 2010).

Figure 10. Model of relationship between climate change and adaptation costs.



Source: retrieved from Ministero dell'Ambiente e della Sicurezza Energetica (2023b).

4.7.3 Financial Support Gap

The economic difficulties that emerged in the previous section can only be addressed through targeted institutional support. Financial measures include simplifying procedures for obtaining subsidies, and insurance premiums and interest rates that incentivize adoption of climate-friendly agricultural methods (Bednar-Friedl et al., 2022). In fact, it is the difficulty of access and the overly stringent requirements that prevent smaller companies from obtaining funds, often including those that need them the most. Matrignano says it effectively:

> *The feeling you get is that if you don't have a starting point or if you don't want to buy what these funds are asking you to buy, you don't get the funds. [...] So, some big companies take everything and you're there saying: "I really just wanted to fence in, I didn't want to do anything else, no big interventions, I'm not interested in a tractor with geolocation; I have 7 hectares that if you shout you can hear". Well, if you don't want to buy a tractor with geolocation or remove and replant all the plants, you won't get the funding.*

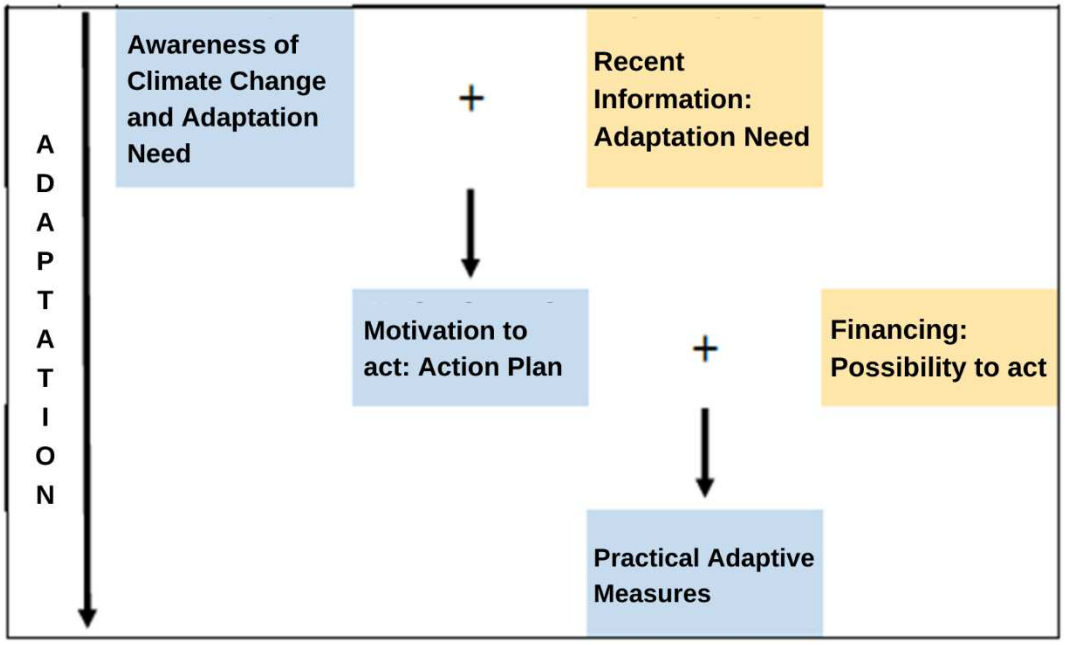
And this feeling seems to be confirmed in interviews with larger companies, which are able to obtain more funds and participate in more projects.

In general, according to the companies interviewed, the negative moment of the wine market and the need to implement expensive adaptation strategies require greater funding from the institutions. As we saw in the literature review (see Section 2.2), if the objective is to counteract climate change and its effects, they are right to make these requests, as only a coordinated approach between the public and private sectors can effectively increase the overall level of resilience (Gasbarro et al., 2019).

4.8 Adaptation Strategies Model

To conclude the analysis of climate change adaptation strategies in the Tuscan wine sector, we tried to develop a model describing the interactions between the aggregate dimensions identified through the Gioia approach in interview data.

Figure 11. From climate change awareness to adaptation measures.



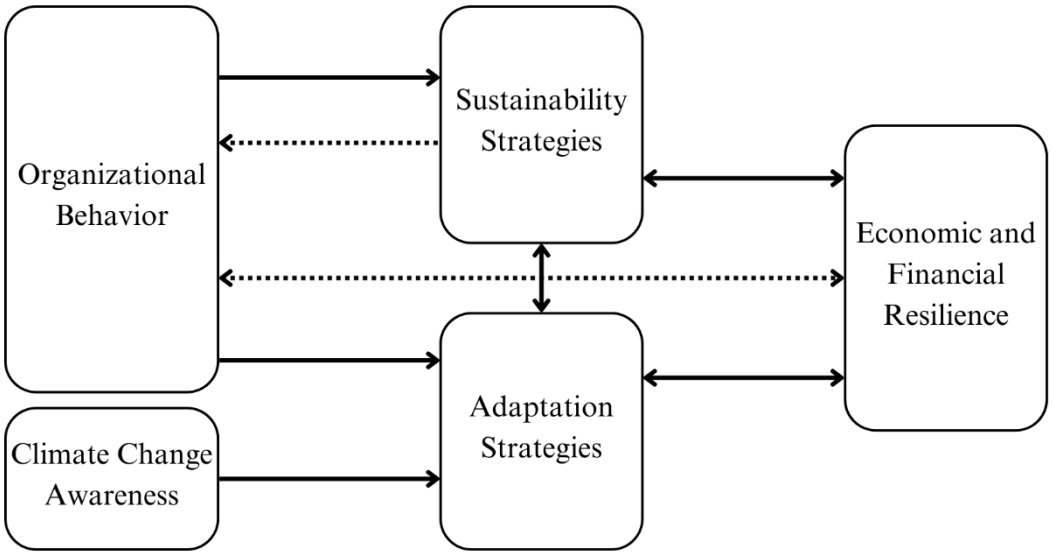
Source: adapted from Ministero dell'Ambiente e della Sicurezza Energetica (2023b).

The starting point was Figure 11, a model of adaptation drivers contained in the first annex of the PNACC, the Italian Climate Change Adaptation Plan (Ministero dell'Ambiente e della Sicurezza Energetica, 2023b).

While climate change awareness and financing opportunities remain two fundamental conditions for the introduction of adaptation strategies, our study expands the scope with the consideration of sustainability strategies and introduces other relevant dimensions with great influence on the decision-making of wine companies.

In our model (Fig. 12), we can see the overarching role of organizational behavior components, namely collaborative dynamics and entrepreneurial influence, in shaping the sustainability and adaptation strategies, while being both generator and dependent on economic and financial resilience. This dimension, on the other hand, is more directly impacted by sustainability and adaptation strategies, that, in turn, cannot be fully implemented without a strong economic and financial foundation. A key interaction is also the one between sustainability and adaptation: these two types of strategies can both reinforce or undermine each other, meaning that they should be developed in an integrated manner.

Figure 12. Scheme of interactions between the dimensions investigated.



Notes: arrows indicate the direction and power of influence of one dimension on another (dotted=less powerful). *Source*: personal elaboration.

Conclusion

As climatic conditions continue to change, particularly for natural resource-dependent industries such as wine production, firms must increasingly incorporate climate information into their strategic decision-making. However, the extent to which they can effectively respond depends on their absorptive capacity, that is their ability to recognize, assimilate, and apply knowledge to adaptation strategies (Galbreath et al., 2020). Our study contributes to this discussion by contextualizing the relationship between climate change and firm adaptation, demonstrating that wineries with higher absorptive capacity, often linked to financial resources, leadership vision, and collaborative networks, are better positioned to implement effective adaptation strategies. Indeed, the findings suggest that companies with greater economic and organizational capacity, such as larger firms like Ruffino and Col d'Orcia, have been able to invest in technological innovations like precision agriculture, AI-driven climate modeling, and automated smart systems, giving them a potential competitive advantage in the future (Galbreath et al., 2020). In contrast, smaller wineries, such as Matrignano, often rely on traditional adaptation methods, facing significant economic constraints that limit their ability to make long-term investments in climate resilience.

At the same time, sustainability strategies and climate adaptation efforts are not always aligned, with companies navigating the tension between short-term survival and long-term transformation. While environmental sustainability remains a priority, with widespread adoption of organic certifications, biodiversity conservation efforts, and energy efficiency measures, the study reveals a lack of integration of social and economic sustainability within many firms. This aligns with the idea that sustainability transformations require deep structural shifts, involving not just environmental changes but also economic, social, political, and technological transformations, which take time and require collective action to overcome system inertia (Chaminade & Randelli, 2020). Notably, despite their strong environmental commitments, several wineries struggle with the economic feasibility of sustainability initiatives, as investments in climate adaptation often come with high costs and uncertain financial returns. The difficulty in balancing climate change adaptation with financial resilience is particularly evident in the insurance market, where high premiums, ineffective coverage for combined climate events, and rigid valuation models make traditional risk mitigation strategies impractical.

However, our findings also suggest that leveraging sustainability as a market differentiator could help wine firms improve economic resilience. Sustainable and organic wines are often

perceived as higher quality, which presents an opportunity for wineries to enhance their market positioning and justify premium pricing (Schäufele & Hamm, 2017). In this sense, sustainable viticulture frameworks act as more than just compliance mechanisms: they are also strategic tools that help wine territories communicate their sustainability commitments to markets and consumers (Flores, 2018). Yet, the study finds that many companies, despite actively engaging in sustainability and adaptation efforts, do not always effectively communicate these initiatives to consumers, missing an opportunity to strengthen their economic position. As the demand for sustainable products grows, wineries that successfully integrate sustainability into their brand identity may find competitive advantages in global markets.

The role of industry-wide collaboration also emerges as a crucial factor in driving sustainability and adaptation success. Our findings indicate that many wineries benefit from partnerships with research institutions, consultants, and other producers, as knowledge-sharing accelerates the adoption of best practices. This reflects broader industry trends, where global wine events could serve as key platforms for benchmarking, fostering innovation, and establishing standardized sustainability guidelines (Golicic, 2022). Despite the individual efforts of many wineries, the transition toward sustainable and climate-resilient viticulture requires a coordinated approach, where industry actors and policymakers work together to develop frameworks that support long-term resilience.

Ultimately, this study highlights the complex interplay between climate change awareness, sustainability strategies, adaptation efforts, and economic resilience in the Tuscan wine industry. While many wineries are actively adapting to climate change through vineyard management techniques, irrigation strategies, and soil conservation practices, significant barriers remain, particularly for smaller firms. Way behind is the grade of implementation of long-term transformational adaptation practices, held back by the significant investments required and, in the specific case of Tuscany, by the strong attachment to *terroir* and tradition in the collective reputation of the regional wine sector. This element, expressed through the widespread adoption of designations of origin, could become an obstacle to the profound changes needed for long-term adaptation strategies.

Firms that proactively integrate climate adaptation into their business strategy, leverage sustainability as a brand asset, and participate in collective knowledge-sharing efforts will be best positioned for long-term success, so it is duty of institutional actors to help small wine producers, which constitute the backbone of Tuscan wine industry, overcome adaptation challenges. To effectively support the climate resilience and sustainability of the Tuscan wine industry, policymakers must implement a comprehensive strategy that addresses financial,

regulatory, technological, and educational challenges. Given the high costs of adaptation, particularly for smaller wineries, financial mechanisms must be expanded and simplified, ensuring greater access to subsidies, low-interest loans, and targeted tax incentives that encourage investments in precision agriculture, climate-resilient grape varieties, and water management systems (Galbreath & Tisch, 2022). Designation of origin regulations should also be loosened, rethinking their role in wine quality standards and allowing producers to safeguard their bond with the territory while enabling them to integrate adaptation practices. For example, the shift in climatic grape growing suitability needs to be addressed beforehand with planned changes of the borders of areas under designation of origin. Additionally, insurance schemes must be revised to better reflect the complexity of climate risks, as current models fail to cover compounded extreme weather events, leaving many producers vulnerable. Beyond financial support, policymakers should streamline third-party sustainability certifications, consolidating existing guidelines to reduce administrative burdens and improve compliance rates, making it easier for wineries to integrate environmental, social, and economic sustainability into their operations (Golicic, 2022).

A key enabler of sustainability transformation is education and capacity-building, which must be prioritized at all levels, from vineyard workers and winemakers to researchers and policymakers. Future industry leaders and decision-makers must be equipped to manage the growing complexities of sustainability, and regional training programs and best-practice workshops should be expanded to support wineries in adopting cleaner production techniques (Galbreath & Tisch, 2022; Wagner et al., 2023). Given the increasing importance of knowledge-sharing and collaboration, policymakers should establish regional climate adaptation networks that facilitate the exchange of scientific research, technological innovations, and best practices between wineries, research institutions, and industry stakeholders. Moreover, leveraging international wine events as knowledge-sharing platforms could further encourage benchmarking against global best practices, strengthening the industry's overall resilience (Golicic, 2022).

At a broader level, policy interventions must also address ecosystem governance, ensuring that sustainability efforts extend beyond commodity production to safeguard public goods such as biodiversity, soil health, and water conservation (Simoncini, 2011). The wine industry must balance economic growth with environmental stewardship, as failing to account for ecosystem services could lead to long-term environmental degradation and resource depletion. Additionally, climate adaptation should be embedded within rural development policies, promoting sustainable land management, biodiversity conservation, and water resource

management to ensure a harmonious balance between viticulture and broader ecological sustainability. Encouraging economic diversification, such as through wine tourism and agritourism, could provide wineries with alternative revenue streams, reducing their financial dependence on grape yields while promoting a sustainability-driven business model.

In conclusion, aligning financial incentives, sustainability regulations, technological innovation, and education is essential to ensuring that Tuscan wine production remains competitive, resilient, and environmentally responsible. Without proactive policy interventions, wineries, especially smaller producers, risk falling behind in their adaptation efforts, increasing their financial vulnerability and exposure to climate-related risks.

Despite offering valuable insights, this study has several limitations. The sample of six Tuscan wine companies, selected through email outreach and snowball sampling, while providing rich qualitative data, may not fully capture the diversity of adaptation strategies across the broader wine industry. This way of sampling also produced a panel of companies not reflecting the overall structure of the Tuscan wine sector, given the disproportional selection of medium and big size companies. The reliance on self-selected participants could lead to a bias toward sustainability-conscious firms, potentially overlooking businesses that are less engaged in climate adaptation or face significant barriers to implementing such strategies. Additionally, while the grounded theory and Gioia methodology ensure a systematic and transparent analytical approach, qualitative research remains inherently interpretive, meaning the findings are shaped by researcher analysis and may not be easily generalizable beyond the studied context (Bell et al., 2019; Gioia et al., 2013). Furthermore, climate adaptation in viticulture is an evolving process, influenced by shifting regulations, technological innovations, and market demands. As such, the insights generated in this study reflect a specific point in time, and future longitudinal research could provide a deeper understanding of how adaptation strategies develop over the years.

To build on these findings, future research could expand the sample to wine producers in other regions and countries, allowing for comparative analyses across different climatic and regulatory environments. Incorporating quantitative methods, such as measuring the economic and environmental effectiveness of specific adaptation strategies, could complement qualitative insights and provide a more comprehensive evaluation of best practices. Moreover, future studies could take a more holistic approach by integrating the perspectives of policymakers, agricultural experts, and environmental organizations, shedding light on the broader systemic factors influencing sustainability and adaptation strategies. Exploring the role of emerging technologies, such as precision agriculture, AI-driven climate modeling, and drought-resistant

grape varieties, could also provide valuable insights into how innovation supports resilience in viticulture. Lastly, examining consumer perceptions and market demand for sustainable wines would help wine producers align adaptation strategies with evolving consumer preferences and industry trends, ensuring both environmental and economic sustainability. These research avenues would contribute to a more robust understanding of climate adaptation in the wine industry, supporting the development of resilient and future-proof practices to make wine production more sustainable.

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Finally, I want to thank Angela for sharing this journey with me.

Appendix I

Protocollo di Intervista

Introduzione

1. **Presentazione**: Introduci te stesso e il contesto dell'intervista, spiegando che l'obiettivo è comprendere l'impatto del cambiamento climatico e le strategie di adattamento utilizzate nel settore vitivinicolo toscano.
2. **Confidenzialità e consenso**: Spiega come saranno trattati i dati e ottieni il consenso per la registrazione dell'intervista.
3. **Durata**: Comunica che l'intervista durerà circa 40 minuti.

Sezione 1: Informazioni Generali sull'Azienda

1. **Informazioni di base**:
    - Nome dell'azienda e posizione geografica (zona di produzione).
    - Superficie vitata, varietà principali di uve coltivate, volumi di produzione, denominazioni.
    - Ruolo del partecipante e coinvolgimento nelle decisioni aziendali legate alla sostenibilità e all'adattamento.
2. **Profilo ambientale e sostenibilità**:
    - L'azienda ha certificazioni di sostenibilità?
    - La sostenibilità è considerata parte integrante della strategia aziendale?

Sezione 2: Impatto del Cambiamento Climatico

1. **Osservazioni sui cambiamenti climatici**:
    - Negli ultimi anni ha riscontrato effetti del cambiamento climatico sulla produzione vinicola?
    - Ha notato cambiamenti nella qualità delle uve o nelle rese dovuti alle condizioni climatiche?
2. **Rischi specifici legati al clima**:
    - Quali rischi climatici preoccupano maggiormente l'azienda?
    - Ha riscontrato un aumento di questi rischi negli ultimi anni? Se sì, potrebbe fare qualche esempio specifico?
    - L'azienda ha sottoscritto polizze assicurative contro il rischio di eventi estremi?

Sezione 3: Pratiche di Adattamento al Cambiamento Climatico

1. **Iniziative agronomiche**:

- Quali pratiche o strategie l'azienda ha già implementato per adattarsi ai cambiamenti climatici?
- Quali sono state le motivazioni principali per implementare queste misure? Erano già presenti prima o sono state adottate recentemente?

2. **Innovazioni e tecnologie**:
   - Ha investito in nuove tecnologie o strumenti per monitorare l'impatto climatico?
   - Se sì, in che modo queste tecnologie hanno influenzato la gestione operativa?
3. **Strategie aziendali**:
   - L'azienda ha considerato cambiamenti nelle varietà di uva coltivate per rispondere meglio alle condizioni climatiche?
   - L'azienda ha considerato un investimento in terreni a maggiore altitudine?
   - Ha riscontrato difficoltà specifiche o impedimenti all'implementazione di queste opzioni?

Sezione 4: Sfide e Implicazioni Economiche nell'Implementazione delle Pratiche di Adattamento

1. **Difficoltà incontrate**:
   - Quali sfide principali ha riscontrato l'azienda nell'adozione di pratiche di adattamento?
   - Potrebbe fornire un esempio specifico di una difficoltà significativa affrontata?
2. **Sostegno e risorse**:
   - Quali risorse, incentivi o supporti istituzionali riterrebbe utili per migliorare l'adattamento dell'azienda ai cambiamenti climatici?
   - Ha collaborato con altre aziende, enti di ricerca o associazioni per affrontare queste sfide?
3. **Valutazione economica delle pratiche di adattamento**:
   - La vostra azienda analizza l'impatto economico delle pratiche di adattamento che implementa? Se sì, quali metodi utilizzate per valutarlo? Ad esempio, monitorate i costi sostenuti e i benefici ottenuti, calcolate l'efficienza delle pratiche, o eseguite analisi di ritorno sull'investimento?
   - Che tipo di impatto ha riscontrato in termini di costi operativi, qualità del prodotto o competitività?

Conclusione

1. **Domande finali**: C'è altro che vorrebbe aggiungere riguardo alle pratiche di adattamento climatico e al loro impatto nel settore?
2. **Ringraziamenti**: Ringrazia l'intervistato per il tempo e la disponibilità, e ricorda che eventuali aggiornamenti o risultati della ricerca potranno essere condivisi, se richiesto.

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