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Climate Change and Viticulture in Liguria: Regional Perceptions, Impacts, and Adaptive Responses

Mousaab Alrhmoun [1,*], Naji Sulaiman [1,*], Andrea Castagna [1], Lorenzo Massa [1], Giulia Mattalia [2], Emilio Aliotta [1] and Andrea Pieroni [1,3]

[1] University of Gastronomic Sciences, Piazza Vittorio Emanuele II 9, 12042 Pollenzo, Cuneo, Italy; andrea.castagna124@gmail.com (A.C.); lorenzomassa2002@gmail.com (L.M.); emilio.aliotta@outlook.com (E.A.); a.pieroni@unisg.it (A.P.)

[2] The Mediterranean Institute of Biodiversity and Marine and Continental Ecology (IMBE), CNRS 7263/IRD 237/Aix Marseille University, Av. Escadrille Normandie Niémen, 13397 Marseille, France; giulia.mattalia@uab.cat

[3] Department of Medical Analysis, Tishk International University, Erbil 4001, Iraq

* Correspondence: m.alrhmoun@unisg.it (M.A.); n.sulaiman@unisg.it (N.S.)

Abstract

Ligurian viticulture is characterized by a fragmented landscape and diverse microclimatic conditions, presenting both challenges and opportunities for grape production under climate change. This study investigates the perceived impacts of climate change on viticulture in Eastern (Levante) and Western (Ponente) Liguria, with a focus on vine growth dynamics, productivity, and the adaptation strategies adopted by local winegrowers. Semi-structured interviews with 48 winemakers revealed significant shifts in grape maturation ($p < 0.001$), earlier harvest dates, and increased vulnerability to fungal diseases ($p < 0.01$), primarily driven by rising temperatures and altered precipitation regimes. A notable rise in extreme temperature events ($p < 0.01$) was reported, with all respondents (100%) observing irregular seasonal temperature fluctuations. Furthermore, climate change was linked to changes in local fauna, particularly the expansion of ungulate populations ($p < 0.001$), leading to increased vineyard damage. In response, growers have adopted a range of adaptive measures, including drought-resistant rootstocks (e.g., M-series), traditional training systems (Guyot, Alberello), and local innovations such as the low pergola in Cinque Terre. Principal component analysis (PCA) revealed region-specific adaptation profiles, underscoring the influence of environmental and agronomic variability on viticultural resilience. Logistic regression identified temperature variability, disease incidence, and precipitation shifts as key predictors of perceived climate impact. The results underscore the urgency of developing regionally tailored adaptation strategies to sustain viticulture in Liguria's complex and changing landscape.

Keywords: climate change; adaptation; environmental changes; grape growing; Mediterranean resilience; winemaking

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1. Introduction

Viticulture is an essential component of agriculture in many regions worldwide, and especially in the Mediterranean basin, where it has been present for millennia [1]. Liguria, a small Italian region in the Northern Tyrrhenian, is no exception to this Mediterranean history of wine cultivation [2]. Yet, its unique geographical features, characterized by steep slopes, coastal proximity, and a Mediterranean climate, create a distinctive terroir that greatly influences the flavor profiles of Ligurian wines. Vineyards are often located in isolated enclaves, leading to a high level of biodiversity. The presence of forests near vineyards can promote soil biodiversity but also pose risks to viticulture, as wildlife such as ungulates can cause significant damage to vineyards. The variability in weather conditions across different plots further complicates vineyard management.

Liguria is home to over 6000 hectares of vineyards, primarily producing DOC (Denominazione di Origine Controllata) wines, such as Rossese di Dolceacqua, Pigato, and Vermentino, integral to the region's economy. Wine production is an important cultural and economic activity in Liguria, with an estimated 40 million bottles of wine produced annually (National Institute of Statistics, 2020). However, in recent decades, climate change has begun to challenge the stability and predictability of grape cultivation, resulting in significant shifts in the dynamics of wine production [3]. This has raised crucial questions regarding how winegrowers perceive the impacts of these changes and what adaptation strategies they employ to safeguard their livelihoods and the quality of their wines.

Ligurian viticulture is notably vulnerable to climate variability due to its reliance on environmental conditions that are susceptible to warming temperatures, changing precipitation patterns, and extreme weather events [4]. According to the Italian National Institute of Geophysics and Volcanology (INGV), average temperatures in the region have risen by approximately 1.5 °C over the last 50 years, and projections suggest further warming up to 3 °C by the middle of the century. These shifts have led to altered growing seasons, shifting harvest times, and an increased frequency of droughts and floods [5]. In particular, higher temperatures have led to altered grapevine development, affecting sugar accumulation, acidity, and overall grape quality, which are critical to the final wine product [6,7]. As a result, the region's wine quality and production patterns have experienced fluctuations that threaten not only the economic viability of small-scale producers but also the identity and authenticity of Ligurian wines, which are rooted in their terroir.

The global wine industry is already adapting to climate change through a variety of measures, ranging from vineyard management changes, such as shifting planting times and altering trellis systems, to experimentation with new grape varieties that are better suited to warmer conditions [8]. The perception of climate change among winegrowers is crucial, as their awareness and attitudes toward climate risks directly influence their decision-making processes and adaptation strategies [9,10]. However, the specific responses of Ligurian winegrowers are not yet explored, despite the region's distinctive landscapes and diverse environmental conditions. Nevertheless, a survey by the Ligurian Regional Agricultural Agency (2023) found that approximately 65% of local winegrowers reported perceiving a significant impact of climate change on their vineyards, with the majority of respondents noting changes in harvest timing and increased pest pressure. Understanding these perceptions is key to designing effective policies that support the transition toward more sustainable and resilient viticultural practices.

In response to climate-related challenges, Italian winegrowers have turned to combining innovative and traditional practices [11]. Some have opted for introducing more heat-resistant grape varieties, while others focus on modifying their vineyard management techniques, including adjusting canopy management, experimenting with irrigation systems, and incorporating organic farming practices to improve soil health and water retention [12]. Adaptation strategies are not merely technical but also socio-economic. They often rely on transferring local knowledge, passed down through generations, combined with new scientific and technological advancements [13]. With an average vineyard size of approximately 1.3 hectares [14], many Ligurian winegrowers face constraints when it comes to implementing large-scale technological adaptations. Because of the small scale, in Liguria, many winegrowers have limited financial resources, which means that the strategies they adopt must be both cost-effective and suitable for the region's specific socio-economic context.

Therefore, this study focuses on the perception of climate change impacts among winegrowers in Eastern and Western Liguria and investigates the strategies they have implemented to cope with these changes. By conducting interviews with local winegrowers, this research aims to identify the impact of climate change on Ligurian viticulture and document farmers' strategies to cope with a shifting climate and what challenges they face. Through this exploration, the paper aims to contribute to a broader understanding of climate change impacts on viticulture, particularly in this sector of the Mediterranean Basin.

2. Methodology

2.1. Data Collection and Field Study

To achieve the study objectives, qualitative research was conducted through 48 semi-structured interviews with Ligurian winegrowers. The region was divided into two macro-areas: Liguria di Ponente (Western Liguria, corresponding to the provinces of Imperia and Savona) and Liguria di Levante (Eastern Liguria, corresponding to the provinces of Genova and La Spezia) (Figure 1), allowing for a comparative analysis of similarities and differences in responses to climate change. In this study, several terms related to viticulture are used to contextualize the local landscape and agricultural practices. Training systems describe the methods used to support grapevine growth, commonly including alberello (bush vine) and pergola, both adapted to Liguria's steep, terraced terrain. Surface indicates the area dedicated to vineyards, typically limited and fragmented due to geographical constraints. Wines denote the local products derived from these grapes, often characterized by freshness, aromatic complexity, and a strong connection to their coastal terroir.

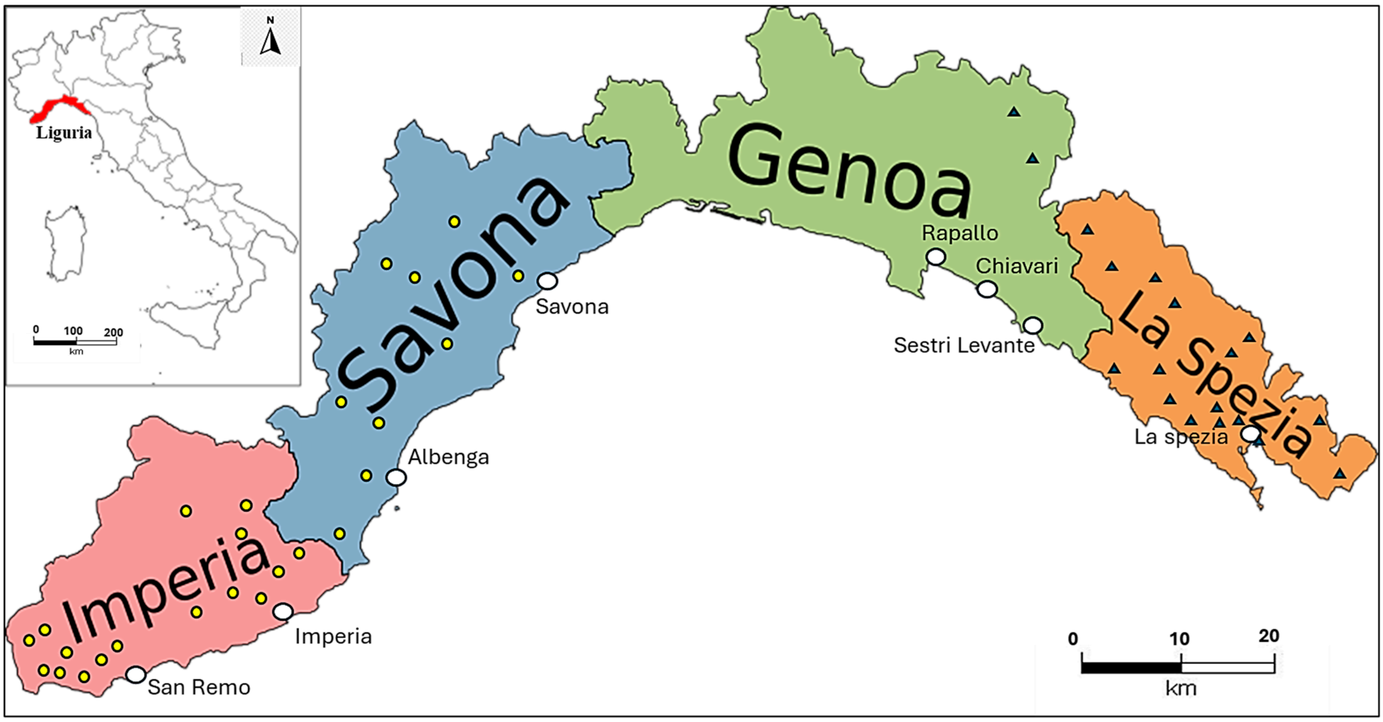

Figure 1. Study area of Liguria within the map of Italy: The blue triangle and yellow circle refer to the sampled locations.

A total of 48 wine producers were interviewed, with 23 participants from Levante Ligure (mainly from the Cinque Terre area) and 25 from Ponente Ligure (see the geographic distribution in Figure 1). Additionally, discussions were held with local innkeepers and restaurateurs to gain a broader perspective on the effects of climate change on the regional wine industry. The interviews followed a uniform structure, covering key themes such as the vineyard's history, production volume, observed impacts of climate change, and modifications in agronomic and winemaking practices. While most interviews were conducted remotely, 15 were conducted in person in April 2024, enabling direct observation of vineyard conditions and local environment changes.

The interview questions were designed to address three primary research objectives: (a) documenting the impacts of climate change on viticulture as perceived by winegrowers, (b) identifying the adaptation strategies implemented by producers, and (c) comparing these perceptions and strategies between Levante and Ponente Liguria. Responses were primarily open-ended, allowing winegrowers to elaborate on their experiences, while some questions required categorical responses (e.g., whether specific adaptation strategies such as irrigation or canopy management had been implemented) (Table 1).

Table 1. Research questions, response formats, and data types for climate change impact and adaptation in Ligurian viticulture.

Research Question	Response Format	Type of Answer
History of the Company and the Interviewee		
Brief description of the company and the producer	Open-ended	String (Text)
Acres of property and the number of bottles produced	Numeric	Integer
General characteristics of the production area	Open-ended	String (Text)
Documenting the impacts of climate change		
Changes over time in the characteristics of the production area	Open-ended	String (Text)
Harvest period in the past versus today	Numeric (years)	Integer
Documenting adaptations to climate change		
Agronomic practices used (treatments, pruning, leaf thinning, topping, irrigation, etc.)	Multiple-choice	Categorical (Checkbox: Yes/No for each practice)
Changes in agronomic practices compared to the past	Open-ended	String (Text)
Changes in winemaking (fermentation issues, alcohol/acid ratio of wines)	Open-ended	String (Text)
Changes in flora and fauna in the vineyard	Open-ended	String (Text)
Rootstocks used: the relationship between rootstocks and climate change	Multiple-choice	Categorical (List of rootstocks with selection)
Training systems used: the relationship between training systems and climate change	Multiple-choice	Categorical (List of systems with selection)
Identifying regional similarities and differences		
Comparison of practices and adaptations observed in Levante and Ponente Liguria	Open-ended	String (Text)
Perceived differences between the two regions in terms of impacts and adaptations to climate change	Open-ended	String (Text)

The data collected were systematically recorded and structured in an Excel database, categorized according to the research objectives.

2.2. Data Analysis

To explore local perceptions of environmental change, this study utilized the LICCI (Local Indicators of Climate Change Impacts) framework, developed to systematically document Indigenous and local knowledge related to climate impacts. The aspects analyzed using the LICCI approach include observations of changes in climate patterns (e.g., rainfall, temperature, seasonal shifts), physical systems (e.g., soil conditions, water availability), biological systems (e.g., changes in plant phenology, pest and disease presence), and socioeconomic systems (e.g., agricultural productivity, land use practices). This framework enabled a structured comparison of environmental knowledge across communities. To analyze the collected data, a mixed-methods approach was employed, integrating both qualitative and quantitative techniques. Thematic analysis was used to identify key patterns in responses, while content analysis helped categorize and quantify common themes related to climate change impacts and adaptation strategies. For the quantitative analysis, descriptive statistics were calculated to summarize key variables. All the statistical analysis was conducted by SAS 9.4 and R version 4.4.2 software. Fisher's exact test was employed to assess statistical differences in categorical adaptation strategies between Liguria di Ponente and Liguria di Levante.

To explore relationships between adaptation strategies and regional characteristics, principal component analysis (PCA) was applied to visualize associations between specific practices and geographic areas. To investigate the impact of climate change on viticulture in the Ligurian region, a logistic regression model was used to predict the presence or absence of climate change effects on viticulture. The dependent variable in this model is binary, representing whether or not climate change has affected viticulture. A value of "1" indicates that climate change effects are observed, such as changes in grape maturation, disease frequency, or fauna populations, while a value of "0" indicates no observable effects of climate change on viticulture.

The independent variables included in the model are related to vineyard management practices, climate factors, faunal changes, and vine health. The climate factors examined include temperature changes, particularly the frequency of extreme temperature days, and the number of hot or warm days during the growing season. Additionally, changes in precipitation patterns, including the frequency of dry spells and increased rainfall, are considered as they could affect water availability and overall vine health. Faunal changes refer to the increase in the abundance of certain species. Lastly, the frequency of grapevine diseases is considered a factor potentially influenced by shifts in climate. The logistic regression model used to predict the likelihood of climate change effects on viticulture based on these independent variables is specified as follows:

$$\text{Logit}\ (P(\text{Climate Change Effect})) = \beta 0 + \beta 1\ \text{Vineyard Practices} + \beta 2\ \text{Temperature Changes} + \\ \beta 3\ \text{Precipitation Changes} + \beta 4\ \text{Fauna Changes} + \beta 5\ \text{Disease Frequency} + \epsilon$$

In this model, the term logit(P) represents the log odds of observing climate change effects on viticulture. The intercept β0 represents the baseline log-odds of observing climate change effects when all predictors are at their reference levels. Each coefficient, β1, β2, β3, β4, β5, reflects the relationship between the respective predictor and the log-odds of observing climate change effects.

The model's performance was evaluated using the Akaike Information Criterion (AIC) to compare models, and goodness-of-fit was assessed using the Hosmer–Lemeshow test. The model's predictive accuracy was further examined by plotting the receiver operating characteristic (ROC) curve and calculating the area under the curve (AUC).

3. Results

The analysis of climate change impacts on viticulture revealed significant shifts in vine growth and productivity. All of the interviewees noted a reduction in grape maturation times ($p < 0.001$), with earlier harvests by up to one month compared to past decades. The most notable advancement was recorded for the Vermentino variety in the Riviera di Ponente during the 2017–2018 season, when harvest occurred nearly one month earlier than the historical average. This shift was associated with unusually warm spring and summer conditions, higher cumulative growing degree days, and below-average rainfall during critical phenological stages, all of which accelerated grape development and shortened the maturation period. This is in line with 83.3% of the interviewees observed alterations in fruiting ($p < 0.01$) and flowering times ($p < 0.01$) (Table 2). However, only 16.7% of respondents reported noticeable changes in crop morphology ($p = 0.23$). Climate change may also influence local fauna, with all respondents highlighting an increase in ungulate populations (roe deer, deer, and wild boars) and changes in species composition ($p < 0.001$), leading to more frequent vineyard damage. The changes reported by winegrowers in terrestrial fauna are primarily linked to shifts in the abundance and prevalence of existing species rather than the introduction of entirely new ones. In particular, populations of ungulates such as deer and wild boars have increased considerably in recent years, intensifying pressure on vineyards and surrounding ecosystems. Additionally, 83.3% of interviewees observed an increase in the frequency of crop diseases ($p < 0.01$), particularly fungal infections such as powdery mildew (*Erysiphe necator*), downy mildew (*Plasmopara viticola*), and Esca disease, a complex trunk disease primarily associated with fungal species such as *Phaeomoniella chlamydospora*, *Phaeoacremonium aleophilum*, and *Fomitiporia mediterranea*, which have been exacerbated by fluctuating weather patterns.

Table 2. Observed climate change impacts on vine growth, invasive species, diseases, temperature, and precipitation trends in Ligurian viticulture.

The Aspects Analyzed Using the LICCI	Criteria	Number of Interviewees				*p*-Value
		Yes		No		
		Number	(%)	Number	(%)	
Changes related to the vine						
	Changes in crop maturation time	48	100.0	0	0.0	<0.001
	Changes in crop growing pattern (crop morphology)	8	16.7	40	83.3	0.23
	Changes in crop fruiting time	40	83.3	8	16.7	<0.01
	Changes in crop flowering time	40	83.3	8	16.7	<0.01
Changes related to invasive species						
	Changes in the abundance of terrestrial fauna	48	100.0	0	0.0	<0.001
	Changes in the species composition of terrestrial fauna	48	100.0	0	0.0	<0.001

Table 2. *Cont.*

The Aspects Analyzed Using the LICCI	Criteria	Number of Interviewees				p-Value
		Yes		No		
		Number	(%)	Number	(%)	
Changes related to vine diseases						
	Changes in the frequency of crop diseases, viruses, and bacteria)	40	83.3	8	16.7	<0.01
Analysis of temperature fluctuations						
	Sunshine Intensity	40	83.3	8	16.7	<0.01
	Frequency of days with extreme temperatures	45	93.8	3	6.2	<0.01
	Frequency of extremely hot seasons	34	70.8	14	29.2	<0.05
	Level of extreme temperature	40	83.3	8	16.7	<0.01
	Frequency of hot/warm days	42	87.5	6	12.5	<0.05
	Frequency temperatures	48	100.0	0	0.0	<0.001
	Frequency of cold days	42	87.5	6	12.5	<0.05
	Variation of temperature in the year	48	100.0	0	0.0	<0.001
Analysis of precipitation trends						
	Changes in rainfall patterns	48	100.0	0	0.0	<0.001
	Changes in the temporal distribution of rainfall	48	100.0	0	0.0	<0.001
	Changes in the frequency of dry spells	40	83.3	8	16.7	<0.01
	Changes in the frequency of heavy rainfall events	44	91.7	4	8.3	<0.01

Temperature fluctuations were another critical factor identified in the study. A significant proportion of winemakers (93.8%) reported an increase in the frequency of extreme temperature days ($p < 0.01$), while 87.5% noted a rise in hot/warm days ($p < 0.05$) and cold days ($p < 0.05$) (Table 2). All interviewees (100%) observed more irregular temperature variations throughout the year ($p < 0.001$), contributing to unpredictable grape ripening patterns. Rainfall patterns have also undergone noticeable changes, with all respondents (100%) indicating shifts in precipitation trends ($p < 0.001$), including changes in temporal distribution and increased frequency of dry spells. Approximately 91.7% of participants reported a rise in extreme rainfall events ($p < 0.01$), posing risks of soil erosion and damage to vines (see Table 2).

3.1. Adaptation Strategies: Rootstocks and Training Systems

The research highlighted key adaptation strategies used by viticulturists in Liguria in response to the challenges posed by climate change. These strategies focus mainly on selecting appropriate rootstocks and training systems that enhance vineyards' resilience to environmental stressors such as drought and extreme temperature fluctuations.

3.1.1. Rootstocks Selection

Rootstocks are critical for ensuring the drought tolerance and overall vitality of grapevines. The study revealed clear differences in the types of rootstocks used in the Levante and Ponente areas of Liguria. In general, most of the rootstocks employed in both regions have relatively deep root systems that allow the vines to withstand periods of water stress. These deep-rooted varieties help ensure that the vines maintain their productivity even during prolonged dry spells (Figure 2). The Levante area, in particular, has seen the adoption of modern M-series rootstocks, which are specifically designed to improve drought tolerance and disease resistance, making them suitable for the changing climate conditions in the region (Figure 2).

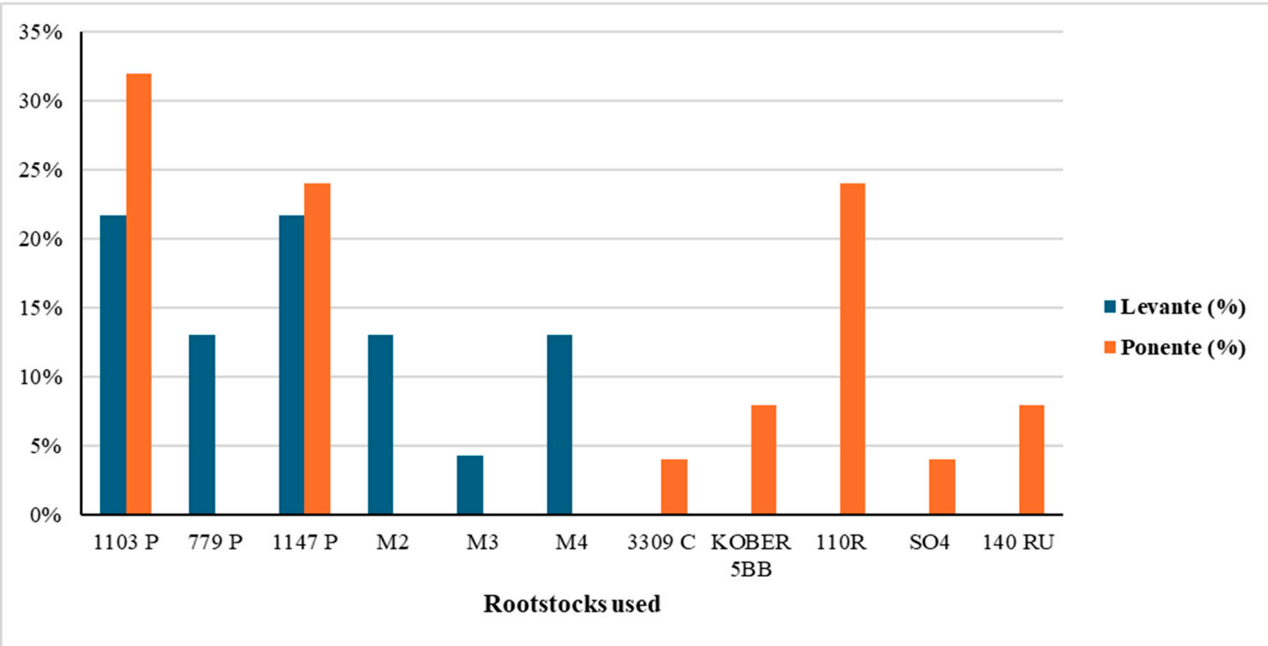

Figure 2. The types of rootstocks used in the Levante and Ponente areas of Liguria.

3.1.2. Training Systems

Training systems are another key adaptation strategy employed in Ligurian viticulture. The research found that winegrowers in both the Levante and Ponente areas commonly use the Guyot system, its simple and bilateral inverted forms, and the spurred cordon system. These systems are designed to optimize vine growth and grape production under varying environmental conditions (Figure 3). However, the semi-structured interviews also evidenced the continued use of two traditional training systems: the Ligurian "alberello" and the low pergola of the Cinque Terre (Figure 4). The "alberello" is a centuries-old system typically found in the Ponente region and is mainly used in older vineyards. This system involves short, free-standing vines pruned to a low, goblet shape. One of its key advantages is its resilience to harsh environmental conditions: the low structure helps protect vines from strong coastal winds, sunburn, and water stress, making it particularly suitable for Liguria's dry, terraced, and wind-exposed landscapes. Moreover, it requires no trellising, which historically made it a practical choice for steep and fragmented terrains. The low pergola, primarily found in the Cinque Terre area, is another traditional system that helps protect the vines from extreme weather conditions while promoting better fruit exposure to sunlight (Figure 3). The adaptation strategies employed in Liguria's viticulture focus on ensuring that vineyards remain productive despite the challenges posed by climate change. Using deep-rooted rootstocks, such as M-series and traditional varieties, helps vineyards adapt to increasing drought conditions, while training systems like Guyot and the "alberello" offer protection against extreme weather. These strategies demonstrate how viticulturists in Liguria respond to climate change through a combination of modern and traditional techniques, ensuring the region's viticulture remains resilient and sustainable.

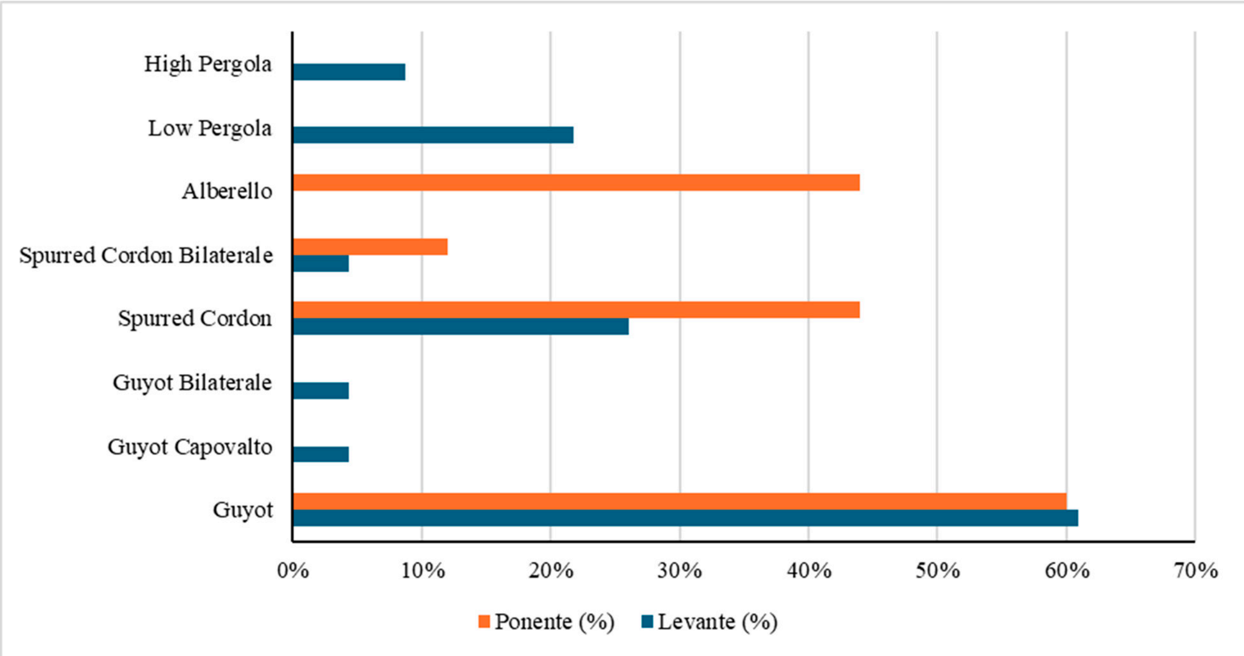

Figure 3. Training systems are employed in Ligurian viticulture.

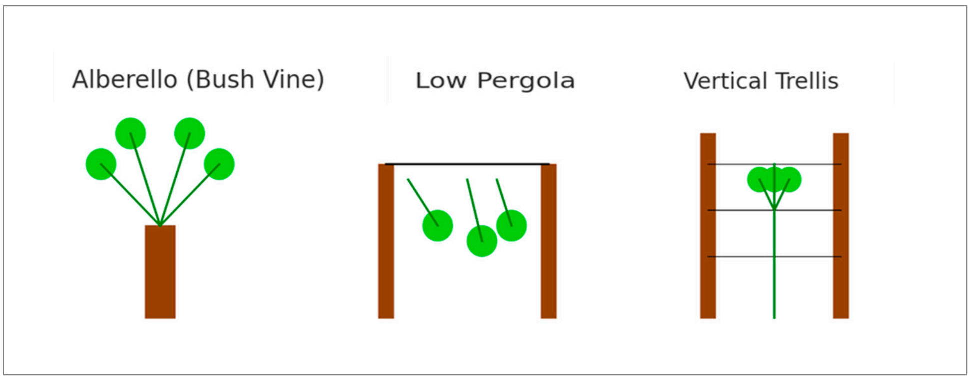

Figure 4. Simple illustrative figure comparing the alberello (bush vine), low pergola, and vertical trellis training systems.

3.2. Regional Variability in Rootstock Selection and Training Systems

The PCA results highlight clear distinctions in viticultural adaptation strategies between Ponente and Levante. Specific rootstocks such as 1103P, 1147P, and 110R are exclusively associated with Levante, whereas Ponente exhibits a broader range of training systems, including Albarello, Spurred Cordon, and Guyot. Some adaptation strategies, such as using KOBER 5BB, 140RU, and SO4 rootstocks, as well as Guyot Bilaterale, Capovolto, and High Pergola, are common to both regions. However, low pergola is uniquely observed in Ponente, indicating a region-specific approach to vineyard management. These findings suggest that environmental and agronomic factors influence the selection of both rootstocks and training systems, reinforcing the need for tailored adaptation strategies in different viticultural zones (Figure 5).

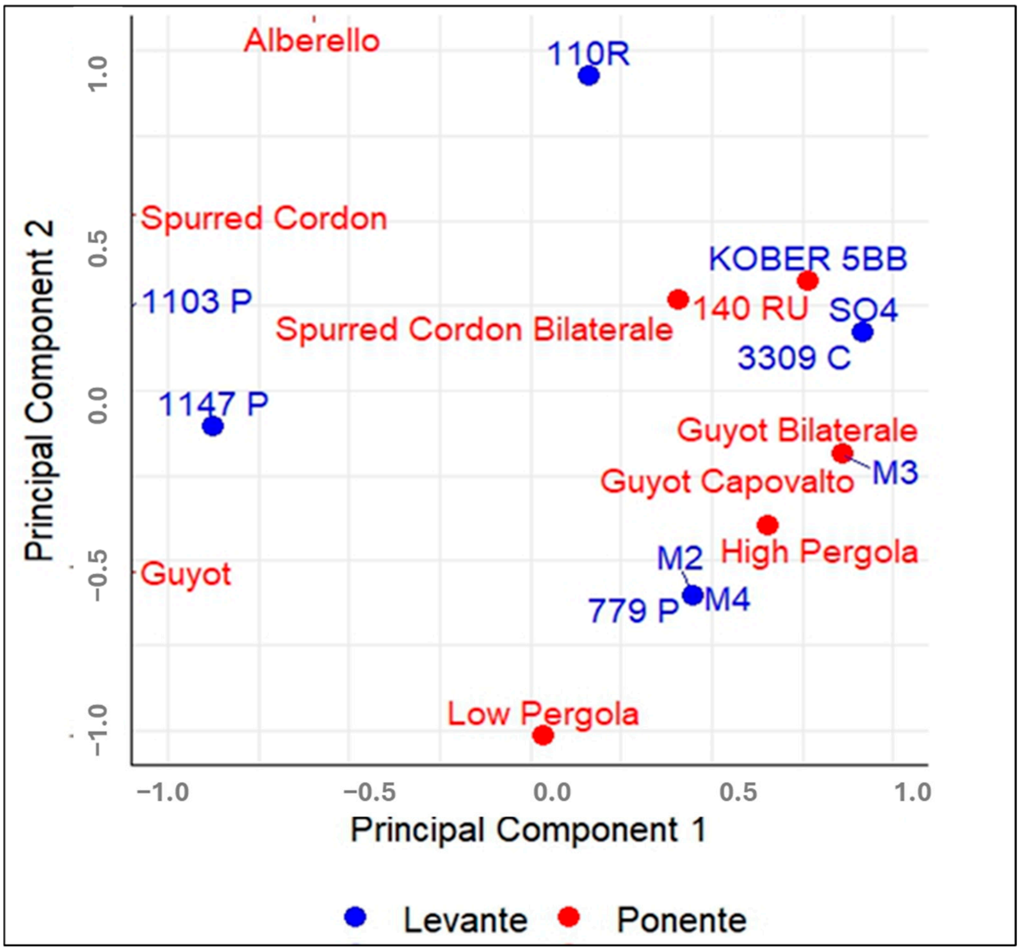

Figure 5. Principal component analysis of rootstocks and training systems in Ponente and Levante.

3.3. Key Factors Influencing Climate Change and Impacts on Viticulture

In our analysis of factors contributing to climate change impacts on viticulture, the frequency of extreme temperature days showed the strongest association with climate change impacts, with an odds ratio of 2.16, indicating that for each increase in extreme temperature days, the odds of observing climate change effects more than double. Similarly, the frequency of hot/warm days and cold days also demonstrated statistically significant positive relationships with climate change impacts, with odds ratios of 1.37 and 1.53, respectively. This suggests that both warmer and colder extremes in temperature increase the likelihood of climate-related changes in viticulture.

Regarding fauna changes, the abundance of terrestrial fauna and species composition did not show statistically significant relationships with the likelihood of climate change effects, with *p*-values of 0.182 and 0.399, respectively. This suggests that while changes in fauna may play a role in the broader ecological system, they might not be as strongly linked to viticulture impacts in this context. Regarding disease frequency, changes in the frequency of crop diseases demonstrated a significant association with climate change impacts (odds ratio of 1.85, *p*-value = 0.045) (Table 3). Lastly, precipitation changes, particularly changes in rainfall patterns and the frequency of heavy rainfall events, significantly influenced climate change impacts on viticulture, with odds ratios of 1.98 and 2.52, respectively. In summary, temperature fluctuations, disease frequency, and changes in rainfall patterns are key contributors to the likelihood of experiencing climate change effects on viticulture. However, factors related to fauna and some precipitation-related changes, such as dry spells and heavy rainfall, showed weaker or non-significant associations in this analysis.

Table 3. Factors influencing climate change impacts on viticulture: Results from logistic regression analysis.

Variable	Factor	Coefficient (β)	Standard Error	Odds Ratio	*p*-Value
Intercept		−0.562	0.201	0.570	0.012
Temperature Changes	Frequency of days with extreme temperatures	0.771	0.164	2.162	0.001
	Frequency of hot/warm days	0.318	0.128	1.374	0.012
	Frequency of cold days	0.426	0.293	1.531	0.045
Fauna Changes	The abundance of terrestrial fauna	0.208	0.096	1.231	0.182
	Species composition of terrestrial fauna	0.271	0.121	1.311	0.399
Disease Frequency	Changes in the frequency of crop diseases	0.614	0.267	1.848	0.045
Precipitation Changes	Changes in rainfall patterns	0.682	0.141	1.978	0.012
	Frequency of dry spells	0.206	0.157	1.229	0.182
	Frequency of heavy rainfall events	0.924	0.138	2.519	0.416

4. Discussion

4.1. Climate Change Impacts on Ligurian Viticulture

The majority of Ligurian winegrowers reported substantial shifts in vine growth cycles, with earlier harvests up to one month sooner than in past decades, alongside significant changes in flowering and fruiting times. They also observed an increase in crop diseases, particularly fungal infections, and notable changes in local fauna, with higher populations of deer and wild boars. Climatic variability, especially irregular temperature fluctuations and altered rainfall patterns, was seen as a driving factor behind these phenomena. In 2023, the World Meteorological Organization [15] reported that global surface temperatures surpassed 1.5 °C above pre-industrial levels, with the Ligurian region experiencing its second-hottest year since 1979 [15]. This temperature increase has significantly affected vine physiology and phenology, leading to premature interruptions in the vegetative cycle and preventing vines from entering complete physiological rest during winter. Warmer temperatures result in higher sugar concentrations in grapes and reduced organic acids, while increased nighttime temperatures alter aromatic profiles and require enological adjustments [7,16]. Temperatures above 35 °C can lead to issues like grape dehydration, sunburn, and reduced levels of polyphenols [7]. Temperature variations in the region are closely linked to changes in rainfall, with recent studies from Arpal showing a decrease in rainfall, especially in the western part of Liguria, contributing to rising temperatures. Climate projections suggest that the western area will experience more frequent droughts, while the eastern region will see increased rainfall, both in intensity and frequency. Water scarcity poses a significant threat to viticulture, causing water stress to vines and environmental damage, such as soil erosion and destabilization of terracing.

Farmers have responded by modifying viticultural practices. Key strategies include choosing drought-tolerant rootstocks, particularly in the Levante, with the adoption of M-series varieties, and adjusting training systems to minimize heat stress and sunburn. Traditional systems such as the “alberello” and low pergola continue to play a critical role, especially in the Ponente region. Additionally, there has been an uptake in the use of protective foliar products like kaolin and biostimulants, along with reduced leaf removal to shield grapes from intense sunlight. Adaptation responses observed in Liguria mirror those identified in other Mediterranean viticultural zones. For instance, Bernardo et al. [17] and Valentini et al. [18] note increased usage of foliar protectants and biostimulants to mitigate heat stress. Reduced leaf thinning is an adaptive measure aimed at decreasing sun exposure and preventing photoinhibition. Moreover, the early harvests reported in our study reflect stress-induced ripening observed in warmer climates, where farmers are compelled to pick grapes before phenolic maturity [17]. The reintroduction of traditional canopy systems, such as pergolas, further echoes practices noted in areas facing similar heat stress challenges.

Thermal stress also affects vine phenology, influencing growth and dormancy cycles. Temperature indices, such as Winkler, Huglin, and Fregoni’s Bioclimatic Index, help assess vine responses to temperature changes [7]. These indices guide decisions during the dry pruning period, which is crucial for managing grapevine exposure and preventing premature regrowth. In tropical climates, vines experience continuous growth, while in cooler regions, they enter dormancy and “bleed” when temperatures rise above 7 °C [8]. The ongoing rise in temperatures may shift grape varieties to warmer zones, accelerating growth but potentially resulting in wines with higher alcohol content [19].

To combat water shortages, many producers have started using irrigation systems, as exemplified by the 2022 Rossese di Dolceacqua vintage, which faced extreme drought conditions and low grape yields due to a severe reduction in rainfall (77 mm compared to the usual 206.3 mm) and historically high temperatures. Vines have a biological defense mechanism to cope with water stress, where stomata close to prevent further water loss. When not overly stressed, this mechanism can be beneficial by allowing the accumulation of secondary metabolites that improve the must. Biostimulants are applied foliarly to support vines under severe water stress to enhance plant resistance [17,20].

Increased rainfall, particularly in the eastern region, leads to higher humidity, which fosters the spread of fungal diseases. Winemakers have reported the prevalence of Powdery Mildew (Oidium) and Downy Mildew (Peronospora), with the former being more common. Downy Mildew, caused by oomycetes, can severely damage vines, leading to premature defoliation, shoot death, and chlorophyll loss, while Powdery Mildew appears as a fine gray-white powder on grapes and can cause cracking. In areas with mild winters, vines infected with Powdery Mildew may produce shoots with existing mold, and high shading and poor ventilation can exacerbate the spread [21]. Low training systems, such as alberello and low pergola, can increase the risk of downy mildew infections because they reduce airflow and create humid microclimates within the canopy that favor pathogen development. Limited ventilation and greater shading prolong leaf wetness, thereby facilitating the establishment and spread of diseases [17,21].

Climate change impacts not only meteorological factors like temperature and rainfall but also the wildlife in agricultural environments. In Ligurian viticulture, the increased presence of ungulates poses a significant problem, as these animals can damage both the vines and the soil, leading to biodiversity loss. Winegrowers have reported a rise in deer, wild boar, and fallow deer populations, with some using fences to protect their plots from these animals. Interestingly, wolves have returned to the region in recent years, helping control the ungulate population [22].

Despite the overall trend toward more frequent droughts in Liguria, winegrowers have reported an increase in downy mildew outbreaks. This apparent paradox can be explained by the interaction between changing rainfall patterns and rising temperatures. While prolonged dry periods limit disease development, sporadic but intense rainfall events create short windows of high humidity and leaf wetness that are highly favorable to *Plasmopara viticola* infection. Moreover, elevated average temperatures accelerate the pathogen's reproductive cycle during these wet periods, leading to more frequent and severe outbreaks when conditions align [18,22]. Local microclimates, influenced by vineyard topography and canopy structure, further exacerbate these effects by retaining humidity and prolonging the duration of leaf wetness. These combined factors explain why, under climate change, downy mildew has not declined but instead become more erratic and, in some years, more damaging [16,21].

Wildlife changes also affect insect species and organisms that serve as vectors for vine diseases. Winegrowers have noticed an increased presence of *Cryptoblabes gnidiella*, *Lobesia botrana*, and the invasive *Drosophila suzukii*. These moths infest grapes, causing damage, particularly during ripening. They often share host plants, forming symbiotic relationships, particularly between *C. gnidiella* and *L. botrana*. The damage caused by these species is influenced by the vineyard's climatic and phytosanitary conditions. To control these pests, many winegrowers apply kaolin to the leaves, which creates a physical barrier to prevent egg deposition [23]. The spread of *Drosophila suzukii*, an invasive species from Southeast Asia, has been widely reported by winegrowers. This insect attacks red grape varieties just before harvest, puncturing the grape skin to lay eggs inside, with the larvae feeding on the fruit. *Drosophila suzukii* also acts as a vector for microbial populations, leading to "acid rot" in affected grapes. However, it only targets red grape varieties with thin skins, as thicker-skinned grapes resist the insect's penetration [24]. Winegrowers commonly use insecticides or chemical treatments to manage these pests and introduce specific antagonistic species to control populations.

4.2. Analysis of Rootstocks Used

Rootstocks protect against pests and influence vine adaptability, climate response, and grape production quality [25,26]. The primary factor in selecting rootstocks today is their drought resistance, a crucial adaptation to climate change impacts on Ligurian viticulture. Deep-rooted, drought-tolerant rootstocks are preferred, particularly in the Ponente and Levante regions. Common choices include 1103 Paulsen, 779 Paulsen, 1147 Paulsen, 110 Richter, and 140 Ruggeri. These rootstocks, *Vitis berlandieri* and *Vitis rupestris* hybrids, are suited to challenging climates. However, some producers in Ponente still use SO4 and Kober 5 BB, despite their lower drought resistance, highlighting that adaptation is also influenced by agricultural practices and training systems [27,28].

In Levante, newer M series rootstocks are gaining popularity due to their excellent drought resistance, soil pH adaptability, and compatibility with local varieties. These rootstocks have shown significant improvements in yields and grape quality. Rootstocks also affect grape quality, particularly through changes in grape chemical composition. Studies, such as those on Pinot Noir, show that rootstock variation can alter the anthocyanin profile, influencing wine color and aging potential [25,29]. Research on Chardonnay and Cabernet Sauvignon indicates that rootstocks can change grape pH and potassium levels, affecting wine characteristics [30]. However, there is a lack of similar studies on typical Ligurian blends, suggesting a gap in local viticulture research.

4.3. Analysis of Training Systems Used

In Ponente, traditional systems like "alberello" (bush vine) remain prevalent, while in Levante, the low pergola system is more common. Although modern systems like vertical shoot positioning (Guyot and Cordone Speronato) are used in both regions, traditional systems offer benefits under changing climates, such as maintaining cooler grapevine clusters and providing better air circulation, which helps with disease resistance [28]. Green pruning practices have also evolved due to climate change. Vineyard owners reported reducing leaf thinning to prevent sunburn on grapes and using agents like kaolin to reflect UV radiation. These changes help mitigate the effects of higher temperatures and heat waves.

The choice of the training system is crucial for vineyard establishment and is impacted by factors such as mechanization, costs, grape varieties, and pedoclimatic conditions [31]. Climate conditions, including temperature, solar radiation, rainfall, and soil factors, influence vine growth and grape quality, making the training system a key decision for vineyard owners. With climate change altering temperature and precipitation patterns, producers have adjusted their cultivation techniques, including training systems and pruning practices, to cope with these changes [28]. Training systems influence grape chemistry, including pH, sugar concentration, and aromatic complexity. Research suggests that traditional systems, especially albarello and pergola, are optimal for the new climatic conditions and positively affect the chemical composition of the grapes [31]. Many local producers are considering returning to these systems to adapt to climate change.

4.4. Local Differences in Adaptation Strategies

The PCA analysis highlights the distinct approaches taken by Ponente and Levante viticulturists in response to climate change. While some adaptation strategies, such as Guyot training and KOBER 5BB rootstocks, are common to both regions, Ponente exhibits greater diversity in training systems, incorporating traditional methods like the low pergola. These findings emphasize the need for region-specific adaptation strategies, with Vermentino considering local environmental and agronomic conditions [32]. In Liguria, where the terrain and climate vary significantly across regions, one-size-fits-all solutions may not be feasible. Therefore, it is essential to develop adaptive practices that account for these regional distinctions while ensuring the long-term sustainability of viticulture [33,34].

4.5. Implications for the Future of Ligurian Viticulture

The observed trends in climate change impacts and adaptation strategies have significant implications for the future of Ligurian viticulture. The resurgence of red wine production in response to changing climatic conditions suggests a potential shift in the region's wine profile. However, maintaining the balance between traditional viticultural practices and modern adaptations will be critical to sustaining Liguria's unique wine heritage. Moving forward, continued research on adaptation to climate change, disease resistance, and soil conservation will be essential in ensuring the long-term viability of Ligurian vineyards. Collaborative efforts among viticulturalists, researchers, and policymakers are more crucial than ever in the years to come for developing collaborative platforms aimed at implementing resilient and sustainable viticultural practices tailored to the evolving environmental landscape of the region. The data we presented here demonstrated the plasticity of the local viticultural and wine-making practices and how local producers navigate climate change with audacious and robust choices. The findings of this study underscore the critical need for integrating climate change adaptation strategies into viticulture to ensure both the ecological and economic sustainability of the sector.

Further integrated examinations of climate change adaptation strategies in viticulture are essential for better land planning and environmental management because they directly address the vulnerability of vineyards to shifting climatic conditions while guiding the development of sustainable practices. Viticulturalists and winemakers face a myriad of challenges that range from altered phenological patterns to increased frequency of extreme weather events, making it imperative that decision-making is supported by robust data-driven tools and localized climate projections [35–37]. By harnessing interoperable datasets and long-term climate models, researchers and practitioners can identify critical microclimatic niches and assess soil–water–plant interactions, providing the groundwork for risk mitigation and the optimization of vineyard locations and designs [35,38].

Furthermore, adopting both short-term and long-term adaptation strategies is pivotal for ensuring the sustainability of the winemaking sector. For instance, varietal selection, which leverages the inherent diversity among grape cultivars, has been recognized as a promising strategy for enhancing climate resilience while reducing the need for excessive chemical inputs [39–42]. When tailored to the specific terroirs and regional climate forecasts, these strategies enable land planning that minimizes environmental risks and supports economic sustainability [36,41,42]. In particular, understanding the localized impacts of increased temperatures and reduced precipitation patterns enables the design of adaptable canopy, soil, and water management practices that are critical for maintaining both yield and quality under climate stress [43–45].

In addition, future research trajectories will have to integrate diverse interdisciplinary research, from biophysical studies that examine grapevine physiological responses to advanced climate projection techniques to social science-centered studies, like the one presented here, that reinforce the importance of comprehensive climate adaptation policies in viticulture [36,45,46]. This combined approach not only could further inform adaptive practices on the ground but also aids policymakers in establishing environmental management systems that are sensitive to spatial heterogeneity and temporal changes [47–49]. Such policies are essential to ensure that urban and rural land planning accounts for climate-induced shifts in viticultural suitability, which is increasingly relevant as new areas become viable for grape cultivation and traditional regions face deteriorating conditions [49,50].

Thus, detailed studies on climate change adaptation in the viticulture sector have far-reaching implications for land use planning and environmental management. By incorporating across-the-board data analytics, innovative varietal breeding, and adaptation strategies in agronomic practices, viticulturalists and winemakers can secure the long-term ecological and socio-economic viability of their operations in a rapidly changing climate [35,38,41,43,49]. Finally, it is worth noting that the study is based on a relatively small sample size, which may limit the generalizability of the findings. Future research with larger and more diverse samples is recommended to validate these results and provide additional insights into the observed patterns.

5. Conclusions

This study highlights the considerable impacts of climate change on viticulture in Liguria, including earlier harvests, shifts in flowering and fruiting periods, and an increased incidence of crop diseases due to temperature fluctuations and altered rainfall patterns. Winegrowers have responded by adopting a mix of traditional and modern adaptation strategies, such as the selection of drought-resistant rootstocks and the use of both historic and innovative training systems. Regional differences in adaptation approaches, such as the specific rootstocks and canopy management techniques used in Ponente and Levante, underscore the importance of site-specific responses to climate challenges.

Given the sensitivity of grapevines to even minor climatic variations, particularly in temperature, precipitation, and solar radiation, these changes can significantly affect phenological timing, grape composition (e.g., sugar, acidity, tannins, aromatic profiles), and susceptibility to pests and diseases. Furthermore, the preservation of local grape varieties and their terroir—the complex interaction of soil, climate, topography, and human practice that defines a wine's identity—may be at risk, potentially forcing producers to shift cultivation zones or modify their practices.

Beyond wine production, climate change poses broader implications for innovation, agroecological transitions, precision viticulture (e.g., AI-driven irrigation and remote sensing), and nature-based tourism. Thus, further field-based research is needed, particularly on the perspectives of local producers and institutional stakeholders. Such studies can inform evidence-based policymaking for sustainable land and water use, regional climate adaptation in agriculture, and cross-border collaboration. Finally, fostering alliances between wine producers and citizen science initiatives rooted in socio-ecological systems may be key to enhancing resilience and ensuring the long-term sustainability of Mediterranean viticulture.

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