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Climate change perceptions across four ecological regions in Italy and Austria

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This study investigates climate change perceptions of inhabitants of four distinct physiographic regions of Southern Europe, including Alpine cattle pastoralists of Carinthia (Western Austria), Venice Lagoon farmers, Southern Sicilian Coast fisherfolk, and Langhe winemakers in Italy. Through semi-structured interviews with 92 households conducted between autumn 2022 and autumn 2023, distributed across the four case studies, nuanced variations in perceptions of climate change impacts and responses were analysed. The results illustrate significant associations between climate change perception and various factors including adaptation strategies, precipitation change, and social network influence. Notably, the perceived impacts relate to a decrease in precipitation which affects agricultural production, vegetation shift, and adaptation strategies. Analyses conducted using mixed-effect logistic regression models uncovered varied regional contexts that influence both climate change awareness and adaptive actions. Additionally, Principal Component Analysis (PCA) was employed to explore underlying structures and identify key variables contributing to regional variations in climate perception. This r analysis offered insights into the factors that shape perceptions and strategies in each region and underscored the importance of context-specific approaches to climate resilience and adaptation planning, considering the socio-economic, environmental, and cultural factors. Tailored adaptation strategies, informed by robust data and stakeholder engagement, are essential for building resilience and sustainability in local communities facing ongoing environmental challenges.

Keywords Adaptation strategies, Alps, Climate change perceptions, farmers, Fishermen, Mediterranean, Pastoralists, Socio-economic factors, Socio-ecological resilience, Winemakers

Climate change presents one of the most pressing challenges of our time, with far-reaching impacts on ecosystems, economies, and societies worldwide[1–4]. There is a growing acknowledgment that perceptions of global phenomena like climate change are deeply intertwined with personal, cultural, and environmental contexts that shape individuals' understandings of and responses to climate change[5–7]. Factors such as cultural background, historical experiences, and socio-economic conditions profoundly influence how individuals perceive and interpret changes in their environment[5,8]. Additionally, the unique environmental characteristics of a region, including its topography, biodiversity, and natural resources, result in distinct impacts of climate change for communities residing in different ecological regions[1,6].

Recognizing and delving into these complex linkages between perceptions of global changes and specific socio-cultural and environmental spaces is crucial for a better understanding of the multifaceted dimensions of climate change adaptation and mitigation[7,8]. It emphasizes the importance of adopting a holistic approach that takes into account not only the scientific and policy dimensions of climate change but also the socio-cultural and environmental contexts within which it unfolds[5,6,9,10].

For instance, the interaction of the impacts of climate change within and the set of pressures and challenges of the specific social-ecological framework, determine the magnitude of the impact on farmers and farming practices[5,8–11]. Moreover, each individual farm and farmer possesses unique characteristics that influence how they experience and adapt to change[5,7].

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Primary producers, such as pastoralists, farmers, fisherfolk, and winemakers, occupy a critical position in the intricate tapestry of climate change[1,5,6]. Their livelihoods are intrinsically linked to natural resources and environmental conditions, rendering them particularly vulnerable to the manifestations of a changing climate[7]. Understanding their perceptions of climate change and the strategies they employ to adapt is essential for crafting effective, management, mitigation, and adaptation policies[5–7]. In this sense, Southern Europe, with its diverse ecological regions spanning from coastal regions to mountainous landscapes, provides a unique backdrop for studying the nuanced responses of primary producers to climate change[11,12] The physiographic diversity offers distinct ecological contexts, each presenting its own set of challenges and opportunities in the face of climate variability[13,14].

Understanding the impact of climate change on smallholder primary producers across different ecosystem regions requires an examination of the specific circumstances, as well as the broader social and ecological context within which they operate[15,16]. By examining perceptions of weather patterns, ecological impacts, socio-economic factors, and adaptation strategies, we aim to provide a comprehensive understanding of how primary producers navigate the complex landscape of climate change across diverse ecological regions[8,11,13].

While numerous studies have examined climate change perceptions, few have compared primary producers' views across distinct ecological regions. Previous research has largely focused on single regions[8,11,13,15]. and has not fully addressed the diverse socio-cultural and environmental contexts of Southern Europe.

Therefore, our study investigates the perceptions of climate change impacts and the adaptation strategies to these impacts among primary producers in four varied ecological regions, including the Alps, Venice Lagoon, the Sicilian Coast, and the Langhe region (Fig. 1). By amplifying the voices of primary producers, we hope to foster dialogue, collaboration, and collective action in confronting the existential threat of climate change in Southern Europe and beyond.

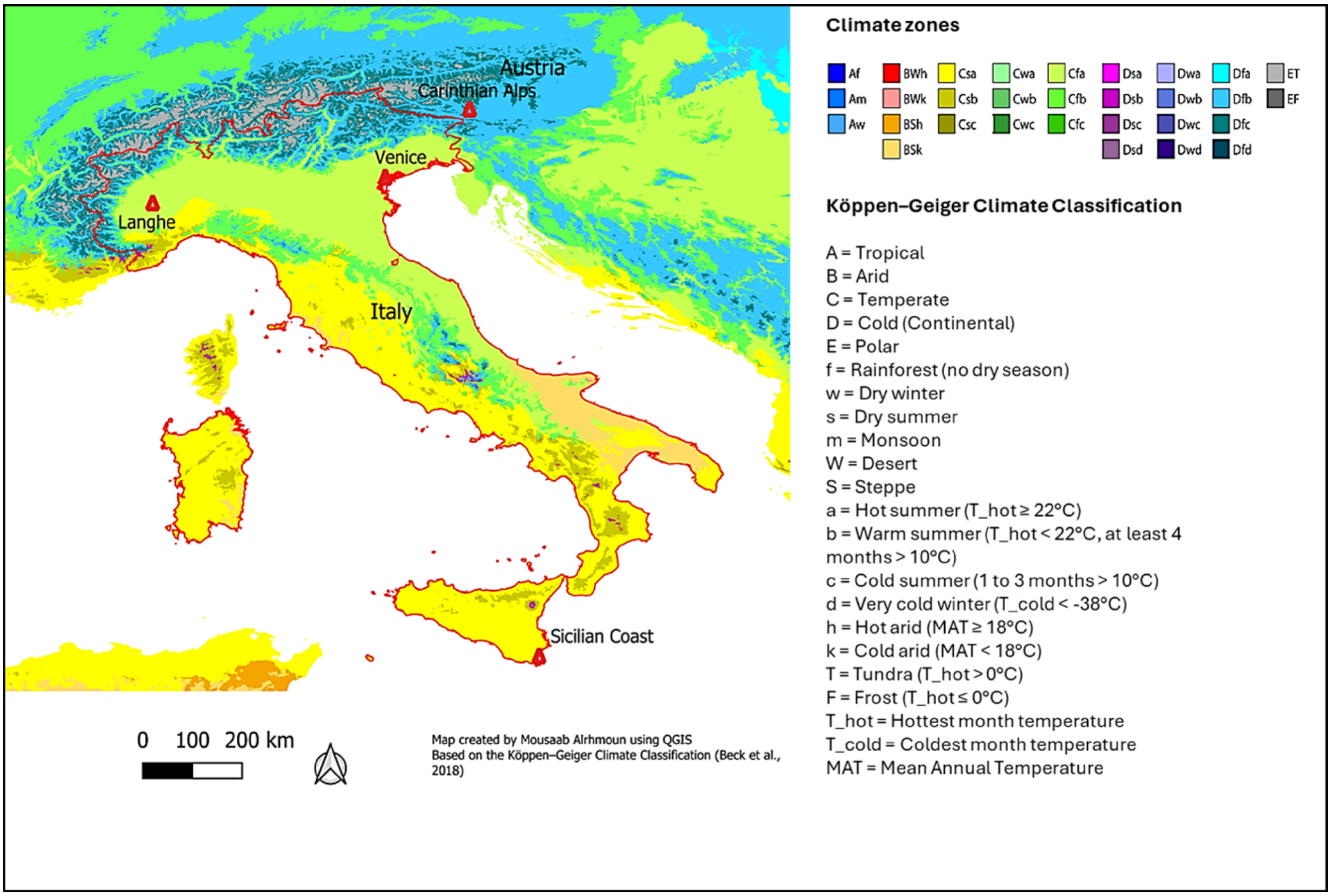

Fig. 1. Köppen-Geiger climate classification zones covering the study areas in Italy and Austria. The map displays the climatic diversity across five study sites: four in Italy (1), Venice Lagoon, Sicilian Coast, Langhe, and Carinthian Alps in Austria. The first author generated the map using QGIS 3.28, based on the 1 km resolution Köppen-Geiger climate classification dataset developed by Beck et al. (2018)[64] and published under a Creative Commons Attribution 4.0 International License (CC BY 4.0).

Results

Regional climate change impacts and observed adaptations

The findings from this study, based on the analysis of the interviews, revealed a unanimous acknowledgement of climate change across all study regions, indicating widespread awareness among community members. However, while climate change is universally recognized, the specific impacts and concerns vary significantly between regions.

The study identified several common climate change impacts across the four ecological regions in Southern Europe, with each region exhibiting unique characteristics. Higher mean temperatures were reported in the Alps, the Venice Lagoon, and Langhe regions, affecting agricultural practices and ecological regions by altering crop cycles, livestock productivity, and vegetation patterns. Extended droughts were observed in all regions, which reduced water availability for agriculture and impacted crop yields. A decrease in snowfall was noted in the Alps and Langhe, affecting water reservoirs and the timing of water availability, especially in mountainous areas. Increased rainfall intensity was noted in the Alps, the Venice Lagoon, and Langhe, leading to flooding and soil erosion that damaged agricultural land and infrastructure. An increase in pest attacks was observed in the Alps, the Venice Lagoon, and Langhe due to warmer temperatures and changing weather patterns, affecting crop health and yields.

In the Venice Lagoon, a decrease in winter frost events influenced crop growth cycles and potentially increased pest populations. The same region also reported more frequent whirlwinds, which damaged crops and infrastructure. Increased hailing was observed in the Alps and Langhe, causing significant crop damage and necessitating protective measures like hail nets. Changes in sea currents were reported in Sicily, disrupting marine ecosystems and fishing activities.

Additionally, the study integrated variables such as the increase of invasive non-indigenous species, decrease in production yield fish catch, and reduction in the range of activity production times into the quantitative analyses. While these variables were considered, the focus remained on common indicators across regions to ensure a consistent and comprehensive understanding of climate change impacts. This approach highlighted the need for region-specific adaptation strategies.

Interviewed primary producers reported several key patterns: an increase in mean temperatures, extended droughts, and intensified rainfall. Carinthian dairy farmers noted warmer summers and extended droughts with occasional heavy rains, leading to extended grazing seasons, increased hay cuts, and reduced milk production. They also observed a shift in wild flora and increased pest outbreaks. The Venice Lagoon farmers experienced reduced agricultural production due to drought and increased salinity, alongside the disappearance of winter frost and increased pest prevalence. Sicilian fisherfolk reported higher seawater temperatures and changes in sea currents disrupting fishing, compounded by increasing overfishing and pollution. Langhe winemakers faced increased temperatures, extended droughts, irregular seasons, and more frequent hailstorms, leading to necessary adaptations in vine growing and wine production.

Variation analysis of climate change perception across the different study regions

The Principal Component Analysis (PCA) results reveal significant variation among the four distinct regions: the Carinthian Alps, the Venetian Lagoon, the Sicilian Coast, and the Langhe region, as illustrated in (Fig. 2A). The Carinthian Alps are characterized by unique socio-economic factors, including adaptation strategies, institutional relations, professions, gender dynamics, vegetation zone shifts, and demographic changes. These factors highlight the complex interplay between adaptive strategies and institutional dynamics. Notably, the shift in vegetation zones, often driven by the altitudinal gradient, significantly impacts climate change perceptions in the Carinthian Alps, highlighting that changes in vegetation patterns due to shifting climatic conditions are a critical concern for this region. Additionally, demographic changes play a pivotal role in shaping the socio-economic landscape, with population dynamics influencing both adaptation strategies and institutional responses to climate impacts.

The Venetian Lagoon faces substantial environmental challenges, with key factors including temperature change, precipitation changes, pest prevalence, and water scarcity. Water issues, particularly pollution, exacerbate the region's vulnerability, highlighting the urgent need for comprehensive water management strategies to address both pollution and scarcity. The interaction between these environmental stressors and socio-economic factors in the Venetian Lagoon underscores the complexity of climate resilience efforts in coastal regions.

The Sicilian Coast, while sharing some similarities with the Venetian Lagoon, uniquely emphasizes the significance of social network influence, such as the need and the importance impact of community-based organizations, cooperative fishing groups, and informal networks on sharing information, coordinating responses to climate impacts, and enhancing collective adaptation efforts. In contrast, the Langhe region's variation is primarily driven by age and employment status, underscoring the importance of demographic and employment dynamics (Fig. 2B) (The findings presented in Table (1) offer a comprehensive examination of climate change indicators across the study regions (Carinthian Alps, Venice Lagoon, Sicilian Coast, and Langhe). Across all regions, there was a unanimous acknowledgement of the significant impacts of temperature change, particularly evident in Langhe with a 100% agreement (χ^2 test value of 0.286). Precipitation change and consequent water scarcity effects were also recognized across all the regions, albeit with variations in percentages (χ^2 test values of 0.534 and 0.552, respectively).

The impact on agricultural production received unanimous agreement in the Carinthian Alps and Langhe, and it was significantly associated with climate change perceptions (χ^2 test value = 0.003).

Notably, adaptation strategies were prevalent across all regions, with Langhe exhibiting the highest percentage of respondents acknowledging these strategies (χ^2 test value = 0.038). Social network influence and demographic changes emerged as crucial factors, although their significance varied across regions (χ^2 test values of 0.05 and 1.776, respectively in the Sicilian Coast, Langhe and Carinthian Alps, Venice Lagoon.

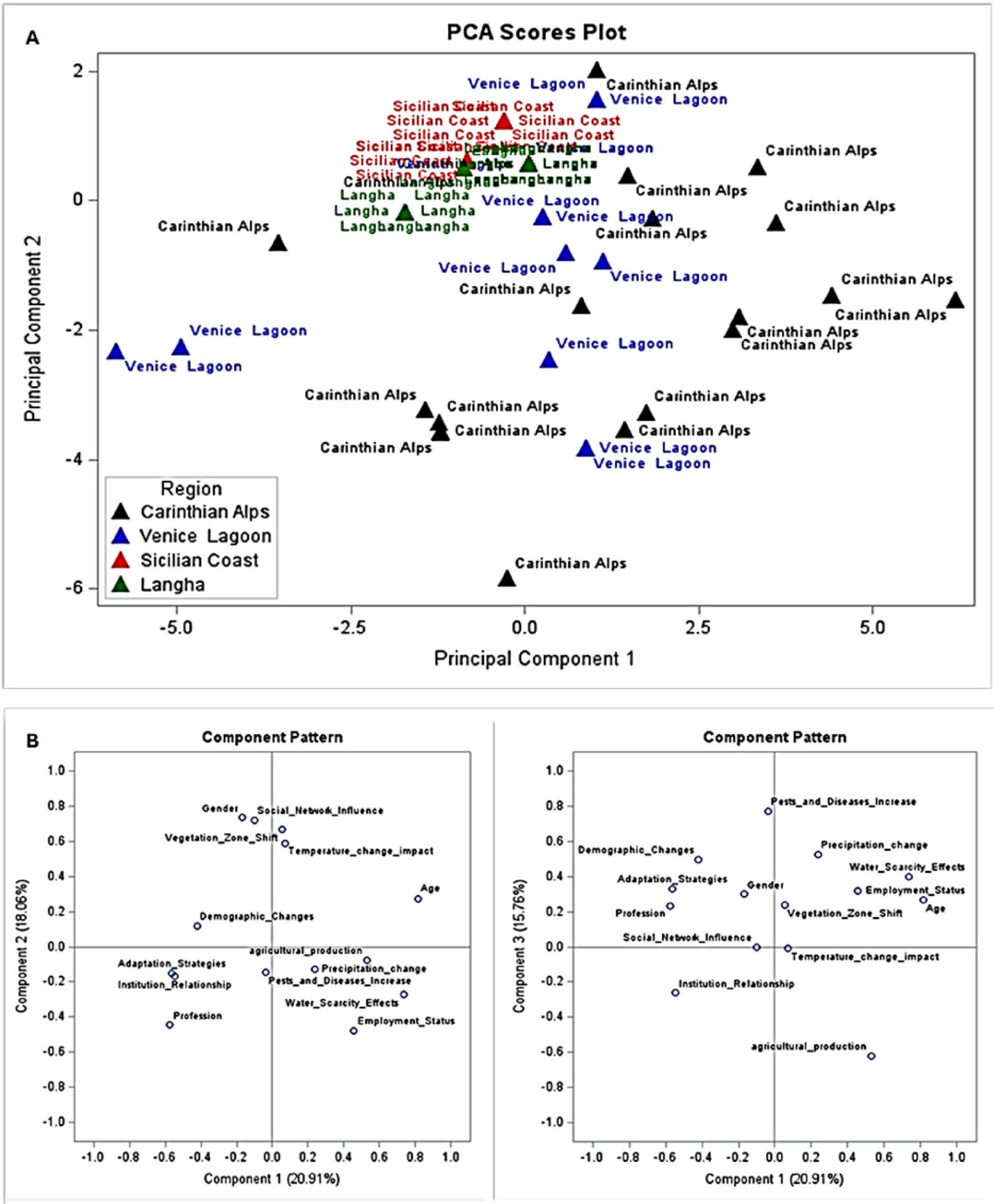

Fig. 2. Variations in climate change perception and environmental impact across the four regions (Carinthian Alps, Venice Lagoon, Sicilian Coast, and Langhe.

The mixed effect logistic regression models were employed to examine the relationship between various explanatory variables and climate change perceptions across the study area encompassing all four zones. Table (2) summarizes each explanatory variable's estimates, standard errors, Wald statistics, and associated p-values.

The results suggest that certain factors have a significant relationship with climate change perception($p < 0.05$, Table 2). For instance, adaptation strategies ($p = 0.024$), precipitation change ($p = 0.001$), and social network influence ($p = 0.002$) are notably associated with climate change effects on precipitation. Therefore, changes in these factors tend to coincide with changes in climate conditions. On the other hand, some social factors like the gender of the respondents and the farmer-institution relationship suggest that their relationship with the perception of climate change impacts is less pronounced or not statistically significant ($p > 0.05$, Table 2). Negative values in the estimates column signify an inverse relationship between the explanatory variable and

Indicator	Response		χ^2 Test	Region							
				Carinthian alps		Venice lagoon		Sicilian coast		Langhe	
	Yes % (n)	No % (n)		Yes % (n)	No % (n)	Yes % (n)	No % (n)	Yes % (n)	No% (n)	Yes % (n)	No % (n)
Temperature change impact	95% (109)	5% (6)	0.286	90% (18)	10% (2)	75% (10)	25%(4)	100%(12)	0%(0)	100%(69)	0% (0)
Impact on agricultural production	89.5% (103)	10.5% (12)	0.003	65% (13)	35% (7)	70% (9)	20%(3)	100%(12)	0%(0)	96%(44)	4% (2)
Precipitation change	96.5% (111)	3.5% (4)	0.534	80% (16)	20% (4)	100% (14)	0% (0)	100%(12)	0%(0)	85% (39)	15% (7)
Water Scarcity Effects	83.4% (96)	6.6% (19)	0.552	20% (4)	80% (16)	80% (11)	20%(3)	100%(12)	0%(0)	100%(46)	0% (0)
Vegetation Zone Shift	95.6% (110)	4.4%(5)	0.4	90% (18)	20% (2)	80% (11)	20%(3)	100%(12)	0%(0)	100%(46)	0% (0)
Pests and Diseases Increase	95% (109)	5% (6)	0.286	80% (16)	20% (4)	85% (12)	15%(2)	100%(12)	0%(0)	100%(46)	0% (0)
Adaptation Strategies	88.2% (98)	11.8% (13)	0.038	60% (12)	20% (4)	80% (11)	20%(3)	50%(6)	50%(6)	100%(46)	0% (0)
*Social Network Influence	92.2% (106)	7.8% (9)	0.05	70% (14)	20% (4)	70% (9)	30%(5)	100%(12)	0%(0)	100%(46)	0% (0)
Demographic Changes	78.2% (90)	11.8% (25)	1.776	50% (10)	20% (4)	90% (13)	10% (1)	100%(12)	0%(0)	78% (36)	22% (10)
Farmer-Institution Relationship	86.9% (100)	13.1% (15)	0.122	30% (6)	20% (4)	70% (9)	30%(5)	50%(6)	50%(6)	100%(36)	0% (0)

Table 1. Summary of the observed indicators of climate change by farmers in the four regions' ecosystems. * In the Alpine Mountain Region the N total =18 and 2 no response. Chi-square ($\chi2$) (two-tailed test); probability level $p \leq 0.05$. The chi-square test was calculated based on the data collection from 115 households in four different regions' ecosystems.

Explanatory variable	Estimates (β)	Standard errors (SE)	Wald statistics	*P-value*
A. Household characteristics				
Age	0.028	0.012	5.234	0.022
Gender	0.21	0.187	1.345	0.246
Profession of household head	−0.657	0.281	6.112	0.013
Employment status	0.438	0.194	3.768	0.042
B. Agricultural characteristics				
Impact on agricultural production	−0.672	0.209	10.493	0.001
Adaptation strategies	0.752	0.178	15.672	0.024
C. Biophysical variables				
Temperature change impact	−0.905	0.312	8.756	0.003
Precipitation change	−1.32	0.287	21.498	0.001
Pests and diseases increase	−0.149	0.163	12.585	0.019
D. Impact variables				
Water Scarcity Effects	−0.531	0.175	6.342	0.012
Vegetation Zone Shift	−0.292	0.118	4.194	0.018
Social Network Influence	0.604	0.201	9.021	0.002
Demographic Changes	−0.376	0.164	4.821	0.028
Farmer-Institution Relationship	0.287	0.142	3.981	0.146

Table 2. Summary of results from the mixed effect logistic regression model models in the study area (all four regions) p-value < 0.05.

climate change perceptions. For instance, as the impact on agricultural production worsens (β = −0.672), or the adverse effects of temperature change (β = −0.905) and precipitation alterations (β = −1.32) intensify, individuals are more inclined to perceive climate change as a significant issue. These findings underscore how experiences of detrimental impacts associated with climate change can heighten awareness and acknowledgement of its effects among individuals or communities.

Table (3) presents the p-values associated with the variables used in the mixed-effects logistic regression model across the different physiographic regions of the study area. A lower p-value indicates a stronger statistical significance. In the Carinthian Alps, variables such as age ($p = 0.381$), gender ($p = 0.498$), and employment status ($p = 0.044$) exhibit higher p-values, suggesting less significant associations with climate change perception. However, the profession of the household head ($p = 0.017$) shows a lower p-value, indicating a more significant relationship. In contrast, the Venice Lagoon region displays varying levels of significance across different variables. Notably, precipitation change ($p = 0.003$) and temperature change impact ($p = 0.013$) exhibit relatively lower p-values, indicating stronger associations with the perception of climate change effects. The Sicilian Coast region also demonstrates significant associations, particularly with variables like precipitation change ($p = 0.022$) and temperature change impact ($p = 0.337$). Finally, in the Langhe region, variables such as adaptation strategies ($p = 0.344$) and demographic changes ($p = 0.916$) show relatively higher p-values, suggesting less pronounced associations with climate change perceptions. Conversely, impact in agricultural production ($p = 0.016$) and

Explanatory variable	*P*-value Region Alpine Mountain	Venice Lagoon	Sicilian Coast	Langhe
A. Household characteristics				
Age	0.381	0.119	0.518	0.822
Gender	0.498	0.092	0.304	0.112
Profession of household head	0.017	0.029	0.041	0.933
Employment status	0.044	0.032	0.0581	0.049
B. Agricultural characteristics				
Impact on agricultural production	0.025	0.912	0.014	0.016
Adaptation strategies	0.118	0.419	0.531	0.344
C. Biophysical variables				
Temperature change impact	0.013	0.098	0.337	0.019
Precipitation change	0.003	0.048	0.022	0.035
Pests and diseases increase	0.028	0.039	0.119	0.041
D. Impact variables				
Water Scarcity effects	0.015	0.722	0.81	0.194
Vegetation zone shift	0.044	0.037	0.412	0.551
Social network influence	0.118	0.626	0.565	0.315
Demographic changes	0.863	0.046	0.818	0.916
Farmer-institution relationship	0.089	0.392	0.028	0.612

Table 3. Details of the variables used in the mixed-effects logistic regression model in the different physiographic regions of the study area.

precipitation change ($p = 0.035$) exhibit lower p-values, indicating stronger relationships with climate change effects in this region.

Discussion

The findings revealed a unanimous acknowledgement of the perceived impacts of climate change across all study regions, indicating widespread awareness among community members. However, while climate change is universally recognized, the specific impacts and concerns vary significantly between regions.

Indeed, while the scientific community often emphasizes the importance of addressing climate change as a global issue[17,18]our study highlights the critical need to recognize and respond to regional and socio-ecological differences. While overarching global strategies are undoubtedly valuable, they may overlook the nuanced challenges and opportunities present within distinct regions, ecosystems and socio-economic dynamics, which are crucial to shaping effective adaptation strategies[5,7,11,18–22].

This regional perspective allows for the identification of region-specific vulnerabilities and opportunities, enabling the tailoring of interventions to meet the unique needs of local communities.

In our study, the socio-economic landscape of farming communities varies significantly across the four case studies. For instance, in the Carinthian Alps, where agriculture and forestry are prominent[23,24]farmers and residents are likely to perceive climate change through the lens of its impact on traditional livelihoods. Additionally, the ageing population in these rural areas may have unique perspectives on climate change, influenced by their deep-rooted connection to the land and the traditional farming practices[1,5,25]. A higher proportion of households are engaged in these sectors compared to regions like Venice Lagoon, where other activities (such as tourism) play more significant roles[26]. The vulnerability of coastal ecosystems may influence climate change perceptions. Artisanal fisherfolk and residents of these coastal communities may witness firsthand the effects of sea-level rise, habitat degradation, and changes in fish stocks[26]. These environmental changes not only threaten their livelihoods but also challenge the cultural and social fabric of these communities, which have relied on fishing traditions for generations[26–28]. In the context of the Sicilian Coast, where agriculture, fisheries, and tourism are integral to the local economy, socio-economic factors play a crucial role in shaping climate change perception[29,30].

Langhe, renowned for its vineyards and wine production, presents yet another socio-economic context. In this study, grape growers and winemakers may closely monitor changes in temperature, precipitation, and growing seasons, as these factors directly influence grape quality and wine production, and consequently on the historical identity of the region's wines, according to many studies[31,32]. Additionally, demographic shifts and changes in land use patterns, such as the conversion of agricultural land for tourism or urban development, may impact the socio-economic resilience of farming communities in this region[33,34].

Primary producers' perceptions of climate change exhibit nuanced differences across the studied regions, reflecting the unique environmental contexts and sector-specific vulnerabilities[35]. While stakeholders in some areas acknowledge changes in weather patterns and vegetation growth, others recognize climate change as a critical issue necessitating proactive adaptation measures.

Farmers in the Carinthian Alps region are keenly aware of changes in weather patterns, such as shifts in snowfall and melting glaciers, which impact water availability and agricultural practices[4,23,25]. Additionally, they observe vegetation zone shifts and increased occurrences of pests and diseases[36,37]signalling the ecological effects of climate change on mountain ecosystems. The rise in temperature burdens pasture animals and affects food production methods, necessitating the use of technical aids like refrigerators[25,38]. Predictions indicate a significant temperature rise by the end of the century, leading to a clear shift of climate regions and a loss of subalpine areas[24]. Additionally, the extension of the alpine season due to milder climates has become a reality, impacting pasture seasons and fodder production[24,25,39–41].

Venice Lagoon farmers are acutely aware of the threats posed by sea-level rise, which is primarily attributed to the melting of polar ice caps and glaciers, along with the thermal expansion of seawater due to rising global temperatures[55]. Due to its shallow morphology, the global warming impacts will be amplified in the lagoon of Venice, where it has been predicted that the intensity of the marine heat waves will be more than four times larger than that in the open sea. Moreover, the compound effects of increased water temperature, combined with sediment runoff, coastal erosion, and pollution from urban areas and agricultural activities, contribute to water quality degradation and biodiversity loss[29,42].

In addition, the rise in water temperature can lead to significant ecological implications, such as changes in the distribution of species and habitats and the proliferation of invasive species and harmful algal blooms, further disrupting the fragile ecosystem of the lagoon[26,43]. These changes not only threaten the survival of native species but also undermine the traditional activities and livelihoods dependent on the lagoon's resources, such as fishing and tourism[43,44]. These environmental changes threaten not only the livelihoods but also the cultural fabric of coastal communities, where traditional practices like fishing are deeply rooted. Ivajnšič et al.[26] found that rising sea levels in the Venice Lagoon affect local fisheries, a concern echoed in other coastal regions[27,28]. In Sicily, socio-economic factors, such as agriculture, fisheries, and tourism, shape perceptions of climate change. Di Maio et al.[29] highlighted the vulnerability of coastal fishing, while Bombana et al.[30] explored how beachgoers in Catalonia perceive climate change impacts. These studies underscore the diverse economic and cultural impacts of climate change, which inform local adaptation strategies.

To address these challenges, stakeholders in Venice and its Lagoon have been implementing adaptation measures aimed at protecting the city and its unique environment. These measures include the construction of barriers and flood defences, such as the MOSE project, which aims to mitigate the impacts of high waters by temporarily sealing off the lagoon from the Adriatic Sea during extreme weather events[44].

Furthermore, initiatives to improve water quality, restore wetlands, and promote sustainable tourism practices are underway to safeguard the lagoon's ecological integrity while supporting the local economy[45]. By embracing nature-based solutions and fostering collaboration among various stakeholders, The Lagoon of Venice seeks to enhance its resilience to climate change and ensure the long-term sustainability of this iconic city and its surrounding lagoon ecosystem.

On the Sicilian Coast, artisanal fishermen may perceive climate change through its impacts on marine biodiversity and fish stocks, driving conservation efforts and sustainable fishing practices[22,47]. Farmers in Sicily's agricultural heartland also observe shifts in precipitation patterns, prolonged droughts, and soil degradation, prompting the adoption of water-efficient irrigation systems and crop diversification strategies[29,48].

Climate change poses significant threats to marine environments and coastal communities on the Sicilian Coast. Rising sea temperatures, ocean acidification, and habitat degradation are among the key challenges faced by stakeholders, including artisanal fishermen and local conservation groups[27,49].

To address these challenges, stakeholders in the Sicilian Coast have mobilized community-based conservation initiatives and sustainable fishing practices aimed at protecting marine resources and enhancing resilience to climate change[50]. These efforts include the establishment of marine protected areas, sustainable fisheries management measures, and public awareness campaigns to promote environmental stewardship among local communities.

Winemakers in the Langhe region observe pronounced climate-related shifts in grape production, including changes in ripening times, sugar content, and grape quality[51]and changes in rainfall[31].

To mitigate these challenges, vineyard owners in the Langhe region have embraced innovative techniques such as canopy management, irrigation optimization, and the introduction of heat-tolerant grape varieties[52]. These adaptive measures aim to enhance vineyards' resilience to climate change impacts while preserving the quality and authenticity of the region's wines[34].

By integrating climate-smart viticulture practices with traditional winemaking techniques, the Langhe region seeks to adapt to changing climatic conditions and sustain its viticultural heritage for future generations[32]. Collaboration among wine producers, researchers, and agricultural extension services plays a vital role in sharing knowledge, exchanging best practices, and building collective resilience to climate change in the wine industry.

The regional variations observed in perceptions of climate change underscore the necessity of context-specific approaches to adaptation planning[8,21,35]. Tailored strategies must account for socio-economic, environmental, and cultural factors shaping local perceptions and responses to climate change[53]. An integrated approach is crucial, engaging diverse stakeholders such as farmers, fishermen, policymakers, scientists, and local communities[54,55]. This collaborative effort ensures the development of solutions that address the unique challenges and opportunities posed by climate change[46,47].

Ecosystem-based adaptation (EbA) approaches play a vital role, leveraging natural ecosystem resilience to enhance climate resilience and promote sustainable livelihoods[11,56]. This may include restoring degraded habitats, conserving biodiversity, and implementing sustainable land and water management practices[32,57,58]. Strengthening community resilience is essential, achieved through capacity building, knowledge sharing, and participatory decision-making processes that empower local stakeholders[53,59]. Moreover, policy support and institutional frameworks are needed to facilitate the effective implementation of adaptation measures[60]including access to finance, technology transfer, and legal frameworks that support climate-resilient development[61,62]. Through these concerted efforts, communities can better adapt to the challenges of climate change while promoting sustainable development and resilience.

Although this study is based on small-sized, specific regional contexts, the findings offer broader implications for encouraging adaptive behaviour in diverse socio-ecological systems. Governments can facilitate adaptation by investing in extension services tailored to regional needs, promoting cross-regional knowledge sharing, and providing financial and technical assistance suited to local vulnerabilities. Additionally, our findings highlight the importance of empowering local networks such as farmer cooperatives, fishing associations, and community groups in driving behavioural change and strengthening resilience. These policy insights are adaptable and can inform the development of flexible, participatory frameworks that address the unique challenges of different communities, leading to more effective and inclusive climate adaptation.

While this study offers valuable insights into farmers' perceptions of climate change and their adaptation strategies, certain limitations should be noted that may affect the generalizability of the findings. The sample size and geographic scope of the study may restrict its applicability to broader populations and ecosystems. Additionally, the reliance on quantitative indicators may overlook the qualitative aspects of farmers' experiences and cultural perspectives on climate change. Notably, the study did not incorporate all variables discussed in the literature or presented in the bibliography, as the analysis was based on the specific interview questions and design of the study. To address these limitations and further advance research in this area, future studies should collect larger samples, employ longitudinal designs, integrate mixed-methods approaches, and explore variations in climate change perceptions at different spatial scales and across diverse socio-economic contexts. Furthermore, gender-sensitive research and participatory approaches could provide deeper insights into the gender dimensions of climate change adaptation and enhance the inclusivity and effectiveness of adaptation initiatives which is exactly what was encouraged by the United Nations Framework Convention on Climate Change (UFFCCC). By addressing these limitations and pursuing future research directions, scholars can contribute to a more nuanced understanding of climate change perceptions and adaptation strategies, informing evidence-based policies and practices aimed at enhancing resilience and sustainability in rural communities.

Conclusions

In conclusion, this study sheds light on the nuanced perceptions of climate change and adaptation strategies among farmers across diverse regions. The findings underscore the significant variability in climate change perceptions and adaptation practices, influenced by socio-economic, environmental, and cultural factors. While some regions exhibit high awareness and proactive adaptation measures, others face challenges in recognizing and responding to climate change risks.

Addressing climate change requires collaborative efforts among stakeholders, including farmers, policymakers, researchers, and local communities. Tailored adaptation strategies, informed by context-specific knowledge and participatory processes, are essential for building resilience and sustainability in rural areas. Gender-sensitive approaches and inclusive decision-making processes can enhance the effectiveness and equity of adaptation initiatives.

Ultimately, this study contributes to the growing body of literature on climate change adaptation, highlighting the importance of considering regional variations and socio-economic dynamics in adaptation planning. By incorporating diverse perspectives and fostering stakeholder engagement and partnerships across sectors, we can work towards building a more resilient and climate-resilient future for rural communities and ecosystems.

Methods

Study area and research design

The study area has been categorized into four distinct ecological regions [65], including coastal, mountainous, agricultural, and fishing regions in Italy and Austria (Fig. 1). These regions were selected to capture a diverse range of socio-ecological contexts, allowing for a comprehensive analysis of climate change perceptions across different environmental settings. Each region was chosen for its unique climatic conditions, socio-economic activities, and cultural practices that influence local communities' experiences and responses to climate change. This diversity ensures a broad understanding of how different geographical and socio-cultural factors shape climate change awareness and adaptation strategies.

Carinthia, Austria's southernmost region, emerges as a compelling focal point for examining the intersection of climate change, agriculture, and cultural heritage. With its stunning mountain landscapes, comprising 93 peaks exceeding 3,000 m, and 1,270 lakes, Carinthia covers an area of 9,536.64 square kilometres and is home to a population of 568,984 residents. Its rich cultural diversity, influenced by Carinthian, Slovenian, and Italian traditions, adds depth to its appeal. Carinthia's reliance on tourism, particularly during the summer months, underscores the importance of sustainable land management practices. Additionally, the region boasts 1,829 managed alpine pastures, with 16% of its area covered by alpine meadows, showcasing its vital role in traditional farming practices[24]. The Eastern Alps are characterized by rugged terrain and unique biodiversity due to the wide elevation range, resulting in peculiar farming and pastoralism to take advantage of the varying climatic conditions[16,17]. Alpine areas are particularly vulnerable to its effects[23]with a temperature increase of 2 °C (more than double the global average)[36,57] experienced throughout the 20th century. A decrease in average precipitation and snow cover and depth reduction was detected[12]. Additionally, the timing and intensity of precipitation events have shifted, with these trends expected to persist[21,22]. While natural science studies have extensively documented the ecological and meteorological impacts of climate change in the Alps[14,17–19]there remains a relative dearth of research on the human dimensions of these changes[8]. This gap is notable, considering Alpine residents are experiencing significant shifts in their environments and climates within their lifetimes, impacting individuals, communities, and local economies[15,24].

The Venice Lagoon, the largest lagoon in the Mediterranean located along the northeastern Italian coast in the Nothern Adriatic Sea, is a complex example of a socioecological system, with a long history of co-evolution between environment and humans that has shaped this unique coastal ecosystem throughout the centuries. The lagoon, encompassing a 550 km^2 area, including Sant'Erasmo and Vignole islands, and the isthmus of Cavallino Treporti, has undergone significant morphological alterations and transformations, like the diversion of the main rivers previously debouching into the lagoon since the 15th century, driven by human interventions and economic activities[27]. These alterations, aimed at creating a more efficient system, have inadvertently increased vulnerability to climate change[27,28]. Through centuries of continuous negotiation with its environment, Venice has shaped its surroundings to suit its needs, transforming the saltmarsh coastal area into the picturesque waterways and islands admired today. This fragile environment, characterized by shifting tides, intricate waterways, and diverse marine life, serves as both a protective barrier and a vital resource for the city and its inhabitants[26–28]. Like other lagoons along low coasts, The Venice Lagoon is highly vulnerable to both natural processes and increasing anthropogenic pressure. It has undergone constant morphological changes driven by the interplay of sea currents, rivers, and wind[27,28]. Erosion and sedimentation, influenced by these dynamic forces, have shaped the fate of the ecosystem, oscillating between periods of erosion and silting[26,28]. However, the Venice Lagoon faces mounting pressures from climate change, pollution, eutrophication, and urbanization, posing significant threats to its ecological balance and cultural heritage[26,27]. Understanding the intricacies of this delicate ecosystem is paramount to addressing the challenges it faces and preserving its invaluable contributions to Venetian life and culture[26]. One of the present challenges is, for example, the abandonment of traditional practices and territories, particularly in the locality of Cavallino Treporti, which has shifted towards mass tourism.

The research area of Porto Palo, Menfi, a small seaside village, is located on the southern western coast of Sicily, approximately 145 km from Tunis. This coastal region is characterized by a Mediterranean to subtropical climate, partly semi-arid with predominantly rocky and sandy terrain[29]. Along the coastline, expansive vegetation dunes are a prominent feature. The coast benefits from ample water resources, with various rivers with torrential nature flowing into the sea from the nearby River Belice and other sources. The Mediterranean Sea is undergoing profound transformations with far-reaching consequences for its marine ecosystems and the communities dependent on them[30]. From the rapid increase in water temperatures to the decline in marine diversity and the proliferation of invasive species, the challenges facing the region's fisheries are numerous and urgent[33,34]. Pollution, including plastic waste, oil spills, and agricultural runoff, poses a significant threat to the Sicilian coast, exacerbated by poor coastal management and marine urbanization[30]. Additionally, the region faces intense maritime traffic, contributing to the degradation of marine ecosystems[37,38]. Overfishing remains a pressing concern, with fish stocks dwindling due to increasing demand and inadequate fisheries management[48,50]. Illegal and unregulated fishing activities or the use of destructive fishing practices further compound the issue, highlighting the urgent need for stronger regulations and enforcement measures. With the decline of fish stocks, local fishing communities are not only losing their economic livelihood, but they also risk seeing their cultural heritage disappear.

The Langhe, situated in southern Piedmont, Italy, is a diverse region characterized by its hilly terrain and agricultural heritage. Divided into three main areas—Bassa Langhe, Alta Langhe, and Langhe Asti and Alessandria—the region is renowned for its vineyards, hazelnut orchards, and picturesque hilltop villages with medieval landmarks[40]. Human intervention over millennia has shaped the landscape, contributing to its unique blend of natural beauty and agricultural productivity[12]. The Langhe region, nestled in southern Piedmont, Italy, is a renowned wine-producing area encompassing diverse microclimates and terroirs, contributing to the unique flavours and qualities of its wines[12,42]. However, Langhe's viticultural heritage faces unprecedented challenges posed by climate change, necessitating a closer examination of its impact on grape cultivation and wine production[33]. Numerous studies highlight the profound impact of climate change on vine cultivation, particularly concerning rising temperatures, declining rainfall, and impacting the timing of phenological stages[42,44,51]. Over the past 50 years, average temperatures in the Langhe have surged by approximately 1.5 °C, prompting shifts in grape ripening and the balance of acids and sugars, ultimately influencing wine quality[46,47]. Increased climatic favorability for diseases and pests, such as the flavescence dorée leafhopper, poses additional threats to vineyards in the Langhe[42].

Research design

The overall research design involves several phases. Firstly, a review of existing literature, research papers, and reports related to climate change perceptions among primary producers was conducted. Based on identified research gaps, research questions were formulated to guide household surveys in various villages across the different ecological regions selected for the study. Subsequently, household surveys were conducted to gather data on farmers, winemakers, and fishermen's perceptions of climate change and their adaptation strategies. The collected data were then analyzed using SAS 9.4 software (SAS Institute Inc., Cary, NC, USA). Finally, the findings were synthesized and concluded to assess farmers' and fishermen's perceptions of climate change and their adaptation strategies across the diverse ecological regions of Italy and Austria.

Data collection

The data collection process was tailored to each of the four distinct ecosystem regions under study, ensuring a comprehensive understanding of the varied impacts of climate change and socio-economic dynamics. A total of 92 households were surveyed from two countries (Italy and Austria) across the four different physiographic regions Table (4). To maintain consistency, a standardized checklist was developed for conducting household surveys, including Focus Group Discussions (FGDs) and Key Informant Interviews (KIIs). Alongside primary

Study area	Physiographic region	No. of participants	Country
Carinthia	Alpine region	20	Austria
Porto Palo, Agrigento province, Sicily	Sicilian coast	12	Italy
Venice and Cavallino Treporti, Venice province, Veneto	Venetian lagoon	14	Italy
Alba, Barolo, Barbaresco, Castiglione Falletto, Diano d'Alba, Dogliani, Grinzane Cavour, La Morra, Mango, Monforte d'Alba, Neive, Novello, Roddi, Serralunga d'Alba, Verduno Cuneo province, Piedmont	Langhe region	46	Italy
	Total	**92**	

Table 4. Number of households interviewed from each village in the different physiographic regions.

data collection, secondary information was gathered from various sources, including unpublished and published documents, reports, books, and maps, to supplement our understanding of the research area.

In Carinthia, Austria, qualitative insights were obtained through semi-structured interviews and questionnaires with mountain cattle farmers during the spring and autumn of 2023. These interviews aimed to explore the nuanced effects of climate change and socio-economic shifts on alpine pastures and pastoral livelihoods. Participants, selected for their extensive experience (minimum of ten years), provided valuable perspectives on the impacts of climate change on agricultural practices and adaptation strategies. The analysis included an examination of historical climate data (temperature, precipitation, and snow cover) and biophysical characteristics (topography, vegetation, fauna, and soil) to assess vulnerabilities and past trends Table (5).

Data collection in the Venice Lagoon focused on the impacts of climate change on the lagoon ecosystem and local livelihoods. In spring 2023, fourteen interviews were conducted with farmers from islands such as Sant'Erasmo and Le Vignole, stakeholders from Cavallino Treporti, and influential collectives in the historic centre of Venice.

In autumn 2022, twelve semi-structured interviews were conducted in Porto Palo, a fishing village, with active or retired small-scale and hobbyist fishermen. These interviews aimed to explore dimensions such as livelihoods, perceptions of fishing practices, institutional collaborations, and future prospects.

In the Langhe wine region, data collection involved both secondary and primary research methodologies. Secondary research included a review of existing literature on biodiversity, climate change impacts, and viticulture practices. This was complemented by primary research, involving a widespread questionnaire survey of approximately 46 wineries across various municipalities, examining the operational history and adaptation strategies of wine producers.

Qualitative interviews across all regions were conducted using both telephonic and in-person modalities to capture a wide range of backgrounds and experiences, focusing on factors such as age, occupation, and socio-economic roles. These interviews aimed to uncover detailed perceptions of climate change impacts and adaptation mechanisms employed by individuals and communities. Comprehensive data was gathered on climate perception, water scarcity, resource availability, and socio-economic factors. Stringent measures were implemented to safeguard respondent privacy and confidentiality. This holistic approach ensured a thorough understanding of climate change effects and adaptation strategies across the different regions. To ensure the robustness and comparability of our approach, we have employed similar methodological frameworks for examining climate change perceptions[12,16,20,22,25,32]. All participants were provided informed consent during the study. All interviews adhered to Free and Prior Informed Consent and followed the ISE 2008 ethical guidelines, and the study protocol was approved by the Ethics Committee of the University of Gastronomic Sciences (UNISG24092024). Interviews conducted in Italy were primarily in Italian, with additional use of Venetian, Sicilian, and Piedmontese as relevant to the study regions.

Supplementary materials (table S1) outline the questions used during the qualitative interviews, providing transparency regarding the topics explored and the methodology employed in gathering insights from the participants.

Socio-economic characteristics of respondents

The study examined the characteristics of respondents and their families across four distinct physiographic regions: Alpine Mountain, Venice and its Lagoon, Sicilian Coast, and Langhe. Table (6) illustrates demographic variations among respondents in different regions, shedding light on the diverse socio-economic profiles across the study areas. Notably, the average age varies significantly, with Venice and its Lagoon having the youngest average age (37 years) and the Sicilian Coast having the oldest (64.8 years). Gender distribution also varies, with more males in the Alpine Mountain region compared to females.

Further analysis of the profession of the household head and their employment status highlights significant diversity across the studied physiographic regions, offering valuable insights into the occupational patterns within each area. For instance, in the Alpine Mountain region, a notable proportion of households are engaged in agriculture and other professions, reflecting the region's reliance on agricultural activities. Conversely, in Venice and its Lagoon region, fewer households are involved in agriculture, with a higher representation of fishermen and other professions due to the area's coastal location. In terms of employment status, the Alpine Mountain region predominantly consists of active households (20), reflecting the region's reliance on labour-intensive activities such as agriculture and forestry. In contrast, Venice and its Lagoon region exhibit a more balanced distribution, with a mix of active (8) and not-active (6) households, possibly influenced by the diverse range of professions and economic opportunities available in the coastal area (Table 6).

Ecosystem	Variable	Description	Relation
Carinthian Alps	Work Practices Changes	Observations on changes in farming practices over time	Neutral
	Temperature Impact on Forage	Impact of climate change on pasture productivity	Negative
	Vegetation Zone Shift	Alterations in plant distribution and biodiversity	Negative
	Climate Hazards Impact	Risks posed by climate-related events to agriculture	Negative
	Water Scarcity Effects	Effects of water scarcity on farming and ecosystem	Negative
	Pests and Diseases Increase	Impact of climate change on pest and disease dynamics	Negative
	Pasture Management Viability	Financial sustainability of farming in changing climate	Negative
	Demographic Changes	Shifts in population demographics and farming community	Negative
	Traditional Knowledge Loss	Decline in passing down of traditional farming practices	Negative
	Land Use Pattern Changes	Alterations in land use impacting farming accessibility	Negative
	Adaptation Strategies	Measures taken to cope with climate change impacts	Positive
	Social Network Influence	Role of community cooperation in adapting to climate change	Positive
	Innovation Adoption Barriers	Factors influencing the adoption of new farming practices	Neutral
	Knowledge Contribution	Role of traditional and scientific knowledge in adaptation	Positive
Venice Lagoon	Farmer Climate Perception	Farmers' awareness and understanding of climate change impacts	Negative
	Cultivation Method Changes	Alterations in farming techniques in response to climate change	Positive
	Drought and Salinity Strategies	Approaches to mitigate the effects of water-related challenges	Positive
	Temperature Change Strategies	Measures taken to adapt to temperature variations	Positive
	New Pest Management	Challenges posed by new pests and methods of control	Negative
	Climate Change Species Risk	Identification of species vulnerable to climate impacts	Negative
	Preferred Forage Plants	Key forage plants favored by farmers	Neutral
	New Plant Identification	Exploration of new crops suitable for changing conditions	Neutral
	Farmer-Institution Relationship	Interaction between farmers and governing bodies	Neutral
	Fishermen Conservation Involvement	Challenges in engaging fishermen in environmental initiatives	Negative
	Fishermen-Lawmakers Contact	Suggestions for enhancing communication between stakeholders	Positive
	Fishing Knowledge Transfer	Transfer of fishing expertise to the next generation	Neutral
	Fishing Future Outlook	Outlook for the sustainability of local fishing industry	Neutral
Sicilian Coast	Climate Perception in Fisheries	Awareness of climate-related effects on fishing	Negative
	Intensive Fishing Impact	Influence of heavy fishing practices on local waters	Negative
	Marine Environment Protection Efforts	Actions taken to preserve the marine ecosystem	Positive
	Illegal Fishing Presence	Incidence of unauthorized fishing in the area	Negative
	Biological Fishing Stop Effectiveness	Viability of halting fishing activities to aid recovery	Neutral
	Institution Relationship	Interaction between fishermen and governing bodies	Neutral
	Fishermen Conservation Challenges	Difficulties in engaging fishermen in environmental initiatives	Negative
	Communication Improvement Ideas	Suggestions for enhancing dialogue between stakeholders	Positive
	Fishing Knowledge Passing Plans	Transfer of fishing expertise to succeeding generations	Neutral
	Knowledge Sharing Interest	Willingness to disseminate fishing expertise to others	Positive
	Fishing Future Outlook	Prospects for the sustainability of local fishing industry	Neutral
Langhe	Temperature Changes	Variations in temperature patterns over seasons	Neutral
	Hot Days Frequency Changes	Alterations in the occurrence of extreme heat events	Negative
	Precipitation Pattern Changes	Alterations in rainfall patterns	Neutral
	Vineyard Biodiversity Changes	Shifts in plant and animal diversity in the vineyard	Negative
	Grape Varieties Fragility	Alterations in grape types and susceptibility to damage	Negative
	Vineyard Management Impact	Influence of climate changes on agricultural operations	Negative
	Relationship Changes with Vineyard	Evolving connection between farmers and their vineyards	Neutral
	Impact on Grape Production	Perception of the impact of higher temperatures, droughts, and changing precipitation patterns on grape production.	Negative

Table 5. Summary of interview variables and their relationship with climate change impact in the four studied areas.

Data analysis

To analyze farmers' awareness of climate change, SAS 9.4 software (SAS Institute Inc., Cary, NC, USA), was used, and Principal Component Analysis (PCA) was used to explore the underlying structure of the dataset and identify key variables contributing to regional variations. This technique reduces the dimensionality of the data while retaining most of its variation. The PCA was performed on standardized socio-economic and environmental variables, including Age, Gender, Profession, Employment Status, Impact in agricultural production, Adaptation

Household Characteristics	Details	Region				Total
		Carinthian Alps	Venice Lagoon	Sicilian Coast	Langhe	
Age	Average age (Year)	*n.d	37	64.8	n.d	50.9
Gender	Male	17	11	12	n.d	50
	Female	3	3	0	n.d	6
Profession of household head	Agriculture, Agribusiness, Agricultural research	19	5	0	0	24
	Fisherfolk	0	1	12	0	13
	Wineries	0	0	0	46	46
	Other profession	1	8	0	0	9
Employment Status	Active	20	8	6	46	80
	Not Active	0	6	6	0	12

Table 6. Characteristics of the respondents and their families by physiographic region in the four regions *n.d: not determined.

Strategies, Temperature change impact, Precipitation change, Pests and Diseases Increase, Water Scarcity Effects, Vegetation Zone Shift, Social Network Influence, Demographic Changes, and Farmer-Institution Relationship. which were binary (yes/no) in nature. Prior to PCA, these variables were transformed by standardizing them, centring by subtracting the mean, and scaling by dividing by the standard deviation. This standardization ensured that each variable contributed equally to the analysis, addressing the sensitivity of PCA to data scales.

Regarding similarity measures, PCA itself uses the covariance or correlation matrix of the standardized variables to compute principal components. In this context, a correlation matrix was used, as it standardizes each variable to have unit variance, accommodating the binary nature of the data. While Jaccard similarity is often employed in clustering or similarity analyses for binary data, PCA focuses on the covariance or correlation structure to reveal underlying patterns and relationships among variables. This approach allowed for a comprehensive exploration of the dataset's structure and the identification of key factors influencing regional variations in climate change perceptions among farmers, fishers, and winemakers across diverse regions in Italy and Austria. To analyze perceptions of climate change and adaptation strategies among farmers, fishers, and winemakers, we employed a mixed-effects logistic regression model. This model offers a robust framework for assessing both overarching trends and region-specific variations, providing valuable insights into the complex relationship between climate change perceptions and regional characteristics.

The mixed-effects logistic regression model allows us to examine the binary outcome variable, representing the perception of climate change (Yes/No), about a set of independent variables. These independent variables encompass both region-specific factors and common variables across regions. Only the age variable was prepared as continuous data.

The fixed effects component of the model captures the overall relationships between the independent variables and climate change perception across all regions. Specifically, we include region-specific fixed effects to account for the impact of each independent variable on climate change perception within each region. This enables us to identify general trends while controlling for regional differences.

In addition to fixed effects, our model incorporates random effects to accommodate variability specific to each region. By including random intercepts for each region, we can capture unobserved heterogeneity and account for within-region correlation in perceptions of climate change.

This approach enhances the robustness of our analysis by accounting for regional differences beyond the variables explicitly included in the model. The model equation is:

$$logit(Y\_ij) = \beta\_0 + \beta\_1 * X\_1 + \beta\_2 * X\_2 + \ldots + \beta\_n * X\_n + u\_i + \epsilon\_ij$$

Where:

- Y_ij is the climate change perception for individual i in region j.
- β_0 is the intercept.
- $\beta\_1, \beta\_2, \ldots, \beta\_n$ are the coefficients for the independent variables.
- $X\_1, X\_2, \ldots, X\_n$ are the independent variables.
- u_i is the random effect for region j.
- ε_ij is the error term.

In the mixed-effects logistic regression model, households indicating awareness of climate change were coded as 1, while those indicating no awareness were coded as 0. The independent variables considered in the study are categorized into four main groups: (A) Household characteristics: including Age, Gender, Profession of household head, and Employment Status. (B) Agricultural characteristics: encompassing Impact on agricultural production and Adaptation Strategies. (C) Biophysical variables: such as Temperature change impact, Precipitation change, Pests and Diseases Increase. (D) Impact variables: covering Water Scarcity Effects, Vegetation Zone Shift, Social Network Influence, Demographic Changes, and Farmer Institution Relationship. Most variables were dichotomous, with values of either 0 or 1.

Data availability
The data that support the findings of this study are available on request from the corresponding author, [GM]. The data are not publicly available due to restrictions.

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MA: conceptualization, software, data visualization, data analysis, writing original-draft, writing reviewing-editing, investigation, methodology; GM: conceptualization, student supervision, writing reviewing-editing; methodology CR: data analysis, writing reviewing-editing NS: conceptualization, writing reviewing-editing, methodology; LK, BS, ALS, GS: data collection; AP: conceptualization, supervision, project administration, writing reviewing-editing.

Declarations

Competing interests
The authors declare no competing interests.

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