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Perspective

Viticulture in Argentina under extreme weather scenarios: Actual challenges, future perspectives

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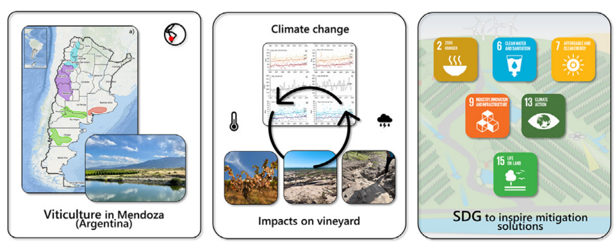
HIGHLIGHTS

- Viticulture in Argentina is a key socioeconomic sector
- Climate change is affecting vineyards impacting society, the economy, and biodiversity
- Extreme rainfall poses serious threats to vineyards due to runoff and soil erosion
- Mitigation strategies are strongly needed to improve the resilience of vineyards
- SDGs can guide stakeholders toward a resilient and sustainable viticulture

GRAPHICAL ABSTRACT



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ABSTRACT

Viticulture in Argentina is an important socioeconomic sector, reflected in a significant wine market and tourism. However, climate change and related extreme events are serious concerns. The main issues are heatwaves, hailstorms, and heavy rainfall, resulting in damage to vineyards. While climate change impacts have already been discussed for regions such as the Mediterranean, the literature lacks an up-to-date overview of Argentine viticulture and potential mitigation solutions. In a country culturally and economically connected to the world of wine, it is strategic to bridge this gap to be prepared for a climatically adverse future. This perspective paper presents an overview of Argentine viticulture and its relationship to climate change. We focus on the Mendoza region, one of the most productive areas and home to cultural landscapes where internationally recognized wines are produced. Climate change is already occurring, a fact we observed by analyzing data from the past decades. We discussed how heatwaves in the lowlands drive farmers to move to the Andes slopes looking for more favorable conditions. But new threats arise, such as extreme rainfall. Due to surface hydrological processes, they can cause land degradation and compromise vineyards. We investigate these phenomena in detail, highlighting how they represent a growing challenge that must be addressed for the sustainable development of future viticulture in the area. Therefore, we propose mitigation strategies for more resilient production, drawing inspiration from the Sustainable Development Goals and suggesting a framework that can be extended to broader contexts worldwide.

1. Introduction

Since the first domestication of the vine (*Vitis vinifera* L.), viticulture has become a widespread agricultural practice worldwide. In several cases, winegrowing areas are important cultural landscapes that integrate ecosystem services with social needs. Viticulture faces serious difficulties due to climate change, which could alter the terroir of unique cultivations. The consequences can be dramatic. Heatwaves have a strong impact on vine plants, causing leaf loss and grape damage, such as in the case of an extreme event in France in 2021 (Lopez-Fornieles et al., 2022). Another problem is the variation in the precipitation regime, which often leads to dry periods alternating with extreme rainfall. Drought is one of the most alarming agricultural hazards posed by climate change. Although controlled conditions of vine water stress can positively af-

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fect wine quality, prolonged lack of water causes irreparable damage (Chaves et al., 2010). Therefore, especially in drier areas, irrigation is a key practice. When rainfall is concentrated in short periods, serious surface processes such as soil erosion, flash floods, landslides, and other severe processes can be triggered. They can significantly compromise the functionality of vineyards (Maetens et al., 2012). Numerous researches have been conducted on this issue, for example, in Spain (Rodrigo Comino et al., 2017) or Italy (Pijl et al., 2020). Hailstorms are also major concerns, especially during grape ripening or before harvest (Vinet, 2002).

In the Northern Hemisphere, European soils accommodate the largest area devoted to viticulture. In 2021, Spain, France, and Italy alone were responsible for roughly half of the global wine production (OIV, 2022). Vineyards are also in Portugal, Germany, and the Eastern European states. Other examples worldwide are China, the United States, and Turkey. The scientific literature is rich in research conducted on the impact of climate change on vineyards in these areas. Interesting recent examples include the effects of heatwaves in Europe (Fraga et al., 2019), the importance of climate risk management in the United States (Babin et al., 2022) or the potential loss of vineyard areas in China (Bai et al., 2022). Viticulture is also widespread in the Southern Hemisphere. The vineyards are planted in Australia, Africa, and South America, where it is an important economic activity. Examples are Chile, Brazil, and Argentina. The latter is a key producing country and seventh in the world regarding area under vines. Viticulture is a leading economic sector, integrating wine production and enogastronomic tourism. The Cuyo region and, specifically, the province of Mendoza host outstanding wine-growing areas. The landscape also has strong cultural attributes. It has been shaped over centuries, starting from a complex traditional irrigation system that began in the prehispanic era (Ponte, 2006). Thus, climate change may affect production and the cultural values that characterize some related areas.

Compared to the Northern Hemisphere, less research on the interaction between climate change and viticulture can be found in the Southern one. Examples include the adaptability of viticulture in Chile (Mills-Novoa et al., 2016) and the impacts of spring frosts in Brazil (Campos et al., 2017). Few studies focus on Argentina. For instance, Cabré and Nuñez (2020) simulated future climate changes in Argentine winegrowing areas by describing potentially critical scenarios. However, the literature lacks a general overview of the topic, in which potential damages are deeply investigated and effective solutions sought. In a country deeply rooted in the wine industry, filling this gap would open the door to more specific research, contributing to the safety of viticulture that cannot be compromised. In addition, it could address policymakers toward an improved landscape planning and natural resource management strategy. Therefore, in this perspective article, we summarized these concepts by proposing an overview of viticulture in Argentina and focusing on the Mendoza area. We explore the current and future challenges related to climate change in vineyards, also discussing possible mitigation strategies in line with the United Nations (UN) Sustainable Development Goals (SDGs).

2. Viticulture in Argentina and Mendoza

Argentinian viticulture extends from 22° to 45° South latitude, mainly located along the piedmont of the Andes Mountains. 92% of the country's vineyard area corresponds to varieties suitable for wine and must production, and 8% for fresh consumption and sultanas. The most cultivated wine varieties are Malbec, Bonarda, Cabernet Sauvignon, Torrontés riojano, and Chardonnay. Four main winegrowing regions can be distinguished: the North, the Cuyo, the Atlantic, and the Patagonian (Fig. 1a). Except for the Atlantic one, many vineyards are located at altitude. The Cuyo region is among the most important in South America. A significant portion is located in Mendoza province (Fig. 1b). Despite the dry climate (rainfall regime is in Fig. 1c), viticulture is a major socio-economic activity. This is possible thanks to oases supported by a complex system of reservoirs and irrigation canals. The province is characterized by the largest area under vines in the country (71% of the total cultivated surface) and is recognized as one of the Great Wine Capitals. Five winegrowing regions are located here: North, East, Center, South, and Uco Valley. The Center and Uco Valley (Fig. 2) are remarkable regarding the production and exportation of qualitative wines. Soils vary from loam to clay loam (based on USDA classification) and are characterized by the presence of coarse material (gravel and boulders), poor organic matter, and good permeability (INV, 2022). Over the past 20 years, the vineyards in these areas have steadily increased their surface through modern and technological systems. Some of the most interesting cultivations are located in the foothills of the Andes, in the Department of Luján de Cuyo. Favorable ecological and climatic conditions lead to a strong viticulture expansion here, even on steep slopes at high altitudes. Winters are harsh, summers are hot, with temperate days and cold nights, resulting in an annual mean temperature of approximately 12–15 °C (Cabré et al., 2016). Milder temperatures and fewer climate change-related heatwaves are the main reasons for this territorial expansion.

3. Climatic threats in Argentine vineyards

3.1. Water, storm, hail

Most Argentinean viticulture takes place in the valleys of the Andes mountains, where the climate is highly influenced by topography. The annual precipitation mostly occurs during spring and summer. However, rainfall is insufficient in some key viticultural areas to cover the vine plant cycle, requiring irrigation. The snowmelt is the primary water source, reaching the cultivation areas by flowing from three main rivers to a dense channel network. A primary climatic threat is a drought. From 2010 to the present, the central-west of Argentina has experienced severe periods of hydrological drought. Reduced snowfall at high altitudes decreases the river flow downstream, leading to restrictions on water consumption for agriculture and domestic use (Rivera and Arnould, 2020). In case of water scarcity, exploitation of groundwater resources increased, an unsustainable solution in the long run (Rivera et al., 2021). One critical aspect is the regime with which rainfall occurs, often concentrated in heavy, localized storms in recent years (Castex et al., 2015). The consequences are severe, such as landslides on slopes and flash floods in lowlands, sometimes involving urban areas (Vich et al., 2014). Argentina is prone to intense hailstorms (Bechis et al., 2022), mainly during spring and summer. They damage plants at delicate phenological stages, such as flowering and ripening (Mezher et al., 2012). Topography influences diurnal winds, resulting in convection initiation (CI) hotspots that trigger hailstorms (Hierro et al., 2013; de la Torre et al., 2015). Impacts on agriculture are considerable, with annual production losses estimated at 10%, mainly caused by large hail (diameter greater than 2 cm) concentrated in 2-3 events per year (Pérez and Puliafito, 2006). Over the past 60 years, several attempts have been made to prevent hail damage in Mendoza province through cloud seeding. However, no scientific evidence demonstrates a statistically significant reduction in the frequency with which these events occur and a reduction in hail size (Rivera and Arnould, 2020). For this reason, it is crucial to focus on forecasting and prevention, studying the mechanisms that generate severe convective phenomena in the region, and testing the activation of warning systems. Also, there is a need to invest resources in improving real-time observations, such as radar, radiosondes, and ground measurement stations.

3.2. Rising temperatures and heatwaves

Rising temperatures are a problem for viticulture in Argentina. The first concern is the loss in the mass balance of glaciers, resulting in earlier snowmelt that affects irrigation management (Zazulie et al., 2018; Hock et al., 2019). High pre-sprouting temperatures advance the date of

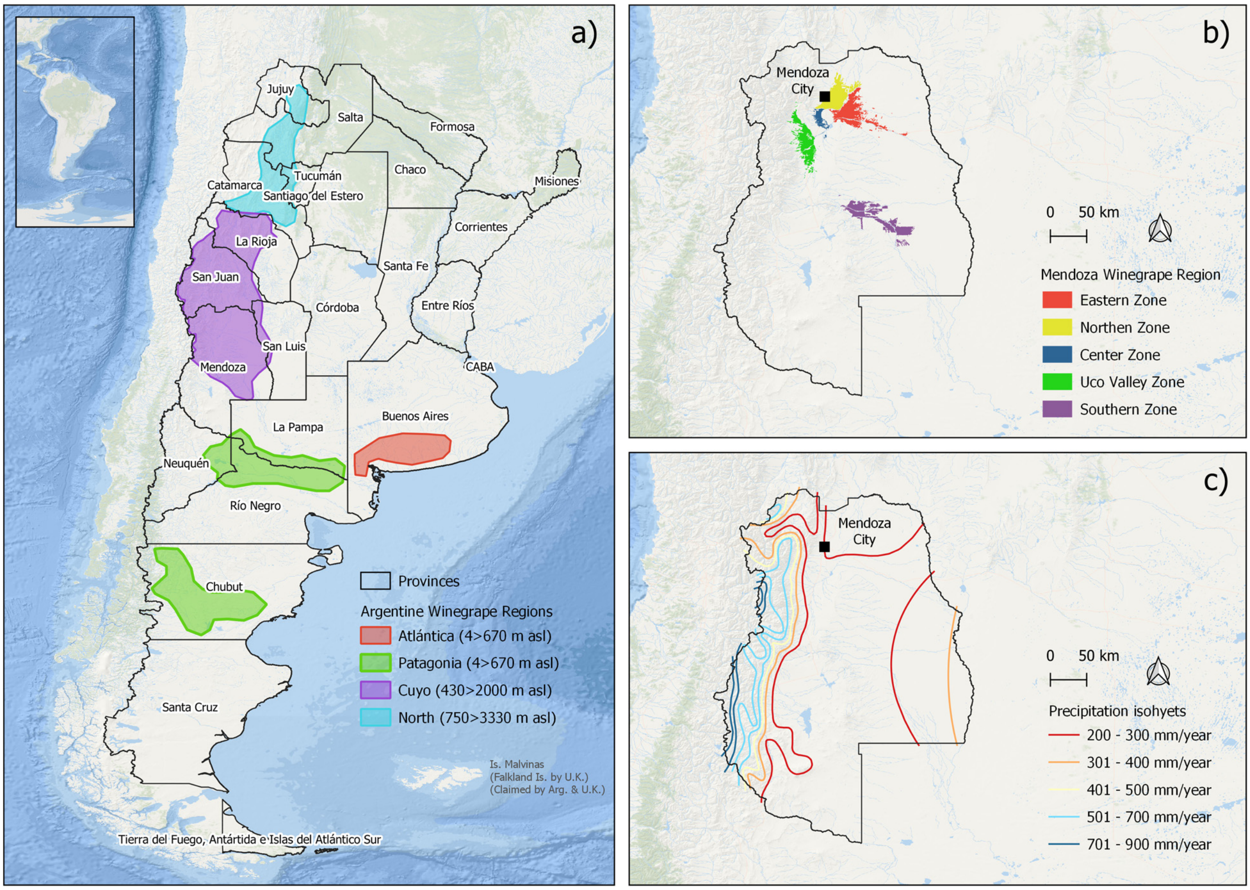

Fig. 1. a) The Argentine provinces and the main winegrowing regions; b) Focus on the province of Mendoza related to the viticultural areas; c) Precipitation isohyets of the province of Mendoza.

Fig. 2. Vineyards located at 1,300 m asl near Andes mountains (Uco Valley, Mendoza province; photo by Paolo Tarolli).

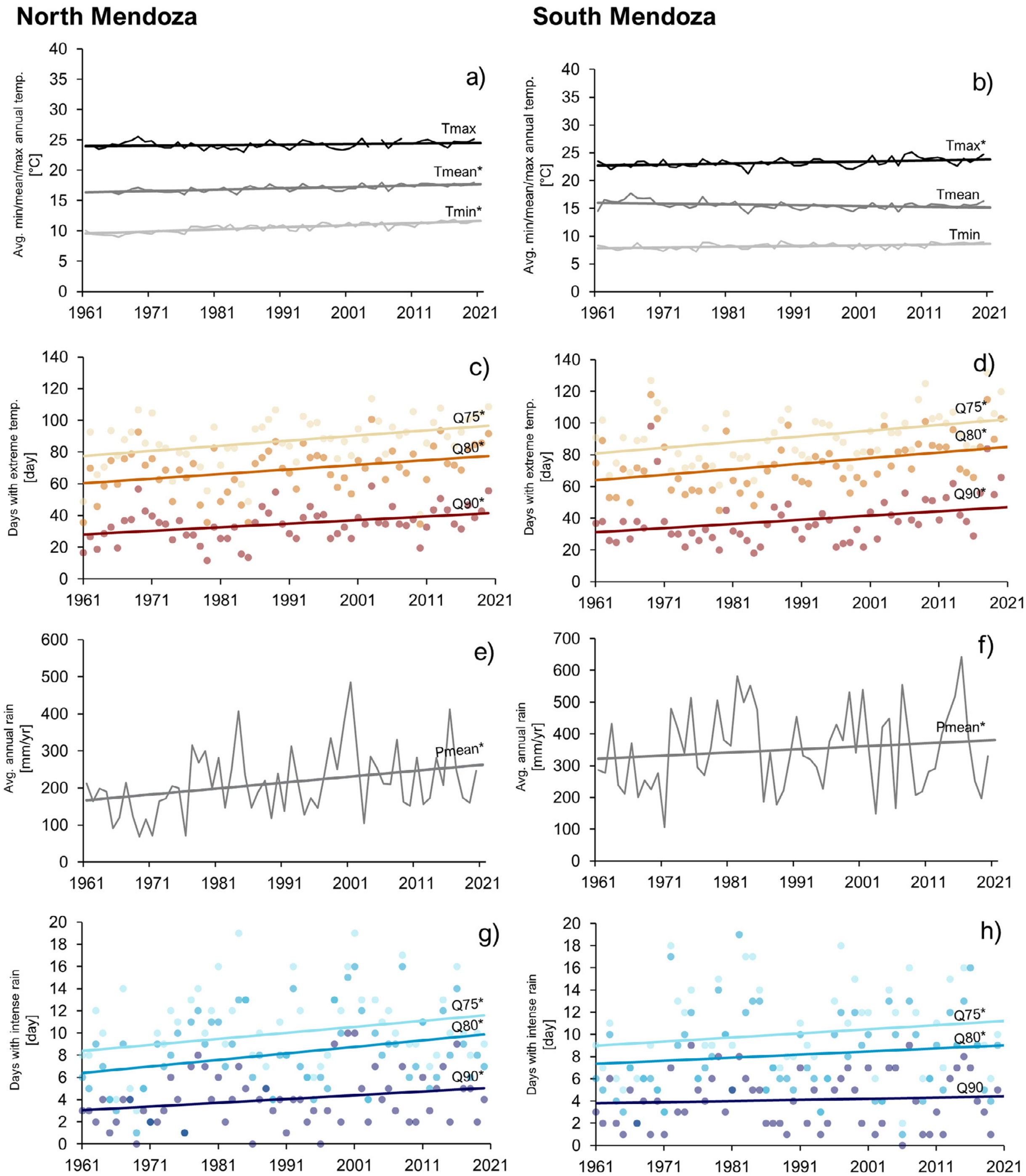

Fig. 3. Analysis of temperature and precipitation at two representative weather stations in Mendoza's north (left column) and south (right column). The data refer to the period 1961–2020 and are recorded daily. a) and b) analyze the trends of minimum, average, and maximum temperature over the period; c) and d) are the number of hot days according to three thresholds (percentiles 0.75, 0.85, 0.90); e) and f) are the average annual precipitation; g) and h) analyze the days with heavy rainfall (percentiles 0.75, 0.85, 0.90). Statistical significance of the linear regressions is indicated by *, calculated by the modified Mann-Kendall test.

bud break and increase the rate of bud growth. Excessive heat can disturb the developing berries, affecting wine quantity and quality. Moreover, the influence of the water deficit producing colorful and flavourful wines rich in phenolic substances cannot be achieved at elevated temperatures (Bonada et al., 2015). Mendoza is an area where a gradual increase in temperatures is occurring. Fig. 3 shows an original analysis of two representative meteorological stations located north and south of Mendoza. The dataset consists of daily temperature and precipitation measurements from 1961 to 2020 (courtesy of the Servicio Meteorológico Nacional; SMN). The data were used for temperature (in this section) and precipitation analysis (section 4.1). Figs. 3a and 3b show the trends of minimum, average and maximum measures. There is a general increase in temperature and a positive slope of the linear regression fit curve. We tested the significance of the trend through the modified non-parametric Mann-Kendall test, which is widely used for time series (Hu et al., 2020). Outcomes show a statistically significant trend (p-value < 0.05) for mean and minimum temperatures in the southern zone and for maximum temperatures in the northern. The latter is increasing in the last decade. Decomposing the dataset into two periods, we observed that the maximum temperature increased by an average of +0.7°C in the period 2010–2020 compared to 1961–2009 (statistically different according to the *t*-student test; p-value < 0.05). High maximum temperature events can evolve into heatwaves, a serious threat to viticulture (Barros et al., 2015). They can damage the flowers during spring flowering, resulting in reduced fruit production and increased berries' temperature and wilting. These events are becoming more frequent in Argentina, especially in the lowland areas of Mendoza (SADS, 2015). We analyzed the frequency with which hot days occurred (Figs. 3c and 3d). The results show that days where the maximum temperature exceeds threshold values (percentiles of the entire time series: 0.75, 0.85, and 0.90) are intensifying due to climate change (p-value < 0.05). Increasingly difficult growing conditions are leading wine growers to expand farmland elsewhere, mainly on the slopes of the Andes in Mendoza province. However, new hazards, such as extreme rainfall events, are arising.

4. New threats due to climate change

4.1. Intense and localized rainfall events

In Mendoza province, the average annual rainfall in the plain is ordinarily low (around 200 mm/year), with high inter-annual variability/heterogeneity in space and time. Climate models indicate that rainfall and snowfall in the Andes may decrease in the future. At the same time, an increase in precipitation, especially in summer, is projected in the lowlands east of the mountain range (Villalba et al., 2016). Cabré and Nuñez (2020) estimated the precipitation anomalies for two climate scenarios (RCP4.5, RCP8.5). For the province of Mendoza, a decrease in precipitation at high elevations (-60 mm) and an increase at lower elevations (+60 mm) is projected for the worst-case scenario (comparison of 1960–2010 and 2075–2099). The latter is already observable in the historical data series. We analyze the average annual precipitation for the period 1961–2020 (Figs. 3e and 3f), observing a significant positive trend (p-value < 0.05) both in the northern (+16.0 mm/decade) and southern (+23.3 mm/decade) areas. The greater water availability led to an expansion of the rural territory and a progressive increase in production. But to understand the benefits of agriculture in detail, it is important to analyze the spatiotemporal regime with which rainfall happens. On the one hand, extreme weather events in Argentina occur with high spatial and temporal variability, a process analyzed by several studies (Penalba and Robledo, 2010; Castino et al., 2017). This is also accentuated by periodic phenomena such as the effect of "El Niño/Southern Oscillation" or "La Niña" events (Trenberth et al., 2014). On the other hand, it was observed that in key Argentine wine regions, an increasing fraction of rainfall occurs in the form of short, intense, and localized events. This was also recorded in Mendoza province (Castex et al., 2015). Our analysis support previews research, indicating that in the period 2010–2020, the total annual precipitation increased compared to 1961–2009 (p-value < 0.5). At the same time, the number of rainy days (> 0.1 mm/day) decreased by 12%. Consequently, the average precipitation during rainy days increased by 17%, including more heavy precipitation episodes. We also analyzed the frequency with which daily rainfalls exceeded certain thresholds (percentiles of the entire time series: 0.75, 0.85, and 0.90). The results show a significant increase (p-value < 0.05) for both stations and for almost all percentiles (Figs. 3g and 3h). Extreme events worry local authorities, farmers, and communities, causing considerable damage to people, vineyards, and their productivity. Among the most severe processes are flash floods, which cause soil erosion, landslides, and flooding (examples are reported in Fig. 4). Water stagnation is another related problem. The soil tends to become saturated and anaerobic, leading to a reduction in the quantity and quality of the grapes to the possible death of plants. Organic matter is easily washed away by excess water, making support measures necessary to maintain optimal fertility conditions. Another indirect effect of heavy rainfall and hyper-humid conditions is the development of vine diseases. Some significant examples involve root rot (such as Rosellinia necatrix or Armillaria mellea), leaf wilt, and possible plant death. As the climate change-related risks increase, farmers need to take the problem seriously, especially if the trend is to move vineyards to higher and steeper areas to mitigate the impact of climate change, such as heatwaves.

4.2. New threats due to vineyards shifting up to the Andes?

Extreme weather events cause severe yield reductions with potential consequences on price fluctuations in grapes and wine markets. Priorities include obtaining heat- and drought-tolerant varieties, modifying traditional agronomic and winemaking practices, promoting efficient water management, and finding new growing areas among the many challenges facing the wine sector. New vineyards are increasingly located at higher altitudes, where average temperatures during the grape ripening period are lower, and heatwaves are rarer. In contrast, the traditional lower flat regions will gradually become less optimal for production. This is due to climate change-induced aridification, making it increasingly difficult to grow vines in the Argentine lowlands. The rainfall deficit turns into a lack of available water for human activities. It causes problems for the vineyards (concept exemplified in Fig. 5 as warm-colored rows representing water-stressed conditions). Therefore, moving the vine frontier towards regions further south or advancing towards higher areas (up to 2,000-3,000 m above sea level) are increasingly considered strategies. The development of higher terroirs represents an excellent alternative to compensate for warmer temperatures and is in line with the global trend of consuming fresher wines with good natural acidity. In addition, as the vineyards increase in height and are closer to the mountains, the UV-B radiation generates thicker and darker skins, which represent an advantage for obtaining higher concentrations of color and aromas (Alonso et al., 2016).

On the contrary, in high-altitude areas, the climate becomes more extreme (hail, heavy rains), and the occurrence of intense runoff phenomena cannot be underestimated. The construction of new vineyards on slopes requires the alteration of the original soil and surface morphology. As a consequence, there could be problems related to water regulation, with repercussions on hydrogeological processes. While excess water can be potentially exploited in agriculture, it also causes soil erosion. In addition to a progressive loss of fertility, it can evolve into a more severe issue of land degradation (Lal, 2001). Without an appropriate soil and water management plan, extreme phenomena such as landslides, flash floods, and mudslides can occur (Wang et al., 2018). These can compromise the functionality of vineyards and threaten the safety of people living downstream. Farmers will likely face these challenges when they plant vineyards on the slopes. The management of the new challenges that viticulture faces worldwide can only be overcome with adequate research and local development that integrates private companies and public institutions linked to the industry and natural resources. The challenges are enormous, but the key to success will be to propose integrated solutions toward a more sustainable management model, focusing on research and innovation as a driver for adaptation.

5. Sustainable solutions for mitigating climate change impacts

5.1. Impact on the socioeconomic sector

For Argentina, the wine industry accounts for almost 0.4% of the national GDP based on nearly 0.1% of its surface. The activity in 18 provinces depicts an industry with broad territorial distribution, reduced surface, and high added value. For 2017, the wine industry generated an overall value of $1.4 thousand million meaning $6.5 thousand per hectare (OVA, 2017). These values include the different business units such as table grapes, bottled wine, bulk wine, raisings, and tourism. In terms of employment, more than 385 thousand persons directly or indirectly contribute to the activity. Under a climate change

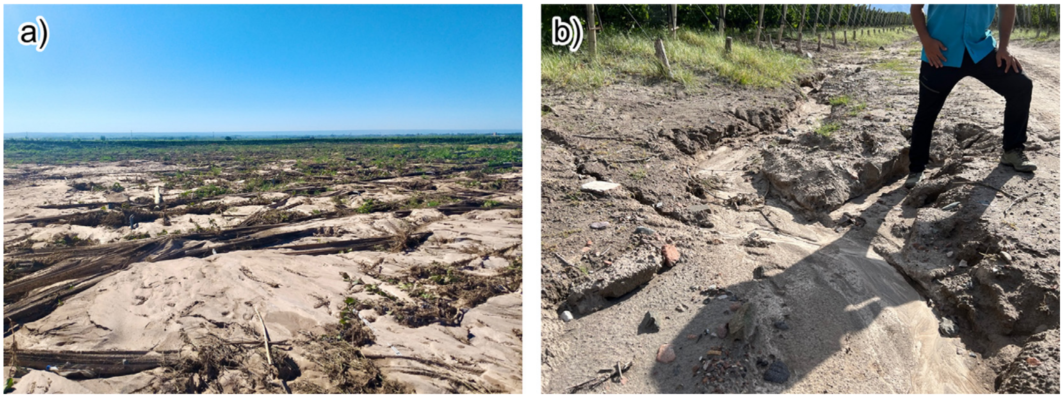

Fig. 4. a) Flash flood damages in a low-slope vineyard in the valley floor of the Andes mountain range (event of February 27, 2021; Uco Valley, Mendoza province photo by Carlos Schilardi); b) Soil erosion in a vineyard located on a slope. Soil eroded from the vineyard inter-rows was transported and deposited along an unpaved road, which is itself deeply damaged by surface runoff after heavy rainfall (event of February 9, 2022; Mendoza River Basin, Mendoza province; photo by Paolo Tarolli).

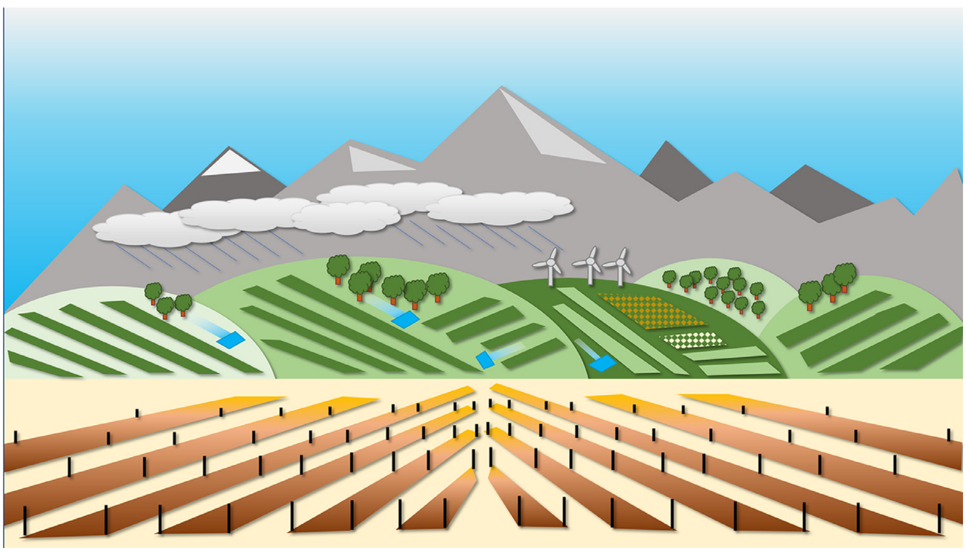

Fig. 5. Conceptual illustration describing vineyards' shift to Argentina's mountains. Lowland plantations suffer increasingly severe drought conditions and heatwaves due to climate change and are represented with a warm brown color. The new vineyards built at higher altitudes benefit from better climatic conditions. A green color, therefore, characterizes rows to describe excellent vegetative conditions. Appropriate water and soil management measures can help mitigate related issues.

scenario, this industry is threatened in terms of added value and social impact. When defining adaptation or mitigation measures, it is essential to have a comprehensive vision of the industry and to understand the different business units and their productive and social constraints. Suppose viticulture in Mendoza must move upward to reduce the vine's exposure to high temperatures. In that case, it is essential to understand where wineries and suppliers should be located and how to connect them. The carbon footprint of increased transport can then endanger an intelligent decision from a climate change perspective. For instance, all workers dedicated to grape cultivation (82% of all wine industry) will require transportation and services, defining associated economic and social costs. Grape transportation to the winery should also be assessed in terms of financial costs and also quality issues that could arise. It is necessary to understand the return on investment to employ other strategies, such as drip irrigation or anti-hail systems. If only 5% of the world market of wine is composed of one-liter bottles over $30 retail price (ultra-premium), the possibility of assuming such costs is reduced. Thus, sustainability requires a comprehensive approach, balancing environmental, social, and economic issues. Consumers look forward to this approach and are willing to pay for these differentiation attributes (Valenzuela et al., 2022). An adequate communication strategy must be designed to increase consumers' awareness and willingness to pay, allowing wineries to invest in climate change mitigation strategies. These communication strategies can include the use of eco-certifications and generic promotion for regional or national agencies can be of significant contribution. In all, management practices need to have sustainability issued from a broad perspective, assessing profit, people, and the planet in a harmonic way.

5.2. Mitigation strategies: monitoring, structural and non-structural solutions

Making viticulture more sustainable can contribute to climate change mitigation, and examples of carbon-neutral production are already realities (Chiriacò et al., 2019). Sustainable viticulture management can lead to more resilient rural landscapes. Primarily, it is important to promote monitoring campaigns to investigate threats. The use of field/remote sensors can lead to detailed mapping and guide mitigation strategies. Among the most interesting measures are the conservation agriculture (CA) guidelines. They are proposed by the FAO to promote biodiversity and natural soil processes, thereby improving resource efficiency (FAO, 2023). It is based on three principles: minimal mechanical soil disturbance, permanent organic soil cover and crop diversification. More resilient viticulture should gradually include these practices in the cultivation process and adopt nature-based solutions (Wang et al., 2022a). For steep-slope vineyards, the cover crop is a crucial practice. Grass can help mitigate erosion by protecting the soil from drops, erosivity, and surface runoff. An alternative solution may be mulching, which

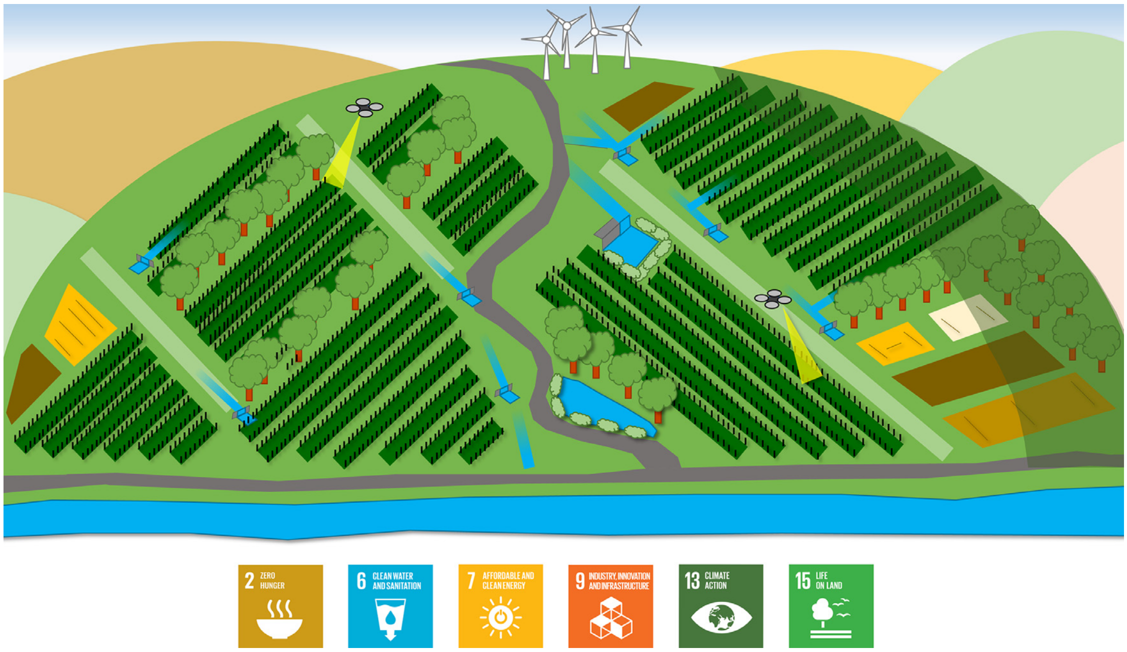

Fig. 6. Illustration of a vineyard landscape in which production needs are combined with the guidelines of SDGs. The vine plants (dark green rows) are integrated with the cultivation of other crops (in brown) and natural areas (represented with trees) to ensure biodiversity and ecological corridors. Sustainable water resource management allows to collect water to face drought periods using micro reservoirs while ensuring the survival of aquatic habitats in a pond system. Finally, cultivation must embrace innovation, such as monitoring with remote sensors and preferring energy from renewable sources.

can be carried out using crop residues such as leaves or chipped branches (Keesstra et al., 2018). In the case of slope instability, an interesting solution is the installation of wooden reinforcement structures. They can be paired with live plants to increase the stabilizing effect through the root system (Sonnenberg et al., 2012). However, on steep slopes, agricultural terraces are still the optimal solutions as they include a wide range of ecosystem services (Xiong et al., 2018). For lowland vineyards, water stagnation is a major issue. The process can be mitigated by adopting specific solutions, such as surface drainage systems. To be functional, they must be constantly monitored through a maintenance programme. Alternative solutions involve sub-surface processes systems, useful to remove deep water by mechanical pumps in wells or by deep tillage. Mitigation strategies for climate change impacts must also consider biodiversity to ensure maximum soil functionality. The selection of indigenous grass mixed with polliniferous species can promote biodiversity and support the vineyard agroecosystem (Straffelini et al., 2022). Other solutions can be adopted to optimize water resources. In this case, water availability during severe drought increases, and biodiversity in agricultural areas is promoted, ensuring habitat development in the rural landscape. An example is the implementation of a network of wetlands, often recognized as among the most effective nature-based work.

5.3. Sustainable Development Goals and future challenges

Global climate change is affecting wine producers in different areas worldwide. To guarantee the survival of this activity, especially in cultural landscapes with a long winegrowing tradition, it is essential to plan for resilient rural management right now. Adapting human activity to a more sustainable future must be a globally shared pathway inspired by solid principles. Among the most ambitious benchmarks are the SDGs. They identify critical social and environmental issues on human and natural themes, indicating resolution strategies and tools to measure progresses. The SDGs can inspire new solutions to make viticulture in Argentina more resilient to global changes (Fig. 6). SDG-2 is established to improve food security and promote sustainable agriculture. The scientific community must promote the transformation of intensive viticulture towards more sustainable production processes. For example, to limit soil erosion while ensuring its fertility and integrity in a vineyard on the slope, it is recommended to implement a soil cover in the inter-row, avoiding bare terrain. Sustainability means efficiency. SDG-6 aims to improve water use efficiency in human activity, including agriculture. With the aridification of large agricultural areas worldwide (Wang et al., 2022b), this issue must be central to long-term wine sector planning. The sparing use of water should be preferred both in lowland areas, most affected by increasingly frequent droughts and on the slopes of the Andes. Vineyards must become hi-tech by implementing systems that indicate to farmers when and where to irrigate. Remote sensing and sensor technology offer new opportunities compared to the past. Argentinian growers can exploit new technologies to implement precision farming systems, such as using high-resolution cartography for surface process mapping and monitoring vine health. Innovation and the use of renewable forms of energy must be at the heart of future viticulture, as indicated by SDG-7 and SDG-9. Solutions can come from the intelligent exploitation of slope microtopography to locate water deposits that can act as emergency reservoirs in extreme drought and as biodiversity incubators, as promoted by SDG-15. It will also be important to avoid monoculture, favoring landscape mosaicisation through implementing other secondary crops and careful design of ecological corridors. Especially for new plantations on Andes slopes, it is advisable to cultivate vines in a complex landscape, where vineyards are integrated with forest areas and rich in water and soil conservation measures. These recommendations could be helpful in making viticulture more sustainable and in laying the foundation for more hydrogeological safe land.

6. Conclusions

Climate change alters the environmental conditions that make some areas of the planet particularly suitable for cultivating vine plants and producing quality wines. This is the case for viticulture in Argentina, especially in Mendoza, home of internationally recognized wines. Increasingly arid climatic conditions, characterized by periods of drought and intense heat waves, are driving farmers to create new vineyards uphill to the slopes of the Andes. A more favorable climate and rainfall regime help preserve production rates, which are increasingly difficult to achieve in the lowlands. However, new threats arise. Among the most worrying phenomena is the increase in extreme rainfall observed in the last few years. Especially on steep slopes, they can cause runoff and subsequent soil erosion, with severe consequences for the integrity of the vineyards. It is worthwhile to understand the new challenges to enable optimal adaptation to the new conditions and ensure the resilience of local viticulture. Sustainable management of water resources, including using new technologies for high-resolution monitoring combined with precision irrigation, can help meet the challenge of climate change adaptation in these important wine-growing areas, both in severe rainfall and lack of water.

Author contributions

P.T., N.C, C.S., and **E.S.** conceived and designed the research; **E.S.** wrote the first draft, and edited the manuscript and figures; **E.S.** and **R.A**. performed the data analysis; **N.C. C.S. R.A. M.J.E.O.** performed literature analysis, co-wrote sections 1, 2, 3, 4, and reviewed the manuscript; **P.T.** reviewed and edited the final version of the manuscript, and supervised the entire research project.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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