

Analysis of grape growers' and wine producers' perceptions in Brazil regarding climate change

Análise da percepção dos produtores de uva e vinho no Brasil em relação às mudanças climáticas

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ABSTRACT

The issue of climate change has received increasing emphasis in studies across various economic sectors, with agriculture being no exception. Among agricultural activities, fruit production is particularly sensitive to climatic variations, and within this sector, viticulture stands out as a segment highly impacted by climate change. In Brazil, grape and wine producers have reported a more frequent occurrence of extreme climatic events, drawing attention to the impacts of these changes on the sector. In this context, this study aimed to analyse grape and wine producers' perceptions across different regions of the country regarding the effects of climate change on viticultural activities, and to identify the adaptation measures they adopt. To this end, a literature review was conducted, followed by a characterisation of Brazil's main grape- and wine-producing regions. Subsequently, primary data were collected through structured questionnaires applied to a sample of 80 producers to assess their perceptions of climate change and adaptation strategies in the sector. The main results indicate that approximately 80% of the surveyed producers report that their production has been affected by climate change in some way, with these impacts linked to productivity and quality. However, adaptation actions remain limited in terms of both the diversity of strategies and their effectiveness. These results highlight the importance of research and climate-monitoring systems in supporting public policy development for the Brazilian grape and wine sector.

Keywords: Climate variability. Adaptive capacity of vitiviculture. Management strategies. Sustainability.

RESUMO

A questão climática tem ganhado ênfase crescente nos estudos em diversos setores da economia, e a agropecuária não tem sido exceção. Entre as atividades agropecuárias mais sensíveis às variações

climáticas está a fruticultura, e, dentro dela, a vitivinicultura se destaca como um segmento altamente impactado pelas mudanças climáticas. No Brasil, produtores de uva e vinho têm observado uma ocorrência mais frequente de fenômenos climáticos extremos, o que tem chamado atenção para os impactos dessas mudanças no setor. Diante desse cenário, este artigo tem como objetivo analisar a percepção dos produtores de uva e vinho nas diferentes regiões do país sobre os efeitos das mudanças climáticas na atividade vitivinícola, bem como identificar as ações de adaptação adotadas por esses produtores. Para tanto, foi realizada uma revisão da literatura, seguida da caracterização das principais macrorregiões produtoras de uva e vinho no Brasil. Posteriormente, por meio de um levantamento de dados primários realizado com a aplicação de questionário estruturado, buscou-se avaliar a percepção sobre as mudanças climáticas e as estratégias de adaptação implementadas pelo setor. Como principais resultados, observou-se que aproximadamente 80% dos produtores participantes da pesquisa afirmam que suas produções têm sido afetadas de alguma forma pelas mudanças climáticas, relacionando problemas de produtividade e qualidade a esses fenômenos. Por outro lado, as ações de adaptação ainda são limitadas, tanto em termos de diversidade de estratégias quanto de efetividade. Esses resultados indicam a importância de pesquisas e do monitoramento climático de precisão a fim de subsidiar novas políticas públicas para o setor vitivinícola brasileiro.

Palavras-chave: Variabilidade climática. Capacidade adaptativa da vitivinicultura. Estratégias de manejo. Sustentabilidade.

1 INTRODUCTION

According to projections by the Food and Agriculture Organisation of the United Nations (FAO, 2021), agriculture in the 21st century will face multiple challenges, including the need to address population growth, which is expected to increase the global population from the current 7.8 billion to approximately 9 billion by 2050. This scenario implies the need to increase production of food, fibre, and energy while simultaneously facing emerging challenges related to carbon emissions, water availability, and climate change, as well as issues such as food security, food safety, and traceability.

On the other hand, the development of agriculture is understood as an evolutionary process that has responded to the challenges of each historical period. Evidence of this can be seen in Brazilian agriculture, which represents a rare case at the global level: through research and innovation, the country, in less than 30 years, has shifted from being a net importer of a large share of domestically consumed products to becoming a major producer across several global agricultural value chains, even achieving a leading position in many of them (Embrapa, 2014).

Within this framework, according to Pillon (2016), the past decades of agricultural production worldwide can be understood as being shaped by three major waves. The first was characterised by the Green Revolution, which followed a monodisciplinary approach, focusing on monoculture, the use of synthetic inputs, and adaptive research, taking place between 1960 and 1990 (Borlaug, 1971).

The second wave began in the 1990s, with the emergence of integrated systems approaches that emphasise sustainable intensification, multidisciplinary, production efficiency, and systems-based research (Alves et al., 2015). The third wave, projected for the coming years, refers to a biologically based agriculture, focusing on complex systems, interdisciplinarity, the use of biological inputs, and open research and innovation (Soares, 2020).

However, issues that were previously less evident to the general public have become part of the global discussion agenda, particularly climate change and its impacts across different sectors of the economy. Thus, without delving into the causes of climate change, it is understood that there is a growing perception of more frequent extreme weather events across regions worldwide, including Brazil.

This increased occurrence of such phenomena — or at least the perception of a greater intensity of climate-related events affecting production regions — has not always led to proportional actions to address the challenges of mitigation and, especially, adaptation. This may result either from a lack of knowledge regarding which actions are most effective in minimising impacts or enhancing adaptation, or from the absence of clearer guidelines from relevant public authorities (Nascimento; Bursztyn, 2011).

In global forums addressing climate change, such as the recent United Nations Climate Change Conferences (COP 26, held in Glasgow, in 2021; COP 27, held in Sharm El-Sheikh, Egypt, in November 2022; and COP 28, held in Dubai in December 2023), new commitments to reduce greenhouse gas emissions have been discussed and adopted by countries each year for the coming decade. At the same time, increasing emphasis has been placed on the importance of adaptation actions.

An important element in recent discussions has been the recognition that agricultural activities, often perceived as major contributors to greenhouse gas emissions, should also be viewed as part of the solution. In this context, adaptation has gained increasing relevance in the debate (FAO, 2023a; FAO, 2023b; Kissel *et al.*, 2023).

According to the United Nations (UN, 2022), one of the main outcomes of COP 27 was the strengthening of the adaptation agenda in response to climate change impacts. In this sense, economic sectors are expected to face growing pressure to adopt adaptive practices. At COP 28, negotiators agreed to establish global targets with specific timelines for different themes and economic sectors; however, adaptation targets were not quantified and did not include clear guidelines on how this process will be financed, particularly in developing countries.

In any case, there is a clear increase in attention to the need for adaptation financing mechanisms, which, in turn, require the development and adoption of practices, technologies, and processes that rural producers can implement in the context of climate change adaptation in agriculture.

Concerning climate change in viticulture, there has been a growing body of scientific literature worldwide, including studies on climate change, carbon, water, and sustainability in relation to the wine sector, as evidenced by the proceedings of the International Organisation of Vine and Wine (OIV, 2021).

As demonstrated in the literature review presented in this article, variations in temperature, precipitation, thermal amplitude, and other factors can significantly affect the performance of grape varieties across different *terroirs*.

Considering Brazil's continental dimensions and its increasingly diversified wine sector, with production taking place in regions with markedly distinct characteristics, understanding which climatic factors are most relevant to viticulture is essential. Furthermore, assessing how producers in each region have perceived changes in these phenomena in recent years is crucial to establishing a more accurate diagnosis and supporting more comprehensive conclusions aimed at adaptation and mitigation strategies for the Brazilian wine sector.

Within this context, the objective of this study is to investigate how climate change has affected Brazilian viticulture across its regions, from the perspective of grape and wine producers, and to analyse how these actors have responded by adopting adaptation measures in their activities.

Thus, the relevance of the topic is justified, as well as the importance of studies that assess the current situation of different producing regions in Brazil in relation to these variables. Identifying signals of significant change and providing information to support decision-making in both the public and private

sectors, thereby enhancing their capacity to respond to emerging opportunities and risks, constitutes a crucial input for the technological and sustainable development of agriculture in the future.

2 LITERATURE REVIEW

2.1 CLIMATE CHANGE AND VITICULTURE

Climate change has become a central topic in political and scientific debates since the early 2000s, particularly following major natural disasters such as Hurricane Katrina, which struck the United States in 2005. The awarding of the Nobel Peace Prize to the Intergovernmental Panel on Climate Change (IPCC) and to Al Gore in 2007 further reinforced the political relevance of the issue; however, part of the literature indicates that effective adaptation measures have not matched this increased international visibility in productive sectors, including the wine sector (Nascimento; Bursztyn, 2011).

Since then, progress has been made, and the main international forum addressing the issue has been the Conference of the Parties (COP), whose most recent edition was held in Dubai in November 2023.

As a result, several economic sectors have begun to assess how they are being affected by, or will be affected by, climate change. This is also the case in the wine sector, which is highly sensitive to climatic variability. The International Organisation of Vine and Wine (OIV) has incorporated specific sections in its conferences and publications addressing climate-related issues in viticulture and winemaking.

Numerous studies have investigated the influence of climate on grape quality, as well as on must and wine characteristics. Araújo *et al.* (2016) highlight the effect of temperature on vine metabolism. Rufato *et al.* (2021) expand the analysis by emphasising the interaction between climate, topography, and soil, suggesting that the sensitivity of viticulture cannot be understood solely in thermal terms. This perspective aligns with Gambetta *et al.* (2020), who emphasise the difficulty of predicting crop responses in complex scenarios, generating uncertainty for both producers and policymakers in regions dependent on this economic activity.

Understanding past climatic conditions and future projections, and estimating their impacts on agrometeorological indices applied to grapevines, is therefore a key strategy for the development of the Brazilian wine sector. This need is particularly relevant given Brazil's tropical climate, where viticulture is distributed across diverse climatic regimes.

According to recent IPCC reports (IPCC, 2021; IPCC, 2022), projections indicate that climate change impacts will intensify throughout this century, affecting ecosystems worldwide. In this context, multiple future scenarios are being modelled to assess the magnitude of these impacts and to guide mitigation and, especially, adaptation strategies.

Among the observed effects of climate change are increased rainfall intensity in many regions, more frequent heat waves, and extreme cold events. Additional impacts include large-scale wildfires in the western United States, Australia, and Portugal, which have affected grape cultivation and wine production. One example is the growing incidence of smoke-tainted wines in the western United States, Canada, and Australia. Many mountainous regions have also shown trends of earlier snowmelt and reduced snow accumulation, affecting water availability for agriculture and contributing to increased drought frequency (Jones *et al.*, 2022).

On the other hand, Xyrafis *et al.* (2022) argue that temperature anomalies and changes in precipitation patterns may have both positive and negative effects on agricultural production at regional or local scales, depending on the affected area. This contrasts with Jones *et al.* (2022), who emphasise

predominantly negative impacts, such as droughts and wildfires, suggesting that assessments must be contextualised by region and grape variety.

Recent studies indicate that climate change is altering the climatic suitability for viticulture, making some traditional regions less suitable while favouring new areas, such as those at higher altitudes or latitudes (Leeuwen *et al.*, 2024). This demonstrates that impacts are not homogeneous and requires the sector to consider not only local adaptations but also the potential relocation of production as a long-term strategy.

Leeuwen *et al.* (2019) identify several adaptation strategies for viticulture, including the development of late-ripening varieties, clones, and rootstocks; increasing trunk height; reducing the leaf area-to-fruit weight ratio; late pruning; shifting cultivation to higher altitudes; and combining different strategies for gradual implementation. Some of these practices require minimal changes in vineyard management, while others may involve vineyard replanting or varietal substitution, potentially affecting terroir typicity.

According to Angelotti (2011), some adaptation measures require long-term research, particularly the development of new grape varieties. Thus, although a wide range of adaptation strategies exists, many require decades of research, highlighting the tension between short-term measures and long-term structural solutions.

Complementarily, Leeuwen *et al.* (2024) emphasise that while some adaptation strategies—such as selecting heat-tolerant varieties, adjusting canopy management, and optimising irrigation—can mitigate the impacts of global warming, these measures have limitations, particularly in regions severely affected by droughts or heat waves. In such cases, the economic viability of viticulture may be compromised, necessitating more substantial adjustments, including relocation to more suitable climatic regions.

Pandolfo (2010), as cited in Rufato *et al.* (2021), projected that in the Serra Catarinense region of southern Brazil, rising temperatures could reduce the areas currently suitable for grape cultivation by more than 50% by 2050 and 2070. According to these authors, earlier budburst and shorter ripening periods are also expected, potentially leading to a decline in wine quality. Monitoring the spatial shift of suitable areas and investing in regionally adapted varieties and genetic improvement are therefore essential.

Furthermore, changes in vineyard management directly affect grape processing, requiring new techniques to maintain wine quality or to develop new products adapted to changing conditions. In summary, climate change has gained significant attention over the past decades; however, as noted by Nascimento and Bursztyn (2011), although awareness has increased, adaptation and mitigation actions have not progressed at the same pace.

2.2 PRODUCERS' PERCEPTIONS OF CLIMATE CHANGE

Several studies have focused on producers' perceptions of the impacts of climate change on grape and wine production. For example, Ryan (2019) investigated the perceptions of producers in New Zealand; Zuniga *et al.* (2024) examined producers' perceptions in Southern California, United States; Battaglini *et al.* (2009) analysed the perceptions of European producers (Italy, France, and Germany); and Vega-Bayo *et al.* (2023) assessed the mitigation strategies adopted by producers in the Rioja region of Spain.

According to Ryan (2019), climate change may affect both the quality and quantity of grapes used for wine production, as well as overall wine production in the study region. The author investigated adaptation planning within the New Zealand wine industry, examining growers' decision-making

processes and their perceptions of climate change. The findings indicate that winegrowers are partially informed about climate change, with some adaptation planning underway; however, most still lack structured adaptation plans.

In Brazil, Vieira, Garcia, and Bruch (2015) conducted a similar analysis in the Vales da Uva Goethe region, in the state of Santa Catarina, southern Brazil. The study aimed to develop an exploratory assessment of the potential impacts of changes in climate dynamics on viticulture within the area defined at the time by the Geographical Indication of the Vales da Uva Goethe. The results showed that only a portion of producers associate variations in grape quantity and quality with the effects of climate change.

Beyond the wine sector, Tanure *et al.* (2024), in a study analysing how farmers' perceptions of climate change influence the adoption of sustainable agricultural technologies in Brazil—particularly in the Amazon and Atlantic Forest biomes—found that farmers' motivations to adopt more sustainable practices are strongly driven by economic incentives. In addition, the overall level of adoption of such technologies remains low, mainly due to a lack of technical knowledge and financial support.

While in Brazil, Vieira *et al.* (2015) identify a weak association between climate variability and grape quality, studies in countries such as New Zealand (Ryan, 2019) show that even in regions highly dependent on viticulture, producers' perceptions of climate risks remain limited. This convergence points to a global challenge: the gap between producers' perceptions and the urgency highlighted in IPCC reports (2021, 2022). In this context, by examining different Brazilian regions, this study contributes to addressing a gap that remains underexplored in the international literature: how producers operating in tropical and subtropical contexts perceive and respond to climate change.

2.3 WINE-PRODUCING REGIONS IN BRAZIL

Changes in temperature, variations in solar radiation levels, and increased atmospheric CO₂ concentrations are expected to influence vine productivity, with direct impacts on grape and wine quality. According to Costa *et al.* (2016), as cited in Xyrafis *et al.* (2022), changes in these environmental factors are likely to affect wine-producing regions differently over the coming decades.

Due to its continental dimensions, Brazil presents a unique viticultural landscape worldwide, as wine production is distributed across three distinct macro-regions. According to Pereira (2021) and Pereira *et al.* (2020), these macro-regions can be classified as follows: the Southern region, representing traditional viticulture; winter wine production in the Southeast and Central-West regions; and tropical wine production in the Northeast region (Figure 1).

According to these authors, traditional viticulture is located in the South and Southeast regions of Brazil, tropical viticulture is concentrated in the Northeast, and the most recent system—winter viticulture—occurs in the Southeast, Central-West, and Northeast regions, in vineyards located at altitudes above 700 meters.



Figure 1 – Three Brazilian wine-producing regions, classified according to climatic production and management characteristics
Source: Adapted from Google Earth and Pereira et al. (2020)

This is, evidently, a macro-level analysis; a more detailed examination of each region would reveal numerous characteristics and nuances that differentiate local terroirs, as highlighted by Leeuwen (2004).

Nevertheless, it is important to recognise that each macro-region presents a distinct set of characteristics, including the historical development of the activity, cultural aspects, cultivation techniques, planting periods, and product-specific features, both in terms of grape varieties and processing outcomes, such as juices and wines.

3 MATERIALS AND METHODS

This study is exploratory and descriptive in nature, based on the collection of primary data through a survey questionnaire. The instrument was developed based on theoretical frameworks related to viticulture, climate change, and producers' perceptions, and was structured to include open-ended, multiple-choice, and multiple-selection questions. The questionnaire was organised into sections covering the following topics: respondent identification; property location and characteristics; perceptions of climate and viticulture; perceptions of climate change; qualitative and economic impacts of climate change on production; and actions or investments aimed at mitigation.

The research was conducted in accordance with ethical principles applicable to studies involving human subjects. All participants were informed about the objectives of the study and participated voluntarily, providing informed consent at the beginning of the questionnaire. The study was submitted to the Human Research Ethics Committee of the Federal Institute of Santa Catarina (CEPSH-IFSC) and was approved under protocol number CAAE 68133023.4.0000.0185. The questionnaire was administered digitally via Google Forms and remained open from August to October 2023.

The sample consisted of 80 grape and wine producers from different regions of Brazil, recruited through voluntary participation following dissemination via academic and sectoral networks, including producers' associations and educational and research institutions. Of the total responses, 79 were considered valid, with one excluded due to incomplete data.

Following the literature review, the three main Brazilian wine-producing macro-regions were characterised. Subsequently, based on the survey results, data were tabulated and analysed using both qualitative and quantitative approaches. Qualitative data were categorised through content analysis, while quantitative analysis was conducted using Microsoft Excel.

4 RESULTS AND DISCUSSION

4.1 CHARACTERISATION OF THE SAMPLE OF GRAPE AND WINE PRODUCERS

The regional distribution of survey respondents was as follows: 70.8% from the Southern region ($n = 56$), 10.1% from the Northeast ($n = 8$), 15.1% from the Southeast ($n = 12$), and 3.7% from the Central-West ($n = 3$). No respondents were recorded from the Northern region of Brazil. This distribution is consistent with the structure of Brazilian viticulture, according to official data on cultivated area, in which the Southern region accounts for 73.4% of total production area (55,710 hectares), followed by the Northeast with 14.68% (11,153 hectares), the Southeast with 11.5% (8,717 hectares), the Central-West with 0.4% (257 hectares), and the North with 0.03% (26 hectares) (IBGE, 2020). For analytical purposes, the three main Brazilian wine-producing macro-regions were considered (South, Southeast/Central-West, and Northeast).

Regarding the profile of participants, among the 79 valid respondents, 78.5% were male and 21.5% female. In terms of age distribution, 26.6% were between 30 and 39 years old; 24.1% between 50 and 59; 20.3% were over 60; 17.7% between 40 and 49; and 11.4% between 18 and 29 years old.

With respect to education level, 11.4% reported having completed secondary education; 11.4% had incomplete higher education; 29.1% had completed higher education; and 44.3% held postgraduate degrees. Participants identified themselves as rural producers (40.5%), entrepreneurs (22.8%), private-sector employees (16.5%), public servants (8.9%), self-employed workers (6.3%), and retirees (3.8%).

These profile data reflect the characteristics of grape and wine producers across different Brazilian regions and corroborate the findings of Ryan (2019) in New Zealand, where producers also exhibit a high level of qualification (74%) and where diverse professional backgrounds contribute to a wide range of expertise within the wine sector, enhancing the robustness of the data collected.

4.2 PRODUCTION AND FARM CHARACTERISTICS OF RESPONDENTS

Regarding the length of time producers have been engaged in viticultural or winemaking activities, a relatively balanced distribution across experience levels is observed: up to 5 years (24.1%), 6 to 10 years (17.7%), 11 to 20 years (24.1%), and over 30 years (13.9%). Studies indicate that producers with higher levels of education or greater experience tend to perceive and adopt adaptation measures more effectively (Tanure *et al.*, 2024; Vieira *et al.*, 2015).

In terms of farm size, 68.5% of respondents own properties smaller than 50 hectares, while 11.4% have farms ranging from 50 to 100 hectares, and 20% exceed 100 hectares. Regarding the area planted with grapes, 40.5% of producers cultivate less than 3 hectares; 38% between 4 and 10 hectares; 10.1% between 11 and 20 hectares; 3.8% between 21 and 50 hectares; and 7.6% cultivate more than 50 hectares.

These findings reinforce the predominance of small-scale production in Brazilian viticulture. This is particularly relevant because smaller cultivated areas, depending on management practices, tend to make variations in productivity, anomalies, and the impacts of climatic events more noticeable, as

well as the need for adjustments in cultivation techniques. This, in turn, enhances the sensitivity and reliability of the perceptions reported by producers in the survey.

4.3 PERCEPTIONS AND IMPACTS OF CLIMATE CHANGE ON VITICULTURE AND WINE MAKING

To investigate producers' perceptions of climate-related events and their impacts on production, specific questions were applied, the results of which are presented in Figures 2 to 4 and discussed below. A total of 94.9% of respondents considered climate to be highly relevant for grape production. This finding is consistent with other studies conducted in Brazil, which show that producers—even those operating small-scale farms—recognise climate as a key determinant of viticulture (Vieira *et al.*, 2015).

When asked about observed changes in climate patterns in their production regions, 81% of respondents reported noticing such variations. This result indicates that Brazilian producers are aligned with the perceptions of producers in other countries, such as New Zealand, where most respondents in Ryan (2019) acknowledged that climate change is real and already occurring. Similar findings have been reported among Argentine producers, who have observed an increase in extreme events (Straffelini *et al.*, 2023), as well as among producers in Southern California (Zuniga *et al.*, 2024) and in Germany, France, and Italy, who highlight changes since the 1990s, particularly related to temperature and precipitation (Battaglini *et al.*, 2009).

However, given Brazil's continental scale, response patterns varied across regions. For instance, none of the respondents from the Central-West region reported observing climate change; however, all of them have been engaged in viticulture for less than five years, which may explain their lower perception of climate variability. This is likely because identifying climate trends generally requires longer time series, as demonstrated by studies from the Brazilian National Institute for Space Research (Inpe), which have documented climate changes across all regions of the country over the past three decades.

According to Inpe studies, the average number of days with heatwave events in Brazil increased from 7 to 53 between 2011 and 2020. The Southern region experienced less severe drought impacts; however, it also recorded above-average rainfall anomalies. The study further indicates that factors such as urbanisation and land-use and land-cover changes have contributed to rising temperatures (MCTI, 2023).

Nevertheless, temperature is not the only relevant factor, as extreme climate events may result from multiple interacting variables. For producers, these events tend to be more noticeable and impactful than gradual changes in average temperatures. Straffelini *et al.* (2023), in a study on climate change in Argentina, report that rising temperatures, heatwaves, droughts, hail, and intense rainfall have led winegrowers to relocate vineyards to higher altitudes in search of more favourable conditions. Similarly, among producers in Southern California, increasing temperatures combined with drought periods have caused phenological shifts in grapevines, such as earlier budburst and harvest, directly affecting vineyard management (Zuniga *et al.*, 2024).

Among the participants in this study who reported observing climate change ($n = 73$), respondents were also asked when they began to perceive these variations in their production regions. More than 60% indicated that they have noticed such changes within the past five years, as illustrated in Figure 2.

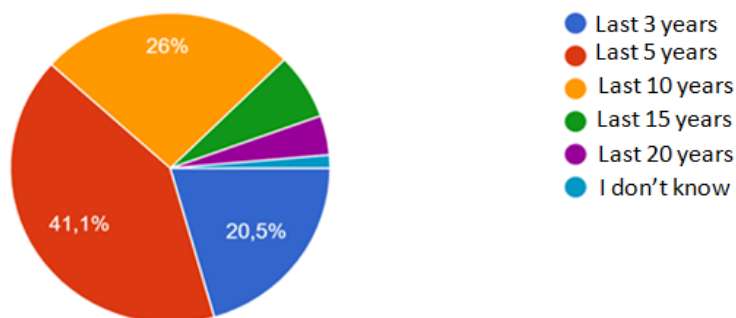


Figure 2 – Duration of Producers' Perception of Climate Variability in Their Production Regions

Source: The authors

Regarding the most frequently observed types of events in the production regions, producers highlighted different climatic phenomena, as shown in Figure 3, with a predominance of perceived temperature variations outside the historical patterns of the region (25.68%); heavy rainfall (25.13%); hail (19.67%); frost (14.20%); and, to a lesser extent, strong winds and flooding (3.82% each); drought (3.27%); Other (2.70%); and Snow (1.63%).

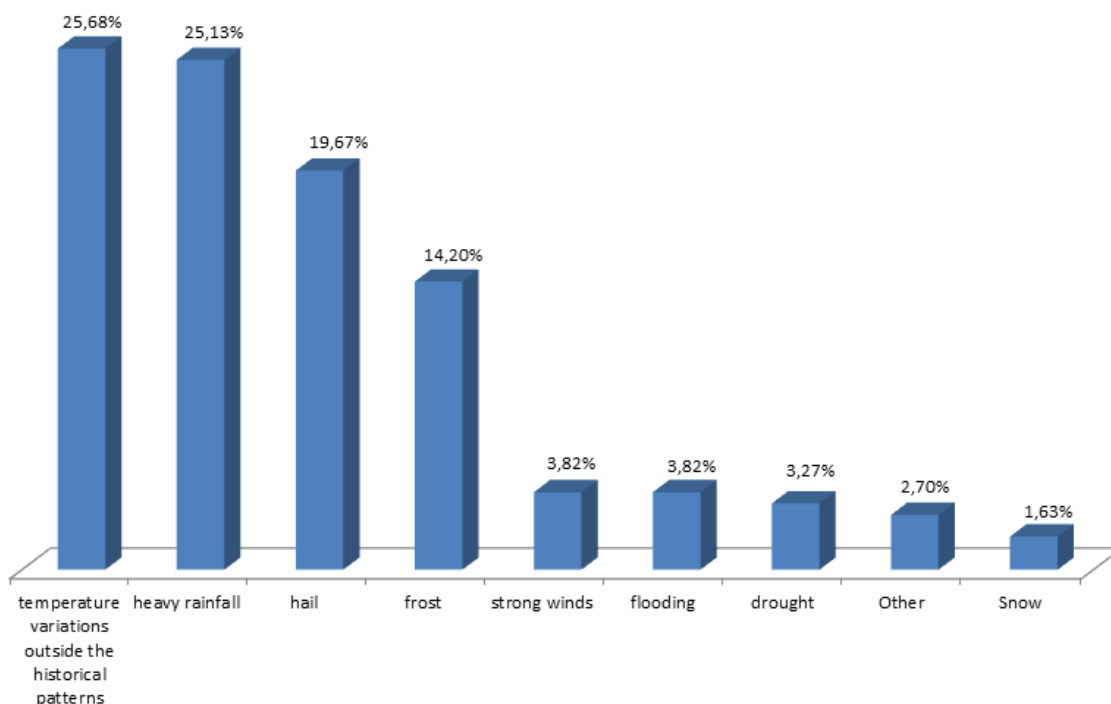


Figure 3 – Producers' Perceptions of the Main Climatic Events Observed as Indicators of Climate Change in Their Production Regions

Source: The authors

The perception of increased temperatures outside historical patterns among Brazilian producers may reflect their level of experience and familiarity with the issue, as it aligns with findings from New Zealand reported by Ryan (2019), where producers identified rising local temperatures as the main impact and most direct consequence of climate change. Despite concerns regarding temperature changes, producers do not always perceive this climatic factor as negative, since solar radiation is associated with the production of high-quality grapes (Ryan, 2019).

In Europe, Battaglini *et al.* (2009) had already indicated that the main climate changes perceived by producers were related to increasing temperatures, hotter summers, and extreme events such as prolonged droughts (Italy) and intense rainfall and flooding (France).

On the other hand, extreme climate events such as heavy rainfall, hail, frost, strong winds, and droughts are a concern not only for Brazilian producers but also for those in New Zealand and Argentina, as they are associated with negative impacts on grape quality (Ryan, 2019; Straffelini *et al.*, 2023). The results further indicate that 90% of Brazilian respondents perceived an increase in the frequency of extreme climatic events. Moreover, they reported that both the number and intensity of such events have increased over the past decade, with a marked intensification in the last five years.

Regarding the degree of impact of climate events on grape production, 80% of respondents stated that their production has been affected in some way by climate change in their region, while 70% classified these impacts as high, based on a scale ranging from high to low. The Southern and Northeastern regions were the main contributors to this result, which may be explained by their longer history and greater experience in viticulture compared to other regions, such as the Central-West, considered a new viticultural frontier in Brazil (Pereira *et al.*, 2020), where respondents reported a moderate level of impact.

Given the high level of perceived impact of climate change on grape production, this study also sought to understand how these events affect production quality (Figure 4). The impacts reported by producers can be grouped into two main categories. The first relates to productivity, highlighting reductions in yield per plant, deterioration in grape health (higher incidence of rot), and consequently, increased use of pesticides. The second category relates to the physicochemical quality of grapes, particularly variations in ripening levels, including increases or decreases in sugar content depending on climatic conditions.

These findings are consistent with perceptions reported by producers in both Old World and New World wine regions, who identify reduced yields, compromised grape health, and declines in both quantity and quality as the main negative impacts of climate change (Battaglini *et al.*, 2009; Ryan, 2019).

Furthermore, studies by Straffelini *et al.* (2023) and Zuniga *et al.* (2024), focusing on Argentina and Southern California, respectively, are consistent with the results of this study, indicating that the main impacts of climate change include reduced productivity and grape quality, as well as compromised vineyard health, particularly due to increased disease incidence under humid conditions.

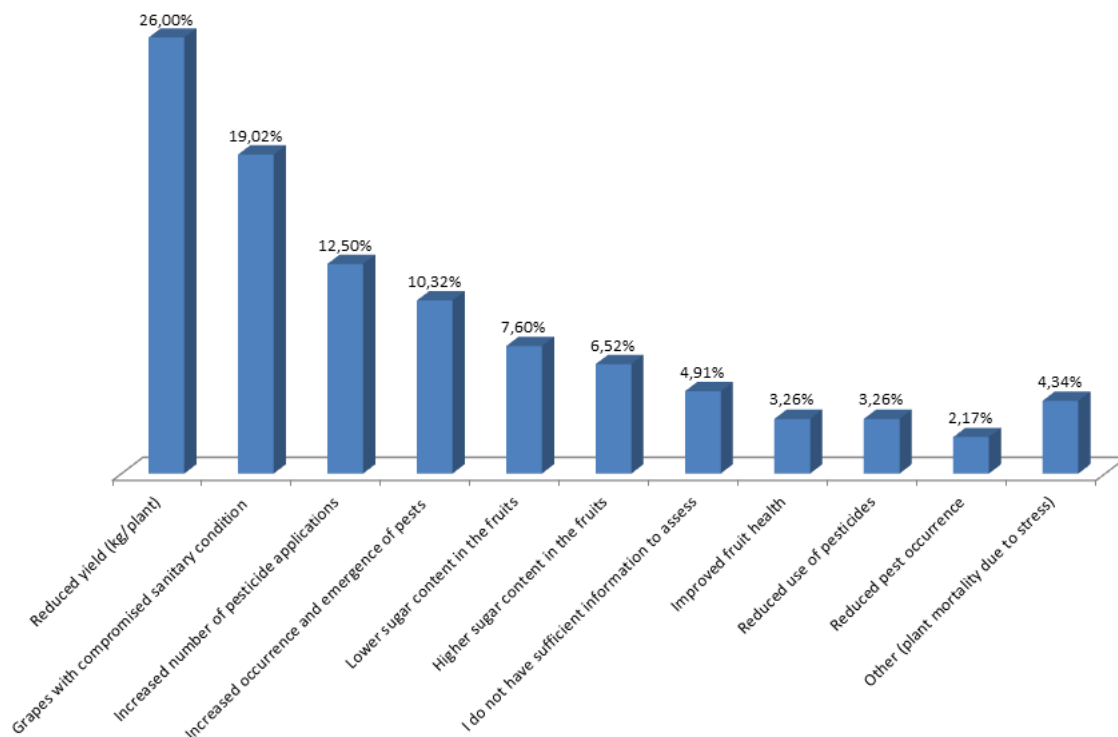


Figure 4 – Producers' Perceptions of the Impacts of Climatic Events on the Quality of Grapes Produced

Source: The authors

In addition to production impacts, producers also reported their perceptions regarding the financial impacts of climate events. More than 80% of respondents indicated that they had experienced economic losses. Estimated damages over the past five years varied considerably: 15.9% reported losses between BRL 26,000 and BRL 50,000; 14.5% between BRL 51,000 and BRL 100,000; and 25% reported losses exceeding BRL 100,000.

Given producers' awareness of the impacts of climate change on viticulture in their regions, this study sought to understand how they have responded. A total of 69.6% of respondents reported adopting adaptation measures. The main strategies identified include: (a) adjusted vineyard management practices, such as late pruning; (b) installation of physical barriers, including windbreaks and plastic covers; (c) increased use of pesticides treatments; (d) adoption of more resilient grape varieties; (e) seeking additional information on local climate conditions; and (f) agricultural insurance.

Compared with New Zealand, where only 32% of producers are considering adaptation plans, Brazilian producers show greater engagement in adaptive actions. However, these are often not structured within medium- or long-term planning frameworks. Nevertheless, across countries, adaptation strategies tend to converge, particularly in vineyard and water management, as well as varietal selection or replacement (Ryan, 2019).

In Europe, varietal change has also been discussed as an adaptation strategy, being more accepted in Germany, while other countries face regulatory constraints related to geographical indications. Additionally, increased disease and pest control and greater demand for technical information on climate and grape varieties have been identified as important responses in countries such as Germany, France, and Italy (Battaglini *et al.*, 2009).

In Argentina, other adaptation strategies have been implemented, including relocating vineyards to higher altitudes (2,000–3,000 m), irrigation under water scarcity conditions, soil and drainage management, vegetation cover, structural support in sloped areas, and the use of sensors and remote monitoring technologies for water and climate management, as well as practices aligned with the Sustainable Development Goals (Straffelini *et al.*, 2023).

In Southern California, adaptation strategies primarily focus on coping with high temperatures, including optimised irrigation management, the use of drought- and heat-resistant varieties and rootstocks, canopy management and shading practices, climate-monitoring technologies, and adjustments to the agricultural calendar (Zuniga *et al.*, 2024). Overall, despite differences in planning and investment levels across regions, there is a clear convergence in adaptation strategies, reflecting a growing concern within the global wine sector.

To assess progress in adaptation planning, producers were asked about barriers limiting implementation. The main constraints identified were budget limitations (50.7%), lack of specific financing (28.8%), and insufficient local climate information (23.3%). These findings are consistent with studies in New Zealand, where lack of information and uncertainty are also major constraints, followed by financial limitations (Ryan, 2019).

Similarly, in Argentina, high costs of adaptive technologies and socioeconomic impacts associated with relocating production areas are key barriers (Straffelini *et al.*, 2023). In Southern California, producers also highlighted limited institutional support and a lack of public policies, as well as financial and informational constraints (Zuniga *et al.*, 2024). In Europe, regulatory constraints related to geographical indications further limit adaptation options (Battaglini *et al.*, 2009). These findings highlight the global complexity of climate change adaptation in the wine sector.

Finally, regarding investment capacity, 69.9% of respondents indicated they would invest if specific credit lines were available, and nearly 70% reported willingness to invest their own resources. For

approximately 60% of producers, the maximum investment would be up to BRL 50,000. These findings reinforce the predominance of small-scale production in Brazilian viticulture, which faces greater financial constraints and, consequently, higher vulnerability to climate change compared to larger enterprises—a pattern also observed in New Zealand and Australia (Galbreath, 2011; Ryan, 2019).

5 FINAL CONSIDERATIONS

The results of this study indicate that producers' perceptions of the impacts of climate change on viticulture have increased significantly. More than 80% reported that their production has been affected, corroborating findings from the Brazilian National Institute for Space Research (Inpe) (MCTI, 2023), which indicate climate changes across all regions of the country over the past 30 years. The impacts were more pronounced in the Southern and Northeastern regions—traditionally important grape-producing areas—where financial losses exceeding BRL 100,000 were reported by approximately one-quarter of respondents.

Despite this growing awareness, the identified adaptation measures remain limited in scope and largely focused on incremental adjustments in vineyard management and increased pesticide use. This raises environmental and economic concerns, as such approaches do not ensure long-term resilience and may generate adverse effects on the environmental and economic sustainability of the wine sector.

These findings highlight the need for public policies, targeted financing mechanisms, and the development of more effective adaptive technologies capable of enhancing resilience and sustainability in Brazilian viticulture. However, it is important to acknowledge the limitations of this study, including the restricted sample size and the exploratory nature of the analysis, which do not allow for generalisation across the entire production chain. Future research should expand the methodological scope by incorporating comparative analyses across countries or regions, as well as technical indicators of climate impacts, in order to support more effective and sustainability-oriented adaptation strategies.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

The authors used ChatGPT (GPT-5.3, OpenAI) for language editing and stylistic

polishing only. All scientific content, analysis, and intellectual input were developed and verified by the authors; we take full responsibility for the accuracy and integrity of the manuscript.

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