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# THE EFFECTS OF CLIMATE CHANGE ON VINES IN THE MAIN GROWING COUNTRIES IN EUROPE

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***Abstract***

*Climate change is one of the most urgent problems of contemporary society and has significant consequences for natural ecosystems and economic sectors, including the wine industry. Through this paper, an assessment of the consequences of climate change on vine is proposed, examining how these climate phenomena have influenced the growth cycles, quality and quantity of grape harvest in different European wine-growing regions. Another purpose of this documentation is to analyze available research and data to identify the contributory role of different factors in climate change. It is also intended to identify and analyze the strategies and solutions adopted by winegrowers to face these climate challenges, including the adaptation of grape varieties, the implementation of sustainable agricultural practices and the use of innovative technologies in viticulture. The results of this review underline the need for a proactive approach and international collaboration to manage climate change in the European wine sector.*

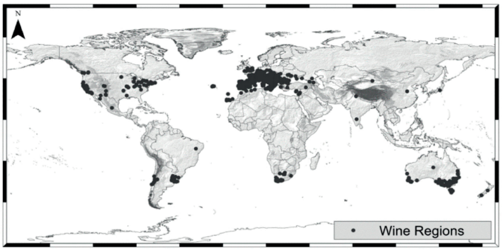
***Key words**: climatic factors, grapes, European region.*

## INTRODUCTION

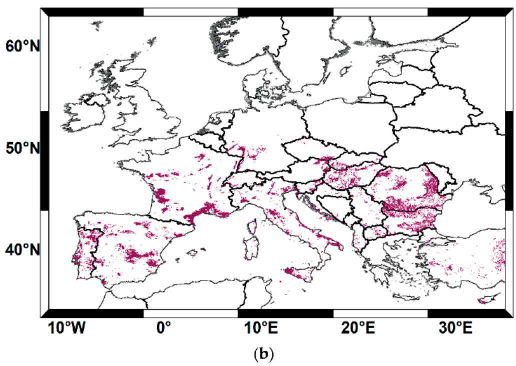
Climate change, also referred to by the acronym CC, is characterized as any change in climatic conditions that is maintained in the long term and is recognized by most researchers as one of the main ecological challenges our society is facing in the 21st century (Pachauri & Reisinger, 2007; Pachauri el al., 2014). A steady rise in temperature, as the main measurable effect of CC, is projected to persist globally, and significant changes are likely to occur in global hydrological and energy cycles (Pachauri el al., 2014; Noguer et al., 2001), resulting in an intensification of radiation as well as the frequency and severity of extreme weather events (Pachauri et al., 2014; Easterling et al., 2000; Bartolini et al., 2008). Europe stands out as a particularly sensitive region to the increase in temperature caused by CC, especially during the warm season, as continued warming is predicted to persist throughout the 21st century on this continent (Giorgi, 2006), where predominant negative impacts are anticipated, including lower harvests, significant variations in agricultural production and a decrease in areas suitable for traditional crops (Olesen & Bindi, 2002). Through this paper, we aim to carry out a comprehensive assessment of the consequences of climate change on the grapevine, the main aspects being: 1) highlighting the significant role of the various factors contributing to climate change in the viticulture industry; 2) assessing how these climatic phenomena have influenced the diversity of growth cycles and shaped the qualitative and quantitative characteristics of the harvest in different European wine-growing regions; 3) identifying and analyzing in detail the strategies and solutions adopted by winegrowers to counteract the negative effects of climate change.

Grapevine (*Vitis vinifera* L.) is one of the most essential crops in Europe, having a significant socio-economic impact. Europe has the largest wine production and the most extensive wine-growing area worldwide, hosting some of the most famous regions and wines. These regions are predominantly located in the Mediterranean area, with a particular concentration in countries with significant wine production, such as Italy, France and Spain (Aurand, 2017). According to the most recent reporting of the

International Organization of Vine and Wine (OIV) (Pachauri & Reisinger, 2007), estimates indicate that the global wine-growing area covers approximately 7.449 million hectares (2018). In the same year, Spain occupied a share of 13% of the world's total wine-growing area, followed by China (12%), France (11%), Italy (9%) and Turkey (6%). These five countries represent approximately half of the entire global vine area. According to the same OIV report (Pachauri & Reisinger, 2007), in contrast to the evolution of the global vine area, world grape production has registered a significant increase in the last two decades, highlighting increases in wine-growing productivity. According to the OIV (Pachauri & Reisinger, 2007), the estimated amount of production reached about 77.8 million tons (103 kg) in 2018, registering a record value, compared to the range of 60-65 million tons at the beginning of the 21st century. The general mode of grape production includes wine grapes (57% of the total), table grapes (36%) and dried grapes (7%). The production of both table grapes and dried grapes is predominant in some countries without a tradition of wine production, such as China (89.7% of total grape production), Turkey (96.8%), India (98.5%), Iran (100%), Uzbekistan (96.3%), Egypt (99.5%) and Brazil (53.5%). In contrast, wine grape production is associated with countries where viticulture is largely dedicated to wine production, such as Italy (86.5%), Spain (96%), France (99.6%), Argentina (93.7%), Australia (90.9%), Germany (99.6%) or Romania (93.1%), listed in descending order in terms of production volume. The four wine producers with the highest production, classified according to the volume obtained, are Italy (54.8 million hectoliters), France (48.6), Spain (44.4) and the USA (23.9), the first three being also the most important exporters globally (Pachauri & Reisinger, 2007). The most significant wine-growing regions worldwide, such as Bordeaux, Burgundy, California, Cape/South Africa, Champagne, La Mancha, La Rioja, Mendoza, Mosel, Porto/Douro, South Australia, Tuscany and others are represented in (Figure 1a). These wine-growing regions are usually located in Recognized Origin areas, while (Figure 1b) highlights the area dedicated to vines in Europe (Kottek et al., 2006; Peel et al., 2007; Fraga et al., 2013).




(a)




(b)

Figure 1. (a) World distribution of the viticultural regions (black circles) (Source: Fraga et al., 2013). (b) Political map of Europe with the vineyard land cover (shading) (Source: Cover, 2018)

## ANALYSIS OF THE ROLE OF CONTRIBUTING FACTORS TO CLIMATE CHANGE IN THE WINE INDUSTRY: AN ASSESSMENT BASED ON RESEARCH AND AVAILABLE DATA

During the 20th century, European regions have experienced significant changes in a varied range of climate factors, showing a large regional variation, according to the (2007) Intergovernmental Panel on Climate Change IPCC report.

Significant changes in temperature were observed during the 20th century, according to research by Santos & Leite (2009). These changes included thermal increases of between 2.3–5.3°C in northern Europe and 2.2-5.1°C in southern Europe, according to the study conducted by Christensen et al. (2007). In fact, changes in the frequency of thermal extremes and precipitation patterns in Europe have been associated with certain atmospheric features, such as the North Atlantic Oscillation (NAO), according to analyzes by Santos & Corte-Real (2006).

By analyzing the results of several simulation models, it is anticipated that the global mean surface temperature will most likely increase by 1°C and 4.5°C, depending on future industrial emissions. The most reliable estimate suggests a warming of between 1.8-2.5°C by the middle of the next century (Carter et al., 1991; Schultz, 2000).

Climate change projections in Europe show a more pronounced warming trend in southern and north-east oriented regions (Christensen & Christensen, 2007; Jacob et al., 2014). Also, significant increases in minimum and maximum temperatures are observed during summer and autumn (Cardell et al., 2019), which coincide with the vine growing season, which takes place between April and October in the northern hemisphere.

The prevalence of continuous temperature increase is a quantifiable factor of climate change, already generating significant changes in global hydrological and energy cycles (Houghton et al., 2001; Pachauri et al., 2014). These transformations, in turn, have amplified the frequency, intensity, and duration of extreme weather events, such as heat waves, droughts or excessive precipitation (Kostopoulou & Jones, 2005; Zeder & Fischer, 2020).

Precipitation and its seasonality also represent an essential atmospheric factor influencing the development of the vine, having a significant control over the soil moisture and the water potential of the vine, especially in non-irrigated wine-growing areas (Huang et al., 2016; Suter et al., 2019). In future perspectives, the current wine-producing regions of southern Europe may experience a reduction in their suitability for viticulture, predominantly due to severe drought (Toth & Vegvari, 2016; Fraga et al., 2018). These regions could face excessively dry conditions for the production of high-quality wines (Kenny & Harrison, 1992), and in some extremely critical situations, may require intensive irrigation (Koundouras et al., 1999; Fraga et al., 2018). Areas such as Andalucía, La Mancha (Spain), Alentejo (Portugal), Sicily, Puglia and Campania (Italy) will likely suffer from severe water shortages. Studies have also indicated that increased summer dryness in southern Europe will lead to a decrease in yield, mainly due to the synergy between warming and drying (Fraga et al., 2016).

Solar radiation also represents an essential element that impacts viticulture. An adequate amount of radiant energy is required, especially during the grape ripening period (Manica, 2006).

Climate change in terms of UV-B radiation has raised concerns in the past, in the context of changes in the protective ozone layer. UV-B radiation influences the composition of grapes, causing changes in secondary metabolites, such as flavonoids, amino acids and carotenoids (Schultz, 2000). Regardless of a possible further increase in UV-B radiation, the combination of high radiation levels and increased temperatures, especially under severe water stress, is often the cause of sunburn damage to both leaves and berries, conditions forecast to become more frequent in Southern Europe (Dinis et al., 2016; Dinis et al., 2018; Santos et al., 2020).

## DYNAMICS OF CLIMATIC PHENOMENA AND IMPACT ON GROWTH AND HARVEST CYCLES IN EUROPEAN VITICULTURE REGIONS

Traditionally, vine is grown in geographical regions characterized by an average temperature in the range of 12-22°C during the growing season (Jones, 2010), having an optimal vegetative response to average daily values between 20°C and 35°C (Droulia & Charalampopoulos, 2021). In order to interrupt bud dormancy and initiate the growth/vegetative cycle, winter cooling is required, with a minimum temperature of 10°C (Amerine & Winkler, 1944; Dokoozlian, 1999), essential also for the accumulation of carbohydrate reserves in the perennial structures (roots, trunks and shoots), preparing them for development in the next year (Bates et al., 2002; Field et al., 2009).

The progress in the development of the vine is closely related to the different stages of its vegetative and reproductive cycles. In regions of many traditional wine-growing areas, such as the extratropics, the vegetative cycle of the vine extends over a full year, while its reproductive cycle spans two years. The reproductive cycle exerts control over some significant characteristics, both quantitative and qualitative, such as the number of grape bunches for the following year and the vegetative cycle is composed of two major consistent stages: the dormancy period and the growing season. The phenological evolution of the vine includes multiple stages or phenophases according to (Figure 2). These phases of the vegetative and reproductive cycles of the vine are mainly under the control of atmospheric conditions (Santos et al., 2020).

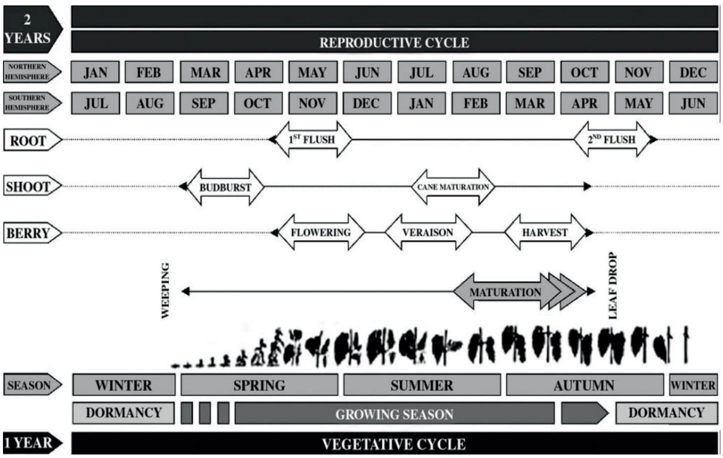



Figure 2. Vegetative and reproductive cycles and vine phenological stages.
Adapted from Eichorn & Lorenz (1977) and Magalhães (2008)

Understanding the influence of high temperatures on the intermediate periods to maturity is essential both for the application of viticultural practices and for the interpretation and identification of trends in the context of climate change. For example, late pruning of vines can be used to delay development and diminish the risk of frost in colder regions (Friend & Trought, 2007). As a general rule, if there is significant damage to the buds in the vine, it is better to keep a larger number of buds at pruning (Sadras & Moran, 2012).

In the time interval between the fall of the leaves and the onset of spring, the vine enters a period of dormancy characterized by the exclusive presence of woody tissue and a reduced physiological activity (Magalhães, 2008). This phase is divided into two sub-periods, controlled by endogenous and exogenous thermal factors, essential for release from the state of dormancy. The first sub-period (endo-dormancy) is initiated by the accumulation of cold (cold units) during autumn and winter, while the second sub-period (eco-dormancy) depends on heat accumulation until budbreak.

Thus, winter cold is a crucial condition for the evolution of vine growth, as low temperatures promote dormancy of buds (Kliewer et al., 1972; Santos et al., 2017), along with other factors such as shortening days and ageing of photosynthetic active parts of the plant. From late winter to early spring, the accumulation of average daily temperatures between 7 and 10°C generally stimulates the end of dormancy and initiation of the vine growth cycle (Amerine & Winkler, 1944).

If the cooling requirement is not adequately fulfilled due to climate change, budding becomes irregular, generating in uneven phenological development in later stages of the season (Tesic et al., 2002; Trejo-Martínez et al., 2009).

There is research suggesting that in the near future, some Mediterranean regions, such as Sardinia and Sicily, could face problems due to excessive temperatures leading to an insufficiency in the accumulation of cooling units and ultimately to the lack of budding. On the other hand, higher temperatures in the latter part of winter influence the eco-dormancy period by reducing the accumulation period of the forcing factor. The cooling requirement in Germany is forecast to be already satisfied at the beginning of winter, but a longer eco-dormancy period is observed until the budding date. In this context, the impact of rising temperatures is more pronounced for European regions characterized by longer dormancy cycles (Leolini et al., 2018).

In the future perspectives, an earlier appearance of budburst and flowering has been forecasted with particular importance in north-eastern Europe. At the same time, the impact of higher temperatures was more pronounced for late compared to very early and early grape varieties in western regions (Leolini et al., 2018).

Phenological diversity in different regions has significant implications in the face of associated extreme events. In Western Europe, where the budburst process occurs earlier, especially in Spain, France and the United Kingdom, there was an estimated increase in the frequency of frost events during budburst (e.g. in Spain: between 9 and 30%, in France: between 3 and 41%, in the United Kingdom: between 3 and 50%). In contrast, Germany and Italy recorded a lower incidence of frost events, ranging between 0% and 16% and between 1% and 11%, respectively (Leolini et al., 2018).

The increased impact of temperatures on budburst is not the only challenge that influences vine phenology. In general, an earlier budburst process leads to an earlier later stage, such as flowering, even if this effect is less pronounced (Fraga et al., 2016).

The initial process of inflorescence differentiation begins near the flowering stage of the previous year (Alleweldt & Ilter, 1969; Morrison, 1991). Warm and sunny periods in this phase favor the development of inflorescence primordia, while cold and cloudy conditions stimulate shoot formation (Buttrose, 2017; Keller 2020). Therefore, the climatic conditions of the previous year have a direct influence on the yield in the following season (Molitor & Keller, 2016). The impact of stressful temperatures during the flowering period is an essential aspect for the final yield (Hale & Buttrose, 1974; Vasconcelos et al., 2009).

Given that the optimal temperature range for the flowering process varies between 20 and 30°C (Kozma et al., 2003; May, 2004), higher or lower temperatures recorded at this stage have a negative impact on flower formation, pollen germination, grape berries formation causing the appearance of several physiological disorders, respectively on the production of grapes (Ewart & Kliewe, 1977).

According to the findings of Ebadi et al. (1995), a 30% reduction in flower size and pollen germination was observed in Chardonnay and Shiraz cultivars under conditions of temperature drops before flowering (Leolini et al., 2018).

Regarding the aspect of quality, high temperatures during the growing season contribute to the accumulation of sugars in the grapes and the breakdown of organic acids, essential factors for the maturity of the grapes. Inadequate temperatures during the growing season can lead to the formation of immature berries, unsuitable for wine production. On the other hand, extremely high temperatures during the ripening period can also affect quality by increasing excessive sugar levels and decreasing acidity, causing low concentrations of anthocyanins and flavonoids (Haselgrove et al., 2000; Downey et al., 2006; Sadras & Moran, 2012), which, in turn, reduce the aromatic characteristics of wines (Jackson & Lombard, 1993; De Orduna, 2010).

Prolonged exposure to extremely high temperatures, such as those above 35-40°C, can have a negative impact on the photosynthetic system of the plant (Berry & Bjorkman, 1980) and can cause damage to the grape skin in the form of burns, thus increasing the incidence of latent fungal infections within the grapes (Steel & Greer, 2006).

Forecasts of future changes in minimum temperatures during the ripening period in the Iberian Peninsula have also been identified, according to studies by Projeção & Portuguesa (2012) and Malheiro et al. (2012), suggesting a possible decrease in wine quality.

According to ProWein's 2019 business report, available at (https://www.prowein.de/) the results of an industry survey of more than 1,700 enterprises indicated that the sensory profiles of wines have changed in recent decades. The conclusion of this study suggests that climate change has the potential to threaten the typicality of wines in traditional wine-producing regions (Molitor & Junk, 2019).

## INNOVATIVE STRATEGIES AND SOLUTIONS ADOPTED BY WINEGROWERS TO ADDRESS CLIMATE CHALLENGES IN VITICULTURE

The adaptation measures addressed by winegrowers can be divided into two levels: in the short-term they can be considered as a first protection strategy and should focus on specific threats, especially on changes in crop management practices for example late vine pruning, goblet vine management, planting density, no-till and minimum tillage systems (MIT), use of foliar protection substances against sunburn, use of rootstocks and resistant varieties in drought, irrigation, shade nets, solar screens for leaf protection, while in the long term, a wide range of adaptation measures should be considered for example (creating varieties adapted to future climatic conditions and the migration of vines to higher altitudes).

Winter pruning as a short-term measure, if performed later, the budburst process is slightly delayed by a few days (Friend & Trought, 2007). However, the variations seem to become smaller in the case of later phenological stages. Discrepancies are more notable when pruning is performed when the vine has 2-3 leaves, without however affecting yield or pruning weight in the following season (Moran et al., 2019). Maturity is significantly delayed when the vine is subjected to a second pruning, long after the budburst period (Friend & Trought, 2007; Martínez-Moreno et al., 2019; Petrie et al., 2017). However, this method remains in the experimental stage, and the long-term consequences on vigor need to be studied in depth. Another short-term measure can be the crown management system that proves remarkably resistant to drought and high temperatures, known as the Mediterranean goblet or shrub vine. Through this management mode, it is feasible to grow vines without resorting to irrigation in extremely arid environments, up to only 350 mm of precipitation/year (Deloire, 2012; Santesteban et al., 2017). Certainly, goblet-style vines tend to produce generally lower yields, but enjoy ease of cultivation at low costs per hectare (Roby et al., 2008). In the search for alternative solutions to improve the drought resistance of the vine, the expansion of the space between the rows can be considered. In regions where water deficit is not a major problem, such as Bordeaux, Champagne and Burgundy in France, wide row spacing is a traditional practice. In the context where water becomes a limiting factor, narrowing the space between the rows contributes to a more efficient use of water, as the capture of sunlight provides the necessary energy for the transpiration process (Van Leeuwen et al., 2019).

According to research by Fischer et al. (2007), it is found that the adoption of strategies to reduce the impact, which lead to lower concentrations of greenhouse gases, can lead to a decrease of about 40% in water requirements in agriculture, compared to unfavorable climatic conditions. No-till and minimum tillage practice systems (MIT) are considered the most efficient because the absence of soil surface disturbance promotes carbon retention

and sequestration according to research by (Kroodsma & Field, 2006).
For sunburn, exploring the alternative of using mineral and chemically inert substances to protect leaves against sunburn is considered a significant option (Pelaez et al., 2000; Glenn et al., 2010).
To prevent the effects of drought on vine, an efficient and ecological adaptation consists in the use of drought-resistant rootstocks to maintain yields and prevent quality losses caused by excessive water stress. This choice represents an environmentally friendly strategy and, once implemented, does not generate significant increases in production costs (Van Leeuwen et al., 2019).
Vines varieties show significant variation in drought tolerance (Chaves et al., 2007). This diversity may be associated with how different cultivars regulate their water availability in response to increasing atmospheric demands and fluctuations in soil water content. Another useful indicator for assessing the drought tolerance of cultivars is how they adjust their water use efficiency in the face of drought challenges. Most varieties originating from the Mediterranean basin (such as Grenache, Cinsault, Carignan) are recognized for their resistance to drought, while others, such as Merlot, Tempranillo or Sauvignon Blanc, do not show the same tolerance. There are also reports indicating that certain local varieties from the Mediterranean islands, such as Xinistery from Cyprus, demonstrate particular drought resistance and could be considered for cultivation outside their region of origin. Choosing to plant drought-resistant varieties in arid environments is an effective strategy in adapting to climate change, which is why these varieties deserve more attention (Gowdy et al., 2019).
The reuse of water for irrigation is configured as a viable economic option for agriculture in the Mediterranean region. This practice helps reduce the need to develop new water sources and provides an adaptive solution to climate change. Recycled water, in many arid and semi-arid regions of the Mediterranean, becomes an accessible alternative resource for agricultural, industrial and urban use not for consumption (Lazarova et al., 2001; Angelakis & Gikas, 2014). The potential benefit can be amplified by expanding and optimizing wastewater treatment facilities. For example, in Spain, about 408 hm3/year (13% of the total available water) is reused, of which 79% is dedicated to agricultural irrigation 320 hm3/year (Raso, 2013). Irrigation is proving to be one of the most efficient methods for increasing yield and crop quality in dry regions (Costa et al., 2007; Forbes et al., 2009; Flexas et al., 2009, Romero et al., 2010).
In the context of creating new vine varieties, White et al. (2006) argue that breeding programs should focus on developing varieties resistant to high temperatures. Related to this direction, Duchene et al. (2012) developed a framework for the genetic crossbreeding of new cultivars more efficiently adapted to future climatic conditions, while maintaining some key characteristics of already existing cultivars. In addition, given the significant diversity of existing vine varieties, it is crucial to maintain natural biodiversity to ensure a more effective adaptation to climate change (Tello et al., 2012).
Viticulture is predominantly limited to regions located below 50ºN latitude. In the future, there are prospects that viticulture will expand to areas with latitudes up to 55ºN, opening possibilities for expanding the areas dedicated to the cultivation of vine. However, this expansion may face resistance due to current regulations in Europe and increased interest in other crops such as wheat, barley and maize (Ingram & Porter, 2015). Regarding wine-producing regions in southern Europe, such as Italy, Spain, and Portugal, projections indicate the maintenance of viticulture viability, although its sustainability may be affected (through lower yields) due to accentuated warming and drying conditions (Moriondo et al., 2013, Toth & Vegvari, 2016).

## CONCLUSIONS

Climate change has caused a significant change in the phenological stages of the vine during the last decades. If the trend of increasing annual temperatures and global warming persists, according to climate model forecasts, the global wine industry will face a concrete threat in the next period. Future risk assessment aims to develop rational and sustainable strategies for winegrowers, thus contributing to adaptation to new climate conditions (Iglesias et al., 2007).

Climate change leads to higher temperatures, periods of drought and intensification of radiation, especially UV-B radiation. These changes have a significant impact on the cultivation process of vine and wine production, affecting both European countries and viticultural markets globally. However, this review presents various adaptation options, offering growers the opportunity to maintain high-quality wine production with sustainable economic yields in the face of climate change (Van Leeuwen et al., 2017).

Although studies on the possible impact of climate change on viticulture are largely advanced, compared to other agricultural fields, there are still important knowledge gaps (Santos et al., 2020).

Understanding the future evolution by analyzing the present thus becomes a need for important information, but also an urgent procedure, considering that the consequences of climate change presented in this study bring particularly significant social and economic implications for the European wine industry. In this sector, the origin and variety of grapes are essential indicators of the quality and specificity of the products. Information on the already observed impact of climate change can be utilized and integrated into sophisticated and precise climate change analysis tools with the aim of obtaining a deeper understanding and define more precisely the effect of this phenomenon on environmental sustainability in the wine sector in the following decades (Droulia & Charalampopoulos, 2022).

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