CIÊNCIA E TÉCNICA VITIVINÍCOLA

Ciência Téc. Vitiv. 37(2) 139-158. 2022

Review

MEDITERRANEAN VITICULTURE IN THE CONTEXT OF CLIMATE CHANGE

VITICULTURA MEDITERRÂNICA NUM CONTEXTO DE ALTERAÇÕES CLIMÁTICAS

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(Received 09.09.2022. Accepted 17.10.2022)

SUMMARY

The exposure of viticulture to climate change and extreme weather conditions makes the winemaking sector particularly vulnerable, being one of its major challenges in the current century. While grapevine is considered a highly tolerant crop to several abiotic stresses, Mediterranean areas are frequently affected by adverse environmental factors, namely water scarcity, heat and high irradiance, and are especially vulnerable to climate change. Due to the high socio-economic value of this sector in Europe, the study of adaptation strategies to mitigate the negative climate change impacts are of main importance for its sustainability and competitiveness. Adaptation strategies include all the set of actions and processes that can be performed in response to climate change. It is crucial to improve agronomic strategies to offset the loss of productivity and likely changes in production and fruit quality. It is important to look for new insights concerning response mechanisms to these stresses to advance with more effective and precise measures. These measures should be adjusted to local *terroirs* and regional climate change projections for the sustainable development of the winemaking sector. This review describes the direct climate change impacts (on phenology, physiology, yield and berry quality), risks, and uncertainties for Mediterranean viticulture, as well as a set of canopy, soil and water management practices that winegrowers can use to adapt their vines to warmer and drier conditions.

RESUMO

A exposição da viticultura às alterações climáticas e a eventos meteorológicos extremos torna o setor vitivinícola particularmente vulnerável, sendo um dos seus maiores desafios no presente século. Apesar da vinha ser considerada uma cultura tolerante a vários stresses abióticos, as áreas mediterrânicas são frequentemente afetadas por fatores ambientais adversos, nomeadamente escassez de água, elevado calor e elevada radiação, tornando-as especialmente vulnerável às alterações climáticas. Devido ao elevado valor socioeconómico que o setor representa na Europa, o estudo de estratégias de adaptação para mitigar os impactos negativos das alterações climáticas são fundamentais para a sua sustentabilidade e competitividade. As estratégias de adaptação incluem todo o conjunto de ações e processos que podem ser realizados em resposta às alterações climáticas. É fundamental melhorar as estratégias agronómicas para compensar a perda de produtividade e as prováveis mudanças na produção e na qualidade da uva. Para avançar com medidas mais efetivas e precisas, é importante encontrar novas perceções sobre os mecanismos de resposta a esses stresses. Essas medidas devem ser ajustadas aos *terroirs* locais e às projeções regionais das alterações climáticas para o desenvolvimento sustentável do setor vitivinícola. Esta revisão descreve os impactos diretos das alterações climáticas na viticultura Mediterrânica (fenologia, fisiologia, produção e qualidade da uva), riscos associados e incertezas futuras, assim como um conjunto de práticas de gestão da canópia, solo e água que os viticultores podem usar para adaptar as videiras a condições mais quentes e secas.

Keywords: Adaptation strategies, climate change, heat stress, models, projections, water stress.
Palavras-chave: Estratégias de adaptação, alterações climáticas, stresse térmico, modelos, projeções, stresse hídrico.

INTRODUCTION

Climate change projections for the Mediterranean

The Earth's system is undergoing deep transformations owing to a strengthening of the anthropogenic forcing (Masson-Delmotte *et al.*, 2021). Higher greenhouse gas concentrations in the atmosphere are dramatically changing the Earth's energy budget, with implications in the spatial patterns of weather and climate, as well as in their

Article available at https://www.ctv-jve-journal.org or https://doi.org/10.1051/ctv/ctv20223702139

temporal regimes. These changes are being manifested not only by significant warming trends worldwide but also by changes in precipitation and other atmospheric variables and climatic impact drivers, though with noteworthy spatial heterogeneities (Masson-Delmotte *et al.*, 2021).

In Southern Europe and the Mediterranean Basin (MED region hereafter), along with the significant temperature increases, drying trends are also projected, thus explaining why this region is commonly considered a "climate change hot spot" (MedECC, 2020). Although changes in precipitation extremes, their probability of occurrence and intensity, are a global concern, the MED region is particularly exposed to a strengthening of dryness conditions. More frequent and severe droughts are projected for this region, with successive record-breaking lengths of consecutive dry day episodes. The projected warming and drying trends, together with an increased frequency and intensity of extreme weather events, are shown to be robust, particularly noteworthy in summer (Giorgi and Lionello, 2008; Lionello *et al*., 2014; Santos *et al.*, 2020a; Tuel and Eltahir, 2020).

In MED, lower precipitation amounts combined with higher temperatures, lower cloudiness and higher solar radiation, will lead to an intensification of evapotranspiration and deficit water soil balances. Water resources and availability will be threatened under these circumstances, exacerbated by a likely increase in water consumption from different sectors (e.g., energy and agriculture). Water competition is thereby expected to rise sharply in the upcoming decades, limiting water for agriculture, namely for crop irrigation, which is a practice that has been generalized throughout the MED region, even in traditionally rainfed crops.

Grapevine (*Vitis vinifera* L.) is a major fruit crop of economic importance worldwide (Macedo *et al*., 2021). In Europe, major wine-producing countries are located in MED. Italy (wine production of 49.1 mhL), Spain (40.7 mhL), Portugal (6.4 mhL) and Greece (2.3 mhL) jointly account for about 38% of the total global wine production, that is, 98.5 mhL out of 260 mhL (OIV, 2021). In 2020, these four countries exported approximately 10 000 million euros of wine. If several regions in southern France, also located in the MED region, are included, these values are even much more expressive. Viticulture and winemaking thus play a crucial role in the socioeconomy of these countries. However, viticulture is undoubtedly exposed and highly vulnerable to changing climates, as grapevines are very sensitive to both climate, which determines the suitability of a given location, and weather, which controls key plant physiological processes (Santos *et al.*, 2020b). Atmospheric conditions govern grapevine phenology, growth and development, as well as grape berry quality parameters and wine attributes. These detrimental impacts can potentially threaten the regional wine characteristics and typicity, eventually altering the wine's regional suitability under future climates (Fraga *et al.*, 2016a).

Therefore, climate change is a major risk for viticulture that requires adequate responses, by implementing sustainable but also cost-effective adaptation measures. However, mitigation strategies should also be envisioned to promote a transition to more resilient and carbon-neutral viticulture, also contributing to accomplishing international climate change policies, such as the Paris Agreement.

The present work will provide an overview of recent studies and developments concerning the climate change impacts and respective risks to viticulture (Section 2) and the corresponding available adaptation options for growers (Section 3) along with their discussion, and some concluding remarks (Section 4).

Climate change impacts and risks

Phenology

Impacts of changing climatic conditions are widely reported on vine phenology (Fraga *et al.*, 2016a; Leolini *et al.*, 2018; Droulia and Charalampopoulos, 2021). Phenology development is fundamentally governed by air temperature forcing. As such, increasing temperatures can accelerate the plant development rate, thus advancing the occurrence of the phenological stages and corresponding timings. In Mediterranean winegrowing regions, under ongoing global warming, earlier phenological timings with shortened growing phenophases were indeed reported (Marta *et al.*, 2010; Santos *et al.*, 2020a). Therefore, these recent-past trends are foreseen to be exacerbated under future climate change and corresponding warmer climates. Jones *et al*. (2005) indicate a high likelihood of earlier phenology occurrence, with shortened phenophases, across most of the European wine regions in response to rising temperatures. Nonetheless, the magnitude of the advancement in phenological stages is expected to vary, depending on the grapevine variety and *terroir* (van Leeuwen *et al.*, 2019*;* Droulia and Charalampopoulos, 2021). Consequently, advancements in different stages are projected to have different implications on grapevine yield, grape berry composition, wine quality and profile.

Budbreak, or budburst, is a key phenological stage for grapevine as it marks the beginning of the growth cycle after dormancy, which impacts the timing of successive phenological stages, thus eventually influencing yield and quality. Warmer temperatures can limit the accumulation of chilling units in the endo-dormancy phase, thus delaying the budbreak. While higher temperatures during late winter may shorten the eco-dormancy phase, the corresponding higher thermal forcing unit accumulations may lead to an early occurrence of budbreak (Leolini *et al.*, 2018; Sgubin *et al.*, 2018; Santos *et al.*, 2020b). Therefore, rising air temperature alone could either delay or anticipate the budbreak, depending on the interactions between temperature response during the endo-dormancy and eco-dormancy phases (Leolini *et al.*, 2020). Furthermore, the inability to fulfil chilling requirements may strongly impact plant growth and development, ultimately affecting fruit quality and yield (Fraga and Santos, 2021). In the northern hemisphere, budbreak commonly occurs between late winter and early spring. In anticipation of global warming, an earlier occurrence of budbreak by 7–11 days is projected for Spain, resulting from a stronger role of more intense thermal forcing accumulation than that of delayed chilling accumulation (Leolini *et al.*, 2018). In addition, the late frost risk is reduced due to increased temperatures (Leolini *et al.*, 2018). Similarly, in Portugal, the projections for the Douro Demarcated Region (DDR) have depicted advancements of budburst by 6 days until the end of the 21st century (Costa *et al.*, 2019). Advanced budbreak with reduced spring frost risk is a likely outcome for many MED regions, whereas increased late frost risks around budburst are projected for western-central European countries (Sgubin *et al.*, 2018; Droulia and Charalampopoulos, 2021).

For the flowering stage, a general advancement is also expected in MED regions. The 'Tempranillo' variety, accounting for ~50% of cultivating red grapevine varieties in Spanish vineyards, is projected to consistently undergo earlier flowering stages by 6–10 days, 3–8 days and 6–8 days in 2050, and 8–16 days, 5–12 days and 7–12 days in 2070, respectively in Ribera del Duero DO (Ramos *et al.*, 2018), Rioja DOCa (Ramos and Martínez de Toda, 2020) and Toro DO (Ramos *et al.*, 2021). The earlier flowering stage is also accompanied by shortened phenophase in these regions, e.g. flowering–veraison and veraison–maturity (Ramos *et al.*, 2018, 2021; Ramos and Martínez de Toda, 2020). Similarly, an anticipation of the flowering timing by up to 8 days until the end of the 21st century is found for DDR under a moderate warming scenario (Costa *et al.*, 2019; Reis *et al.*, 2020). In some conditions, an advanced flowering stage can occur with higher temperatures and soil water deficits, consequently leading to reduced berry quality and/or yield at harvest (Fraga *et al.*, 2016a,b; Mosedale *et al.*, 2016).

The shift towards earlier phenophase onsets will have direct impacts on the conditions of the subsequent stages, such as veraison and maturation. The magnitude of the advancement in veraison is commonly larger than for the other two preceding stages (van Leeuwen *et al.*, 2019; Ramos and Martínez de Toda, 2020; Yang *et al.*, 2022a,b). These earlier phenological timings may lead to grape ripening under excessively high temperatures, where berries can accumulate undesirable high sugar contents, together with low organic acid and phenolic composition (e.g. anthocyanins and flavonoids) (Mosedale *et al.*, 2016; van Leeuwen *et al.*, 2019; Santos *et al.*, 2020b; Yan *et al.*, 2020).

Physiology

Although it has been proven that vine is relatively resilient to summer stress (Schultz and Stoll, 2010), the presence of vegetative and reproductive symptoms driven by periods of severe dryness, occasionally intensified by heatwaves and/or excessive solar radiation, are indeed very frequent (Fraga *et al*., 2020). This situation was verified with exceptional severity in the summer of 2022, largely exacerbated by scarce precipitation in the previous seasons and years, under a prolonged severe-to-extreme drought episode.

Under these extreme conditions, characterizing the effective contribution of each environmental stressor is an unachievable task (Zandalinas *et al.*, 2017). Moreover, it was reported that their synergistic combination, compared to the response to each stress individually, may even worsen the deleterious impacts on grapevine physiological and oenological performance (Edwards *et al.*, 2011; Bernardo *et al.*, 2018). The effects of these summer stressors depend primarily on their severity (timing and duration) and the phenological phase affected (Carvalho *et al.*, 2015).

From the fruit set until veraison, berry cell division can be seriously affected, impairing fruit size, berry weight and yield, due to a reduction of photo-assimilates availability from veraison onwards (Duchêne *et al.*, 2010, Duchêne *et al.*, 2011, Parker *et al.*, 2013). Likewise, prolonged periods of drought can also affect the initial stage of flowering and the accumulation of storage compounds essential for vines' longevity (Ollat and Gaudillère, 2000). Stomatal closure is one of the most reported impacts of water deficit on plants, limiting photosynthesis, due to decreased CO_2 availability in the intercellular spaces (Schultz and Stoll, 2010). This effect, coupled with high photosynthetic photon flux density (PPFD), frequently causes mechanisms of downregulation of photosynthesis and photoinhibition of the photosystem II (PSII) (Tombesi *et al.*, 2014). Stomatal closure, by itself, can also hinder the thermal dissipation due to excess radiation, increasing leaf temperature and hampering CO_2 assimilation. To some extent, plants can osmotically adjust to water shortage, minimizing the photo-inhibitory damages of excessive radiation by promoting positive effects of stomatal mechanisms and cellular metabolism (van Leeuwen *et al.*, 2019). Therefore, grapevine stress tolerance strategies in Mediterranean areas encompass the ability of osmotic adjustment, coupled with the magnitude (timing, intensity, and duration) of the summer stress, as well as the acclimation of PSII photochemistry to heat and radiation damages (Venios *et al.*, 2020).

Preventing photo-inhibition and overheating of leaves can also be accomplished by changing leaf angles and leaf winding. These mechanisms help reduce the leaf's intercepted radiation and are mainly noticed under severe water deficits and high temperatures (Chaves *et al.*, 2010). Similarly, leaves exposed to severe summer stress exhibit increased cuticle thickening, boosting not only the reflection of excessive radiation but also their drought resistance (Lovisolo *et al.*, 2010). Some grapevine varieties, namely 'Perlette', can change their foliar angle between the limbus and the petiole from 53º to 80º when subjected to periods of drought, high temperature and radiation (Smart, 1974). The downregulation of photosynthesis can also be triggered by the Rubisco's unstable activity and regeneration during severe environmental conditions since its affinity to carbon dioxide can be impaired, leading to photo-respiration, and thus decreasing the synthesis of carbohydrates (Galmes *et al.*, 2010). It was also reported that Rubisco activity, and consequently photosynthetic efficiency, is species-dependent and mainly affected by water deficit conditions (Flexas *et al.*, 1998, Bota *et al.*, 2004, Zha *et al.*, 2021). Nonetheless, in this context of low photochemical efficiency, in which high light and high temperature conditions can often exacerbate the damage of water deficit, the dissipation of non-radiative energy through the light-harvesting complexes (LHC) of PSII may represent the most effective protection mechanism against high solar radiation levels, temperature and drought (Palliotti *et al.*, 2009, Villalobos-González *et al.*, 2022). In addition, the activation of the xanthophyll cycle is paramount under these conditions, promoting photo-protection by improving the thermal dissipation of energy (non-photochemical quenching), preventing the production of reactive oxygen species, and increasing the thylakoid membrane tolerance to lipid peroxidation (Demmig-Adams and Adams, 2006, Dayer *et al.*, 2019).

Yield and quality

The balance between vine development, growth and berry quality requires an optimal exposition of vines to mean air temperatures, typically ranging from 12 ºC to 25 ºC for the production of photo-assimilates, water availability over the growing cycle, and at least 700–900 µmol photons/m^2/s of solar radiation (Arias *et al.*, 2022). In Mediterranean-type climate viticulture, this balance is being compromised by the pace of climate change, causing yield losses and affecting berry composition and quality (Santos *et al.*, 2020b). Although most European winegrowing regions may benefit from increased CO_2 concentrations that can partially offset dryness, resulting in higher yields, Southern Europe, particularly the Iberian Peninsula, are expected to experience productivity losses of up to 8 tons/ha due to severe water shortage (Malheiro *et al.*, 2012, Fraga *et al.*, 2016a). Under warmer and drier conditions, the advancement effects on vine phenology, and the shortening of phenophases, associated with detrimental effects on photosynthesis and leaf area, can lead to decreases in biomass accumulation, and thus yield losses compared to longer growing seasons (Bernardo *et al.*, 2018). Alongside, wine production is also expected to decrease by 20–26% in the forthcoming decades due to progressively warmer and drier conditions (Droulia and Charalampopoulos, 2021). Climate projections in rainfed Mediterranean vineyards are foreseen yield losses up to 2% until 2040, and by 3 – 5.4% until 2070, as well as decreases in berry phenolic and technological (pH, sugars and organic acids contents) maturation and wine quality (Valverde *et al.*, 2015). Nonetheless, most studies suggest that rainfed vineyards will remain feasible considering the future climate scenarios (Santos *et al.*, 2020b), albeit some adaptation measures may be critical. In some Mediterranean areas, such as the Douro Region (Portugal), climate change impacts on yield are expected to be site-specific and very heterogeneous, with some likely beneficial effects on the most humid area of the region (Baixo-Corgo), contrasting with the yield losses predicted for the driest and warmest areas (Cima-Corgo and Douro-Superior) of the region (Fraga *et al.*, 2017).

Beyond yield losses caused by shifts of the ripening stage to the warmest and driest period of the summer season, berry composition and potential quality can also be impaired through imbalanced concentrations of sugars, organic acids and secondary metabolites (Fraga *et al.*, 2016a). Besides, the timing and duration of environmental stresses during the summer can promote distinct effects on the source/sink relationships, berry metabolism and composition (Carvalho *et al.*, 2019, Venios *et al.*, 2020). While high temperatures during flowering inhibit fruit set and decrease yield, its occurrence after fruit set stimulates sugar accumulation at the expense of organic acids, anthocyanins, amino acids and volatile compounds (Savoi *et al.*, 2016, Lecourieux *et al.*, 2017, Clemente *et al.*, 2022), leading to over-ripened fruits with low acidity, high soluble solids, and thus higher alcohol content, as well as aroma and colour modifications (Mira de Orduña, 2010; Mozell and Thach, 2014; Pons *et al.*, 2017). Within certain thresholds, sunlight exposition triggers the production of grapevine secondary metabolites, with a central role in the antioxidant defence system and wine quality potential (Cohen *et al.*, 2008). For example, Sadras and Moran (2012) reported a delayed onset of anthocyanins accumulation in 'Shiraz' and 'Cabernet Franc' berries exposed to high temperatures after veraison, suggesting that stress exposure shortly before veraison could partially restore the anthocyanin/sugar ratio disrupted by enduring summer stress conditions.

Likewise, a wide range of specific metabolites for grapevine protection and berry quality against summer stress was also reported, such as shifts in the accumulation of osmoprotectants, carbohydrates, malic and tartaric acids, polyols, and amino acids (Suzuki *et al.*, 2014, van Leeuwen and Destrac-Irvine, 2017). Associations with higher berry and must pH in grapevines exposed to high temperatures and drought conditions were also observed, though this relationship is affected by increased potassium accumulation, being also temperature dependent, particularly during the ripening phase (Coombe, 1987).

In berries, the combination of high temperatures, radiation, and drought can also impact the offset and decoupling of berry sensory traits through an acceleration of berry shrivelling and mesocarp cell death, with significant effects on berry size, and therefore a more substantial potential for increasing the concentration of phenolic compounds (Bonada *et al.*, 2013). However, high temperatures trigger the degradation of berry anthocyanins that can limit, or even reverse, the positive effects of water deficit on wine's floral and fruity aromas (Bonada *et al.*, 2015). Berries also accumulate osmolytes (proline leucine, isoleucine, and valine) to adjust berry osmotic potential under drought conditions (Ollat and Gaudillère, 2000, Wada *et al.*, 2008, Lovisolo *et al.*, 2010, Suter *et al.*, 2021). Though being varietal dependent, the role of amino acids on berry osmotic adjustment should also integrate the current knowledge of the central modulators of osmotic potential during ripening (malate, tartrate, glucose, and potassium before veraison, and glucose and fructose after veraison), increasing scientific based knowledge to optimize the existing management practices and develop novel strategies for Mediterranean viticulture adaptation in a context of climate change (Bernardo *et al.*, 2018, Gambetta *et al.*, 2020).

Uncertainties, modelling and policies

The risk assessment by modelling climate change impacts on the cropping system is crucial to provide information to policymakers and farmers (Fraga *et al.*, 2012). However, inherent uncertainties exist in such a modelling exercise. Firstly, extensive uncertainties exist concerning the trajectory of future anthropogenic forcing on the climate system, as it depends on global and national policies, social-economic development, technological advancements, the rate of the energy transition, land use and environmental change, among others (IPCC, 2021). Uncertainties on how these changes will unfold (anthropogenic uncertainties) are often integrated by developing a range of plausible emission scenarios, that is different pathways of emissions and corresponding atmospheric concentrations of Greenhouse Gases (GHG) and other substances (e.g. aerosols) (Moss *et al.*, 2010; Meinshausen *et al.*, 2011; van Vuuren *et al.*, 2011). The commonly applied scenarios are the so-called Representative Concentration Pathways (RCPs) (Meinshausen *et al.*, 2011) and the more recently developed Shared Socioeconomic Pathways (SSPs) (The CMIP6 landscape, 2019). The state-of-the-art projections of annual mean temperature under SSP-5 for MED are shown in Figure 1.

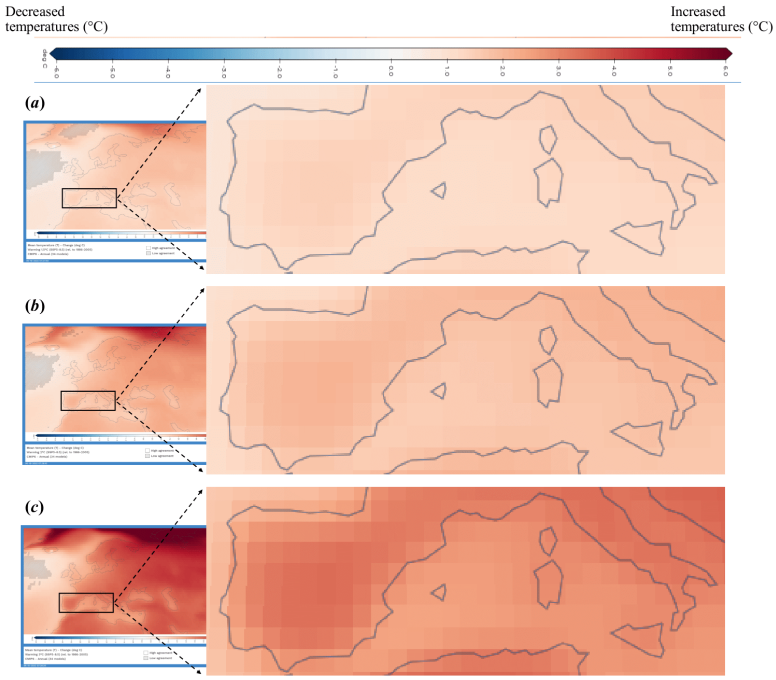

Figure 1. Projected annual mean temperature changes in the MED region relative to the historical period of 1986-2005 under the Shared Socioeconomic Pathways (SSP)-5 scenario with anticipated global warming levels by (***a***) 1.5 °C, (***b***) 2 °C and (***c***) 3 °C within the Coupled Model Intercomparison Project 6 (CMIP6) (Iturbide *et al.*, 2021; Gutiérrez *et al.*, 2021).

Projected temperature increases vary depending on different anticipated global warming levels, corresponding to different emission levels and social-economic developments (Figure 1). However, a warmer scenario is expected to result in a higher temperature increase in MED, e.g. 2–3.5 °C with warming level by 3 °C (Figure 1).

Both RCPs and SSPs provide essential inputs to prescribe simulations of Global Climate Models (GCMs). GCMs are fundamentally required tools to simulate climate change signals (IPCC, 2021). However, irrespective of improvements made, these GCMs only represent approximations of the real Earth's climate system, and often cannot fully represent sub-grid scale processes due to their relative coarse horizontal resolutions (~50-300 km) (Taylor *et al.*, 2012; Eyring *et al.*, 2016). Regional Climate Models (RCMs) are often employed to dynamically downscale the outputs of GCMs to a higher resolution, thus providing downstream inputs to impact models. The benefits of RCMs are to provide a better resolution of the interactions between orography, land–sea and the planetary boundary layer, among other components, thereby showing an enhanced ability to capture mesoclimates, regional weather patterns and extreme weather events at a local scale (Rummukainen, 2016). Therefore, coupling GCMs with RCMs is an essential tool to carry out the risk assessment of climate change impacts and the development of local-to-regional adaptation strategies.

However, either GCMs or RCMs adopt different physical parameterizations, approximations and assumptions (Jacob *et al.*, 2014; Eyring *et al.*, 2016). This gives rise to model structure uncertainties, which need to be duly accounted for by utilizing an ensemble of GCM-RCM pairs/chains in climate impact assessment studies (Asseng *et al.*, 2013; Tao *et al.*, 2018; Yang *et al.*, 2019). Nevertheless, systematic bias still exists in the outputs of GCM-

RCM chains, thus hampering their direct use in climate change impact assessments. The uncertainties relating to systematic biases can be reduced by applying appropriate bias-adjustment methods (Maraun, 2016). Depending on the variable and bias type, various methods can be applied. All of these methods intend to adjust specific statistical properties of the simulated time series toward observational time series (Cannon *et al.*, 2015; Lange, 2019). Hence, the quality of the adjustment and the degree of bias reduction depends on both the method applied and the observation dataset used (Maraun, 2016). Furthermore, reducing the bias of one statistical property can also introduce errors into another property, or distort the physical consistencies between variables.

The uncertainties of simulated climate change impacts can also derive from how the cropping system is simulated. The process-based crop models are useful tools to capture the complex interactions among genotype × management × environment (Rosenzweig *et al.*, 2013). Similar to GCMs/RCMs, uncertainties of applying these models mainly derive from their structure and calibration approach adopted. Structural uncertainties mainly result from the mathematical equations, approximations and parameterizations of sub-grid scale processes (Wallach and Thorburn, 2017; Wallach *et al.*, 2017; Seidel *et al.*, 2018). Different models usually adopt different function forms and parameterization approaches, thus yielding different simulation outputs when the same input data is used. Several studies have reported that the main source of uncertainties in projected climate change impacts derives from inconsistencies among crop models, with fewer uncertainties arising from climate modelling (Asseng *et al.*, 2013; Tao *et al.*, 2018, 2020).

Reducing the structural uncertainties should target experiments to gain insights into specific biophysical processes (Asseng *et al.*, 2015; Rötter *et al.*, 2018). Applying crop models to a new environment often involve the calibration of some parameters to reflect local conditions (Rosenzweig *et al.*, 2013, Seidel *et al.*, 2018, Yang *et al.*, 2017, 2018, 2020). However, the employed calibration approach may not be the one to give the best set of parameter values that minimize prediction errors of observations (Yang *et al.*, 2021). Different calibration approaches have different statistical assumptions and calibration procedures (e.g. steps and choosing parameters), leading to different sets of estimated parameter values. A general methodology to address calibration uncertainties consists of various approaches, e.g. combining both Frequentist and Bayesian methods (Bayarri and Berger, 2004; Wallach and Thorburn, 2017). Overall, studies devoted to modelling climate change impacts should explicitly address structure and calibration uncertainties, which facilitate the development of standard application guidelines for the crop modelling community, also enabling a common framework for the comparison of results from different studies.

Adaptation strategies

Canopy management

It is well-known that agronomic strategies should be implemented to improve the sustainability and competitiveness of the viticultural sector. A great number of possible adaptations that could be implemented to handle adverse conditions exist. Among others, the use of more tolerant rootstocks and grapevine varieties, the implementation of breeding programmes, changes in vineyard slope, canopy management, adoption of efficient irrigation strategies, improvement of soil management, and application of biostimulants and foliar protector compounds (Brito *et al.*, 2019) are among the most commonly recommended.

Modifications in the plant material (e.g., rootstocks, varieties and clones) and viticultural techniques (e.g., changing trunk height, leaf area to fruit weight ratio, the timing of pruning and training systems) are among the most important adaptation options. Vineyard efficiency in terms of light interception and water consumption in warm and dry condition, can be improved by modifying training systems, shortening the trunks which requires lower water needed (van Leeuwen *et al.*, 2019). The Mediterranean goblet is particularly resistant to drought and high temperatures, being possible with this training system to grow dry-farm vines in very dry conditions, down to a mere 350 mm of annual precipitation (Santesteban *et al.*, 2017). If harvesting goblet-trained vines could be mechanized, this would significantly reduce production costs for this otherwise drought-resistant training system (van Leeuwen *et al.*, 2019). In terms of water dynamics, and comparing training systems, the adaptative potential to dry areas of Guyot-pruned vines (due to their shorter trunks) was also reported when compared to spur-pruned cordon (Malheiro *et al.*, 2020). During the last decades, the main aim of the training systems was to increase the leaf photosynthetic efficiency, by increasing the leaf area and light exposure of grapes. But now, training systems should be reevaluated with reverse purposes: on the one hand, declining the water demand by reducing the leaf area while preserving a satisfactory sugar content in the fruits and, on the other hand, leaving the grapes in shade as much as possible (Duchêne *et al.*, 2014) or protecting bunches from excessive solar radiation.

However, to mitigate the negative effects of abiotic stress, foliar protectors have been increasingly used in recent years. Kaolin is a white clay formed by aluminosilicates ($Al_2Si_2O_5(OH)_4$) mostly formed from kaolinite (Dinis *et al.*, 2022) (Figure 2).

Figure 2. Kaolin application in the Douro Region.

The use of this foliar protector in the mitigation of some environmental stresses has been increasingly studied in recent years (Glenn *et al.*, 2010; Dinis *et al.*, 2016; Brito *et al.*, 2019; Frioni *et al.*, 2019). Its effectiveness is related to the white protective particle film that is formed on the leaf's surface, which promotes the reflection of excess radiation (higher albedo), reducing the risk of leaf and fruit damage due to heat load accumulation and solar injury; kaolin decreases foliar temperature - Figure 3 (Glenn and Puterka, 2005; Glenn, 2012). The mode of action, as well as an overview of the effects of kaolin on crop performance, are extensively reviewed by discussing the interactive effects on morphological, physiological, biochemical, growth, yield and harvest quality responses. Lobos *et al.* (2015), in Chile, showed that kaolin could increase the photosynthetically active radiation (PAR) and UV reflection by 26 to 155% in vines trained to vertical-shoot-positioned systems (VSP), whereas Frioni *et al.* (2020), in northern Italy, with 3% kaolin on VSP 'Pinot Noir' canopies, with fully exposed leaves, found 17% lower PAR and 50% higher PAR reflectance (Frioni *et al.*, 2020). This strengthened reflection leads to a decrease in leaf temperature (Brillante *et al.*, 2016; Dinis *et al.*, 2018a). The literature postulates that the efficacy of kaolin in leaf cooling is directly relates to drought severity and air temperature, being maximized during hot days when leaves lose their ability of evaporative cooling via transpiration. Similarly, if kaolin is correctly applied to the canopy at bunch level (covering the entire foliar area), it reduces berry temperature.

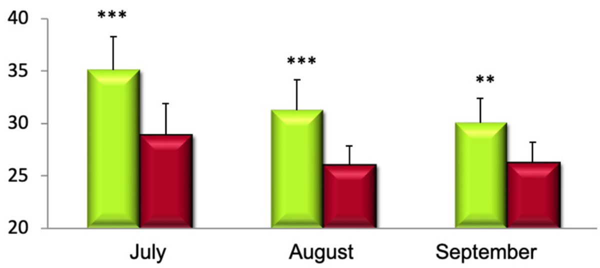

Figure 3. Foliar temperature measurement (left) and values of temperature (ºC) of kaolin-treated leaves (red) and control ones (green) during the season in 2013 in the Douro Region.

Application of appropriate doses of kaolin could be crucial to avoid an undesired reduction in external single-leaf net CO_2 assimilation rates, which can be assessed by an Infra Red Gas Analyser (IRGA) - Figure 4. Reversely, high doses (6% or more) act as antiperspirants, reducing CO_2 assimilation and transpiration rates, which can be advantageous when it is desired to avoid excessive concentration of sugar in the berries (Dinis *et al*., 2022). Positive effects on gas exchange parameters under water deficit conditions are regularly reported (Glenn *et al*., 2010; Dinis *et al*., 2018a; Frioni *et al*., 2019, 2020; Palliotti *et al*., 2019; Bernardo *et al*., 2021a).

Figure 4. Individual leaf gas exchange measurements with an infrared gas analyzer (IRGA, LC pro+ , ADC, Hoddesdon, England).

However, the amount of net CO_2 assimilation and transpiration rates vary among sites, vineyards plots, varieties and terroir. In Portugal, field-grown kaolin-coated vines of cv. 'Touriga Nacional' had shown consistently higher stomatal conductance rates, with leaf water potential (Figure 5) between –0.7 and –1.5

MPa at midday, compared to control vines, as well as higher net CO_2 assimilation rates (+58.7%) and intrinsic water use efficiency (iWUE) (Dinis *et al.*, 2018a,b). Also in Portugal, the percentage of average change of gas exchange parameters of cv. 'Touriga Franca' kaolin-treated relative to untreated vines in a two-year study at two different winegrowing regions (Alentejo and Douro) showed the positive effect of this particle film, especially in very hot years (2017) compared to fresher ones such as 2018 (Bernardo *et al.*, 2021a) - Figure 6.

Figure 5. Leaf water potential measurement with a Scholander pressure chamber.

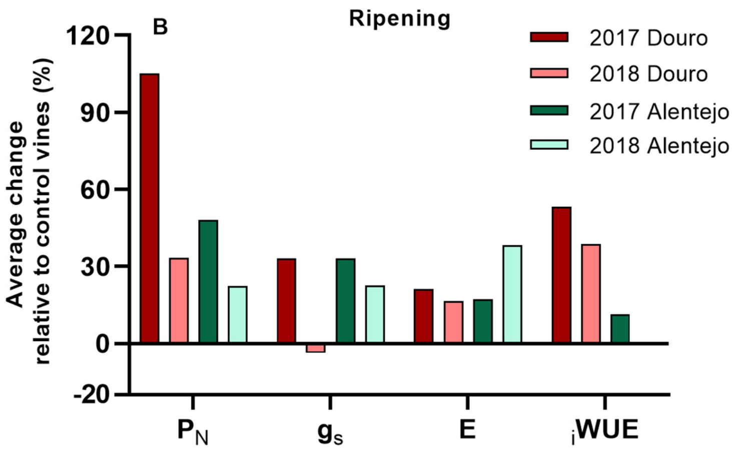

Figure 6. Average change of gas exchange parameters of cv. 'Touriga Franca' treated with kaolin relative to untreated vines in a two-year study at different winegrowing regions (Alentejo and Douro). P_N – net photosynthetic rate; g_s – stomatal conductance; E – transpiration; iWUE – intrinsic water use efficiency.

The most relevant positive effect of foliar kaolin pulverization in grapevines under drought and summer stresses is the canopy photochemical efficiency protection and the full and prompt restoration of leaf gas exchange parameters, once the water supply is restored and temperature returns to optimal ranges between 25-35 ºC (Greer and Weedon, 2011). Kaolin avoids leaf chlorophyll degradation and increases carotenoid concentrations under stressful conditions (Dinis *et al.*, 2016, 2018b). Kaolin improved grapevine plasticity and ability to deal with prolonged periods of summer stress, optimising their capacity to control light absorption and manage the absorbed light (Bernardo *et al.*, 2021b). Regarding carotenoids, (xanthophyll cycle, VAZ) the quantity of violaxanthin, neoxanthin and zeaxanthin (Vx+Nx+Zx) are augmented in kaolin-treated vines, possible due to the reduction of abscisic acid (ABA) accumulation in treated leaves (Frioni *et al.*, 2020). In drought periods, ABA synthesis is mandatory and indole-acetic acid (IAA) accumulation is limited in the guard cells leading to a deacrease in stomatal conductance due the stomatal closure (Dinis *et al*., 2018a). Under these conditions, it was found a reduction in ABA concentration in leaves sprayed with kaolin (Dinis *et al.*, 2018a).

The fruit cooling effect induced by the kaolin contributed to higher fruit quality (Dinis *et al.*, 2016, 2020). In mature grape berries, kaolin boosts the amounts of phenolic compounds, such as total phenolics and tannins, rising the antioxidant activity. Several studies on an extensive range of grapevine varieties, such as 'Cabernet Sauvignon', 'Pinot Noir', 'Merlot', 'Muscat Hamburg' and 'Touriga Nacional', showed that kaolin application promoted the increase of total anthocyanins concentration in the grape (Shellie and King, 2013; Brillante *et al.*, 2016; Conde *et al.*, 2016; Dinis *et al.*, 2016). Shellie and King (2013) showed an increased soluble solids concentration of cv. 'Cabernet Sauvignon,' while Ferrari *et al.* (2017) showed that in both 'Malbec' and 'Sauvignon Blanc' varieties no effect was noticeable. The kaolin application could provoke a delay in maturation due to the shadow induced leading to higher organic acids concentration and total acidity as observed (Ferrari *et al.*, 2017; Dinis *et al.*, 2020). Nonetheless, in a study with cv. 'Sauvignon Blanc', no changes were found in organic acids concentration, wine acidity and pH derived from kaolin-treated plants (Coniberti *et al.*, 2013). Dinis *et al.* (2020) found a significant influence of kaolin in the grape metabolome, providing berries with high phenolic compounds, tartaric and malic acids, total acidity, and lower sugar content. A positive influence on wine was also observed, having higher acidity and lower alcohol levels, and also seems to have improved the aroma. Ferrari *et al.* (2017) obtained higher scores, given by experts, to wine (concerning typicity, aroma and body) resulting from kaolin-sprayed plants.

Soil and water management

Cover crops are used to improve the soil structure and erosion control, and enrich nitrogen and organic matter content, while regulating the excessive grapevine vigour (Pardini *et al.*, 2002). There are several positive impacts of soil organic carbon (SOC) in agroecosystems, such as enhancing soil structure (micro- and macro-aggregates) and cation exchangeability, improving infiltration, water holding capacity and preventing topsoil loss (Eynard *et al*., 2005). Cover crop root systems create vertical pores, enhancing the rate of infiltration and stabilising organic carbon-rich topsoil, whereas above-ground biomass reduces the dispersive impact of raindrops (Novara *et al.*, 2019). A study carried out in Chile found that the introduction of leguminous cover crops (or combinations of them) increased soil nitrogen (N) to such an amount that they can supply grapevines with up to 40 kg N/ha (Ovalle *et al.*, 2010).

Marks *et al.* (2022) suggest a distinct management-based approach to increasing SOC stocks by the sowing of cover crops in place of herbicide-managed bare earth. This approach seems to have a mechanistic benefit. It increases SOC as a function of inputs, such as root and shoots biomass, root exudates and microbial biomass as a function of atmospheric carbon (C) fixation and translocation (Peregrina *et al.*, 2014). Both SOC stocks and labile organic C were increased in the presence of cover crops *versus* the traditional, herbicide-managed practice (Marks *et al.*, 2022). Inherent differences (intrinsic and management) demonstrate the importance of specificity when selecting the correct management practice to suit a particular vineyard site and desired outcome. Cover crop combinations that involve nitrogen-fixing (leguminous) have been shown to improve soil health and fertility.

Nevertheless, it is important to select the correct combination of cover crops best suited the climate and vineyard management strategy (Figure 7). Under Mediterranean-like climatic conditions (hot and dry), overly vigorous grasses are unlikely to provide adequate water balance, which could be achieved, for example, with ryegrass (Marks *et al.*, 2022) which is less vigorous and requires less water demand.

Few studies have investigated the influence of complete floor cover crops (inter- and intra-row) on the grapevine, especially when when grown under semi-arid conditions. In a vineyard with cv. 'Chenin blanc' and under dryland conditions in South Africa, a permanent cover of indigenous weeds frequently cut by a bush-cutter competed with grapevines during the growing season, thus decreasing vegetative growth and yield (van Huyssteen and Weber, 1980). Other studies found similar effects, but changes in the canopy architecture and decrease of the grapevine vigour and crop yield were only observed after several years (Gontier *et al.*, 2011). In a four-year experiment carried out in France by Gontier *et al.* (2011), a reduced crop yield and vigour, and an increased sugar and phenolic content in grapevines under a complete grass cover cropping were noted. However, in North Carolina and for 'Cabernet Sauvignon' vineyards, Giese *et al.* (2014) found no depressive effect on productivity caused by complete floor covers. Muscas *et al.* (2017) found that cover crops reduced grape production by modifying yield components in different ways: legume mixture decrased the cluster weight, whereas grass mixture led to a lower number of clusters per vine along with lower cluster weight. Cover crops also influenced the must typicity. Grass mixture increased sugar, and polyphenols content, whereas legume mixture and natural covering caused a decrease in total polyphenols and anthocyanins contents, respectively. Muscas *et al.* (2017) suggest that the effects of cover crops seem to be mediated through nutrient availability and content in grapevines. Thus, using competitive cover crops, while reducing yields, can improve must quality.

Figure 7. Natural cover cropping in the Douro Region.

Cover crops can also change vineyard insect pest dynamics. This management tool can affect pest dynamics by altering plant and natural enemy diversity (top-down effects), as well as modifying nutrient status and vigour of vines, that is, bottom-up effects (Thomson and Hoffmann, 2013; Veres *et al.*, 2013). Cover crops have shown variable effects on pest densities. The competition for water and nutrients, could lead to a lower plant vigour, which reduced leafhopper density due to a poorer host quality (Costello and Daane, 2003). However, a higher abundance of the vine mealybug, *Planococcus ficus* Signoret, was observed as a consequence of the suppression of tillage, which promoted the development of ant populations provoking the disruption of its natural enemies (Mansour *et al.*, 2012). *P. ficus* is a key widespread pest in the main grapevine growing areas that severely reduces the economic yield of table grapes and the quality of wine grapes, in addition to being a vector of several viruses and diseases (Daane *et al.*, 2012). Muscas *et al.* (2017) found that all the *P. ficus* biological parameters examined were affected by the soil management practices. Mealybugs reared on grapevines subjected to soil tillage and legume covering exhibited a faster growth time and higher survival, fecundity and fertility than those developed on natural covering and grass plots. The vine mealybug showed higher performance on grapevines with a higher nitrogen content and vigour.

Water stress impacts the grapevine growth, development, yield and quality of grapevine production. This issue is fully relevant in Mediterranean regions, in which the climate is characterized by high values of potential evapotranspiration and low values of precipitation during the growing season, leading to frequent high water deficits in the soil, plant and atmosphere.

Vineyard water management is particularly important to minimize the negative effects of hot and dry periods,. Traditionally, winegrowers have relied solely on winter rains stored in soils with relatively limited water availability (e.g. most Portuguese winegrowing regions), supplemented by the occasional rainfall occurring during the growing season, which is a relatively rare event in southern Portugal. In this sense, water supply by irrigation has progressively been applied to vineyards in southern Europe, although strictly regulated in controlled appellations (e.g. Port wine production in the DDR).

Irrigation management requires an accurate determination of crop evapotranspiration (the combination of soil water evaporation and plant transpiration). The measurement of evapotranspiration (ET) and its two main components can be approached with a variety of methods, depending on the timescale and component of interest. Reviews of the different methodologies for measuring ET with particular attention to Mediterranean conditions can be found in the literature (e.g. Rana and Katerji, 2000). They include classical techniques used in crops such as grapevines, which can be classified into hydrological, micrometeorological and plant physiological approaches. With increasing access to data from satellites and *unmanned* aerial vehicles (e.g. drones), different remote sensing methods have been used to estimate ET (Courault *et al.*, 2005; Ghiat *et al.*, 2021).

For irrigation purposes, grapevine water requirements are usually estimated from the evapotranspiration of a well-known reference surface, typically a grass reference (Allen *et al.*, 1998), and then related to crop evapotranspiration using specific crop coefficients. This variable corresponds to the use of the maximal value of ET, with adequate available soil water for optimum plant growth, under the climate and cultural practices considered.

Still, grapevine irrigation must be managed in such a way as to prevent severe water deficits, which may cause detrimental impacts at physiological and biochemical levels and high defoliation. On the other hand, it should not promote the dilution of berry metabolites and competition for excessive vegetative vigour (source-sink imbalance), as well as excessive shading of the bunches, especially during maturation (Magalhães, 2015). As an illustration, in the early phenological stages (budburst to flowering), a degree of absent to very light water stress is recommended, while in post-veraison moderate water stress is required (Deloire *et al*., 2004). In this way, deficit irrigation strategies (regulated deficit irrigation, sustained deficit irrigation, and partial root-drying) have been implemented, sustaining yield and quality and increasing crop water use efficiency (Geerts and Raes, 2009; Chaves *et al*., 2010). These strategies should include soil (e.g. soil moisture) or grapevine water status indicators (e.g. leaf water potential) to define a threshold level of water stress (Mirás-Avalos and Araujo, 2021; Rienth and Scholasch, 2019). In addition, automated plant-based sensors (Cifre *et al*., 2005; Ferreira *et al.*, 2012), geographic information systems and crop models are being used, optimizing precision irrigation, thus increasing water and energy use efficiency and vineyard profitability (Bellvert *et al*., 2020).

CONCLUDING REMARKS

This review highlights the effects of climate change on Mediterranean viticulture. After selecting the most tolerant varieties, selection of the training system is the primary measure to combat thermic and water stress, and facilitate better management of the plant's water use. After this measure, foliar protectors, coverings and even irrigation can help vines to improve their performance and consequently their yield quality. The possible adaptation strategies to cope with climate change still hold several uncertainties. Nevertheless, the adaptation strategies, duly adjusted to local *terroirs* and regional climate change projections, will contribute to the sustainable development of the winemaking sector, by providing guidelines for decision-making concerning the ongoing management of vineyards, but also for planning climate-smart vineyards in the upcoming decades, that is vineyards designed to better respond to climate change pressures. Not only stakeholders but also policymakers can play a key role in the required sectoral transformation, e.g., by designing appropriate and effective policies and regulations, at both the national and EU level, to facilitate the intended gradual transition of the entire wine production chain. This range of different strategies will contribute to a winemaking sector more resilient to climate change and its derived risks, but also more sustainable in the long-term, both environmentally and socioeconomically.

ACKNOWLEDGEMENTS

This work was supported by National Funds by FCT–Portuguese Foundation for Science and Technology, under the project UIDB/04033/2020, and by the project I&D&I AgriFood XXI, operation NORTE-01-0145-FEDER-000041, co-funded by European Regional Development Fund (FEDER) through NORTE 2020 (Programa Operacional Regional do Norte 2014/2020). L.-T. Dinis thanks the FCT and UTAD for the research contract (D.L. Law no. 57/2017).

CONFLICTS OF INTEREST: The authors declare no conflict of interest.

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