Grapevine abiotic stress assessment and search for sustainable adaptation strategies in Mediterranean-like climates. A review

Sara Bernardo¹ · Lia-Tânia Dinis¹ · Nelson Machado¹ · José Moutinho-Pereira¹

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Abstract

Foreseen climate change points to shifts in agricultural production patterns worldwide, which may impact ecosystems directly, as well as the economic and cultural contexts of the wine industry. Moreover, the combined effects of environmental threats (light, temperature, and water relations) at different scales are expected to impair natural grapevine mechanisms, decreasing yield and the quality of grapes. Hence, the interaction between several factors, such as climate, *terroir* features, grapevine stress responses, site-specific spatial-temporal variability, and the management practices applied, which represents an effective challenge for sustainable Mediterranean viticulture, allowed researchers to develop adaptive strategies to cope with environmental stresses. Here, we review the effects of abiotic stresses on Mediterranean-like climate viticulture and the impacts of summer stress on grapevine growth, yield, and quality potential, as well as the subsequent plant responses and the available adaptation strategies for winegrowers and researchers. Our main findings are as follows: (1) environmental stresses can trigger dynamic responses in grapevines, comprising photosynthesis, phenology, hormonal balance, berry composition, and the antioxidant machinery; (2) field research methodologies, laboratory techniques, and precision viticulture are essential tools to evaluate grapevine performance and the potential quality for wine production; and (3) advances in the existing adaptation strategies are vital to maintain sustainability and regional wine identity in a changing climate. Also, these topics suggest that rational and focused management of grapevines may enlighten grapevine summer stress responses and improve the resilience of agro-ecosystems under harsh conditions. Despite the challenge of developing different strategic responses, winegrowers should clearly define their objectives, so applied research can provide rational technical support for the decision making process towards sustainable viticulture.

Keywords Climate change · Mediterranean climate · Growth · Yield · Berry quality potential · Resilience

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✉ José Moutinho-Pereira
moutinho@utad.pt

¹ Centre for the Research and Technology of Agro-Environmental and Biological Sciences (CITAB), University of Trás-os-Montes e Alto Douro, Apt. 1013, 5001-801 Vila Real, Portugal

1 Introduction

In the recent past, higher temperatures and moderate water deficit have increased wine quality in most wine-growing

regions, whereas yields have generally decreased. However, based on the latest climate projections worldwide, this pattern will undoubtedly change (van Leeuwen and Darriet 2016). Scientific evidence sharply states that climate change represents a dominant challenge for viticulture in the upcoming decades (Giorgi and Lionello 2008; Fraga et al. 2012; Hannah et al. 2013). Over the last 10 years, the number of publications regarding abiotic stresses in *Vitis vinifera* L. increased by around 90% as shown by the results on PubMed, showing the significance of climate change and abiotic constraint impacts on viticulture, as well as the scientific efforts performed towards climate change adaptation. Driven by multiple factors, such as the emission of greenhouse gases, temperature, precipitation, and human activities, climate change is expected to directly impact ecosystems, thus leading to shifts in agricultural production patterns (Hannah et al. 2013; Fraga et al. 2016). The major perceptible effect of climate change is the increase in the growing-season mean temperatures that can be already observed (Jones et al. 2005). Several climate-based models predict temperatures to increase up to 3.7 °C until the end of the century, respecting the reference period of 1985–2005 (Jones et al. 2005; Malheiro et al. 2010; Fraga et al. 2012; IPCC 2014). Despite the lower consensus regarding rainfall trends, it is widely accepted that the patterns will vary in terms of periodicity and intensity depending on the region (IPCC 2014). These changes can also have impacts in the Mediterranean region, which lies in a transition zone between the arid climate of North Africa and the moderate temperate and rainy climate of central Europe. Exhibiting a typical Mediterranean climate (mild and wet winters; warm and dry summers), the suitability of the Mediterranean region for grapevine production also arises from the complex topography, coastline, and vegetation that covers this region (Giorgi and Lionello 2008; Hannah et al. 2013).

Even though the best wine quality rankings encompass Mediterranean-like climate countries, the impacts of climate change on viticulture and winemaking go beyond the economic and cultural dynamics of this industry. Future trends point to an impairment of numerous plant natural mechanisms, affecting grapevine growth, physiology, and berry ripening, which can cause severe losses regarding yield and the quality of vines (Fig. 1). Due to the overall projected impacts of climate change on agriculture, assessing the magnitude of the potential risk for vines will assist the development of rationale and sustainable adaptation strategies for winegrowers (Iglesias et al. 2007). Also, the study of climate change effects on viticulture will lead to a better understanding of grapevine stress responses. Through the development of different grapevine stress assessment methodologies, it might be possible to increase the quality, profitability, efficiency, and sustainability of the wine industry in a changing climate. Hence, adaptation strategies should be explored to sustain grapevine yield and quality towards a sustainable viticulture (Fig. 2).

Fig. 1 Impacts of climate change on grapevine canopy (**a**) and clusters (**b**) in Mediterranean-like climate regions, particularly in the Douro Valley, Portugal

Adaptation strategies include all the set of actions and processes that can be performed in response to climate change (Akinagbe and Irohibe 2014). A classic example of an adaptive strategy applied in viticulture is the sustainable management of vineyards, which can act as a carbon sink and improve the resilience of agro-ecosystems under harsh conditions, providing a batch of ecosystem services (Brunori et al. 2016). Besides, by adjusting natural and human systems, three significant purposes can be achieved: (1) reduce the risk of damage, (2) develop the capacity to manage certain damages, and (3) find opportunities with climate change (Ollat and Touzard 2014).

Recent multidisciplinary research had focused not only on the impacts of climate change on the physical, biological, and molecular aspects of grapevines but also on the current adaptation strategies that can be generally applied (Mosedale et al. 2016; Neethling et al. 2016). However, we still require more information on the combined effects of environmental threats (light, temperature, and water relations) at local and regional scales, especially in Mediterranean-like climate countries,

Fig. 2 Conceptual framework of climate change dynamics and its impacts on grapevine stress responses towards a sustainable viticulture

where the environmental thresholds can be reached during the summer season.

Although some research has been carried out on grapevine varietal resilience to summer stress, there is still little scientific understanding of varietal sensibility regarding interactions between environmental parameters and plant adaptation responses (Ollat and Touzard 2014). Moreover, few studies have addressed the sustainability and the validation of the adaptation strategies nowadays available in an industrial and applied context (Ollat and Touzard 2014; Duchêne 2016). Also, there is uncertainty regarding the capacity of winegrowers to adapt to changing conditions. In this sense, the first purpose of this paper is to review current knowledge regarding summer stress impacts in Mediterranean areas, on a socio-economic and biological perspective, as well as the responses triggered in grapevines by those stimuli. Next, we will focus on short-term and long-term adaptation strategies that can be adopted by the winegrowers to cope with summer stress. Then, some field and laboratory methodologies will be considered to approach grapevine performance and fruit quality potential. Finally, we will discuss future perspectives and research topics regarding adaptation strategies applied in viticulture, which could support the decision-making process towards sustainable adaptation strategies.

2 Climate change on Mediterranean-like climate regions

According to Wardlaw (1972), stress can be defined as a factor that is potentially unfavorable to an organism, and it is nowadays unanimous that those factors can be either environmental (abiotic) or caused by other organisms (biotic). Despite the increasing scientific concern focused on abiotic and biotic

stresses, other variables must be taken into consideration when extending this concept to a field crop, such as yield and quality (Keller 2010a; Cramer et al. 2011). The overall effects of individual or combined climate change-related variables, such as interactions between high radiation levels and high temperatures, and both soil and atmospheric water deficits, may have negative impacts on vineyards yield, specifically in most Mediterranean-like climate regions (Fraga et al. 2012; Ferrandino and Lovisolo 2014). In fact, under the current management conditions for much of the Mediterranean region, decreases in crop yields up to 40% are predicted (Iglesias et al. 2007). Also, yield variability is predicted to increase, while a decrease in water availability is foreseen, alongside an increase in water demand (Iglesias et al. 2007). Decreasing water resources in some areas may also affect soil structure while reduced soil drainage may lead to increased salinity (Hu and Schmidhalter 2005). However, it is expected that an increase in the frequency and intensity of floods would be likely to occur in some areas presenting significant winter rainfall, leading to the loss of Mediterranean species diversity (Fraga et al. 2013; van Leeuwen and Darriet 2016).

2.1 Viticultural climatic indices

Several bioclimatic indices have been proposed for estimating the risk of moisture-induced diseases, which showed that areas displaying a Mediterranean-like climate would tendentially present low risks of contamination, particularly in southern Europe (Fraga et al. 2013; Calonne et al. 2017). While drier environments may lead to higher insect and viral outbreaks, wet periods are expected to trigger cryptogamic and bacterial diseases, which can indirectly disturb population dynamics of insect pests (Katsaruware-Chapoto et al. 2017). In fact, current research suggests that mildews remains the

major phytosanitary threat in most wine-growing regions, even in dry climate vineyards, as a result of the irrigation practices applied, but also because of the fact that mildews can be highly damaging, thus requiring a rapid intervention (Calonnec et al. 2017). Moreover, existing pests are likely to expand, as well as invasion by new insect pests as a consequence of the foreseen increased frequency of extreme weather events, temperature, carbon dioxide levels, and changes in moisture conditions (Jaworski and Hilszczański 2013). However, an accurate quantification of the potential impact of climate change on biotic stresses represents an important challenge, since pest and host responses to environmental shifts are highly variable and complex (Katsaruware-Chapoto et al. 2017).

Along with these considerations, the Mediterranean region features unique characteristics (cover vegetation, coastline, and topography) that may modulate the regional climate, which is particularly decisive in viticulture, where the concept of *terroir* is closely related to wine quality and typicity (van Leeuwen and Seguin 2006; Giorgi and Lionello 2008). The *terroir* not only includes the key elements of a delimited geographical area defined from society but also embraces the physical elements of the vineyard itself: the vine, subsoil, location, drainage, and microclimate, which altogether are essential to delineate vine-growing regions (Unwin 2012). Nonetheless, it is difficult to define the ideal terms of the natural environment (climate, soil, and geology) and their interactions with human factors, agronomic approaches, and the vine water uptake conditions, which can modulate the quality of wines (Choné et al. 2001a; van Leeuwen and Seguin 2006).

The integration of climatic variables, such as heliothermal conditions over the growing cycle, temperature summation, rainfall, potential soil water balance over the growing cycle, night temperature during berry ripening or seasonal weather data, with other non-climate-related indicators (e.g., potential quality of grapes at harvest and management practices) improved winegrowers' adaptive strategies, both in time and space (Tesic et al. 2002; Malheiro et al. 2010). This ongoing process in decision-making can be supported by the improvement and development of several viticultural climatic indices, describing the climate of wine-growing regions worldwide at different scales. One of the earliest indices was the heat unit concept, using a growing degree base of 10 °C (degree-days) since grapevines need a specific heat accumulation to complete the growing cycle (Winkler and Amerine 1944). The cool night index (CI), which accounts for minimum temperatures during maturation, and the diurnal temperature range, are other thermal indices that can estimate the production of high-quality wines (Tonietto and Carbonneau 2004; Ramos et al. 2008). However, grapevine variety and day-temperature can also influence the effect of night temperature on the ripening process (Kliever and Torres 1972). Based on the potential water balance of the Riou Index (Riou et al. 1994), Tonietto and Carbonneau (2004) developed the dryness index (DI) that considers the soil–water

availability at the beginning of the growing cycle, besides the potential evapotranspiration and precipitation. Also, these authors integrated the Huglin heliothermal index (HI) in their proposed model, which adjusts the value of heliothermic index for different latitudes, and created a multicriteria climatic classification system (Geoviticulture MCC System) for the grape-growing regions worldwide (Tonietto and Carbonneau 2004). This system represents a research tool for viticultural zoning, allowing the assessment of the potential suitability for grape production at different scales for economically sustained viticulture in a changing environment.

2.2 Summer stress impacts

Shifts in climate patterns leading to abiotic stresses encompass the set of environmental conditions that decrease growth and yield below optimal levels (Skirycz and Inzé 2010). The most common abiotic stresses comprise drought (water deficit), salinity, soil acidification, high temperatures, and excessive radiation exposure, being difficult to discriminate the individual impacts of each stress in an open field situation, since all these environmental factors are interrelated (Tester 2005). Generally, the term summer stress describes the combination of various abiotic stresses, such as water deficit, high sunlight, and high temperature, which are more severe during the summer season (Cramer et al. 2011). The relationship between sunlight exposure and temperature of grape clusters is important to perceive grapevine metabolism, since many of the biochemical pathways are both light and temperature sensitive (Spayd et al. 2002). Previous studies have shown that shaded berries were often 2.4 °C above ambient temperature, whereas sun-exposed clusters were up to 12.4 °C above ambient (Millar 1972; Smart and Sinclair 1976). Similarly, Crippen and Morrison (1986) reported that sun-exposed clusters were warmer than shaded clusters during the day and cooler during the night, indicating greater net radiation loss by the sun-exposed berries at night. Moreover, it is widely known that high temperatures can cause damages throughout the growing cycle, including scorching of leaves, sunburn, leaf senescence and abscission, shoot and root growth inhibition, fruit damage, and reduced yield (Vollenweider and Günthardt-Goerg 2005; Wahid et al. 2007). Another related topic is the increased incoming radiation, particularly in the UV-B range, which despite having a positive impact on skin phenolics, is also likely to affect grape aromas, and consequently the quality potential of wines (Schultz 2000; van Leeuwen and Darriet 2016; van Leeuwen and Destrac-Irvine 2017).

Vine water status depends, not only on climatic parameters, but also on soil water retention capacity, while a period of high frequency and intensity of water stress, when transpiration exceeds the ability of the root system to supply water to the transpiring leaves, may impair photosynthesis, due to severe the water deficit (Choné et al. 2001a; van Leeuwen and

Destrac-Irvine 2017). However, since grapevine features a reasonable tolerance to drought, moderate water deficit may induce changes in the source to sink relationships (competition for carbon resources), reducing both shoot vigor and berry size, and consequently increasing skin surface/mass berry ratio (Castellarin et al. 2007). Besides, mild water deficits are known to cause embolism in the xylem shoot apex, which can have positive effects on berry skin anthocyanin and tannin content in red grape varieties, due to the lower competition between vegetative growth and reproductive development for sink resources (Schultz and Matthews 1993; Choné et al. 2001a). These findings also suggest that vines exposed to moderate water deficit may have richer must and wine quality (Choné et al. 2001a).

3 Grapevine stress responses

Plants perceive abiotic stress signals and acquire complex and dynamic defense responses, either elastic (reversible) or plastic (irreversible), depending on the duration and intensity of the stress (acute vs. chronic), as well as the organ or tissue involved (Cramer et al. 2011). Since grapevine features a reasonable tolerance to drought, moderate water deficit may induce changes in the source to sink relationships (competition for carbon resources), reducing both shoot vigor and berry size, and consequently increasing skin surface/mass berry ratio (Castellarin et al. 2007). Besides, the association between several biotic and abiotic factors and the capacity of a plant to adapt to extreme stress conditions may determine plant resilience, despite being genotype dependent (Cramer 2010). Stress, in turn, has several biological consequences for the plants, hampering the adaptation, profitability, quality, and even the survival of many crops with high economic impact on a global scale (Fraga et al. 2012). These considerations influence the complexity of the response. The most common stress responses include shifts in photosynthesis, growth, changes in protein synthesis, hormonal metabolism, transcription, signaling networks, and stimulation of the cellular defense machinery (Vierling and Kimpel 1992; Moutinho-Pereira et al. 2004; Zhu 2016).

3.1 Effects on phenology, growth, and yield

Climate plays a crucial role regarding the development of vines, through optimal thermal requests, water availability over the growing cycle, and radiation intensities and extent, which may compromise plant growth, yield, and quality (Mira de Orduña 2010; Dinis et al. 2014). In nature, plant responses to abiotic stresses may follow a different sequence of internal events. However, the initial growth inhibition arises before inhibition of photosynthesis or respiration (Pellegrino et al. 2005; Zhou et al. 2007). Plants' ability to osmotically adjust

or conduct water may modulate their growth, meaning that during stress exposure, morfo-anatomical and metabolic changes will gradually occur (Cramer et al. 2011). The structural dynamic of the grapevine canopy over the growing cycle is closely linked to growth and production of grapes of high-quality potential (Wahid et al. 2007). However, increasing sunlight penetration into the canopy structure can have impacts on the ratio between older and younger leaves at berry softening stage, mainly when reaching environmental thresholds. These consequences are likely to trigger impairments in the vegetative growth and the reproductive development and functioning of plants (Wahid et al. 2007). Some studies have considered the effects of environmental stresses and canopy management practices throughout the growing cycle, enlighten the dynamic between grapevine microclimate and farming practices and their effects on fruit ripening, yield, and quality potential (Smart 1985; Jackson and Lombard 1993; Dokoozlian 1996; Mabrouk and Sinoquet 1998). Phenology is considered one of the first biological indicators of stress used to quantify the magnitude of climate change impact in vines during the main grapevine phenological stages (bud break, flowering, and *veraison*) and at harvest (Menzel et al. 2006; García de Cortázar-Atauri et al. 2017). Several models have been applied to predict the onset of vines phenology, and to enlighten the factors that may interfere in the development of vines under different conditions (Duchêne and Schneider 2005; Parker et al. 2011; Daux et al. 2012; Jones 2013). These studies based on phenology evolution models showed that all main grapevine phenological stages would advance in the upcoming years, being more perceptible in northern vineyards, while earlier onset of grapevine phenophases often precedes changes in growth (García de Cortázar-Atauri et al. 2017).

Previous research established that increasing mean temperatures are negatively correlated with the number of flowers per inflorescence (Keller et al. 2010). Besides, the upward shift in seasonal temperatures is expected to settle the typical development pattern of grapevines towards an earlier onset of flowering, *veraison*, and harvest (García de Cortázar-Atauri et al. 2017). Earlier *veraison* suggests that the critical ripening stage may deviate towards the warmest period of the season, affecting yield and fruit composition, mainly sugars, organic acids, and phenolics (Fraga et al. 2012; Ferrandino and Lovisolo 2014).

Generally, the number and size of grape clusters formed during grape development determine harvest yield, which is influenced by several key stages of vine phenology and seasonal conditions; however, the response of berry growth and physiology to abiotic stresses varies during the ripening process (van Leeuwen and Destrac-Irvine 2017). In fact, although region dependent, several studies have observed a relationship between increasing summer stress and reduced grapevine yield and quality (Pratt 1971; Petrie and Clingeleffer 2005; Watt et al. 2008; Duchêne 2016). For instance, water stress

induces a lower yield by restraining photosynthesis, meaning that only a limited amount of berries can achieve the full ripeness (Zulini et al. 2007). In addition to carbon metabolism impairment, water stress also affects nitrogen metabolism and assimilation, through decreases in nitrate reductase activity (Bertamini et al. 2006). Moreover, Huffaker et al. (1970) suggested that a pronounced decrease of the nitrogen assimilation pathway could be associated with biochemical adaptations to drought, through the reduction of energy requirements during stress exposure, which prevents the accumulation of nitrite and ammonium. These findings suggest that it is vital to develop management tools, adapted to match specific cultivar/rootstock/site combinations, in order to maximize grapevine quality in a changing climate.

3.2 Effects on photosynthesis

The physiological processes of grapevine initiate when the average temperature is around 10 °C; however, above 35 °C, plants start triggering adaptation mechanisms (Ferrandino and Lovisolo 2014). The most pronounced effects of summer stress on plant physiology comprise the decrease of photosynthetic rates by photoinhibition of photosystem II (PSII) and reduction in stomatal conductance (Moutinho-Pereira et al. 2007; Pinheiro and Chaves 2011; Dinis et al. 2015). Non-photochemical quenching (NPQ) is the primary protective mechanism against photoinhibition, involving xanthophylls for the dissipation of excessive non-radiative energy (Hendrickson et al. 2004). Moreover, summer stress increases respiratory activity, which can overcome CO₂ fixation, leading to unbalanced growth (Millar 2003).

Studies have revealed that high temperatures induce anatomical and structural changes in the organization of the photosynthetic membranes of chloroplasts, leading to a decrease in the photosynthetic and respiratory activities (Zhang et al. 2005; Wahid et al. 2007). For instance, Yamada et al. (1996) showed that chlorophyll fluorescence, the ratio of variable fluorescence to maximum fluorescence (F_v/F_m), and the basal fluorescence (F_0) are physiological parameters correlated to stress tolerance (Yamada et al. 1996). Similarly, other authors have reported a sustained decrease in F_v/F_m of dark-adapted grapevine leaves along with an increase in F_0 , suggesting the occurrence of photoinhibitory damage in response to high temperature and drought (Gamon and Pearcy 1989; Zulini et al. 2007). Moreover, studies regarding the effect of rootstock on grapevine physiological performance in a stressful environment appear to be interlinked with photochemical changes and stomatal limitations (Iacono et al. 1998; Toumi et al. 2007).

Nonetheless, the combined effect of water deficit, high temperature, and light are presumably the main constraints for photosynthesis, particularly under severe soil water deficits (Flexas et al. 1998). Chlorophyll degradation is also a consequence of summer stress and appears to be associated

with the production of reactive oxygen species (ROS) (Camejo et al. 2006; Guo et al. 2006). Besides pigment degradation, high temperatures, light, and drought can also decrease soluble protein contents and alter the rate of rubisco regeneration (Todorov et al. 2003; Salvucci and Crafts-Brandner 2004). In fact, though some authors have observed a decrease in rubisco regeneration in stressed plants, little effect was observed on rubisco activity, indicating that this activity, and consequently photosynthetic efficiency, depends on the water deficit conditions and the species under study (Flexas et al. 1998; Galmes et al. 2010).

3.3 Oxidative stress and antioxidants

One of the main physiological consequences of abiotic stress lays on the inevitable leakage of electrons from different cellular compartments to oxygen (O₂), which disturbs redox homeostasis by the overproduction of ROS, ultimately leading to a state of oxidative stress (Sharma et al. 2012). In turn, oxidative stress can lead to shifts in enzymatic activity and the regulation of genes, which may compromise plant survival. ROS exist either as radicals, such as superoxide anion (O₂^{•-}), hydroxyl (•OH), peroxy (RCOO•), and alkoxy (RO•) radicals, and non-radicals, all of them capable of propagating chain reactions and targeting biomolecules (DNA, lipids, pigments, and proteins) (Møller et al. 2007; Sharma et al. 2012). Although photochemical events, as well as photorespiration, are considered to represent the main sources of ROS during day light exposure, enzymes like NADPH-oxidase, xanthine oxidase, peroxidases, and amine oxidase can also contribute to ROS production (Schmidt and Schippers 2015). Furthermore, hydrogen peroxide (H₂O₂) has received particular attention as a signal molecule involved in the regulation of specific biological processes, in numerous series of environmental stresses (high light, heat, salinity, drought, and cold stress) and pathogen invasions (Bienert et al. 2007). In grapevines, H₂O₂ is also considered a key regulator of small heat shock proteins and many genes of the anthocyanin metabolic pathway (Grimplet et al. 2009; Guo et al. 2016).

Phenolic accumulation is also linked with several environmental disturbances (Ferrandino and Lovisolo 2014). Indeed, under high temperatures exposure, the probably increased degradation and inhibition of anthocyanins synthesis may lead to higher H₂O₂ production with forwarding induction of the antioxidant machinery (Mori et al. 2015; Conde et al. 2016; Bernardo et al. 2017). Flavonoids act as primary antioxidants in plant responses to a wide range of stresses, inhibiting ROS production and reducing ROS levels once they are formed (Agati et al. 2012). Due to the multiple disturbances to which plants are exposed, it becomes essential to expand the research on their enzymatic and non-enzymatic antioxidant defenses, as well as concerning the signaling mechanisms and metabolic pathways behind plant stress responses.

3.4 Hormonal balance

Hormones are essential regulators of plant stress responses, with abscisic acid (ABA), ethylene, and auxins, representing the most preponderant for the defense mechanisms acquired by plants (Pieterse et al. 2012). Several studies extensively reported the oxidative effects of environmental stresses on plant responses and their interaction with hormones (Spoel and Dong 2008; Cramer et al. 2011; Dinis et al. 2018). Changes in ABA concentrations are correlated with abiotic stress regulation, while biotic stress responses are in turn mediated by other hormones such as salicylic acid, ethylene, and jasmonic acid (Rejeb et al. 2014). Besides, hormonal dynamics, like auxin-ABA crosstalk, have been demonstrated to increase the sensitivity to ABA in plants (Tognetti et al. 2012). ABA plays a central role in stress responses, acting either rapidly, without involving transcriptional activity (e.g., control of stomata aperture) or slower, when stress signals trigger transcriptional responses, such as the regulation of growth and germination (Hubbard et al. 2010; Pieterse et al. 2012). Moreover, ABA also regulates essential physiological responses to summer stress, including photoprotection and stomatal conductance. Under water deficit, ABA plays a vital role in controlling water relations in grapevines, by increasing its concentration and flux in the xylem vessels and influencing hydraulic conductance, aquaporin gene expression, and embolism repair (Schachtman and Goodger 2008). Furthermore, interactions between ABA signaling pathways and sugars have been reported to control sugar transport in grapevines (Cramer et al. 2011). The onset of grapevine ripening is proved to be tied to sugar accumulation, being followed by a marked increase in ABA concentration (Gambetta et al. 2010). Additionally, the synergetic effect of ABA and sucrose, concerning anthocyanin accumulation in grapevine, was observed through ABA exogenous application trials, highlighting the role of ABA during grape ripening (Pirie and Mullins 1976; Xi et al. 2012). Also, Conde et al. (2011) highlighted the role of ABA exogenous application in triggering drought resistance mechanisms, due to the increased expression of transport proteins, improved carbon metabolism, and through the expression of stress resistance-related proteins.

During a stress-induced stimulus, apart from its function through signal transduction pathways on cells, ABA may also regulate some genes, and gene products that control the expression of stress adaptive-specific genes, featuring a pivotal role in plant survival under environmental fluctuations (Ferrandino and Lovisolo 2014; Sah et al. 2016). In this sense, some authors suggested that ABA may increase berry quality potential through the accumulation of secondary metabolites, since many key genes of the flavonoid biosynthetic pathways were proven to be upregulated during the ripening stage (Tardieu et al. 2010).

3.5 Effects on berry composition

Abiotic stresses, particularly high temperatures, may cause shifts in grape chemistry, which are reflected in over-ripened fruits, with low acidity, high sugar, and thus increased alcohol levels, as well as aroma and color modifications (Mira de Orduña 2010; Mozell and Thach 2014; Darriet et al. 2017). Within specific ranges, sun exposure of grape clusters boosts the production of secondary metabolites, which play a central role in fruit and wine quality potential (Cohen et al. 2008). Indeed, the temperature has been shown to play an essential role in anthocyanin synthesis, since modifications in phenolic compounds are relevant, cultivar dependent, and temperature associated. Under field conditions, Sadras and Moran (2012) observed decoupling of anthocyanin and sugar contents in red wine varieties exposed to stressful environments, suggesting that a moderate water deficit before *veraison* could partially restore the anthocyanin/sugar balance, impaired by summer stress. While low temperatures do not influence anthocyanin concentrations, higher temperatures ($T \geq 30$ °C) can lead to a decrease in anthocyanin synthesis, and even to its inhibition, when temperatures rise above 37 °C. As a consequence, wine quality can be affected by the reduced grape color and increased volatilization of aroma compounds (Buttrose and Hale 1971; Coombe 1987; Spayd et al. 2002; Tarara et al. 2008). Moreover, Darriet et al. (2017) pointed that the absence of herbaceous notes in wines may be associated with exposure to high temperatures during berry ripening. Grape berry composition is also affected by sunlight, since many of the biochemical pathways are both temperature and light sensitive. In fact, increased UV-B radiation has shown positive effects on skin phenolics accumulation, and in the development of berry aroma and aroma precursor profiles (van Leeuwen and Destrac-Irvine 2017).

In berries, apart from total anthocyanin levels, compositional changes related to summer stress have been also associated with the increased formation of malvidin, petunidin and delphinidin derivatives in berries (Tarara et al. 2008). As summer temperature rises to atypical values, the anthocyanin biosynthetic genes are downregulated, reducing berry skin anthocyanin biosynthesis (Conde et al. 2016). For instance, Tarara et al. (2008) showed that high temperatures are associated with decreases in grapevine delphinidin, cyanidin, petunidin, and peonidin based anthocyanin contents, but found no influence on malvidin derivatives' concentrations.

The expected earlier onset of grapevine vegetative cycle also brings considerable consequences for grape composition, such as increased berry sugar contents and lower acidity. Increased sugar contents, leading to higher alcohol content in wine, can alter wine flavors and mouthfeel, which triggers a reduction in anthocyanin content and consequently the color potential of red grapevine varieties (Keller 2010b). Summer stress can also have effects on the content of organic acids in

grapes. Malic and tartaric acids represent the most common organic acids in grapevine fruits, featuring variable regulation over the ripening stage (Conde et al. 2007). Typically, although both acids reach their highest concentrations near *veraison*, it is believed that once synthesized, tartaric acid remains stable whereas malic acid is metabolized and used as an energy source during the ripening process (Sweetman et al. 2014; Rienth et al. 2016). Recent research points that water stress during the summer season, along with high light and temperature, can induce changes in aroma, increased skin phenolic content, and reduced malic acid concentrations in berries (van Leeuwen and Destrac-Irvine 2017). Also, since berry volume increases during ripening, decreases in tartaric acid concentration are often assigned to a dilution effect (Dokoozlian 2000; Conde et al. 2007). In this sense, while tartaric acid is moderately stable to upward temperature, malic acid levels are firmly dependent on temperature and maturity (Buttrose and Hale 1971; Mira de Orduña 2010). Moreover, decreases in total grape acidity are usually linked with higher pH, though this relationship is affected by increased potassium accumulation, which is also temperature dependent, particularly during the ripening phase (Coombe 1987).

Therefore, climate change has brought an impending challenge to wine industries, derived from grape composition and condition, such as the increased temperature of harvested grape delivered to the winery, higher environmental temperatures during the fermentation process, increased berry sugars and lower acidity levels (Mira de Orduña 2010).

4 Adaptation strategies

The effects of climate change, along with the future climate projections, pose severe challenges to the winemaking sector. However, winegrowers display great uncertainty regarding future climate trends, being thus essential to improve practical and scientific-based knowledge to enhance adaptive vine responses (Jones et al. 2005; Neethling et al. 2016). Therefore, adaptation strategies should be developed and optimized to sustain yield and quality. The climate projections are predicting shifts in the ripening period of grapes, meaning that winegrowers will have to adapt, by delaying the growth cycle of the vine. In various wine-growing regions, this will require a highly modified approach to viticulture, through the implementation of strategies to delay ripeness rather than techniques to improve it (van Leeuwen and Destrac-Irvine 2017). Adaptation measures can be focused on specific threats (short-term), aiming to the optimization of grapevine development and growth, or could embrace a strategic response (long-term), letting actions to be taken before critical thresholds are reached (Schultz 2010; Fraga et al. 2012).

4.1 Short-term

The evolution of viticultural techniques applied worldwide allowed winegrowers to focus on additional aspects of grapevines' adaptation to a changing environment, such as the choice for grape quality potential rather than yield, which has significant implications across the soil, canopy and harvest management (Battaglini et al. 2008; Barbeau et al. 2014; van Leeuwen and Darriet 2016). The increasing interest in understanding soil influence on vine and grape growth and development, as well as the evolution of the grape maturation concept, promoted a greater balance between technological parameters, such as the ratio between sugar and acidity levels, and the physiological variables associated with ripening, such as phenolic maturation (van Leeuwen and Seguin 2006; Neethling et al. 2016; van Leeuwen and Destrac-Irvine 2017). Moreover, the recognition of vine vigor and grape yield as essential fractions of grapevine maturation process and quality, revitalized some existing practices such as adjustments of bud number per cane, shoot trimming, soil amendments, the introduction of cover cropping, and rational leaf removal (Martínez de Toda et al. 2014; van Leeuwen and Darriet 2016).

4.1.1 Cultural practices

Once grape harvesting is occurring earlier in the season because of summer stress, short-term adaptive measures can be undertaken towards vine phenology delay to avoid quality reduction (Keller 2010b; van Leeuwen and Darriet 2016). For this purpose, viticulturists can use training systems with higher trunks to decrease bunch zone temperature and limit maximum temperatures on dry and stony soils. On the other hand, winegrowers can adopt the so-called *goblet* training system, used over centuries, characterized by shorter trunks and lower total leaf area, to promote water use efficiency (Lereboullet et al. 2013; van Leeuwen and Darriet 2016). The main drawback of this system is converting mechanical harvest into a difficult challenge (van Leeuwen and Darriet 2016). Besides, late pruning can delay bud break, and thus, the subsequent phenological stages. Reduced leaf area/fruit mass ratio can also delay maturity and decrease sugar/acid ratio in grapes (Parker et al. 2015). Rational hedging and selective defoliation can promote a sustainable ripening, improving the balance between skin phenolics' synthesis and UV-B radiation exposure in the bunch zone. The reduced sunlight exposure on grapes will promote a cooler microclimate, allowing grapes to retain more acidity, and a slower sugar accumulation (Lereboullet et al. 2013; Teixeira et al. 2013; van Leeuwen and Darriet 2016).

Previous studies have shown the effect of pre-flowering leaf removal on grapevine growth, wood carbohydrates reserves, and chlorophyll fluorescence (Risco et al. 2014;

Drenjančević et al. 2017). Palliotti et al. (2011) reported that early defoliation was effective in limiting yield per vine and berry weight, while improving berry skin mass in consecutive years, besides improving the control of vigor. Such features, alongside increased anthocyanin contents in berries, suggest that this technique may improve grape composition and wine quality potential (Palliotti et al. 2011). Also, regulation of vine vigor can be obtained through vine inter-row practices, for instance, by using cover cropping during wet growing seasons and, instead of removing it, applying the *mulching* technique, which will promote the self-reproduction of cover vegetation during dry growing seasons (Møller et al. 2007; Lereboullet et al. 2013; Teixeira et al. 2013; van Leeuwen and Darriet 2016). Furthermore, if feasible, changes in row orientation should also be considered, since this is one of the main factors influencing solar radiation interception (Hannah et al. 2013). Another alternative to avoid the effects of climate change is the use of irrigation strategies that modify vine water uptake conditions. Despite the positive effect on yield, sugar, and skin phenolics, irrigation systems represent an economic, environmental, and social cost, since water scarcity is increasing, while a balanced decrease in the water use can improve grapevine water use efficiency without changing *terroir* expression (Chaves et al. 2010; Fraga et al. 2012; Lereboullet et al. 2013). In the driest wine-growing regions, van Leeuwen and Seguin (2006) pointed that only deficit irrigation can bring economically acceptable yields with high-quality potential grapes. However, the ideal water status, aiming to grape quality, is highly dependent on yield. Under dry conditions, severe water stressed vines might lead to fine red wines as long as yield is low, whereas higher yields may benefit berry quality potential when water deficit is mild (van Leeuwen and Seguin 2006).

Besides its effects on vegetative growth, several authors have studied the management of cultural practices towards the improvement of berry growth and ripening, which may also have impacts on sugar accumulation and berry quality potential (Matsui et al. 1986; Greer and Weedon 2014; Oliveira et al. 2014; Hochberg et al. 2015). For instance, the application of shading panels on “Semillon” grapevine variety has been suggested to delay ripening and decrease canopy temperatures, besides sugar concentration in grapes (Greer and Weedon 2013). However, other authors found no differences in berry sugar accumulation during ripening in “Shiraz” grapevines exposed to high air temperatures, suggesting that vine responses to summer stress are possibly varietal dependent (Soar et al. 2009).

Nutrient management represents an essential issue for winegrowers since it impacts grapevine growth, yield, berry composition, and the quality of wines (Leibar et al. 2017). Although research in grapevine nutrition has been conducted in several wine growing regions, little is known regarding micronutrient distribution and uptake in grapevines (Pradubsuk and Davenport 2011). Under environmental

constraints, increasing evidence suggests that appropriate mineral nutrition may play a critical role in increasing both yield and stress tolerance mechanisms in agricultural crops (Cakmak 2005; White and Brown 2010). Besides, consumers and legislators are requiring sustainable production practices, aiming to decrease vineyard inputs and environmental impacts, which may lead to changes in the nutrient management of vines (Leibar et al. 2017). The effects of nutrient management in grapevines can be either direct, unbalancing berry composition and wine aroma, or indirect, through the influence on vegetative growth (Proffitt and Campbell-Clause 2012). Generally, grapevine nutrient requirements are moderate; however, abiotic stresses can compromise the nutritional balance of vines, leading to a lack of acidity in wine, when the fertilization is excessive, while nutrient deficiency has been reported to increase plant oxidative processes (Delgado et al. 2004; Waraich et al. 2012). Hence, since macronutrients display different roles in vines, appropriate nutrition is essential for sustaining plant structural integrity and many key physiological processes (Moutinho-Pereira et al. 2001; Waraich et al. 2012).

Nitrogen (N) application effects in grapevines have been widely explored, pointing to increased vegetative growth, pruning weights, and lateral shoot length (Choné et al. 2001b; Keller 2010a, b). In grapes, several studies suggested a relationship between moderate N applications and increased berry size and fruit set (Bell and Robson 1999; Zerihun and Treeby 2002; Martín et al. 2004). However, Martín et al. (2004) found no change in “Tempranillo” grapevines yield and berry size as a response to N application under the conditions of their trial. In the same study, the authors observed that increased N doses delayed berry sugar accumulation during ripening and that an average N supply (50 g N vine^{-1}) increased skin anthocyanin content, which significantly increased wine color. Nonetheless, Keller et al. (2001) showed that an appropriate N supply might reduce symptoms of inflorescence necrosis, improve fruit set and acidity, and also decrease grape sugar. At a leaf level, Kato et al. (2003) reported that plants grown under high light and high N supply had greater tolerance to photo-oxidative damage and increased photosynthesis capacity, than those grown under similar high light with a low N supply, indicating that adequate N levels in plants may trigger their defense mechanisms.

4.1.2 Application of protective compounds

Exogenous application of some protective elements, such as phytohormones (e.g., ABA, gibberellic acid, jasmonic acid, salicylic acid, etc.), signaling molecules, elicitors (methyl jasmonate, yeast extracts, etc.), osmoprotectants (proline, glycine betaine, etc.), trace elements (selenium, silicon, etc.), and nutrients, have been found to be helpful in alleviating the damage of summer stress in plants (Wahid et al. 2007;

Hasanuzzaman et al. 2013). In grapevines, many studies regarding the preharvest application of several treatments demonstrated benefits in managing plant stress responses and improving stress tolerance (Table 1). For instance, a number of authors demonstrated that exogenous applications of ABA, auxins, salicylic acid, gibberellin and kinetin, enhanced yield and graft union formation, increased total phenols, and promoted changes in berry sugar, acidity, and color (Köse and Güleriyüz 2006; Deytieux-Belleau et al. 2007; Zhang 2011; Blazquez et al. 2014; Abdel-Salam 2016b; Degaris et al. 2017; El-kenawy 2017). Moreover, Meng et al. (2018) reported that melatonin pre-harvest application could benefit phenolic content and antioxidant activity in the “Merlot” variety (Meng et al. 2018). Similarly, Böttcher et al. (2013) suggested

that the application of an ethylene-releasing compound in grapevines might stimulate auxins biosynthesis, which may assist the development of late ripening strategies for winegrowers (Böttcher et al. 2013).

Alternatively, other types of treatments can be applied to increase grapevine leaf and berry pigments, such as the application of humic acid or polyamines (Abdel-Salam 2016a; Mirdehghan and Rahimi 2016). Many authors have focused their research on the development of environmentally friendly practices, like kaolin application, to sustain yield and quality in a challenging climate, through the reduction of leaf and fruit berry surface temperature, thus improving the antioxidant machinery (Glenn 2012; Boari et al. 2015; Dinis et al. 2015). In fact, foliar application of solar protectants, has already shown

Table 1 Effects of preharvest treatments on several *Vitis* spp. varieties

Treatment	Concentration	Variety	Protective effect	References
Absciscic acid (ABA)	26 mg L ⁻¹ 300 mg L ⁻¹	‘Shiraz’ ‘Cabernet franc’ ‘Chambourcin’	Reduced transpiration Inhibition of shoot growth Induced endodormancy Increased grape color	Degaris et al. (2017) Zhang (2011)
Indol-3-acetic acid (IAA)	35 mg L ⁻¹	‘Merlot’	Changes in sugar, acidity, color and <i>Botrytis</i> sensibility	Deytieux-Belleau et al. (2007)
Kinetin	250–500 mg L ⁻¹	‘Erenköy’	Improved graft union formation	Köse and Güleriyüz (2006)
Benzyldadenine		‘Italia’		
Gibberellin	100 mg L ⁻¹	‘Tamnara’	Delayed fruit set	Blazquez et al. (2014)
Salicylic acid	100–150 mg L ⁻¹	‘Thompson’	Improved cluster and berry weight	El-Kenawy (2017)
Chitosan	500 mg L ⁻¹		Increased yield, total leaf area, and chlorophyll content	
Fulvic acid	500 mg L ⁻¹		Changes in acidity and total phenols levels Delayed ripening	
Methyl jasmonate	2.24 g L ⁻¹	‘Tempranillo’	Increased phenylalanine content	Garde-Cerdán et al. (2016)
Ethephon (C ₂ H ₆ ClO ₃ P)	144 mg L ⁻¹	‘Shiraz’	Stimulation of IAA biosynthesis Induced ethylene synthesis	Böttcher et al. (2013)
Kaolin (Al ₂ Si ₂ O ₅ (OH) ₄)	50 g L ⁻¹	‘Touriga Nacional’ ‘Sauvignon blanc’	Reduced leaf and berry skin temperature Increased ABA and IAA levels Improved water use efficiency, stomatal conductance and photosynthesis Changes in antioxidant activity Improved sucrose synthesis and photoassimilate transport capacity in leaves Decreased DNA methylation Stimulated anthocyanins accumulation	Coniberti et al. (2013) Dinis et al. (2016, 2017, 2018) Conde et al. (2018) Bernardo et al. (2017)
Melatonin	100 mg L ⁻¹	‘Merlot’	Increased phenolic content and antioxidant activity	Meng et al. (2018)
Glycinebetaine	7.65 g L ⁻¹	‘Pinot noir’	Increased leaf area and specific leaf weight	Mickelbart et al. (2006)
Humic acid	300 mg L ⁻¹	‘Ruby’	Higher cluster weight	Abdel-Salam (2016)
Citric acid	2 g L ⁻¹		Increased total phenols, anthocyanins and total chlorophyll content	
Ascorbic acid	2 g L ⁻¹		Increased chlorophyll content	
SNAP (S-nitroso- N-acetylpenicillamine)	22 mg L ⁻¹	‘Sultanina’		Riquelme et al. (2017)
Polyamines	322 mg L ⁻¹	‘Olhoghi’	Changes in phenolic content	Mirdehghan and Rahimi (2015)
Putrescine	291 mg L ⁻¹	‘Rishbaba’	Increased antioxidant activity and anthocyanin levels	
Spermidine				
Urea	1.61 g L ⁻¹	‘Garnacha’ ‘Graciano’ ‘Tempranillo’	Changes in grape amino acid content	Garde-Cerdán et al. (2014) Gutiérrez-Gamboa et al. (2018)

promising results regarding grapevine increased yield, physiological performance, and general fruit quality potential, in the context of climate change at a local scale (Coniberti et al. 2013; Dinis et al. 2016; Bernardo et al. 2017; Dinis et al. 2017; Conde et al. 2018; Dinis et al. 2018).

Nitrogen composition in must also plays an important role on grape and wine quality potential, affecting yeast metabolism, fermentation kinetics, the amino acid content, and synthesis of volatile fermentative compounds, since the amino acids are precursors of volatile compounds (Bell and Henschke 2005; Arias-Gil et al. 2007). Despite the existence of some contrasting results about the impact of foliar nitrogen sources application on amino acid composition of must (Gutiérrez-Gamboa et al. 2017; Gutiérrez-Gamboa et al. 2018; Pérez-Álvarez et al. 2017), the majority of the studies report an increase in must amino acids and yeast available nitrogen (YAN) content in grapevines treated with nitrogen sources (Choné et al. 2006; Lacroux et al. 2008). However, these studies suggest that the effects of foliar application of nitrogen sources in grapevines might be varietal dependent.

Even though these short-term measures might enlighten specific plant stress-based responses and the possible mechanisms behind them, an interdisciplinary and applied approach should be adopted, in order to fully understand those processes in different wine-growing regions (Keller 2010b).

4.2 Long-term strategies

Long-term measures rely on a strategic response encompassing changes in varietal and land allocations, changes to cooler sites with lower solar exposure, or to higher altitudes, selection of appropriate rootstocks, besides genetic enhancement approaches (Giorgi and Lionello 2008; Cramer et al. 2011; Fraga et al. 2016). Genetic variability and plasticity may maximize the adaptation potential of the existing varieties, including clonal diversity, to specific growing regions, to produce a broad range of different wines from the same varieties, or to breed new varieties better adapted to diverse wine-growing regions (Dai et al. 2011; Duchêne 2016; van Leeuwen and Destrac-Irvine 2017). These adaptations may be also oriented towards late-ripening varieties, or genotypes found among the traditional varieties in some wine-growing areas (Mozell and Thach 2014). Through the development of climatic data-based models, it would be possible to predict the grapevine pheno-phases onset in the future, which may optimize adaptation strategies and action boundaries for winegrowers over the growing cycle (Parker et al. 2011; Parker et al. 2013; Fila et al. 2014). Besides, other studies have focused on achieving high fruit to leaf ratio and late *veraison* dates, breeding new varieties with reduced sugar content and thus low alcohol levels. However, few studies have addressed the actual weight of the genetic variability in sugar metabolism (Duchêne 2016). Since stress has numerous impacts on

different grapevine quality and yield components, recent research has been focused on the varietal characterization of phenolic profiles in order to breed or unveil new varieties whose color would be less affected by high temperatures (Kliewer and Torres 1972; Fournier-Level et al. 2009; Huang et al. 2012; Barnuud et al. 2013).

Despite the challenge of developing different strategic responses, winegrowers should clearly define their objectives to provide rational technical support to the wine industry and to improve scientific-applied knowledge.

5 Grapevine performance and fruit quality assessment

5.1 Field research methodologies

Plant stress manifestation can often be silent, yet there are certain symptoms in different plant organs that can be accurately detected. Also, there are symptoms exhibited by plants that are common to biotic and abiotic stress exposures (Jackson 1986). Overall, field crops present a set of signals that reflect the simultaneous occurrence of various stresses, such as water deficit, nutrient deficiency, high temperature, radiation, and salinity (Ramegowda and Senthil-Kumar 2015). In agricultural crops, several parameters, such as yield and berry weight, are of the utmost relevance, with productivity representing essential data to estimate the resistance of a plant to specific environmental deviations. In viticulture, it is also common to quantify the number of grape bunches to more accurately estimate the influence exerted by the vine training systems on yield (Keller 2010b).

Stress induces a plant response, which can cause several changes to the grapevine, thus serving as a warning for the viticulturist, and a protection signal. Tropisms and nastic movements are phenomena where the plant reacts to different stimuli, environmental or biotic, for instance, in cases of excessive light, one of the most frequent types of tropism is the paraheliotropism, in which the plant's leaves move to reduce injuriously intense light (Keller 2010a). Winding leaves can be also indicative of some biotic or abiotic stress exposure, as well as their yellowing and the appearance of necrosis. In berries, water deficit can be also detected by their deformed appearance, showing dehydration signals (Chaves et al. 2010).

The morphological characteristics of the plant, in each phenological stage, are also important to monitor the phytosanitary status of grapevines, allowing to obtain values of growth and development, which are useful to estimate the plant resilience potential to specific environmental deviations (Keller 2010b).

There are various non-destructive and prompt tools to accurately evaluate the physiological state of the plant in real time, which can be quantified in vivo, revealing detailed

information about photosynthetic performance, nitrogen and water status of each plant, from the leaf to the whole canopy. The high level of environmental heterogeneity hinders the conduction of physiological field measurements, particularly in regions where climate varies frequently (Sebastian et al. 2016). Thus, stable and reliable measurements of physiological parameters are only possible when experiments are conducted between morning to mid-afternoon on a sunny day, since photosynthetic rates measured in overcast days are usually lower and inaccurate (Greer and Weedon 2012). Measurement of gas exchanges with IRGA (infra-red gas analyzer) is the most commonly used approach for research purposes to evaluate photosynthesis by individual leaf or by whole canopy. Gas exchange measurements provide direct measures of net rate photosynthetic carbon assimilation and data regarding stomatal conductance, internal CO_2 concentration, transpiration, leaf temperature, and photosynthetic photon flux density (PPFD).

During the process of light harvesting, excited chlorophylls dissipate the excessive energy in the form of heat and fluorescence, the latter being possible to determine under field conditions and in real time (Krause and Weis 1991). The use of a pulse-amplitude-modulated fluorimeter allows researchers to calculate fluorescence yield, PPFD incident on the leaf plane, leaf temperature, maximum and effective quantum efficiency of PSII, apparent relative electron transport rates, and photochemical and non-photochemical fluorescence quenching (qP and NPQ, respectively). Fluorescence parameters represent an essential tool to assess crop tolerance to individual or combined stresses, which can be fully understood with the JIP test. The JIP test is a tool to analyze the polyphasic rise of Chl *a* fluorescence transient from basal to maximal fluorescence (F_0 and F_m , respectively), corresponding to the redox states of PSII and photosystem I (PSI), and to electron transfer effectiveness (Papageorgiou 2004). The polyphasic fluorescence rise (O, J, I, and P steps) is observed after the illumination of dark-adapted leaves, providing information on the relationship between function and structure of PSII reaction center and core complexes (Dinis et al. 2015).

In grapevines, water status represents an important factor for berry growth and quality potential that can be influenced by environmental and cultural conditions. Besides, the evaluation of crop water status is also required to monitor vine water uptake conditions, through the development of sustainable irrigation strategies and by measuring or modelling variations in soil water content, or by means of physiological indicators so the crop water demands can be supplied (Choné et al. 2001b; Pellegrino et al. 2005; Gambetta 2016). The pressure chamber is a plant-focused monitoring system that integrates both soil and climatic conditions for determining plant water status (Scholander et al. 1964). Pressure chamber measurements can provide values of predawn leaf water potential, daily leaf and stem water potential, and can be

performed in open-field or at laboratorial environments (Choné et al. 2001b). The evaluation of bulk leaf water relations parameters, mainly the capability for osmotic adjustment, and the maximum bulk modulus of elasticity of cells, is an important tool which can be also monitored with this equipment through the development of pressure–volume curves (Rodrigues et al. 1993; Moutinho-Pereira et al. 2007).

Leaf chlorophyll content is also closely related to plant stress and senescence (Steele et al. 2008). The amount of solar radiation absorbed by a leaf results from its contents in photosynthetic pigments, with the chlorophylls representing the essential pigments for the conversion of radiative energy to stored chemical energy (Foyer et al. 1982). Moreover, Chl gives an indirect estimation of the nutritional status, since much of the leaf nitrogen is incorporated in Chl (Steele et al. 2008). For instance, the portable N-tester tool measures leaf nitrogen status, which enables fast and accurate field specific recommendations to monitor N application during the growing season (Spring and Zufferey 2000). In grapevines, inexpensive and rapid alternative solutions have been recently developed for analyzing leaf pigments by non-destructive optical methods, which are applicable in a field setting and on a larger leaf area (Buschmann and Nagel 1993). These methods are based on numerical transformations derived from spectral reflectance or absorbance, providing reliable estimations of leaf Chl to the researcher or winegrower (Moutinho-Pereira et al. 2012).

5.2 Laboratory research tools

Laboratorial methods can complement the valuable information recorded in the field, besides adding essential data and outcomes. Some methods assess the general physiological state of the plant, such as pigment quantification, sugars and starch content, protein levels, and the evaluation of lipid peroxidation (Bertamini 2003; Lazo-Javalera et al. 2015). Stress imbalances plant homeostasis, triggering specific processes and pathways that will promote a response. Hormonal signaling, which regulates specific physiological responses (e.g., stomatal closure) reveals a broader perception of stress by the plants (Ferrandino and Lovisolo 2014). Therefore, hormones tracking and quantification can provide vital information regarding, not only hormonal signaling pathways, but also hormonal crosstalk and stress responses (Sah et al. 2016).

The quantification of total or individual ROS gives a perception of the plant redox state, besides, in association with ascorbate quantification data and osmolytes content, it may also provide an overview of the plant defense mechanisms. The antioxidant potential is also relevant when assessing plant stress-based responses, which can be estimated by the presence of compounds with antioxidant activity, while many of them also exhibit biological activity with relevance for health purposes (Cramer 2010; Sah et al. 2016). Besides, complementary analysis can be undertaken in berries to evaluate fruit

quality potential, such as the determination of colorimetric parameters and biometric features. Nevertheless, a molecular approach is also crucial to understand, in a robust, assertive, and clear way, the regulation of plant stress-based responses (Cramer et al. 2011).

5.3 Precision viticulture tools

Precision viticulture is a strategy that integrates the advanced information technologies and field research methodology data, aiming to maximize production efficiency, quality potential, and profitability, while minimizing environmental impacts (Hall et al. 2002; Rey-Caramés et al. 2015). Modern and sustainable viticulture requires objective and regular monitoring of key parameters for rational and differentiated agronomic management of vineyards regarding spatio-temporal variability of growth, yield, and grape composition at a local scale (Ferreiro-Armán et al. 2006). Through the acquisition of spectral data from several platforms (satellites, aircrafts, and remotely aerial systems), remote sensing is one of the tools used in precision viticulture to assess fine-scale temporal and spatial changes in soil moisture, canopy growth, water status, chlorophyll, and carotenoids levels, as well as grape composition and quality potential (Ferreiro-Armán et al. 2006; Lamb et al. 2008; Meggio et al. 2010; Zarco-Tejada et al. 2013). For instance, a recent study of Silva et al. (2018) introduced a model combining hyperspectral imaging and support vector regression to predict anthocyanin concentration, pH index and sugar content in “Touriga Franca” variety, which can be potentially used for a wider variety of grapevines in an environmentally friendly approach. Also, Acevedo-Opazo et al. (2008) proposed a possible site-specific approach to characterize grapevine water status variability. Several studies showed that remote sensed hyperspectral data could be also used for grapevine varietal mapping, representing a practical tool for winegrowers to manage grapevine variability, and for inventory purposes (Hall et al. 2002; Ferreiro-Armán et al. 2006). Hence, the association of high resolution information and the development of site-specific agricultural management can produce a potential computer-based model, allowing the characterization of spatial-temporal variability at a vineyard level, with minimum impacts for the vine (Hall et al. 2002). Moreover, along with all the field research methodologies applied in grapevines, this technology represents a novel reliable approach to support the decision-making process.

6 Conclusion

Climate change and its impacts represent a primary concern for the winemaking sector, which boosted interdisciplinary scientific research to cope with a challenging world (Jones et al. 2005). Future climate trends may point to shifts in vine

growing regions, where it will be difficult to maintain the high-quality standards with the traditionally cultivated varieties (Hannah et al. 2013; IPCC 2014; Mozell and Thach 2014). Moreover, evidence suggests that climate change will affect both grapevine physiology and biochemistry, as well as the methods usually used during the winemaking process. Therefore, focused adaptation strategies should be adopted to maintain grapevine yield and quality potential in a changing environment (Schultz 2010; van Leeuwen and Destrac-Irvine 2017). As *terroir* defines each wine-growing region, understanding the interrelation between contextual factors (physical, environmental, social, and economic) and climate change, at local and regional scales, should be the first step to identify and prioritize sustainable adaptation strategies (Neethling et al. 2016; Ollat et al. 2017). To address these issues, it is crucial to coordinate efforts on the description of standard methods, development of data management tools, besides the maintenance and enhancement of cultivar and clone collections through multidisciplinary programs, which will define our capacity to adapt to climate change (Ollat et al. 2017).

Despite the increasing research on grapevine environmental stresses, we still require more information regarding how plants, micro-organisms, and pathogens, will respond to an increase in CO₂ concentration, temperature and water deficit under field conditions. Hence, future research may be focused on these issues (Mozell and Thach 2014).

Besides the direct impact of high temperatures and radiation on grapevine physiology, grape berry chemistry, and wine character, the secondary effects associated with climate change have to be also considered. For instance, climate change has triggered the incidence of forest and bushfires that, along with the significant damage of green areas, will bring consequences for the viticulture and enology sectors (Overpeck et al. 1990; Mira de Orduña 2010).

From the field to the winery, further efforts should be made to measure the global wine-sector contribution to climate change so that new adaptation strategies can be developed to the wine business in a sustainable process (Schultz 2010).

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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