Current viticultural techniques to mitigate the effects of global warming on grape and wine quality: A comprehensive review

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Abstract

Climate is the main factor affecting grape and wine quality in Mediterranean viticulture. Global warming provokes an increase in the accumulation of soluble solids in grapes, together with a lower content of anthocyanins and acidity. This result in stuck and sluggish fermentations causing economic losses in the winery. Climate adaptation strategies are essential to minimize the detrimental effects of global warming on grape and wine quality. This review summarized the effect of viticultural techniques to delay grapevine ripening with emphasis on canopy management and we overviewed the effects of high temperatures on grape and wine quality. Some viticultural techniques such as severe shoot trimming, minimal pruning, late winter pruning and apical leaf removal may delay grapevine ripening close to 15 days. Forcing regrowth is the most interesting technique since it allows to delay grape ripening at least of two months which can be essential in warm grapevine production areas.

Keywords: apical leaf removal; climate change; delaying ripening; forcing regrowth; late pruning; minimal pruning; severe trimming

1. Introduction

Viticulture is one of the agricultural sectors of major economic importance in Mediterranean climate zones (Costa et al., 2016). Environmental conditions such as soil and climate are determinant key factors affecting grapevine productivity, grape and wine quality and the sensory attributes of wines (van Leeuwen & Seguin, 2006). These characteristics strongly impact the sale price of the grape and with it, winegrowers incomes (Gutiérrez-Gamboa & Moreno-Simunovic, 2019).

Several scientific manuscripts have reported the impacts of climate change on viticulture sector and the first reports began to be published at the beginning of the XXI century (Easterling, Meehl, Parmesan, Changnon, Karl, & Mearns, 2000; Parmesan & Yohe, 2003). During this decade, the most cited articles on the subject were published, especially those published by Schultz (2000) and Jones, White, Cooper and Storchmann (2005), who found that growing season mean temperatures from 1950 to 1999 have increased in most of the viticultural regions.

Early phenological timings and shortening of grapevine growing season have been reported by several authors due to the current global warming. (Fraga et al., 2016; García de Cortázar-Atauri et al., 2017; Jones & Davis, 2000; Sadras & Moran, 2012; Webb, Whetton, & Barlow, 2011). These changes occur during the warmer period of the grapevine growing and entails to detrimental impacts on grape and wine quality, thus threatening the wine typicity of a given region and ultimately its viticultural suitability (Compés & Sotés, 2018).

Climate change has also affected grapevine variety distribution in different wine growing regions (Alonso & O'Neill, 2011; Battaglini, Barbeau, Bindi, & Badeck, 2009; Mozell & Thachn, 2014). Some regions such as Northern Europe may benefit from climate change since it has been demonstrated that the cultivation of grapevine varieties such as Merlot and Cabernet Franc could be performed at 50º Latitude North (Moriondo et al., 2013). The increase in the average temperature of the growing season from 13.7 ºC (1989-2003) to 14 ºC (2004-2013) has provided to the United Kingdom an interesting opportunity for the grapevine cultivation not only for the production of sparkling wines but also for white wines and potentially red wines. Currently, the vineyard surface in the United Kingdom has increased by 148 % from 2004 to 2013 (Nesbitt, 2016).

Many current traditional wine growing regions have been or will be affected by climate change (Jones et al., 2005). To achieve good quality wines is important that the berry ripening period occurs under temperate temperatures (Gutiérrez-Gamboa, Carrasco-Quiroz, Martínez-Gil, Pérez-Álvarez, Garde-Cerdán, & Moreno-Simunovic, 2018; Mira de Orduña, 2010). The best conditions for wine production are generally achieve at the moment in which the grapes reach a complete ripening when temperatures are still high (25 to 30 ºC) enough to obtain an optimal maturity, but not too high (> 30 ºC) (van Leeuwen & Seguin, 2006; van Leeuwen et al., 2019a). This allows to preserve a balanced level of sugar to acid ratio in the grape juice, low astringency and bitterness in grapes and wines, and a floral and fruity aromatic expression in the wines (van Leeuwen & Seguin, 2006; van Leeuwen et al., 2019a).

As temperatures increase during growing season, the grapes tend to ripen earlier along its develop (Martínez-Gil, Gutiérrez-Gamboa, Garde-Cerdán, Pérez-Álvarez, & Moreno-Simunovic, 2018; van Leeuwen & Seguin, 2006). Due to this, winegrowers should to adapt to this difficult situation by delaying grapevine phenology, in order to reach the harvest in less warm conditions (van Leeuwen, Roby, & Ollat, 2019b). Certain viticultural techniques have been proposed by the experts such as the choose of late ripening varieties or clones, use of more vigorous rootstocks, increase the proportion of the use of autochthonous varieties, adaptation of training systems, irrigation or late pruning (Gutiérrez-Gamboa, Liu, & Pszczólkowski, 2020a; van Leeuwen et al., 2019b). However, these solutions are not enough to mitigate the effects of global warming in viticulture. Therefore, the aims of this review are: i) to analyze the effects of high temperatures on the grapevine, grape and wine; ii) to analyze the most promising viticultural techniques against the effects of high temperatures, with a special focus in those techniques of canopy management that produce a strong delay of berry maturation and iii) to propose research guidelines for future investigations.

2. Global warming incidence on the current viticulture

Grapevine productivity and fruit quality are the most important concerns in viticulture because they directly determine the profits of the viticulturists. Despite the fact that both variables depend on the genetic of the variety, it is widely known that environmental conditions and cultural practices alter yield components and fruit composition (Keller, 2020). Therefore, it is essential to gain a deep insight into the impacts of the global warming on grape yield and quality (Table 1).

2.1. Effects of high temperatures on grapevine ripening

Currently the viticulture has experienced a series of modifications due to the increase of temperatures, which has had direct impacts on grapevine ripening (Gutiérrez-Gamboa, Pérez-Donoso, Pou-Mir, Acevedo-Opazo, & Valdés-Gómez, 2019a; van Leeuwen & Darriet, 2016). Different authors worldwide have reported accelerated phenological stages for grapevines as well as, earlier dates of phenological events including harvest (Fraga et al., 2016; Jones et al., 2005; Ramos & Martínez de Toda, 2020; Schultz, 2000). Model outputs have predicted an increase in the average temperature of 2ºC for the next 50 years for global wine producer regions (Jones et al., 2005; Schultz, 2000). Predictions of advances from 8 to 11 days for budburst and from 16 to 24 days for veraison have been reported for the end of the 21st century for white grapevine varieties cultivated in Alsace (Duchêne, Huard, Dumas, Schneider, & Merdinoglu et al., 2010). A precocity towards the end of the 21st century of at least 40 days earlier than the current ones has been reported for each phenological stage in grapevines (Sgubin et al., 2018; van Leeuwen et al., 2019a).

Currently, grapevine budburst and anthesis take place 8-10 days earlier than to those occurred in 1950s, while veraison date advanced from 18 to 23 days for the same period in Rheingau (Germany) (Stock, Gerstengarbe, Kartschall, & Werner, 2005). In Alsace (France), from 1972 to 2002, all the grapevine phenological stages moved forward and the period between budburst and harvest shortened significantly (Duchêne & Schneider, 2005). In Bordeaux (France) harvest dates have moved forward by two weeks in the past 20 years (Jones & Davis, 2000). In Napa and Sonoma valleys (United States), grapevine budburst advanced by 18-24 days between 1951 and 1997 (Nemani et al., 2001). Even in the southern hemisphere, based on the model calculations, the harvest dates for Cabernet Sauvignon and Chardonnay grapes will be shifted forward by 2-3 weeks in most of the Australian wine regions in 2050, compared to 1990 (Webb, Whetton, & Barlow, 2007). The greatest consequence of the advance on grapevine phenological stages is that the grape ripening is taking place under warmer conditions than before.

2.2. Effects of high temperatures on grapevine yield

Grapevine yield depends of the number of buds per grapevine, the number of clusters per bud (bud fertility), the number of berries per cluster, and the berry weight (Keller, 2020). Number of buds per grapevine is manually determined by the pruning severity however, all the other yield components are dependent by the environment and genotype interactions (Dry, Longbottom, Mcloughlin, Johnson, & Collins, 2010; Petrie & Clingeleffer, 2005).

2.2.1. Floral initiation

Grapevine flowers formation from the inflorescence primordia occurs at the time of bud burst in the next season (Vasconcelos, Greven, Winefield, Trought, & Raw, 2009). To maximize number of inflorescence primordia are necessary warm temperatures, high irradiance, nitrogen stress and an adequate supply of water (Guilpart, Metay, & Gary, 2014; May, 2000; Vasconcelos et al., 2009). Recently, it was reported that bud fruitfulness was mostly influenced by bud light interception, while the size of inflorescence primordia was positively correlated with shoot growth capacity and the carbohydrate level of buds (Collins, Wang, Lesefko, De Bei, & Fuentes, 2020). However, extreme high temperatures (> 35 ºC) during the floral initiation phase could make the buds unfruitful (Keller, 2020; Zheng, del Galdo, García, Balda, & Martínez de Toda, 2017a). High daytime temperatures of 35-40°C during flowering had a detrimental effect in fruit set and ovule fertility and resulted in fewer berries per cluster (Ebadi, Coombe, & May, 1995; Greer & Weston, 2010). Flowering and fruit set are strongly influenced by temperature changes and extreme temperatures (>35°C) during the flowering period detrimentally affect fruit set (–48 to 38 %) and final yield (–27 %) (Pagay & Collins, 2017).

2.2.2. Fruit set

The flower differentiation and the percentage of fruit set determine the number of berries per cluster and the availability of carbohydrate is the determining key of these factors (Intrigliolo, Mirás-Avalos, & Lakso, 2018; Lebon, Wojnarowiez, Holzapfel, Fontaine, Vaillant-Gaveau, & Clément, 2008). Similar to the loss of inflorescences before flowering, high temperatures could cause shoots to grow rapidly and to compete fiercely with the flower formation for the carbohydrate supply, resulting in flower abortion (Bowen & Kliewer, 1990; Keller, 2020). Manipulation of carbon supply caused reductions in fruit set in Concord and Riesling varieties and they were most sensitive to these reductions during the period between 5 and 12 days after flowering (Intrigliolo et al., 2018). Berry size of grapes that set after bloom is determined by the number of cell divisions before and after bloom, the extend of these cells and the degree of weight loss (Coombe, 1976; Keller, 2020). Both low (< 15 ºC) and high temperatures (> 35 ºC) may reduce cell division before the lag phase of berry growth and by consequence to limit berry size (Cohen, Tarara, Gambetta, Matthews, & Kennedy, 2012; Keller, 2020).

2.2.3. Berry size

During the second phase of grape berry development, a rapid loss of berry weight can be registered, causing berry shrinkage phenomena (Gutiérrez-Gamboa, Pardo, & Moreno-Simunovic, 2019b). The softening and deformability of fruit caused by this disorder are due to breakdown of cortex parenchyma cell walls, the latter which are mainly composed of cellulose, hemicellulose and pectin (Hunter et al., 2018). Berry shrinkage phenomena has been described in Syrah and Merlot grapevine varieties (Carlomagno, Novello, Ferrandino, Genre, Lovisolo, & Hunter, 2018; Carrasco-Quiroz, Martínez-Gil, Gutiérrez-Gamboa, & Moreno-Simunovic, 2020; McCarthy, 1997; Rogiers, Smith, White, Keller, Holzapfel, & Virgona, 2001; Rogiers, Greer, Hatfield, Orchard, & Keller, 2006; Šuklje, Zhang, Antalick, Clark, Deloire, & Schmidtke, 2016), where yield losses are estimated at around 25 % of the total production (Krasnow, Matthews, Smith, Benz, Weber, & Shackel, 2010; Rogiers et al., 2001). Heat events have strongly effects on berry ripening and they cause a high incidence of berry shrivel and sunburn (Greer & Weston, 2010). Shrinkage disorder is associated to berry dehydration and direct sun exposure of clusters so extreme temperatures can trigger its process (Carlomagno et al., 2018). However, specific mechanisms or events leading to berry shrinkage phenomena are not yet fully elucidated and research is continuing globally (Hunter et al., 2018).

2.2.4 CO_2 accumulation

Due to global warming, it is considered that the continuously rising temperatures and atmospheric CO_2 concentration will be likely to increase the canopy photosynthetic potential thus increasing the grapevine productivity (Palliotti, Tombesi, Silvestroni, Lanari, Gatti, & Poni, 2014; Schultz, 2000). Air temperatures exceeding 40 ºC for 14 days reduced photosynthesis close to 35 % while transpiration increased nearly threefold, which was explained by the increase in stomatal conductance (Greer & Weston, 2010). A higher atmospheric CO_2 concentration could improve the water-use efficiency (WUEc) of grapevines, which may benefit the yield in arid or semi-arid regions (Gutiérrez-Gamboa, et al., 2019a; Schultz, 2000). Recent researches conducted in free air carbon dioxide enrichment (FACE) systems reported significant effects of elevated CO_2 exposure to grapevines on some vegetative growth parameters, primary productivity, grapevine bud fertility, and yield potential (Santos et al., 2020). Elevated CO_2 stimulated growth, yield, stomatal conductance and transpiration in Riesling and Cabernet Sauvignon grapevines, while during berry development, elevated CO_2 resulted in higher single berry weight and did not affect fruit quality (Wohlfahrt, Tittmann, Schmidt, Rauhut, Honer, & Stoll, 2020a; Wohlfahrt, Tittmann, Schmidt, Rauhut, Honermeier, & Stoll, 2020b). These results evidenced a cultivar-dependence in the response of elevated CO_2 in terms of bud fruitfulness (Wohlfahrt, Collins, & Stoll, 2019). A higher WUEc (net CO_2 assimilation/stomatal conductance) may have critical implications for the future adaptation of non-irrigated viticulture against the increase of temperatures and the periods of rainfall deficit.

2.2.5. Spring frost risk

Recently, climate change influence on spring frost risk has been discussed controversially in the scientific literature (Santos et al., 2020). High temperatures in winter may be beneficial to grapevine productivity in cold viticulture regions because the risk of winter frost injury is getting lower (Rigby & Porporato, 2008). Spring frost damage occurs when the budburst is produced before the date in which the last frost event take place in the spring (Santos et al., 2020). Spring frost and budburst are projected to occur earlier in the growing season according to the model predictions of climate change in viticulture (Santos et al., 2020). Some reports showed that the last frost events will move to earlier dates at a faster rate than budburst and, hence, reduce spring frost risk in the future (Molitor, Caffarra, Sinigoj, Pertot, Hoffmann, & Junk, 2014; Santos et al., 2020), while other reports were inconsistent or predicted increased risks of spring frost damage in viticulture (Leolini, Moriondo, Fila, Costafreda-Aumedes, Ferrise, & Bindi, 2018; Molitor & Junk, 2019a; Mosedale, Wilson, & Maclean, 2015; Santos et al., 2020). On the whole, the global warming may lead to a higher yield but extreme weather conditions such as heatwaves, continuous drought and spring frost may result in a severe yield reduction.

2.3. Effects of high temperatures on grape and wine quality

Changes of berry composition evolve during ripening and are affected by cultural practices, environmental conditions and the grapevine genotype (Keller, 2020). Considering all the above-mentioned aspects it is necessary to get a good understanding of how the environmental factors could affect the synthesis of soluble solids, organic acids, and phenolic, nitrogenous and volatile compounds in grapes to perform a good choice of viticultural practices, that allow to mitigate the effects of global warming in the vineyard (Martinez de Toda, Garcia, & Balda, 2019).

2.3.1. Soluble solids

Grape sugar content accounts close to 90 % of soluble solids at harvest of which between 95 to 99 % of these sugars are present in the form of hexoses, glucose and fructose (Keller, 2020). Berry sugar accumulation depends on the import of sucrose from photosynthesizing leaves or woody storage organs via the phloem (Davies, Boss, Gerós, Lecourieux, & Delrot, 2012). Then, under the action of invertases, hexoses start to accumulate rapidly in berries at veraison (Gerós, Chaves, & Delrot, 2012; Keller, 2020). Temperatures play an important role on berry sugar accumulation and the optimum temperature range for the photosynthesis of grape leaves are between 25 and 35 ºC (Hochberg, Batushansky, Degu, Rachmilevitch, & Fait, 2015). High temperatures modify primary and secondary fruit metabolisms, desynchronizing sugar and organic acid metabolisms and delaying sugar and polyphenol accumulation during ripening (Torregrosa et al., 2017). Thus, high temperatures usually lead to an acceleration of sugar accumulation in berries except in extremely hot regions, where temperatures exceed the photosynthetic optimum during a considerable part of the growing season (Gutiérrez-Gamboa & Moreno-Simunovic, 2019; van Leeuwen & Seguin, 2006). Differently from what may seem obvious, despite the fact that high temperatures accelerate grape ripening, the effects on final sugar content are relatively small (Coombe, Bovio, & Schneider, 1987). In this way, for a given variety, the maximum sugar content has a limit and it is possible that grape berries not achieve a soluble solids concentration above 25 ºBrix unless the berry dehydration and shrinkage occur (Keller, 2020).

Cool climate wine regions may benefit from the global warming since grapes could obtain an optimum technology maturity (Anderson, 2017). Due to the increase of temperatures, in most of the wine regions across the world, it will be easier to produce wines with a high alcohol content (Jones et al., 2005). Nowadays, there is a new trend in which consumers prefer wines with a moderate or low alcohol content due to health reasons (Palliotti et al., 2014). Due to this, some wine regions have switched from occasional addition of sugars to the must to partial sugar or alcohol removal by physical methods such as reverse osmosis (Gil et al., 2013; Pham, Stockdale, Wollan, Jeffery, & Wilkinson, 2019; Delrot et al., 2020).

A serious problem in the current viticulture is that the increase in alcoholic level may alter the inherent style of wines in some winegrowing regions (Santos et al., 2020). "Txakoli" is characterized as a very fresh white wine in Vizcaya, Guipúzcoa and Álava (Spain). However, global warming has led to an increase in the amount of alcohol degree of these wines in the last years close to 13 %, which is totally inadmissible to the initial concept of "Txakoli" (Hidalgo, 2011). Ice wines are traditional premium wines from many cool climate regions that are produced when grape berries are exposed in fall or early winter to a frost event bellow to −7 °C and are pressed in the frozen status (Molitor & Junk, 2019b). For this purpose, water in the grapes is in the form of ice crystals and the juice is then concentrated, leading to the production of these unique dessert wines (Molitor

& Junk, 2019b). However, these conditions are expected to become increasingly rare in the future and therefore, the ice wine production is jeopardized (Santos et al., 2020).

2.3.2. Organic acids

Organic acids are involved in the primary metabolic pathways as energy production and amino acid synthesis and also participate in the response to osmotic stress and discouraging predation of fruit (Waterhouse, Sacks, & Jeffery, 2016). Organic acids are the main determinant of pH affecting appearance, microbial and chemical stability in wines and they have direct effects on taste, mainly sourness and also the mask the sweet taste (Jackson, 2017; Waterhouse et al., 2016). The major organic acids in grapes are tartaric and malic acids while others such as acetic, citric, lactic and succinic acids may be present in the grapes at low concentrations (Mato, Suárez-Luque, & Huidobro, 2005). Most organic acids are accumulated early in the berry development. Tartaric acid is mainly synthesized between bloom and veraison in leaves and in the pulp of berries, and its synthesis in leaves mainly occurs when the leaves are expanding (Cholet et al., 2016). Deficit irrigation before veraison may limit tartrate accumulation while after veraison, tartrate content per berry is usually stable due to its insensitiveness to light and temperature, while the decrease in tartrate concentration is mainly attributed to the dilution effect caused by berry expansion (Duchêne et al., 2020; Mira de Orduña, 2010). Malic acid accumulation in grapes mostly occurs before veraison as well, and the optimum temperature range for the accumulation is between 20-25 ºC; but when temperatures are more than 38 ºC, the malic acid synthesis declines greatly (Keller, 2020). Carbon source for respiration in the berries after veraison is changed from glucose to malate (Keller, 2020). Heating throughout veraison and ripening stages reduced grape malate content, consistent with effects typically seen in warm seasons (Sweetman, Sadras, Hancock, Soole, & Ford, 2014). However, when minimum temperatures raised by 4–6 °C, malate content in grapes was not reduced, suggesting that the regulation of malate metabolism differs during the day and night (Sweetman et al., 2014). Temperature desynchronizes sugar and organic acid metabolism in grapevine ripening and remodels their transcriptome (Rienth, Torregrosa, Sarah, Ardisson, Brillouet, & Romieu, 2016).

During the ripening phase, water supply or high temperatures could increase K^+ concentration in grapes, thus increasing pH (Mira de Orduña, 2010). K^+ is the most abundant cation in grapes and is essential for plant signaling, osmoregulation, maintaining cation-anion balance, cytoplasmic pH regulation, enzyme activation and protein and starch synthesis (Rogiers, Coetzee, Walker, Deloire, & Tyerman, 2017). High K^+ and pH may alter wine color, microbiological stability and fermentation process (Keller, 2020). In warm viticultural regions, the increase of temperatures may result in grapes with low levels of titratable acid, and high levels of pH and K^+. Due to this, the winemaking process may become more expensive because low-acid grape juice requires the addition of tartaric acid to balance the high sugar level and to enhance microbial stability (Keller, 2020).

2.3.3. Phenolic compounds

2.3.3.1. Anthocyanins

Anthocyanidins are responsible for the red color in grapes and red wines and contribute to their astringency and bitterness (Gombau et al., 2019). Anthocyanins are synthesized in the cytoplasm and accumulate in the vacuoles, where they are stored as colored coalescences called anthocyanin vacuolar inclusions (Flamini, Mattivi, De Rosso, Arapitsas, & Bavaresco, 2013). The enzyme UDP-glucose: flavonoid 3-*O*-glucosyl transferase (UFGT) catalyzes the glycosylation of both anthocyanidins and flavonols (Ford, Boss, & Hæj, 1998). In red grapes, anthocyanin accumulation begins at veraison, along with the activation of the UFGT enzyme (Downey, Dokoozlian, & Krstic, 2006). Firstly, only glycosides from dihydric anthocyanins, such as cyanidin and peonidin are accumulated, followed by trihydroxylated anthocyanins, such as delphinidin, petunidin, and malvidin (Downey et al., 2006).

Grapevines cultivated in warm sites produce grapes with a high content of soluble solids and certain phenolic compounds such as anthocyanins and flavonols, while grapevines cultivated in cooler sites, produce grapes with a high content of flavanols and hydroxycinnamic acids (Gutiérrez-Gamboa & Moreno-Simunovic, 2019; Martínez-Gil et al., 2018). The optimum range for anthocyanin accumulation in berries is 17 to 26 ºC and low temperatures, particularly, low night temperature, enhance coloration in red grapes (Pirie, 1977; Kliewer & Torres, 1972). Cluster exposure to high temperature and radiation may increase anthocyanins, flavonols, and flavanols synthesis in grapes due to the rise in the activity of the phenylalanine ammonium lyase (PAL) enzyme (Flamini et al., 2013). However, temperatures above 35 ºC produce an increase in respiration rate and a decrease in photosynthesis in grapevines, which leads to a decrease in the production of sugars and the degradation and inhibition of the accumulation of certain secondary metabolites, especially anthocyanins (He et al., 2010). On the other hand, high levels of UV-B radiation have been shown to increase anthocyanin accumulation, total polyphenol index and stilbene content in grape skin (Berli, D'Angelo, Cavagnaro, Bottini, Wuilloud, & Silva, 2008). Likewise, exposure to UV radiation induces the accumulation of stilbenes in grapes through the induction of the expression of the stilbene synthase (STS) (Petit et al., 2009).

High temperatures could delay the onset of anthocyanin accumulation, leading to low anthocyanin concentration in grapes at harvest (Sadras & Monzon, 2006). Moderate sunlight exposure is necessary for anthocyanins biosynthesis (He et al., 2010). However, intense sunlight could cause sunburn in exposed berries, inhibiting the color development, especially grapevines cultivated in hot viticultural regions (Chorti, Guidoni, Ferrandino, & Novello, 2010; van Leeuwen & Darriet, 2016). Due to global warming, the sugar accumulation is more and more rapid and berry ripening takes place during a warmer period of the season than in the past decades. Therefore, anthocyanins concentration in grapes not reach its optimum value at the same moment that technological maturity does it. Moreover, since the extractability of anthocyanins increases along ripening, a shortened ripening period may cause a reduction in the extractability of anthocyanins at harvest (Allegro, Pastore, Valentini, Muzzi, & Filippetti, 2016). This phenomena is well known as "anthocyanin sugars decoupling" (Martínez de Toda & Balda, 2015; Sadras & Monzon, 2006). This decoupling may bring to wine industry two devastating consequences: i) if grapes are harvested at the conventional technological maturity level, the grape quality may not be the optimum in terms of phenolic compounds and their related sensory attributes; ii) if the winegrowers postpone the harvest date in order to reach higher concentrations of anthocyanins, the berries may become dehydrated, and achieve an extremely high total soluble solids content and by consequence, to produce wines with high alcoholic content. Moreover, this decoupling has been reported for other relevant metabolites, such as organic acids, proanthocyanidins, amino acids and volatile compounds (Bonada, Jeffery, Petrie, Moran, & Sadras, 2015; Cohen et al., 2012; Delrot et al., 2020; Etienne, Génard, Lobit, Mbeguié-A-Mbéguié, & Bugaud, 2013; Gutiérrez-Gamboa et al., 2018).

2.3.3.2. Flavanols

Grape flavanols or commonly called tannins are synthesized in the skins and seeds during the early stages of berry development (Keller, 2020). Tannins are considered responsible for astringency and bitterness and may form copigmentation complexes with anthocyanins, enhancing wine color (Li & Duan, 2019). Seed flavanols synthesis occurs after fruiting and reaches its maximum level close to veraison, while the content of the skin flavanols is high at flowering and its accumulation continues from the fruit set up to one or two weeks after veraison (Downey et al., 2006). The polymerization of both seed tannins and skin tannins increases at veraison (Downey, Harvey, & Robinson, 2003). Seed tannins bind strongly to cell walls, so their extractability declines gradually along ripening (Cadot, Miñana-Castelló, & Chevalier, 2006). Based on this, "phenolic maturity" comprises the accumulation and extractability of anthocyanins, the polymerizations of tannins and the reduction extractability of seed tannins, which occurred at harvest. Clusters exposed to sunlight may enhance flavanol accumulation in the skin and increase the length of polymeric flavanols (Downey et al., 2006). Possibly, the biosynthesis of flavanols in grapes increase in relation to the increase in temperatures (Keller, 2020). However, in warm viticultural regions, as berry ripening is occurring under increasingly hot conditions, the period between veraison and harvest probably becomes shorter thus, there is less time for the synthesis of flavanols. On the contrary, in cool viticultural regions, the increasing temperatures may help to enhance the wine quality due to the increase in the accumulation of flavanols in grapes.

2.3.3.3. Flavonols

Flavonols are mainly synthesized in the skins of berries, where they appear to function as photoprotectors (Flamini et al., 2013). Grape flavonol concentration is increased by high exposure to sunlight before the veraison period, which is induced by the transcription factor genes of the MYB family (Matus et al., 2009). Light modulates the expression of flavonol synthase (VvFLS), a key flavonol structural gene, and of

VvMYBF1, a transcriptional regulator of flavonoid synthesis (Koyama, Ikeda, Poudel, & Goto-Yamamoto, 2012; Teixeira, Eiras-Dias, Castellarin, & Gerós, 2013). In this sense, flavanols act as natural UV radiation protectors in grape skins because they strongly absorb UV-A and UV-B wavelengths (Flamini et al., 2013). The lack of expression of the enzyme flavonoid 3′,5′-hydroxylase in white grapes limits the exclusive presence of flavonols to quercetin, kaempferol and isorhamnetin derivatives, while red grapes also contain myricetin, laricitrin and syringetin derivatives (Mattivi, Guzzon, Vrhovsek, Stefanini, & Velasco, 2006; Castillo-Muñoz, Gómez-Alonso, García-Romero, & Hermosín-Gutiérrez, 2010; Flamini et al., 2013). The main flavonol of most white varieties is quercetin, which represents more than 70 % of total flavanols (Castillo-Muñoz et al., 2010), while, in most of the red varieties, myricetin is the most abundant flavonol (Mattivi et al., 2006; Flamini et al., 2013). In Chardonnay, water stress increased the content of flavonols and decreased the expression of genes involved in the biosynthesis of stilbene precursors (Teixeira, Eiras-Dias, Castellarin, & Gerós, 2013). Higher altitude cultivation widely promoted the production of anthocyanins and flavonols, particularly cyanidin-type anthocyanins and quercetin-type flavonols from the flavonoid 3'-hydroxylase (F3'H) branch of the flavonoid biosynthetic pathway (Xing, He, Xiao, Duan, & Pan, 2015). Notably, the altitude may produce a decline in the vineyard temperature due to adiabatic cooling of the air which allows a decrease between 0.60 – 0.65 ºC every 100 m of altitude (Pszczólkowski, Villena, & Carbonneau, 2010).

2.3.4. Nitrogen compounds

Proline and arginine are usually the most abundant amino acids synthetized throughout ripening by the grapevines varieties (Bell & Henschke, 2005; Stines, Grubb, Gockowiak, Henschke, Hoj, & Heeswijck, 2000). Arginine is one of the most important nitrogen sources during the alcoholic fermentations since yeast can easily assimilate it, while proline is the only amino acid that is not assimilable by yeast under anaerobic growth conditions (Gobert et al., 2017; Varela, Pizarro, & Agosin, 2004). Based on this, proline to arginine ratio was reported to determine the proportion of non-assimilable (proline) to assimilable (arginine) nitrogen, providing a useful index of the likely nutritional value of the must from a particular variety to yeast metabolism (Bell & Henschke, 2005). At low nitrogen content in musts, stuck and sluggish fermentations may occur at the wine cellar, leading to wine spoilage and the production of undesirable volatile compounds such as hydrogen sulfide, giving to the wines rotten egg and sewage aromas (Ugliano, Kolouchova, & Henschke, 2011).

Glutamine and glutamate can be converted to many other amino acids in grapevines by enzymatic reactions (Keller, 2020). Under favorable conditions, grapevines convert surplus glutamine to arginine, while during drought stress glutamate may be converted in proline (Gutiérrez-Gamboa, Alañón-Sánchez, Mateluna-Cuadra, & Verdugo-Vásquez, 2020b; Keller, 2020). Proline accumulation allows grapevines to lower their hydric water potential while maintaining turgor pressure during periods of drought (Liang, Zhang, Natarajan, & Becker, 2013). Hydric stress in Cabernet Sauvignon grapevines resulted in an increase in soluble solids content in grapes and in the proline levels in grapes and wines (Ju et al., 2018). Significantly high proline levels were accumulated in grapes in response to drought in Chardonnay and Syrah grapevines (Canoura, Kelly, & Ojeda, 2018). Differentially expressed genes (DEGs) were significantly up-regulated functioning in the proline biosynthesis and metabolism pathway, in a drought treatment compared to control (Haider et al., 2017). Studies have reported that proline metabolism influences signaling pathways by increasing reactive oxygen species (ROS) formation in the mitochondria via the electron transport chain

(Liang et al., 2013). Enhanced ROS production due to proline metabolism has been implicated in the hypersensitive response in plants (Liang et al., 2013). On the other hand, a high-water availability and a low reference evapotranspiration in grapevines resulted in a high content of several amino acids in grapes with the exception of proline which had an opposite effect (Gutiérrez-Gamboa, Garde-Cerdán, Rubio-Bretón, & Pérez-Álvarez, 2020c). Global warming in the current viticulture provokes a low synthesis of several amino acids in grapevines, together with a high synthesis of proline due to drought conditions. This may result in stuck and sluggish fermentations in the winery since proline is not metabolized by yeast. Therefore, an accurately prevention and diagnostic of stuck and sluggish fermentations must be carried out at the wine cellar since the resumption of fermentations is a long and expensive process.

Higher alcohols and esters production is mainly related to amino acid metabolism in the yeast cell and their concentration depends of yeast assimilable content (YAN) of the must. (Bell & Henschke, 2005). Higher alcohols content shows an initial increase at low levels of YAN and tends to decrease after a YAN concentration higher than 200-300 mg N/L (Ugliano, Henschke, Herderich, & Pretorius, 2007). The production of ethyl esters, as well as of acetate esters, including ethyl acetates, is generally increased when YAN raise up higher than 300 mg N/L (Ugliano et al., 2007). High temperatures may decrease the synthesis of amino acids in grapes compared to cool temperatures during the season (Gutiérrez-Gamboa et al., 2018, 2020c). This could result in the production of wines with high levels of higher alcohols, which can be detrimental to the aromatic quality of the wines. Certain studies have reported that higher alcohols can significantly suppress the strawberry, dairy, fruity, coconut, wood and vanilla aroma of wines (de la Fuente-Blanco, Sáenz-Navajas, & Ferreira, 2016). In this sense, a higher alcohol content of 299 mg/L in model wines suppressed the fruity aroma of young red wines, while a higher alcohol content of 281 mg/L suppressed the oak aroma of aged wines (de la Fuente-Blanco, Sáenz-Navajas, & Ferreira, 2017). In addition, the presence of high content of higher alcohols in model wines caused a significant decrease in the preference of wines by a sensory panel carried out by experts (de la Fuente-Blanco et al., 2017). Therefore, global warming can also have detrimental effects on the aromatic quality of wine.

2.3.5. Volatile compounds

Grape aroma is composed by a wide range of volatile compounds, belonging to different chemical groups (González-Barreiro, Rial-Otero, Cancho-Grande, & Simal-Gándara, 2015). Terpenoids, C_{13} norisoprenoids, ethyl and acetate esters, benzenoid compounds, thiols, C6 compounds and alcohols make up the varietal wine aroma (Ganss, Kirsch, Winterhalter, Fischer, & Schmarr, 2011). These compounds are distributed in both the flesh and the skin of the berry, though mostly in the latter and their concentration increases through berry maturity (González-Barreiro et al., 2015). Terpenoids and C_{13} norisoprenoids are the most important varietal volatile compounds found in grapes and contribute to wines with floral and fruity aromas (González-Barreiro et al., 2015).

2.3.5.1. Terpenoids

Grape volatile terpenoids consist of monoterpenes, sesquiterpenes and triterpenes and 80-90 % of them are present in glycosylated form in grapes, which can be released during wine making or wine aging (Bönisch et al., 2014). Grapevine varieties can be classified by their concentration of terpenes in Muscat varieties, whose free terpenes concentration reach 6 mg/L; semi-Muscat or non-Muscat varieties whose free terpenes concentration varies between 1 and 4 mg/L and, neutral varieties, in which the concentration of free terpenes is less than 1 mg/L (de Torres, Schumacher, Alañón, Pérez-

Coello, & Díaz-Maroto, 2015; Marais, 2017). Certain enzymes such as 1-deoxy-D-xylulose-5-phosphate reductoisomerase (DXR), 1-deoxy-D-xylulose-5-phosphate synthase (DXS) and terpene synthases (TPS) are the key enzymes for terpenoid biosynthesis (Schwab, Davidovich-Rikanati, & Lewinsohn, 2008; Zeng et al., 2016). Optimum temperature range for the synthesis of terpenoids in grapes is close to 10 ºC and 20 ºC (Marais, 2017). Terpenoid content may be negatively correlated with the average daily maximum temperature during ripening probably because terpenes are loss by volatilization (Marais, 2017). Contrary to this, it has reported that the optimum temperature for DXS activity was at 37 °C (Battilana et al., 2011). Constitutive expression of DXS enzyme increase the expression of alkaloid terpenes and essential oil constituents such as cineole, linalool and *α*-terpineol (Muñoz-Bertomeu, Arrillaga, Ros, & Segura, 2006; Peebles, Sander, Hughes, Peacock, Shanks, & San, 2011). In this way, monoterpenes can enhance the resistance of grapevines to heat stress and thus, their exposure to heat may improve terpenoid emission as defense mechanism (Vickers, Gershenzon, Lerdau, & Loreto, 2009).

2.3.5.2. C_{13} norisoprenoids

C_{13} norisoprenoids derive from the biodegradation of carotenoids such as *ß*-carotene and lutein and contribute to floral and fruity attributes to wines (Keller, 2020). The most important C_{13} norisoprenoids that are present in grapes and wine are *ß*-damascenone, 1,1,6, -trimethyl-1,2-dihydronaphthalene (TDN), vitispirane and *ß*-ionone (Mendes-Pinto, 2009). These compounds contribute significantly to the varietal aroma of certain grapevine varieties such as Chardonnay, Chenin Blanc, Semillon, Sauvignon Blanc, Cabernet Sauvignon and Syrah (Bindon, Dry, & Loveys, 2007; González-Barreiro et al., 2015). VVCCD1 genes are involved in the formation of carotenoid dioxygenases

(CCD) (Schwab et al., 2008). These are the key enzymes responsible for the specific oxidative degradation of a wide range of carotenoids that allow the formation of C_{13} norisoprenoids in grapes (Mendes-Pinto, 2009). High temperatures promote post-veraison carotenoid degradation, and temperature threshold could be possibly higher than 30 ºC (Hickey, Kwasniewski, & Wolf, 2018). In addition, both cold (20 ºC) and heat stress (38 ºC) allowed to increase the expression of gene CCD (Scherzinger & Al-Babili, 2008).

2.3.5.3. C6 compounds

C6 compounds also contribute to grape varietal aroma and its content is abundant in various aromatically neutral varieties (González-Barreiro et al., 2015). Generally, C6 compounds are absent in berries and other intact plant tissues and they are formed after mechanical damage by enzymatic oxidation of polyunsaturated fatty acids (Waterhouse et al., 2016). These compounds are responsible for the herbaceous aromas of grapes and wine, and in general, are in greater concentration in unripe grapes (Waterhouse et al., 2016). C6 compounds derived from cell membrane lipids through the lipoxygenase (LOX) pathway (Podolyan, White, Jordan, & Winefield, 2010). This pathway allows the hexanal formation from linoleic acid hydroperoxide, and the synthesis of (Z)-3-hexenal and (E)-2-hexenal from linolenic acid hydroperoxide, which occurs through the hydroperoxide lyase (HPL) (Oliveira, Faria, Sá, Barros, & Araújo, 2006). Finally, the alcohol dehydrogenase (ADH) enzyme reduces the aldehydes to their corresponding alcohols found in grapes, such as 1-hexanol, (Z)-3-hexenol and (E)-2-hexenol (Oliveira et al., 2006). Regarding the effects of temperatures on C6 compounds synthesis, it has reported that the two recombinant LOXs reached the maximum enzymatic activity at 25 °C (Podolyan et al., 2010).

2.3.5.4. Methoxypyrazines

Methoxypyrazines are a group of heterocyclic aromatic organic compounds that are present in green plant tissues and contribute to green, vegetal and herbaceous character of grapes and wines (Gutiérrez-Gamboa et al., 2020a). Methoxypyrazines synthesis begin with the condensation of ammonia with leucine or valine and glyoxal to form a 3-alkyl-2(1H)-pyrazin-2-one and its tautomer 3-alkyl-2-hydroxypyrazine (Harris, Ryona, & Sacks, 2012). Several environmental factors such as cluster shading, water availability and nitrogen fertilization can affect the accumulation of IBMP in grapes. Basal leaf removal performed at 10 to 40 days after anthesis may to reduced IBMP synthesis in grapes (Scheiner et al., 2010). Cluster shading carried out since veraison, using pieces of sackcloth, resulted in wines with lower IBPM concentration than the sun exposed clusters (Sala, Busto, Guasch, & Zamora, 2004). The wines produced from goblet-trained grapevines contained lower IBMP concentration than the ones from bilateral cordon trained grapevines (Sala et al., 2004). IBMP concentration analyzed at 2 weeks before veraison was highly correlated to its levels at harvest, suggesting that light exposure conditions, mostly influence IBMP accumulation, but not IBMP degradation (Ryona, Pan, Intrigliolo, Lakso, & Sacks, 2008). Global warming may lead to wines with low content of IBMP, which could be beneficial for cool viticultural climates since the wines produced from Sauvignon Blanc or other related cultivars could have less herbaceous character.

2.3.5.5. Volatile thiols

Volatile thiols such as 4-mercapto-4-methylpentan-2-one (4MMP, 1), 3-mercaptohexyl acetate (3MHA, 2), and 3-mercaptohexan-1-ol (3MH, 3) are important sulfur compounds involved in the aromatic profile of Sauvignon Blanc wines and in other white and red varieties such as Colombard, Chenin, Gewürztraminer, Semillon, Petit

Manseng, Arvine, Merlot, and Cabernet Sauvignon (Pons et al., 2017). These compounds belong to the class of varietal aromas because they result from the cleavage of odorless precursors present in grapes or musts by yeast during alcoholic fermentation (Roland, Schneider, Razungles, & Cavelier, 2011). Biosynthesis of volatile thiol precursors has been related to moderate water deficit since water deficit leading to shoot growth cessation and the accumulation of secondary metabolites in the berry (Pons et al., 2017). Severe water deficit affects berry ripening dynamic and leads to a lowering of volatile thiol precursor levels in grapes (Peyrot des Gachons et al., 2005; Pons et al., 2017). Šuklje et al. (2014) showed that UV radiation reduction significantly decreased the concentration of varietal thiols, while defoliation increased its concentration in Sauvignon Blanc wines produced in South Africa. Wu et al. (2019) reported that thiol 3-sulfanyl hexanol precursors exhibited lower content in the berries that were exposed by about +1.5°C in mean value compared to the berries collected from the control.

3. Viticultural practices techniques to mitigate the effects of global warming

Delaying grape berry ripening to moderate temperatures could be an interesting strategy to mitigate the effects of global warming in viticulture since the grape can mature under relatively cool conditions. As was discussed in previous sections, a cool ripening phase is favorable to keep the acidity, nitrogenous and aroma components of grapes, as well as their phenolic maturity. To our knowledge, three types of viticultural strategies could be used to delay the grape ripening (Palliotti et al., 2014). i) To change the establishment of the vineyards; ii) To change plant material and iii) To adapt different viticultural techniques (Fig. 1, 2). This strategy is the most interesting since it can be applied directly into the established vineyards. Certain viticultural techniques can be applied to delay grape ripening based on three basic principles: 1) Source to sink ratio limitations; 2) Managing carbon and nutritive competition between vegetative and reproductive growth; 3) Postponing all the phenological stages thus delaying ripening phase.

3.1. Source to sink ratio limitation techniques

During the growing season, leaves are considered the main source of carbohydrates since perennial organ cease exporting sugar between bunch closure and veraison (Weyand & Schultz, 2006). After shoot growth stop, ripening berries and maturing shoots are the main sinks of sugar within the grapevine though the starch is also accumulated in roots, dormant buds and perennial woods (Pellegrino, Clingeleffer, Cooley, & Walker, 2014). At veraison, defoliation induced an alteration in carbohydrate distribution in the whole grapevine, as revealed by decrease of starch content and an increase in soluble solids content (Vaillant-Gaveau et al., 2014). These modifications affect the number of inflorescences per clusters in the grapevine in the subsequent season (Vaillant-Gaveau et al., 2014). By contrast, fruit removal at veraison resulted in a significant increase of carbohydrate reserves in the grapevine, although the efficiency of sexual reproduction was not improved in the subsequent season (Vaillant-Gaveau et al., 2014).

Grape quality is mostly determined by grapevine total leaf area and by the percentage of total leaf surface exposed to sunlight and the initiation primordia (Kliewer & Dokoozlian, 2005). Optimum leaf to fruit ratio level to obtain a correct maturity in terms of total soluble solids, berry weight, and berry coloration at harvest, range from 0.6 to 1.2 m^2/kg for single canopy (Gutiérrez-Gamboa, Díaz-Galvéz, Verdugo-Vásquez, & Moreno-Simunovic, 2019c; Kliewer & Dokoozlian, 2005). A leaf to fruit ratio below 0.6 m^2/kg may lead to a lower capacity of soluble solids accumulation in grapes and thereby, slowing the ripening grape process (Keller, 2020). In the past vintages, the reduction in leaf to fruit ratios was always unwanted due to the risk of not being able to adequately ripen the grape. Currently, high temperatures are prolonged during growing season and even with a low leaf to fruit ratio, the grapes could also reach high levels of soluble solids (Palliotti et al., 2014). Therefore, grapes could ripen at a relatively cool weather condition modifying source to sink ratio. Since leaf to fruit ratio is determined by leaf area and crop load, we can reduce this ratio reducing leaf area through shoot trimming (Santesteban, Miranda, Urrestarazu, Loidi, & Royo, 2017; Zheng, García, Balda, & Martínez De Toda, 2017b) or performing a post-veraison apical defoliation to the cluster zone (Palliotti et al., 2013a). On the other hand, it is possible to modify this ratio altering yield through minimal pruning (Zheng et al., 2017a). Source limitation does not merely consist of the reduction of leaf area, it can be also realized by limiting the photosynthesis of well-functioning leaves. In this category, it is possible to apply shading nets (Chorti et al., 2010; Palliotti et al., 2014), as well as antitranspirant sprays (Gatti et al., 2016a).

3.1.1. Severe shoot trimming

Shoot topping (ST) is the cultural practice in which is removing the shoot tip, and also is called as tipping in the field of viticulture (Keller, 2020). ST involves both the removal of a major sink for nutrients (shoot tip) and a sharp reduction in active leaf area. ST stimulates one to several lateral shoots to develop below the cutting point (Wolf et al., 1986). Growth of lateral shoots is highly influenced by the timing of topping and by the edaphoclimatic conditions of the vineyard (Molitor et al., 2015; Palliotti et al., 2014). Lateral shoots may also develop even without shoot topping since the influence of apical dominance is reduced when the main shoot form approximately 18 to 20 leaves (Keller, 2020). Therefore, this competition may not be the main course of the delayed ripening and the direct reduction in photosynthesis activity also should be taken into account (Bondada, Covarrubias, Tessarin, Boliani, Marodin, & Rombolà, 2016; Herrera et al., 2015).

Conventionally, ST is mainly used for balancing grapevine shoot vigor, improving the canopy microclimate and providing feasibility for mechanized operation. However, ST could exert more effects depending on its application timing and intensity degree. ST leaving at 15 nodes before flowering did not affect the grapevine leaf to fruit ratio, yield components and must composition compared to untrimmed grapevines, while ST performed during flowering improved fruit set (Collins & Dry, 2009; Poni, Zamboni, Vercesi, Garavani, & Gatti, 2014). ST performed one week after bloom over the 9 to 10th node increased yield and total soluble solids, while reducing acidity for most of the experimental varieties (Cartechini, Palliotti, & Lungarotti, 2000).

Severe shoot trimming is a cultural technique in which is removing a large part of the shoot. A severe shoot trimming, cutting the shoot on the node located above the last bunch after fruit set, delayed the date of veraison about 20 days and at the same date of harvest, shoot trimming treatment had lower soluble solids (12% to 15 % reduction), pH (0.1 to 0.3) and total anthocyanin content (10 % reduction), and reduced bunch size and yield by around 10 % (Martínez de Toda, Sancha, & Balda, 2013). Post-veraison severe trimming could reduce sugar accumulation without affecting anthocyanin concentration (Herrera et al., 2015). Similarly, it has been showed that post-veraison (when soluble solids reached 15 ºBrix) severe trimming (10 nodes) decreased yield, total soluble solids, pH and cluster compactness without reducing total anthocyanins in grapes (Bondada et al., 2016).

Based on the above mentioned, severe trimming allows a delay in berry ripening, while early trimming (before fruit set) usually negatively affects the percentage of fruit set, impacting grapevine yield at harvested. A late severe trimming performed at post-veraison stages may cause an irreversible reduction in leaf area since fewer laterals could be produced and their aforementioned effects may occur only on the final stage of grape ripening. Therefore, we suggest that the optimal moment to perform a severe trimming is when the diameter of berry is close to 3 and 4 mm approximately, one week after berry set. If a severe shoot trimming performed at this moment, the development of the berry will be affected during the whole period of berry growth and thus, it would be maximally influenced by shoot trimming. It was reported that a severe shoot trimming performed one week after berry set delayed the harvest date of Grenache by two weeks, reaching similar total soluble solids and a higher anthocyanin concentration than the grapes harvested from untrimmed grapevines (Martínez de Toda, Sancha, & Balda, 2014). Mechanical trimming performed three weeks after fruit set significantly reduced leaf area and yield, resulting in higher water availability in trimmed plants. The whole ripening process was delayed by trimming: mid-veraison was delayed by about 5 days, and the delay in sugar accumulation and acid degradation was longer, while the differences were more marked in malic than in tartaric acid concentration (Santesteban et al., 2017). It is important to perform the trimming treatments without reducing the grapevine leaf area to fruit ratio below 0.50 m^2/kg to not negatively impact the grapevine capacity in the following season (Martínez de Toda et al., 2013).

3.1.2. Leaf removal

Leaf removal (LR) is a common viticultural practice used for canopy management in the vineyard. Generally, LR is carried out on basal leaves to improve cluster microclimate and the fruit composition and to decrease disease pressure (Mosetti et al., 2016; Smith & Centinari, 2019). After veraison, basal leaves are no longer the main source of photosynthetic product so the removal of them does not affect the ripening process (Poni, Intrieri, & Silvestroni, 1994). However, if all the leaves above the bunch zone are removed at veraison, total photosynthesis activity may decrease considerably because the leaves on the apical two-third of the canopy are the most functional ones at the moment and as a result, is produced a ripening delay (Palliotti et al., 2014).

Mechanical LR to the leaves located in the cluster apical zone, performed one month after veraison leaded to a remotion of 35 % of the total lea area and reduced leaf to fruit ratio by 36 %. This resulted in a delay in the accumulation of soluble solids in Sangiovese grapes by 2 weeks (Palliotti et al., 2013a). These authors suggested that leaves should be removed when the grapes reach a content of soluble solids close to 16–17 °Brix in order to delay effectively the sugar accumulation in grapes after LR. Similar results were reported for Sangiovese and Montepulciano grapes when a post-veraison mechanical LR was performed (Lanari, Lattanzi, Borghesi, Silvestroni, & Palliotti, 2013). Mechanical LR in the leaves located in apical cluster zone performed to grapevines when the grapes reached 12 °Brix, delayed technological ripening in Sangiovese grapes by more than one week than the grapes harvested from no defoliated grapevines, without affecting color and phenolics content in grapes (Palliotti et al., 2013a). However, a recent study highlighted that early defoliation reduces bud fertility in rainfed vineyards cultivated under Mediterranean climate conditions, suggesting that this practice should be avoided under those conditions (Lopes, Egipto, Zarrouk, & Chaves, 2020).

To our knowledge, severe shoot trimming is a simple practice to perform in the vineyard since it can be easily mechanized and may achieve similar effects to those exerted by apical leaf removal. The defoliation of the apical zone is very easy to mechanize, and due to the fact that the leaves to be removed are separated from the cluster zone, it allows a high-speed work of the machine, since there is no risk of causing damage to the exposed clusters. Basal LR will not be discussed in this section since it is not an interesting technique to delay the ripening of the fruits in grapevines.

3.1.3. Minimal pruning

As early as in the 1930s, Professor Albert Winkler from UC Davis conducted trials and he found that unpruned grapevines had greater ability to self-regulate. Research over 30 years in Australia showed that traditional severe pruning could be unnecessary in a wide number of viticultural regions since it may lead to low wine quality, generally associated with tbe development of shaded, tight bunches with large berries and difficulties in the pests and diseases management (Clingeleffer, 2010). Minimally pruned grapevines generally produce must with better organic acid composition, greater wine color and higher phenolics content than commonly pruned grapevines (Clingeleffer, 2010). In Spain, a long-term study about minimal pruning (MP) on Grenache grapevines showed that MP always produced higher yield than control grapevines growing under drought conditions of La Rioja (Spain) (Martínez de Toda & Sancha, 1998). In another long-term study, it was showed that MP increased yield by 56 % and reduced total soluble solids by 9 % compared to conventionally hand pruned (CHP) grapevines, delaying fruit maturity by 17 days (Zheng et al., 2017a). At similar total soluble solids, MP grapevines leaded to lower berry weight and cluster weight (24 and 57 %, respectively), and higher yield (51 %) than the grapes harvested from CHP grapevines (Zheng et al., 2017a). In addition, the musts from MP fruit had higher total anthocyanin concentration (+17 % in 2014 and +21 % in 2015) than CHP fruit (Zheng et al., 2017a). However, in this report, the improvement of total anthocyanins and wine color was more related to smaller berry size rather than the higher anthocyanin synthesis per unit area of berry skin.

Requiring low cost of time and money and producing high yield (Table 2), MP is a viticultural technique with great application prospect, especially when the climate is warmer since one of the most conspicuous effects of MP is to delay berry ripening providing a cooler ripening condition for the grape development, favoring the accumulation of anthocyanins, as well as keeping grape acidity. The MP basis fundamental is that the vegetative and reproductive cycles are delayed as a consequence of the high crop load. Thus, both the shoot and cluster number are considerably high, while their individual development is small, producing a very drastic change in grapevine physiology. This change may lead to a high degree of grapevine self-regulation that does not require a subsequent cluster thinning. This self-regulation capacity depends on the growing conditions, but if it is not achieved, it would be necessary to thin the clusters in the case of an excessively high production. This practice may be mechanically performed with a conventional grape harvester.

3.1.4. Shading nets

The most important factor for photosynthesis is the light, and the rate of photosynthesis depends on the quantity and quality of light (Keller, 2020). Shading net applications over the grapevine reduce the photosynthetic photon flux at the leaf surface available for photosynthetic process and thus, may to delay berry ripening (Novello & de Palma, 2013). These implications are probably explained because the shade nets can lower the temperature of the canopy and the fruit by up to 7 ºC (Lobos et al., 2015). In this sense, most of the studies about the effects of shading nets showed that excessive canopy shading might lead to poor berry quality, which is specifically expressed in high malate content and poor color in grapes and wines (Chorti et al., 2010; Palliotti et al., 2014). Leaf and cluster shading produced higher content of malate, potassium, and pH, while decreased the content of anthocyanins and total soluble phenols in fruits, without affecting sugar and potassium accumulation (Morrison & Noble, 1990). Cluster shading at veraison significantly reduced the anthocyanin accumulation due to the inhibition of the VvmybA1 gene, which is involved in anthocyanins synthesis (Jeong, Goto-Yamamoto, Kobayashi, & Esaka, 2004). In this way, UV-light barriers significantly reduced individual and total flavonol concentrations, while temperature had little or no effect on their concentrations (Spayd, Tarara, Mee, & Ferguson, 2002). Partial shading of the grapevine canopy at different phenological stages reduced yield losses and decreased the concentration of anthocyanins in grapes, which was related to the excessive radiation (Oliveira, Teles, Barbosa, Olazabal, & Queiroz, 2014). In another report, it was reported that shade cloths may efficiently palliate temperature spikes, especially in the last weeks before harvest, while transmitting enough radiation into the grape zone compared to uncovered grapes (Martínez-Lüscher, Chen, Brillante, & Kurtural, 2017).

Leaf shading may be an interesting strategy to face global warming in viticulture since it could slow down the ripening process, however, cluster shading could be an undesirable tool in viticulture since it may negatively affect the grape color. Despite the application of shading nets is a viable technique, several issues should be clarified for a better performance: 1) The relationship between timing/duration of shading and the degree of ripening delay to be obtained; 2) Better understanding of the shading effects of different grapevine sides; 3) The technical feasibility of artificial shading nets.

3.1.5. Mulching strategies

Mulch is a type of ground cover that may be made from several materials and it is placed on the soil vineyard surface for different reasons that include soil amelioration, improvement of canopy microclimate and weeds control (Ross, 2010; Ferrara et al., 2012). Related to global warming, vineyards with mulch tend suffer less thermal and water stresses (Fraga & Santos, 2018). Three main types of much may be applied in the vineyard such as organic (grape marc, compost, vine pruning, green waste, animal manure, mussel shells), living and inorganic (plastic, stones or glass) mulches (Ross, 2010).

Organic mulching is a sustainable practice widely used in horticultural crops and prevents soil erosion, retains soil moisture, improve some physico-chemical soil properties, regulates soil temperature and reduces evaporation (Medrano et al., 2015; Fraga & Santos, 2018). Organic mulching modifies soil reserves, minimizes soil evaporative losses and by consequent improves water filtration affecting directly water use efficiency (WUEc) (Pinamonti, 1998; Davies et al., 2011; Medrano et al., 2015). However, water conservation effect of straw mulches is more pronounced in the case of high-frequency irrigation and the cumulative water losses decreases with an increase in straw mulch thickness (Myburgh, 2013). In this way, rice-straw mulching combined with surface irrigation could be an interesting tool for maximizing water use efficiency (Zhang et al., 2014). On the other hand, it was reported that plastic-straw treatments may decrease root soil temperature up to 10 ºC compared to plastic treatments carried out in the soil surface (Holzapfel, Smith, Greer, Dunn, & Hardie, 2014). In this study, the increase in soil temperature leaded to an elevating root reserve mobilization and a shortening on grapevine reproductive development. Based on this, these authors suggested that not only air temperature may alter berry maturation under similar yield levels, but also the root environment can have important effects on reproductive development. Bavougian and Read (2018) reported that soil temperatures were mostly higher under mulches and lower under intra-row groundcovers compared to the use of glyphosate in Marquette grapevines cultivated in southeast Nebraska (USA). These authors did not report differences in mid-day photosynthetically active radiation (PAR) reflectance and mid-day grapevine water potential among the intra-row treatments. Therefore, these authors suggested that in vineyards where soil fertility and moisture are non-limiting, it is not necessary to maintain a bare soil strip.

Mulches elaborated from inorganic materials have a more physical effects on the vineyard soil and microclimate and may be used to alter radiation and heat (Ross, 2010). Reflective mulch utilization in vineyards cultivated under cool climate conditions lead to an enhancement of microclimate within the canopy, increasing sunlight reflected from the vineyard floor into the grapevine cluster zone, especially in early stages of the growing season allowing to improve yield without affecting berry chemical composition (Coventry, Fisher, Strommer, & Reynolds, 2005; Hostetler, Merwin, Brown, & Padilla-Zakour, 2007; Sandler, Brock, & Vanden Heuvel, 2009; Osrečak, Karoglan, & Kozina, 2016). In addition, under these conditions, polyethylene sleeves installed for seven weeks in the spring leaded to an advancement of budbreak by 3 to 6 days, bloom by approximately 10 days and fruit maturation by 7 to 26 days depending on the vineyard site (Bowen, Bogdanoff, & Estergaard, 2004). Contrary to this, color plastic mulching may be used as water stress mitigation strategy in warm climate viticulture, especially in anisohydric varieties that hold a low capacity for regulating transpiration. In this way, double color plastic mulch installed with a white color facing up and black on the inside facing the soil in a Syrah vineyard located in the Colchagua Valley (Chile) resulted in a 50% reduction in irrigation volume compared to the control (Gil et al., 2018). Fraga and Santos (2018) analyzed the impacts of mulching application under future climates, reporting that this strategy may indeed mitigate some detrimental climate change impacts on yield.

Some negative oucomes from the application of mulch in the vineyard exist because mulches can be expensive, messy, may brack down quackly limiting their usefulness, and may may obstruct mechanization of the vineyards (Ross, 2010). Therefore, it is important to choose the correct type of mulch and to match it carefully depending to the situation and towards the desired outcome (Ross, 2010).

3.1.6. Antitranspirant sprays

Stomata can control gas exchange in the leaf as well as the diffusion of CO_2 into plant, being essential for grapevine photosynthesis (Pou, Medrano, Tomàs, Martorell, Ribas-Carbó, & Flexas, 2012). Light, soil water deficit and vapor pressure deficit (VPD) are the most important environmental factors, affecting stomatal closure in crops cultivated in the Mediterranean area (Klein, 2014). The use of antitranspirants may reduce transpiration losses, conserving water loss and by consequence, preventing berry shrinkage (Das & Raghavendra, 1979). As grapevine stomatal conductance decreases, photosynthetic activity also decreases and the magnitude of this reduction depends on the isohydric or anisohydric behavior of the variety (Gutiérrez-Gamboa et al., 2019a). This is the physiological background of the use of antitranspirant sprays since their application to grapevines may reduce yield and delay grape ripening. In this way, a film-forming anti-transpirant applied to grapevines before flowering reduced yield and bunch compactness through smaller final berry size, improving the berry quality (Gatti et al., 2016a; Palliotti, Poni, Berrios, & Bernizzoni, 2010). Vapor Gard applied after veraison on Sangiovese grape leaves slowed significantly the accumulation of berry sugars without affecting the storage of carbohydrates and total nitrogen of shoots and roots (Palliotti et al., 2013b). Antitranspirant sprays application is considered as a flexible and easy-to-do technique since the desired effects can be obtained by adjusting dosage and timing and this operation does not require specific equipment or skills (Palliotti et al., 2014).

Particle film technology is a remarkable tool leading to a decrease in the environmental stress conditions for fruit production (Kok & Bal, 2018). This inexpensive technology similar in principle to the category of antitranspirants, involves the application of engineered clays, such as kaolin (an aluminum phyllosilicate, $Al_2Si_2O_5(OH)_4$), to cover leaves and fruits with thin nanoparticles films (Brillante et al., 2016). During the last decades, the application of kaolin-based sunscreens has become a common alternative to reduce sunburn in apple trees, where the color fruit development requires the direct sunlight exposition (Glenn, Prado, Erez, Mc Ferson, & Puterka, 2002). Recently, the adoption of this strategy in viticulture is increasing due to the effects of high temperatures and heat stress on canopy physiological process, sunburn, yield and berry quality (Frioni et al., 2019a, 2019b). The kaolin sunscreens work by reducing canopy temperature with an average of about 4 °C and up to 6 °C and it maintain a high the photosynthetic activity preventing irreversible photoinhibition phenomena and avoiding physiological damage with chlorotic and necrotic leaves, dehydrated berries and sunburn damages (Frioni et al., 2019b). Preliminary reports showed that article film applications to grapevines significantly reduced berry surface temperatures by 0.7 and 1.5 °C without affecting berry physico-chemical parameters at harvest (Smith, 2005; Lobos et al., 2015). Recent studies have shown different results on kaolin’s impacts on grapevine physiology. In this way, Brillante et al. (2016) showed that kaolin treatments increased grapevine intrinsic water use efficiency (WUEc) without affecting berry and bunch weight and quality. Dinis et al. (2018a) reported that kaolin-particle film suspension decreased leaf temperature by 18 % and minimal chlorophyll fluorescence and increased leaf water potential up to 41 % and maximum photochemical quantum efficiency of PSII compared to non-treated grapevines. In another report, Dinis et al. (2018b) showed that plants treated with kaolin showed higher values of stomatal conductance, net CO_2 assimilation rate and intrinsic water use efficiency probably due to a slight decrease in abscisic acid and an increase in indole-3-acetic acid. However, the effects of kaolin-based sunscreen on grapevine physiological responses may be affected by the plant water availability and thermal stress. Frioni et al. (2019a) reported that kaolin improved leaf cooling and slightly reduced photosynthetic and water loss rates in grapevines growing in absence of water stress, whereas kaolin treatments in grapevines growing under water deficit and upon re-watering leaded to a lack of photo-inhibition and the maintenance of leaf evaporative cooling, warranting an early recovery of leaf functions upon re-watering. Garrido, Serôdio, De Vos, Conde and Cunha (2019) reported that kaolin applied to Alvarinho leaves increased the photosynthetic activity of both exocarps and seed integuments of berries growing under low light conditions in the canopy probably due to the higher reflection of PAR to the inner zones.

Regarding the effects of kaolin applications to grapevines on grape and wine quality, some authors reported that foliar kaolin based-reflective films allowed to increase the content of anthocyanins in grapes improving anthocyanins to soluble solids ratio at fruit maturity without affecting grape and wine volatile composition (Ou, Du, Shellie, Ross, & Qian, 2010; Song, Shellie, Wang, & Qian, 2012; Shellie & King, 2013a, 2013b; Shellie, 2015; Kok & Bal, 2018). In this way, kaolin-based reflective film applied to grapevine canopy may decrease leaf and berry surface temperature and reduce heat stress which allows to avoid anthocyanins to sugar decoupling. Thus, kaolin may behave as an interesting tool to viticultural sustainability since it could already save water use in vineyard and its applications to the canopy is inexpensive and does not requires special devices.

3.2. Management of carbon and nutritive competition between vegetative and reproductive growth

3.2.1. Late irrigation

At veraison, shoots begin to form a periderm which means the onset of shoot maturation and along with this process, shoot growth begins to cease (Keller, 2020). Water irrigation applied at this moment could be a useful strategy to resume shoot growth and thus, reducing available photosynthates for the clusters (Novello & de Palma, 2013). Late irrigation (LT) effect is greater if it is combined with shoot trimming because the latter operation could promote the growth of a number of lateral shoots which could enhance the photosynthates competition (Palliotti et al., 2014; Santesteban et al., 2017). However, LT is not very used commercially due to the concern by viticulturists about the "dilution effect" and diseases pressure (Palliotti et al., 2014). Dense grapevine canopies that result from abundant water supply may also produce a decrease in wine color due to the potential shading of clusters (Keller, 2020). Therefore, compared to other viticultural techniques, LT may not be the best choice if the goal of the viticulturist is only delay grape ripening. Many viticulturists habitually think that the application of irrigation during the ripening phase could lead to the dilution of berry composition or even to lead to an increase in yield however, such fears may be not correct (Gil Cortiella, Úbeda, Barrio-Galán, & Peña-Neira, 2020). In fact, after veraison, xylem flow is blocked while sugar and water increments are linked, and phloem sap is the unique source of photosynthates (Coombe & McCarthy, 2000). Therefore, the berry enlargement during ripening depends on the import of photosynthates rather than the water absorption by roots.

3.3. Techniques related to postpone the phenological stages

The timing of budburst exerts a great influence on the subsequent vegetative and reproductive growth (May, 2000). Therefore, it is possible to postpone all the phenological stages including technological maturity by delaying the budburst date (Friend & Trought, 2007). Fortunately, this could be performed through different pruning methods such as late winter pruning or forcing bud regrowth (Frioni et al., 2016; Gu, Jacobs, McCarthy, & Gohil, 2012).

3.3.1. Late winter pruning

Late winter pruning (LWP) may delay budburst by a few days and it is mainly performed to avoid the risk of spring frost injury of vegetal tissues (Gatti et al., 2016b). The action mechanism of this phenomenon is the apical dominance. In this way, grapevine shoot growth starts in the distal buds of a cane and the development of the basal buds is often inhibited by the budburst of distal buds (Keller, 2020). Therefore, after a late pruning, basal buds are forced to break. LWP performed after budburst removes reserves that have been already mobilized by the plant and located in the vegetative growing organs, and the plants can probably get weak (Hidalgo, 2011). However, the grapevines has a greater capacity to recover under global warming, so this weakness is not a big concern in viticulture (Keller, 2020).

In recent years, several studies about LWP have been published with the particular goal to delay grape ripening. However, its effects depend largely on the moment of its application on grapevines (Palliotti et al., 2014). LWP at stage E (leaves unfolded) and F (inflorescence clearly visible) could delay the budburst date by 17 and 31 days, respectively (Frioni et al., 2016). However, the losses of yield were significant and LWP performed at both stages failed to postpone the subsequent phenological stages in a vineyard cultivated under the warm conditions (Gatti et al., 2016b). LWP performed at the stage G (inflorescences separated) delayed fruit ripening and reduced yield, number of inflorescences in winter buds, and soluble solid in grapes, while it increased titratable acidity and total anthocyanins concentration in grapes (Frioni et al., 2016). Additionally, no yield was obtained after LWP performed at stage H-I on grapevines (40% to 50% of flower caps fallen). LWP performed at the stage C failed to delay the late phenological stages and did not exert important effects on grapevine yield and berry composition (Zheng, García, Balda, & Martínez de Toda, 2017c). However, LWP performed at the G (inflorescences separated) and H (flowers separated) stages delayed all the grape phenological stages and the grapes ripened in a colder period than the control ones. Nevertheless, grapevine yield was reduced significantly by these treatments (41 and 67 %, respectively) and LWPH increased the ratio of anthocyanin to sugar and helped to keep high acidity levels in the berry. In another report, it was reported that LWP delayed berry maturity by up to 3 weeks in Shiraz and by 2 weeks in Cabernet Sauvignon (Petrie, Brooke, Moran, & Sadras, 2017). The authors showed that yield response varied between pruning dates. In this way, Shiraz grapevines pruned at E-L 15 phenological stage recorded a reduction in yield close to 50 %, while the yield of the treatments performed in other phenological stage ranged from a 24 % reduction to a 55 % increase relative to the control.

The main cause in yield reduction by LWP seems to be the losses of flowers and/or the reduction in fruit set percentage in the current season, instead of the losses in inflorescences within buds in the previous season. LWP is a viable approach to delay berry ripening as long as it is carried out late enough. However, the application of severe LWP on grapevines may lead to an unacceptable low yield, negatively affecting vineyard economical returns. Therefore, it is of wide importance to find out and study the best moment to perform LWP on grapevines with the aim to delay fruit sugar accumulation without affecting yield. To our knowledge, few studies have focused on this point and there is no general agreement. Thus, the prospects of LWP application in vineyards will depend mainly on whether a good balance between berry quality and yield that can be obtained via this technique.

3.3.2. Forcing regrowth

Double pruning or forcing bud regrowth is an innovative technique that has been proposed for hot viticultural regions to face global warming (Gu et al., 2012). This technique consists of cutting growing shoots, leaving several nodes with the aim of forcing the development of new buds and thus break the bud paradormancy. Forcing bud regrowth have allowed to move berry ripening towards cooler periods of the growing season (Martínez-Moreno et al., 2019). Grapevines treated with forcing techniques produce smaller berries and lower pH in musts, and higher content of total acidity, anthocyanins, tannins, and total phenolics than non-forced grapevines (Gu et al., 2012). A recent report showed that forcing bud regrowth on Tempranillo grapevines cultivated under semi-arid conditions allowed to delay berry phenology and harvest date at least in 49 days compared to control (Martínez-Moreno et al., 2019). Berries harvested from grapevines treated with the forcing technique showed lower pH and higher titratable acidity than the grapes from unforced grapevines at similar soluble solids, and the ratio anthocyanin to sugar was significantly higher in the berries collected from the grapevines under forced treatments (Lavado et al., 2019; Martínez-Moreno et al., 2019; Martinez de Toda, Garcia, & Balda, 2019). While forcing bud regrowth technique improves grape potential for wine making, it may drastically reduce yield, both in the season of application and in the subsequent (Martínez-Moreno et al., 2019). By releasing the apical dominance after shoot decapitation is promoted a clear and rapid hormonal disequilibrium, which would be the key to identify the so-called switches that initiate bud growth (Pou, Balda, Albacete, & Martínez de Toda, 2019). Grapevine regrowth from the formed latent buds after the application of forcing bud regrowth treatments might be upregulated by cytokinin and promoted by the absence of abscisic acid (Pou et al., 2019).

Recently it has been reported an original variant of this technique that is able to obtain fruit with different levels of maturity on a same grapevine (Poni et al., 2020). The results of this study show that primary clusters in grapevines subjected to forced treatments reached target maturity with a delay of 7 to 12 days compared to unforced control, whereas forced-crop, picked at the latest available date showed higher total soluble solids, anthocyanins and phenolics than the primary crop while retaining higher acidity. In this way, forcing regrowth treatments allowed to delay ripening of both crops improving fruit quality at harvest (Poni et al., 2020). These results can be explained because basal leaves belonging to forcing shoots reached higher assimilation rates than the ones from primary shoots and this type of forcing did not compromise fruitfulness of the basal primary nodes, which set at about 1.2 inflorescence primordia/shoot (Poni et al., 2020). The authors of this study suggested that forcing applied in fruit-set was preferable to the ones performed in full flowering and in groat-sized berries stages in terms of milder ripening delay and by a balanced leaf to fruit ratio.

Some requirements or preconditions should be met to incorporate the application of this technique in the vineyard management: i) the formed dormant buds should have high fertility levels; ii) the buds should achieve the paradormancy stage which can be very time consuming; iii) the released dormant buds should preferably be those located at the apical first or second node of each trimmed shoot with the aim to leave the first three basal dormant buds that will be retained after winter pruning undisturbed (Poni et al., 2020); iv) the basal dormant buds are required to reach a regular bud induction to provide suitable pruning wood for the following grape-growing season (Poni et al., 2020); v) the unlock dormant buds should be have enough time to undergo induction and differentiation of the inflorescence primordia (Poni et al., 2020). Therefore, the stage of grapevine phenology in which forcing bud regrowth is performed play a crucial importance on ripening, yield and quality of grapes. The cluster formation for the next season begins with the formation of leaf primordia within the compound bud, but normally do not break during the current growing season due to the latent bud paradormancy. This effect is due to the inhibition produced by shoot tips, lateral shoots, and/or basal leaves (Martinez de Toda et al., 2019). However, the buds can be forced to break up during the current season since they are not fully dormant and do not require chilling. In order to force budbreak and shoot regrowth, the source of the inhibition needs to be physically or chemically removed (Pou et al., 2019).

Dormant buds' formation usually coincides with the shoot growth period (Keller, 2020). Therefore, it is possible that the forcing bud regrowth may to break even in early phenological stages (i.e. 6-8 leaves separated) of grapevines. Nonetheless, the later the operation is carried out, the more budbreak can be obtained. In addition, the forcing bud regrowth must be done before veraison, since dormant buds gradually lose the ability to break in 2-3 weeks, along with the slowing down of shoot growth.

4. Conclusions

Several viticultural techniques may be used to face the effects of high temperatures and global warming, and this review highlighted those that allows to delay grape ripening. Certain adaptations techniques as changes in altitude and exposure of vineyards or the use of late-ripening grapevine varieties, clones and rootstocks may delay the grape ripening for a few days, when these are applied separately. However, if they are used more than one, its cumulative effect could lead to a delay in berry ripening for a few weeks. Other viticultural techniques may delay the grape maturation by 15 to 20 days, each one depending on the adopted strategy, such as late or minimal pruning, severe trimming or apical leaf removal. Several of them hold independent physiological basis, so more than one can be applied to the vineyard, achieving cumulative effects and by consequence, achieve a considerable delay in grape ripening. Forcing bud regrowth, is a current trending topic in viticulture since it allows to delay all phenological stages, including the grape ripening for more than two months. Therefore, we have multiple viticultural techniques to adaptation to the current climate situation and we have time to perfect and fine-tune these techniques for a better worldwide viticulture.

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Figure captions.

Figure 1. Main viticultural techniques performed against high temperatures and global warming. ***Footnotes***: a) Severe shoot trimming performed after fruit set in a Garnacha vineyard conducted in Gobelet training system. b) Severe shoot trimming performed after fruit set in a Tempranillo vineyard conducted in vertical shoot position (VSP) trellis system. c) Severe shoot trimming performed after fruit set in a Maturana Tinta vineyard conducted in VSP trellis system. d) Minimal pruning in a vineyard conducted in VSP trellis system. e) Minimal pruning during winter dormancy. f) Minimal pruning in the herbaceous development stage of the berry.

Figure 2. Forcing regrowth of grapevines. ***Footnotes***: a) Shoot pruning (1, 2) and shoot development as a result of the budburst of the formed dormant buds (1A, 1B, 2A, 2B). b) Shoot pruning performed in May to provoke forcing bud regrowth. c) Forcing bud regrowth into pruned shoots performed in May. d) Delaying of phenological stages; (1) the most advancing ripen cluster produced from traditional winter pruning and (2) the inflorescence as result of forcing bud regrowth. e) Ripening delay obtained by forcing bud regrowth performed after fruit set: the image was taken on October 30 and the phenological stage corresponds to veraison.

Table 1. Summary of the effects of high temperature on grapevine physiology and grape quality.

Temperature	Effects on grapevine physiology and grape quality
> 55 ºC	Plant death
> 40 ºC	Partial or total drying of leaves and grapes
	Disruption of cell membranes and irreversible protein degradation
> 35 ºC	Damage to the photosynthetic apparatus
	Anthocyanin degradation in the grape
> 30 ºC	Decrease on anthocyanin synthesis and increase in its degradation
	Decoupling between anthocyanins and sugars and acidity of grapes
> 25 ºC	Decrease on volatile compounds synthesis and increase in its volatilization in grapes from red grapevine varieties
> 20 ºC	Decrease on volatile compounds synthesis and increase in its volatilization in grapes from white grapevine varieties

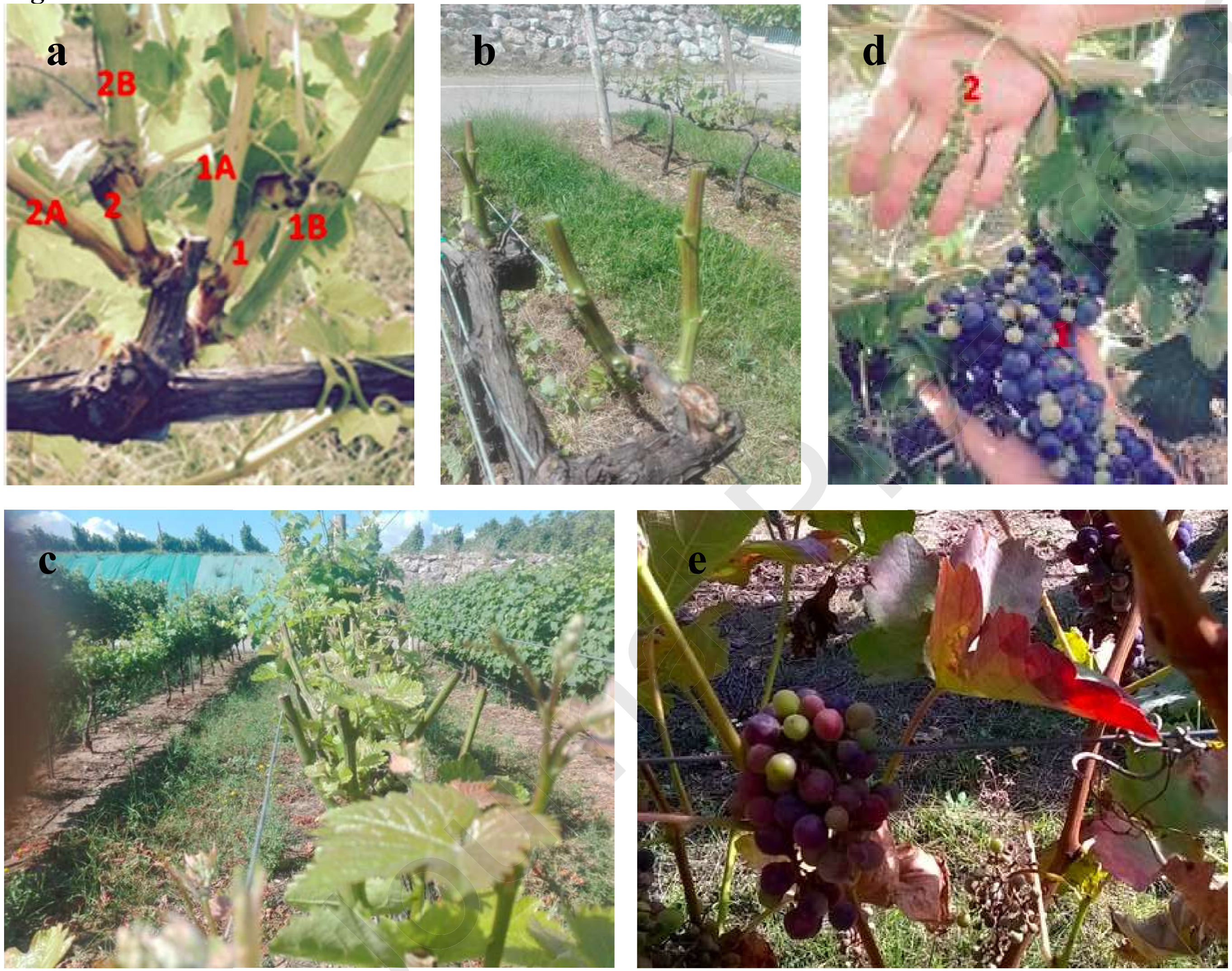
Table 2. Summary of the effects of the main viticultural techniques performed against high temperatures and global warming.

Viticultural technique	Delaying ripening	Sugar anthocyanin decoupling	Productivity	Grape and wine acidity	Operational time
Shoot trimming	~20 days	≤	=	>	2 to 3 h/ha plus
Apical leaf removal	~20 days	≤	=	>	2 to 3 h/ha plus
Minimal pruning	~20 days	<	>	=	40 h/ha less
Late winter pruning	~20 days	≤	≤	≥	=
Forcing regrowth	~2 months	<	≤	>	40 h/ha plus*

* assuming that the operation is manually performed and not mechanized.

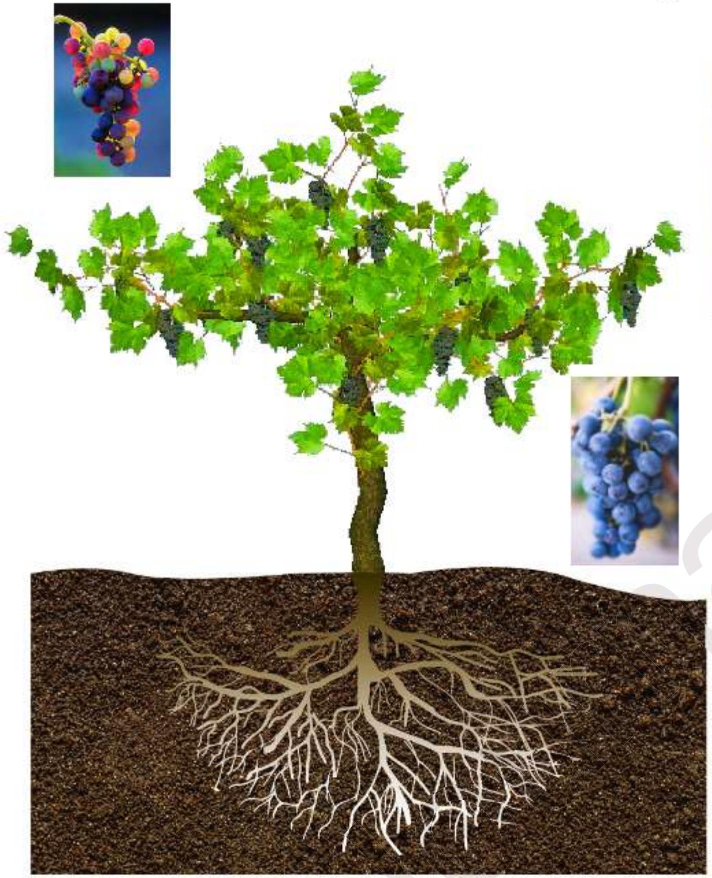
Figure 1.

Figure 2.



Graphical abstract

Current viticultural techniques to mitigate the negative effects of climate change on grape and wine quality: A comprehensive review



Severe shoot trimming

Minimal pruning

Leaf removal

Late pruning

Forcing regrowth

Highlights

- Viticulture is one of the main sectors in Mediterranean zones

- Global warming increase sugar and decrease in anthocyanins and acidity in grapes

- Climate adaptation strategies are essential to face global warming in viticulture

- Certain viticultural techniques may delay grapevine ripening close to 15 days

- Forcing bud regrowth delay ripening two months being essential in very-warm areas