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Relationship between wine composition and temperature: Impact on Bordeaux wine typicity in the context of global warming—Review

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ABSTRACT

Weather conditions throughout the year have a greater influence than other factors (such as soil and cultivars) on grapevine development and berry composition. Temperature affects gene expression and enzymatic activity of primary and secondary metabolism which determine grape ripening and wine characteristics. In the context of the climate change, temperatures will probably rise between 0.3°C and 1.7°C over the next 20 years. They are already rising and the physiology of grapevines is already changing. These modifications exert a profound shift in primary (sugar and organic acid balance) and secondary (phenolic and aromatic compounds) berry metabolisms and the resulting composition of wine. For example, some Bordeaux wines have a tendency toward reduced freshness and a modification of their ruby color. In this context it is necessary to understand the impact of higher temperatures on grape development, harvest procedures, and wine composition in order to preserve the typicity of the wines and to adapt winemaking processes.

KEYWORDS

Climate change; typicity; quality; wine; grapes; temperature increase

Introduction

As Peynaud (2013) wrote in “Le goût du vin”: “the quality of a wine means all its qualities, that is to say the properties that make it acceptable or desirable. Quality is the result of a balance between a wine and its characteristics, the consumer, with his preferences and culture, and the packaging (Peynaud and Blouin 2013).”

In the Bordeaux vineyard, the temperate climate, the clay-limestone soils, and the viticulture practices impart freshness to the wines, give red fruit aromas (strawberries, raspberries) and a clear, deep ruby color to the red wines, whereas white varieties develop aromas of broom, blackcurrant bud, grapefruit, and passion fruit. These characteristics are easily identifiable and define Bordeaux wine typicity.

The typicity of a wine reflects the terroir. The notion of terroir is defined by several intercrossing parameters as shown in Figure 1. Among them, the effect of interactions between the natural environment (soil and climate) and the vegetal material is known to be a major driver of wine typicity and quality (Seguin 1983; Jones, Snead, and Nelson 2004; Van Leeuwen and Seguin 2006; Webb, Whetton, and Barlow 2008; Van Leeuwen et al. 2009b; Van Leeuwen and Darriet 2016). It has been shown, moreover, that weather conditions have a greater influence than other factors (Jones and Davis 2000; Van Leeuwen et al. 2004; Santos et al. 2010).

It is well established that grapevine maturation is governed by environmental factors, climate being the most important of these (Downey, Dokoozlian, and Krstic 2006; Cohen, Tarara, and Kennedy 2008; Tarara et al. 2008; Matus et al. 2009; Dai

et al. 2011; Sadras, Moran, and Bonada 2013; Kuhn et al. 2014). Furthermore, several studies have shown that major compounds are influenced by a microclimate when other factors remain unchanged (Price et al. 1995; Haselgrove et al. 2000; Bergqvist, Dokoozlian, and Ebisuda 2001; Spayd et al. 2002; Downey, Dokoozlian, and Krstic 2006; Cohen, Tarara, and Kennedy 2008; Tarara et al. 2008; Dai et al. 2011; Sadras, Moran, and Bonada 2013). Not surprisingly, therefore, the links between climate and wine quality, as mediated by berry properties, have attracted considerable attention.

In the context of the global warming, the last 3 decades have been successively warmer at the earth's surface than any preceding decade since 1850. The frequency of heat waves has increased in large parts of Europe, Asia, and Australia whereas changes in rainfall patterns have not been uniform (Field et al. 2012; IPCC 2014; Pachauri et al. 2014).

Climate changes have been observed in Bordeaux as well as worldwide. Climate data have been collected by ISVV (Institut des Sciences de la Vigne et du Vin, Bordeaux, France) since 1960 and it has become apparent that temperatures have been rising (Figures 2 and 3), whereas rainfall remains stable (Figure 4). These observations are in line with the abovementioned scientific observations. Table 1 shows observations of increasing temperatures in viticultural regions worldwide. Figure 3 shows that the sum of temperatures above 10°C has increased in Bordeaux by an average of 20°C each year. In Figure 2, it can be seen that over a period of 53 years there has been a gain of 15 days at more than 30°C and a loss of 10 days

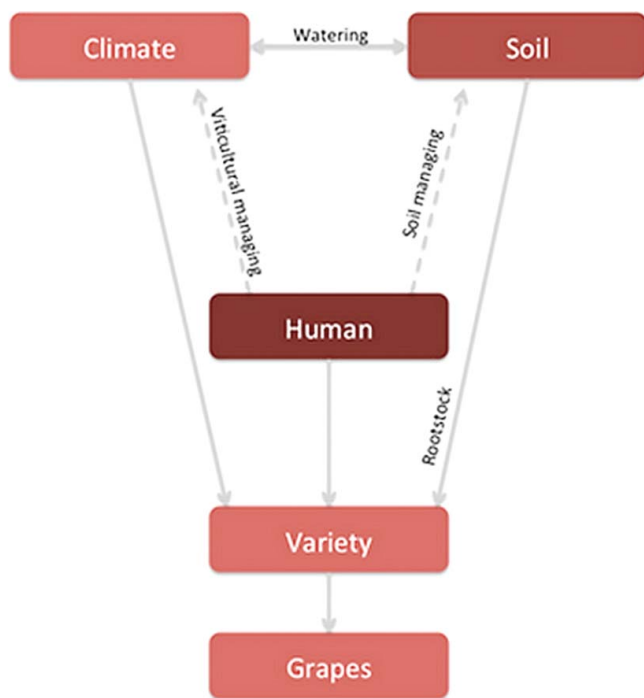


Figure 1. Quality origins: notion of terroir (Peynaud and Blouin 2013).

at less than 5°C. As Figure 3 shows, there was little evolution of rainfall in Bordeaux over the same period.

Depending on our future industrial emissions, global mean surface temperatures will probably rise between 0.3°C and 1.7°C during the period 2016–2035 (IPCC 2014). Increasing temperatures will impact firstly grapevine physiology, which has already suffered from global climate change in recent decades. Berry sugar and, consequently, alcohol content in the wine have increased while acidity has decreased, unbalancing the sugar to total acid ratio and wine balance. Phenolic maturity has not always been achieved and aromatic characteristics have been modified. All these elements demonstrate that despite the evolution of cultural practices (pruning or rootstock vigor), climate change is causing a profound shift in typicity by affecting winemaking processes, wine microbiology, and chemistry as well as sensory aspects (Duchêne and Schneider 2005; White et al. 2006; Webb, Whetton, and Barlow 2007; Pieri 2010; Parra et al. 2010; Santos et al. 2012; Cook and Wolkovich 2016).

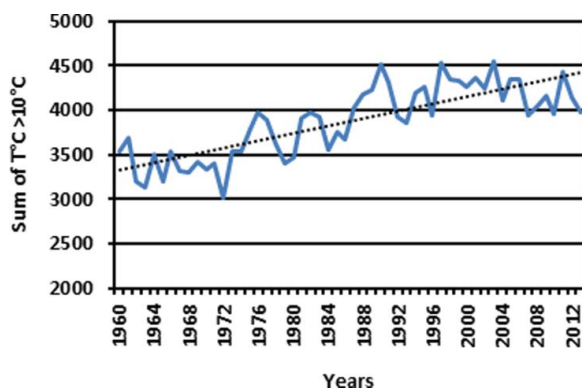


Figure 2. Aggregate temperatures ($T^{\circ}\text{C}$) > 10°C in Bordeaux from 1960.

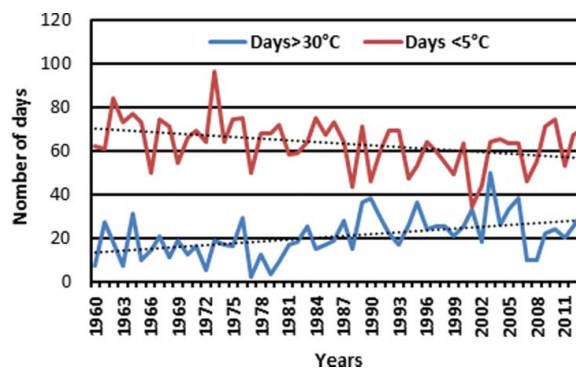


Figure 3. Evolution of the number of days > 30°C and < 5°C in Bordeaux from 1960.

Several studies have investigated the effect of climate and climate change on grapevine physiology and metabolisms. Nevertheless, many of these studies are global and show direct effects without explaining the underlying phenomena (Petrie and Sadras 2008; Soar, Sadras, and Petrie 2008). Some others studies are very specific and taking into account of only one parameter without relating effects neither on grapes nor on wine (Buttrose and Hale 1971; Parra et al. 2010). Moreover, very few studies have really succeeded in separating temperature effects from solar radiation effects; although these factors are related, the different metabolisms involved in the grapevine response are not yet well understood (Spayd et al. 2002; Cohen, Tarara, and Kennedy 2008; Tarara et al. 2008; Sadras and Soar 2009).

Taken together, these studies tend to explain the shift that has been observed in several viticultural regions. In Bordeaux, the typicity of the wines has been modified over recent hot vintages, producing lower yields, cooked fruit notes, terracotta color for red varieties, and more of a tropical fruit nose for white varieties. The aims of this review are to merge and clarify the data which are available today concerning the sensitivity of grapes and wine chemistry to increased temperatures in order to better understand the physiological responses of grapes relating to their quality and typicity expression in wines.

Phenological consequences of increasing temperatures

Temperature is the most critical factor influencing wine grape phenology (Jones et al. 2005a), with its influence on the development cycle and thus grapevine phenology. The weather conditions of each vintage have an impact on wine quality by modifying the ripening process, which is sensitive to climatic variations (Gray 2002). A long period of warm days can induce heat stress in the plant, which leads to premature veraison, the elimination of the berries through abscission, permanent enzyme inactivation, and partial or total failure of flavor development (Jones 2013). Similarly, aggregate temperatures have been shown to have a significant effect on veraison and harvest (Jones et al. 2005a). Higher temperatures increase metabolic rates and affect metabolite accumulation, hence advancement in the key phenological stages. Heat stress leads to increased transpiration (Winkler et al. 1974; Coombe 1987), which perturbs water potential in the whole plant, thus

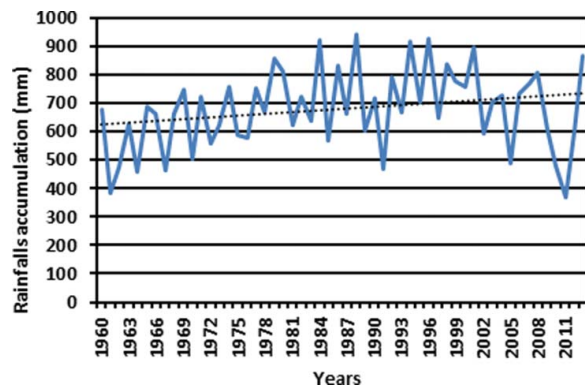


Figure 4. Evolution of accumulated rainfall in Bordeaux from 1960.

disturbing physiological processes such as photosynthesis (Tsukaguchi et al. 2003).

As mentioned previously, it is already well established that grapevine is responding to climate change; phenologically via (1) earlier phenological events (Jones and Davis 2000; Webb, Whetton, and Barlow 2007; Ramos, Jones, and Martínez-Casasnovas 2008; Tomasi et al. 2011), (2) a shortening of phenological intervals (Jones and Davis 2000), and (3) a lengthening of the growing season and an early harvest (Jones and Davis 2000; Duchêne and Schneider 2005; White et al. 2006; Webb, Whetton, and Barlow 2007; de Orduña 2010; Tomasi et al. 2011). These phenomena have also been observed in Bordeaux, as can be seen in Figures 5 and 6.

(1) The earlier occurrence of phenological events has been observed through ripening records. Two aspects define what is considered as a hot vintage (e.g., 2003) as opposed to a regularly observed temperature increase. During hot vintages development is accelerated, for example, in 2003 in Alsace (France) budburst and flowering date were approximately 15 days in advance compared with the previous 40-year mean (Duchêne and Schneider 2005). The summer of 2003 was exceptional, with temperatures that were probably higher than in any year since 1370 (Chuine et al. 2004). A “normal” temperature increase allows a gain of 0.5 days per year for flowering and a gain of 0.3 days per year for veraison in the Bordeaux region (Figure 5). Similar observations have been made in many wine regions (France, Spain, Germany, and Italy) where an average of 6–18 days of earlier phenological events have been observed over the last decades (Jones and Davis 2000; Ramos, Jones, and Martínez-Casasnovas 2008; Van Leeuwen et al. 2009a; Bock et al. 2011; Tomasi et al. 2011). These modifications in phenology have direct effects on wine quality as the ripening period is warmer. Duchêne and Schneider (2005) reported that potential alcohol levels at

harvest have increased by 2.5% (by volume) over the last 30 years and that they are highly correlated to significantly warmer ripening periods and earlier phenological events.

(2) The interval between events is more important than the actual date of each phenological event. It gives an indication of the overall climate during those periods: shorts intervals are associated with optimum conditions that facilitate rapid physiological growth and differentiation (Jones and Davis 2000), whereas long intervals between events indicate less than ideal climate conditions and delay in growth and maturation (McIntyre, Lider, and Ferrari 1982). Many studies show that the period between budburst and harvest has been brought forward and shortened (Jones and Davis 2000; Duchêne and Schneider 2005; Tomasi et al. 2011). In (Jones et al. 2005b), the study of 15 varieties in France, Italy, Spain, Germany, and Slovakia revealed significantly shorter intervals between events (4–14 days) that were strongly influenced by changes in spring and summer temperatures and/or heat accumulation indices. In the work of Tomasi et al. (2011), the growth period from bloom to veraison shortened year after year indicating that events are becoming increasingly closer in time. In the Bordeaux region, the shortening between phenological events impacts vegetative growth prior to flowering. The earlier the flowering the more advanced the harvest date is, whereas the period between flowering and harvest is not modified (Figure 6).

(3) As harvests start 2–3 weeks earlier compared with 30 years ago (Lebon 2002), ripening takes place at the end of the summer rather than at the beginning of autumn. Temperatures are higher in August and September and this could explain the trend toward earlier veraison/harvest dates. Both Petrie and Sadras (2008) and Webb, Whetton, and Barlow (2011) observed similar trends toward earlier harvests throughout many regions and for different varieties in Australia. In France and Italy, some correlations have been found between earlier harvests and global warming (Tomasi et al. 2011; Neethling et al. 2012). Finally, it is important to note that the growing season of wine grapes varies from region to region but averages are around 170–190 days (Mullins, Bouquet, and Williams 1992). However, in a context of global warming, a lengthening of the growing season has been observed. For example, in Bordeaux it lasted 162 days in 1986 against 246 days in 1977 (Jones and Davis 2000).

Consequences of rising temperatures on sugar and total acid content

As temperature affects grapevine physiology, fruit ripening will be impacted. The first component of maturity is technological

Table 1. Reports of increasing temperature in viticultural regions worldwide

Country	Increase (°C)	Duration	Reference(s)
France (Loire Valley)	1.35	1946–2009	(Neethling et al. 2012)
Spain	1.0–2.2		(Ramos, Jones, and Martínez-Casasnovas 2008)
USA (California, Oregon, and Washington)	0.9	1948–2002	(White et al. 2006)
18 Australian regions	2.47	1996–2006	(Petrie and Sadras 2008)
Veneto (Italy)	2.3	1964–2009	(Tomasi et al. 2011)
Alsace (France)	2	1972–2012	(Duchêne and Schneider 2005)
France	0.9	Last century	(Moisselin, Schneider, and Canellas 2002)

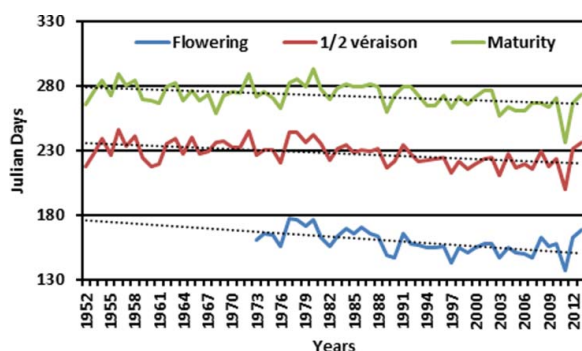


Figure 5. Evolution of phenological stages of Cabernet Sauvignon in Bordeaux from 1960.

maturity, which concerns the sugar to total acid ratio. Primary plant metabolism is directly connected to photosynthesis and metabolism allocations are related to the final composition of the berries. Moreover, this first component is a major index used to determine harvest date.

Several studies have shown that ripening occurs in increasingly warmer conditions, that these more favorable ripening conditions are largely responsible for the higher levels of potential alcohol, and that dry and warm conditions reduce acidity in berries (Coombe 1987; Jones and Davis 2000; Duchêne and Schneider 2005; Ramos, Jones, and Martínez-Casasnovas 2008; Van Leeuwen and Darriet 2016).

a) Sugar metabolism

Final sugar content depends on photosynthetic activity and accumulation/concentration mechanisms. Temperature will play on 2 mechanical aspects: leaf stomata opening and the enzymatic induction of sugar biosynthesis (Lecourieux et al. 2014). To investigate these physiological processes, several studies have used greenhouses, growth chambers, and field experimentations. It appears that Buttrose and Hale (1971) observed an increase in total soluble solids (TSS) (+1.5 °Brix) in Cabernet Sauvignon berries at higher temperatures (30°C). In the same way, Kliewer and Torres (1972) observed that Cardinal, Pinot noir, and Tokay berries had equal to greater TSS (0–2 °Brix) at higher temperatures (35°C). Nevertheless, regarding more specific sugars, Sepúlveda and Kliewer (1986)

found that heat stress (40°C) generally increased glucose and fructose accumulation in the trunks and roots of Chenin Blanc and Chardonnay but had the opposite effect on all the other above-ground fractions.

The hypothesis proposed is that at high daytime temperatures (>30°C) the vines were not able to use all the heat energy effectively. Kriedemann and Smart (1971) reported that an increase in leaf temperature from 33°C to 41°C resulted in about 40% reduction in the rate of photosynthesis. A decrease in net photosynthesis means a possible reduction in the rate of translocation of photosynthate from leaves to fruit. Moreover, Kliewer and Lider (1968) observed uneven ripening on exposed clusters at higher temperatures (+4–19°F) and greater sunlight (+43–62%). Regarding degrees Brix of fruit by the final harvest, the abovementioned experiments resulted in slower fruit maturation and significantly lower degrees Brix as compared with control vines. Moreover, these experiments highlight, in showing a different response from each variety, that varietal effects must be taken into account.

Merlot and Cabernet Sauvignon varieties have tended to produce higher sugar levels (Crippen and Morrison 1986; Jones and Davis 2000; Petrie and Sadras 2008). Schultz (2000) reported that when CO₂ increases from 364 to 605 ppm at the optimum leaf temperature (34°C), photosynthetic activity is doubled. This may explain the trend toward obtaining sweeter berries. Earth's atmosphere is becoming warmer due to the accumulation of greenhouse gases; carbon dioxide concentrations have increased by 40% since pre-industrial times (Field et al. 2012). At the same time, the extremely high sugar concentrations reached at harvest nowadays, especially in warm climates, may be associated with optimum levels of technological or phenolic and/or aromatic maturity (de Orduña 2010); despite the precocity of phenological events, winemakers tend to wait until the harvest with the aim of optimizing grape aromatic maturity. Toward the end of ripening, an increase in berry sugar concentration may be due to a loss of water (Conde et al. 2007) with a corresponding reduction in berry volume. These mechanisms may be improved by high temperatures which also modify other physiological processes such as secondary metabolism (Huglin and Schneider 1998; Roby et al. 2004; Deluc et al. 2009; Keller 2010; Deluc et al. 2011; Dai et al. 2011; Pillet 2011).

Sugars are keys modulators for a wide range of primary and secondary metabolism pathways in response to grapevine environment perception as well as abiotic stress (Smeekens et al. 2010; Pillet et al. 2012). The control of this response pathway is due to a regulation of gene expression (Pillet et al. 2012; Lecourieux et al. 2014). Pillet et al. (2012) have identified 2 genes from the sugar regulation family involved in heat stress responses in grapevine: *VvGOLS1* (galactinol synthase 1) and *VvHsfA2* (heat stress factor A2). In plants, galactinol acts mainly as a galactosyl donor for the biosynthesis of raffinose family oligosaccharides (RFOs), which act as signals that mediate plant stress tolerance (like ROS- reactive oxygen species) (Kim et al. 2008; Valluru and Van den Ende 2011). Specifically, RFOs are synthesized from sucrose by subsequent additions of activated galactose parts given by galactinol. However, nothing is known about galactinol function and accumulation in stressed berries in terms of fruit development and quality.

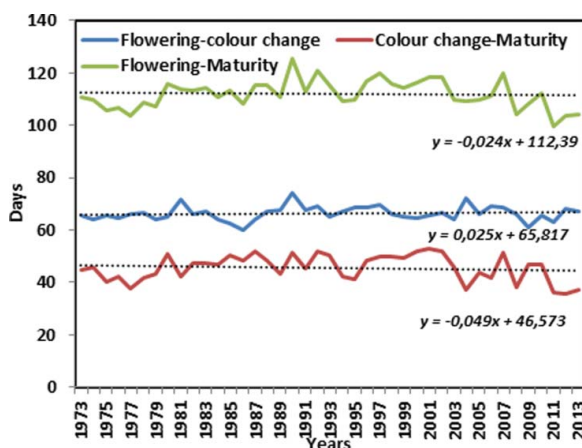


Figure 6. Number of days between phenological stages.

Similarly, the anthocyanin biosynthetic pathway in the berry skin may be correlated with the concomitant accumulation of sugars in the flesh. For example, mannose has the greatest effect on berry color whereas mannitol has no effect (Pirie and Mullins 1976; Coombe 1992; Vitrac et al. 2000). Moreover, many studies have shown that sucrose treatment effectively promotes anthocyanin synthesis in *V. vinifera* cell cultures (Larronde et al. 1998; Vitrac et al. 2000; Agasse et al. 2007; Agasse et al. 2009). This regulation has been explained by the ability of several sugars to induce gene-encoding enzymes in the anthocyanin biosynthesis pathway. For example, chalcone synthase (CHS), dihydroflavonol reductase (DFR), leucoanthocyanidin dioxygenase (LDOX), and flavanone 3-hydroxylase (F3H), and promoters associated with these genes could be regulated by sugars (Gollop, Farhi, and Perl 2001, 2002; Zheng et al. 2009).

b) Organic acid metabolism

Like sugars, titrable acidity has been shown to reflect the degree of berry ripening (Bergqvist, Dokoozlian, and Ebisuda 2001; Spayd et al. 2002). Sugar accumulation and acid degradation during ripening are 2 indices used in most viticulture regions. Due to the important role of organic acids, tartaric and malic acids, in wines, the physiological response from grapes to decreasing acids in the face of warmer temperatures has been investigated.

Tartaric acid is one of the main grape acids which accumulate toward the beginning of green berry development and which remain stable until harvest (Cholet et al. 2016). Its metabolism does not seem affected directly by high temperatures ($>30^{\circ}\text{C}$) (Kliewer 1965; Kliewer and Lider 1968; Buttrose and Hale 1971; Huglin and Schneider 1998; Dai et al. 2011). The final level of tartaric acid can be modified by a faster turnover of glucose via the hexose monophosphate shunt and may account for intensive tartaric acid formation under hot conditions ($30/35^{\circ}\text{C}$) (Kliewer and Lider 1968; Loewus 1971; Ruffner, Hawker, and Hale 1976; Saito and Kasai 1978). Nevertheless, a considerable temperature effect is already known for total acidity. Research to date has focused principally on the second main grape acid: malic acid.

The subsequent drop in acid components observed during ripening is directly due to a decline in malic acid (Dai et al. 2011). Kliewer and Lider (1968) showed that grape clusters developing in the shade had double the malic acid content of clusters exposed to sunlight (berry temperatures in sunlight were 6.7°C above those in shade). Malic acid is heat sensitive ($>46^{\circ}\text{C}$); its degradation is considerably increased and is caused by a shift in the acid breakdown pattern (e.g., PEP carboxylase optimum activity is at about 38°C) (Lakso and Kliewer 1975; Ruffner, Hawker, and Hale 1976; Lakso and Kliewer 1978; Huglin and Schneider 1998). On the other hand, in a context of climate change, increased CO_2 concentration tends to suppress decarboxylations such as malic acid degradation by malic enzyme (via β -decarboxylation).

Total acidity in grapes depends on levels of both tartaric and malic acid, whose pathways can be connected. However, to date, few studies have advanced research on this topic and the control of malic/tartaric acid is still poorly understood. Nevertheless, higher temperatures have effectively been shown to

affect the balance between the synthesis and the degradation of these acids (Lakso and Kliewer 1975; Cholet et al. 2016).

c) Effect of sugar/organic acid ratio on quality

An imbalance of the sugar to total acid ratio can have a negative impact on winemaking. With higher sugar concentrations in berries, the microbiological and physical-chemical stability of wines, as conferred by the balance of sugars and organic acids, has been discussed by de Orduña (2010). The ethanol level and pH, directly linked to the sugar/acid ratio, can lead to numerous microbiological, technological, sensory, and ultimately financial consequences.

i. Sensory issues

An increased alcohol level in wine will impact its taste. Ethanol is involved in the sensation of sweetness and bitterness, and is suspected of: (a) increasing the perception of astringency, (b) contributing to a burning sensation (Nurgel and Pickering 2005; Demiglio and Pickering 2008; Fontoin et al. 2008), and (c) suppressing “fruitiness” in wines by masking the perception of esters and by increasing the volatility of wine aroma compounds (Grosch 2001; Escudero et al. 2007; Le Berre et al. 2007; Goldner et al. 2009; Robinson et al. 2009; de Orduña 2010; King, Dunn, and Heymann 2013).

ii. Technological and economic issues

Jones (2007) reviewed reports on increased alcohol levels in wines from around the world and suggested that 50% of the increase may be attributable to climate change. The increase in the number of wines on the market with alcohol levels above 13–15% by volume is notable, as well as complaints about “heady” or “hot” wines by wine critics (de Orduña 2010). This is why an alternative to full strength wine has been developed: wines with reduced alcohol content. These offer many benefits for society (effects on productivity, activities involving alcohol, car accidents, etc.) and public health (reduced calorie intake, lower risk alcohol-related diseases, etc.). All available technological information is well documented by Pickering (2000).

iii. Microbiological issues

Making wine by the fermentation of grape juice from berries with a high sugar content can result in a slowing down or even stoppage of the alcoholic fermentation (AF) (Bisson 1999). Sugar stress may inhibit growth or cause lysis in microorganisms; moreover, ethanol can be toxic for yeast at high concentrations (Ribereau-Gayon et al. 2012). Sugar stress was also found to up-regulate glycolytic and pentose phosphate pathway genes, leading to increased formation of fermentation by-products, including glycerol and acetic acid which cause over-fullness and vinegar odor, respectively (Erasmus, Vandermerwe, and Vanvuuren 2003; Nurgel et al. 2005).

iv. Physico-chemical stability issues

High ethanol levels are also a limiting factor for malolactic fermentation (MLF). This secondary fermentation, carried out by lactic acid bacteria in most red and some white wines, can be affected. Bacterial cell-membrane integrity may be deteriorated by high alcohol levels and high pH values, which are 2 points

already observed in warmer climate conditions (Graca da Silva et al. 2002; Ribereau-Gayon et al. 2012). Moreover, with low acid content in berries, wines might also be compromised. Alongside flavor and color, the pH of a wine is one of the most important and controversial parameters of quality (Conde et al. 2007); if a wine is too low in acidity it tastes flat and dull. Moreover, pH has an influence on tannin-protein interactions and therefore on astringency; when the pH rises, astringency is reduced (Fontoin et al. 2008; Demiglio and Pickering 2008). Several studies have shown that acidity allows wine to maintain its freshness; high pH values influence the equilibrium of wine aromas by modifying the concentration of important volatile terpenoids and esters (Ramey and Ough 1980; Williams, Strauss, and Wilson 1980; Díaz-Maroto, Schneider, and Baumes 2005; Moreno-Arribas and Polo 2009). In addition to aroma equilibrium, an increase in pH encourages the formation of the colorless hemiketal anthocyanin form, which reduces color in young red wines (Ribereau-Gayon et al. 2012). Furthermore, higher pH values also favor oxidative reactions and may affect wine color throughout ageing; untypical wine colors have been observed during ageing in hot years, although no information can be found on this subject in the available literature (Tonietto et al. 2014).

Consequences of rising temperatures on wine structure and color

Besides sugars and organic acids, higher temperatures also modify the accumulation of other compounds that are quantitatively less important but highly relevant for grape and wine quality. Phenolic compounds play a crucial role in the color and structure of wines on the palate. This second component gives a wine its taste, its ageing capacity, and its color, which is the first thing that consumers judge.

Two families of phenolic compounds are involved: flavonoid and non-flavonoid.

Non-flavonoid components include hydroxycinnamic acids, which are major compounds in wine grapes. They are involved in oxidative browning, particularly for white musts, but they are not examined in the context of global warming in the present study.

In wine grapes flavonoid compounds are well known. Three families can be distinguished: tannins, anthocyanins, and flavonols. Tannins include a range of polyphenolic compounds from small oligomeric forms to large proanthocyanidin (PA) polymers, also known as condensed tannins. These oligomers and polymers are composed of monomeric subunits analogous to the flavan-3-ol monomers, such as (+)-catechin and (–)-epicatechin. Anthocyanins have pigmentation properties, which confer color and stability directly related to their structure. The proportion of each anthocyanin type is variety dependent. Very abundant in grapes, they give the red-purple color to the skins and to young wines. Lastly, flavonols are orange pigments. It is the condensation reactions with anthocyanins and tannins in wines which are, in part, involved in the evolution of the color of young wines to old wines, respectively from a ruby red color to a terracotta color.

The influence of light and temperature on grape flavonoid composition was investigated and well-reviewed by Downey

et al. in 2006. The biosynthesis of flavonoids, which is the culmination of 2 metabolic pathways, the shikimate and the phenylpropanoid pathways, was described in detail.

a) Tannin metabolism

Several studies have been carried out on PA composition in grapes during maturation for the purpose of determining their composition prior to extraction into wine. Grape skin PAs were shown to differ from those in seed primarily by the presence of prodelphinidines but also by their higher and increasing mDP (mean polymerization degree), as well as by the presence of lower amounts of galloylated derivatives (Prieur et al. 1994; Souquet et al. 1996; Gawel 1998; Chira et al. 2009; Bordiga et al. 2011). Tannins also contribute to the color stability of wine by forming long-lived polymeric complexes with anthocyanins (Somers 1971; Ribereau-Gayon et al. 2012).

Heat stress (>35°C) has led to an increase in PA concentration in berries (Ewart and Kliewer 1977; del Rio and Kennedy 2006). Overnight heating produced both a higher amount of skin PA at veraison and a significant increase in the proportion of hydroxylated tannin monomers (Cohen, Tarara, and Kennedy 2008; 2012). Similar effects have been reported in sun-exposed berries (Crippen and Morrison 1986) reiterating the complexity and the importance of discriminating between UV radiation and temperature effects. However, Downey, Harvey, and Robinson (2004) attributed a higher concentration in PA and a higher mean degree of polymerization for berries exposed to sunlight.

A delay in seed ripening as compared with other berry parts was observed in the study of Sadras, Moran, and Bonada (2013). A sensory profile was established for 4 cultivars. Their results showed that half of the cultivars had significant differences in descriptors such as skin/seed astringency, seed tannin intensity, seed crushability, skin disintegration over 2 consecutive vintages. Given that seeds and skins are the main sources of tannins; the delay observed between the ripening of the seeds and other berry parts affects, consequently, mostly phenolic maturity. Different oenological implications for both red and white wines need special consideration. Some winemaking practices, with different extraction techniques, obviously lead to different tannic sensory effects (Kennedy 2008), which are correlated to the concentration, and the degree of tannin polymerization also varies as a function of the original biological material (Geny et al. 2003) and it seems clear that extractability may be impacted. Moreover, it was found that tannins from skin are the greater contributors to astringency, but tannins from seeds also contribute to bitterness (Kennedy, Saucier, and Glories 2006). Viticultural and oenological practices will need to take this information into account.

To go further, Leucoanthocyanidin reductase (LAR) and anthocyanidin reductase (ANR), which respectively catalyze the synthesis of (+)-catechin and (–)-epicatechin, have been investigated. Biosynthetic genes are expressed during flowering and at the beginning of growth as well as during color-change in skins. *VvMYB5a* and *VvMYBPA1* are known to be involved as well as *VvLAR* (Tanner et al. 2003; Gagné et al. 2009). Nonetheless information on their sensitivity to light and temperature is incomplete. Koyama et al. (2012) studied the effect of light

quality (UV and visible light) on the biosynthesis of flavonoids, especially PAs and flavonols. Results showed that structural genes *VvLAR1*, *VvANR*, *VvCYTB5*, and *VvCHS3*, as well as transcription factors *VvMYBPA1* and *VvMYBPA2* were induced by visible light but not by UV light. On the contrary, *VvMYB5b* and *VvLAR2* were insensitive to light exposure (Matus et al. 2009). This suggests that the MYB transcription factor is regulated during the development process and has only a minor role in the light regulation of PA biosynthesis, whereas *VvMYBPA1* and *VvMYBPA2* have major roles in the light regulation of PA biosynthesis. The same study also showed that the 2isogenes of LAR respond differently to light: *VvLAR1* seems to be induced by visible light, and *VvLAR2* seems to be insensitive to light in young berry skins. This result does not seem fruit dependent as Takos et al. (2006) found the same pattern for apple skins.

b) Flavonol and anthocyanin metabolism

In grapes and wines there are 2 groups of phenolic compounds relating to color: flavonols and anthocyanins.

Flavonols are yellow pigments, generally considered to act as UV protectants and free-radical scavengers (Flint, Jordan, and Caldwell 1985; Smith and Markham 1998; Ferreyra et al. 2012). With exposure to UV, flavonol glucosides have been shown to increase in vegetative and reproductive tissues (Hrazdina and Parsons 1982; Ryan et al. 1998; Reay and Lancaster 2001). This effect has also been reported in sun-exposed fruit, which shows higher content in flavonol glucosides, while shaded fruit had lower flavonol content (Price et al. 1995; Haselgrove et al. 2000; Spayd et al. 2002; Downey, Harvey, and Robinson (2004; Downey, Dokoozlian, and Krstic 2006; Matus et al. 2009). More precisely, Downey, Harvey, and Robinson (2004) reported that the level of flavonols in both leaves and fruit of the grapevine were almost negligible when those tissues had not been exposed to light as well as the gene encoding flavonol synthase (*FLS*). If UV has a direct impact on flavonol content, high temperatures have, in contrast, been shown to have no effect on flavonol levels (Spayd et al. 2002; Mori, Sugaya, and Gemma 2005).

Secondly, anthocyanins are responsible for the color of red grapes and wine (Ribereau-Gayon et al. 2012). Various studies conducted from before veraison up to harvest have shown that elevated temperatures (when they become detrimental: 30–35°C) decrease anthocyanin concentration in berries (Buttrose, Hale, and Kliever 1971; Kliever and Torres 1972; Spayd et al. 2002; Mori et al. 2007; Tarara et al. 2008; de Orduña 2010; Sadras and Moran 2012). Experiments conducted in greenhouses by Buttrose and Hale (1971) and experiments conducted by Kliever and Torres (1972) in phytotron showed that a cool climate increases coloring, whereas hot daytime and nighttime weather reduced and even completely inhibited, coloring. Nevertheless, low nocturnal temperatures did not reverse the effects of high daytime temperatures. Thus, optimal anthocyanin accumulation occurs when grapes are exposed to cool nights (15°C) and mild daytime temperatures (25°C) during ripening. More recently, Schultz (2000) and Cozzolino et al. (2010) have studied grape berry composition over 10 successive vintages with reference to the main growing parameters known to be

changing with global warming: temperature, rainfall, and CO₂ emissions. These studies found lower anthocyanin concentration in warmer regions. These global methods give only little information, insufficient to understand the mechanisms that underlie the effect of temperature on anthocyanin accumulation in grape berry skins, so it is important to use direct methods in controlled conditions (Bonada and Sadras 2015).

As we have seen, among the environmental factors that affect anthocyanin metabolism, temperature has been one of the most difficult to study. Studies in field conditions are complex and results are highly variable. For a researcher it is still difficult to separate the effects of temperature and light, which explains the small number of studies undertaken (Spayd et al. 2002; Tarara et al. 2008; Azuma et al. 2012). Among them Azuma et al. (2012) showed that anthocyanin accumulation in grape berry skins is dependent on both low temperatures and light. They focused on MYB-related genes: *VIMYBA1-2*, *VIMYBA1-3*, and *VIMYBBA2* (which encode MYB-related transcription factors that regulate anthocyanin biosynthesis pathway genes, as discussed above). Each of the 3 MYB-related genes responds differently to temperature and light treatments. *VIMYBA1-2* might be a light-response gene while *VIMYBA1-3* needed light and temperature to induce its expression. The expression pattern of *VIMYBA1-3* seems similar to the anthocyanin evolution profile in berry skins. The pattern of *VIMYBA1-2* expression was widely different. Although anthocyanin accumulation was severely suppressed in the 15°C/low-light conditions, the expression level of *VIMYBA2* was only slightly diminished. These results suggest that the final anthocyanin content in the grape berry skin is determined not only by the expression levels of MYB-related genes but also by modulation of the accumulation of flavonoids.

Mori, Sugaya, and Gemma (2004) reported that high temperatures decreased anthocyanin accumulation in the skin due to the decrease in UFGT (UDP-glucose: flavonoid 3-O-glucosyltransferase) activity. Since the development of molecular analysis tools, many studies have focused on the mRNA levels of anthocyanin biosynthetic enzyme genes (*CHS2*, *CHS3*, *CHI1*, *F3H2*, *DFR*, *LDOX* and *UFGT*) and an MYB-related regulator gene (*VvmybA1*) (Deluc 2008; Yamane et al. 2006; Ferrier 2008). Most results have shown that the products of *VvmybA1* are able to control the expression of anthocyanin biosynthetic enzyme genes. However, mRNA still accumulated in the berry skins even though anthocyanin accumulation was almost completely inhibited during the high temperature treatment (>30°C). If anthocyanin accumulation can be affected by high temperatures, it may be the case that anthocyanin degradation could also be affected. In 2006, Yamane et al. showed that inhibition of enzyme activities of the anthocyanin biosynthetic pathway and/or low translocation of substrates for anthocyanin biosynthesis may also contribute to the inhibitory effect of high temperatures on anthocyanin accumulation.

Temperature also affects growth regulators implied in the flavonol pathway, such as ABA. It is well known that a low temperature and ABA promote grape coloring (Kataoka et al. 1982). The concentration of ABA in the berry skin was 1.6-fold higher at 20°C than at 30°C and this affects the expression levels of *VvmybA1*. Whereas cool nights could not reverse the anthocyanin decrease in heated berries (Kliever and Torres

1972), ABA treatment has been demonstrated to enhanced anthocyanin accumulation under high nighttime temperatures to almost the same level as under low nighttime temperatures (Mori et al. 2005).

c) Impact on wine of phenolic compound modulation

Although flavonols, Pas, and anthocyanins, originate from the same flavonoid pathway, there are inherent differences in their regulation and chemical reactivity. The fluctuation of phenolic compounds in grapes is significant; polyphenolic profile is greatly dependent on genotype and environmental interactions. In wine, somesthetic sensations are partly due to the organoleptic quality (body and mouthfeel) of the finished product. A positive relationship was observed between mDP (mean degree of polymerization), %G (the percentage of galloylation), and the %ECG (the percentage of B-ring trihydroxylation) of PAs and astringency in wines (Schwarz and Hofmann 2008; Chira et al. 2009; Ma et al. 2014; Rinaldi et al. 2014). Moreover, Tonietto et al. (2014) identified a negative correlation between warm viticultural conditions and red wine color intensity, indicating that viticultural climate has a major influence on red wine color. Nevertheless, no studies have as yet linked global warming to a risk of an advanced ageing of wine color or a risk to ageing capability. Furthermore, the anti-oxidant power of phenolic compounds and their reactivity may have an impact on interactions with aromas.

Aromatic consequences of rising temperatures

In wines, aromatic compounds are divided into 3 classes: primary, secondary, and tertiary. Primary aromas are produced during grape ripening and are directly associated with the berry. Secondary aromas are produced during alcoholic fermentation, and tertiary aromas are defined as ageing aromas. These last 2 aromas can be modulated with winemaking practices but, in a context of global warming, primary aromas will be the first to be modified.

Primary, or varietal, aromas are compounds derived from the secondary metabolism of grapes, such as pyrazines, derivatives of carotenoids, furanones, terpenes (monoterpenes or sesquiterpenes), or volatile thiols. They are involved, for the first, in vegetal characteristics, for the others in fruit and floral characteristics. During grape maturation, aromatic potential increases. Nevertheless, musts are less odorous than wines. This is explained by the fact that not only are primary aromas found in grapes but precursor forms also exist. These non-odorous precursors are released by yeast during fermentation. Each family is found in every variety (both red and white) but in different quantities; each aroma of each family is not, however, found in every variety, each variety contributing its own particular aromatic notes (Rapp and Mandery 1986; Gonz  lez-Barreiro et al. 2015).

The benefits of cool grapes for the production of high quality wines have been widely recognized for a long time (Allen, Lacey, and Boyd 1994; Marais 1998; Marais, Hunter, and Haasbroek 1999; 2001; Jones et al. 2005b). It has been demonstrated that higher temperatures lead to a lower level of aromatic expression in white grape varieties, while in cool conditions the

aromas (isoprenoids and pyrazine) of white cultivars such as Gew  rztraminer, Sauvignon Blanc, or Riesling are preserved (Jackson and Lombard 1993; Belancic et al. 1997; Roujou de Boub  e, van Leeuwen, and Dubourdieu 2000; Tonietto and Carbonneau 2004; Peyrot des Gachons et al. 2005; Jones and Goodrich 2008). Higher temperatures have thus been correlated with more delicate vintages. Warmer growing conditions and greater cluster exposure to sunlight are associated with higher TDN (1,1,6-trimethyl-1,2-dihydronaphthalene) concentrations in finished wines. While TDN concentrations around the sensory threshold are generally acceptable to consumers, excessive levels are considered undesirable, especially in young Riesling, as they impart overly strong notes of kerosene or petrol associated with advanced ageing (Kwasniewski et al. 2010).

Sauvignon Blanc has also been shown to be a variety that is growth- and production-sensitive to climatic conditions. The effect of canopy microclimate on wine quality has been specifically investigated by Marais, Hunter, and Haasbroek (1999), who described 2 different wine styles, the first being “cool climate,” reminiscent of “green pepper” and “asparagus,” and the second being “warm climate” with a “fruity” and “tropical” style. We can conclude that aromatic equilibrium in wines is very sensitive and due to this sensitivity the typicality of wines can easily be impacted. This is why Sauvignon Blanc wines have been divided into 2 classes: “green” (vegetal, herbaceous, asparagus, green paper, capsicum, tomato leaf) and “tropical” (gooseberry, grapefruit, and passion fruit). Falc  o et al. (2007) demonstrated that 2 styles of Cabernet Sauvignon wine could be obtained depending on whether it is from higher or lower altitudes. Wines made with grapes from higher altitudes were correlated with a “bell pepper” aroma, whereas wines made with grapes from lower altitudes were correlated with “red fruit” and “jam” aromas. Nevertheless, a strong negative correlation was observed between seasonal temperatures and vineyard altitude. It is worth emphasizing the importance of characterizing the terroir as a whole in order to better understand the characteristics of a wine.

a) Metabolism of “green” aromas

Pyrazines have been identified as the molecule family most involved in vegetal olfactory notes. These varietal aromas can be found in grape berries as free volatile molecules. Among others, methoxypyrazines (MPs) are present in wines (Ebeler and Thorngate 2009) and are typical in both Sauvignon Blanc and Cabernet Sauvignon (Dunlevy et al. 2009; Forde et al. 2011; Coetzee and du Toit 2012). Three MPs have been described in grapes: 2-methoxy-3-sec-butylpyrazine (SBMP), 2-methoxy-3-isopropylpyrazine (IPMP), and 2-methoxy-3-isobutylpyrazine (IBMP). It has been known for a while that wines from warm regions tend to have lower “vegetative-herbaceous” aromas and a lower IBMP (2-methoxy-3-Isobutylpyrazine) content than wines from cool regions (Lacey et al. 1988; Allen and Lacey 1993; Ferreira et al. 1998; Kotseridis et al. 1998; Roujou de Boub  e, Van Leeuwen, and Dubourdieu 2000; Chapman, Matthews, and Guinard 2004; Green et al. 2011; Ribereau-Gayon et al. 2012). As an explanation, Belancic and Agosin (2007) suggested that IBMP could decrease faster with warmer nighttime temperatures as it occurs with malic acid.

This could be related to a higher proportion of days over 30°C for the vintages where the lowest MP concentrations were obtained (2003 and 2005 in their study). Nevertheless, in ripe fruit, a fall in IBMP is not photo- but temperature-dependent. However, the biosynthesis of MPs is known to be influenced by sunlight (Dunlevy et al. 2010; Vallarino et al. 2011; Guillaumie et al. 2013). In several studies, exposing berries to light demonstrated 2 effects on the concentration of MPs: (1) an increase in the concentration of MPs, which is more marked in immature berries and (2) photodecomposition of the MPs in ripening grapes. It seems that the concentration of MPs in grapes may be the result of a balance between the biological formation and the photo-degradation of MPs throughout the ripening process. MPs might form largely in the earlier stages of grape development and photo-degradation might be greater in the ripe fruit (Allen and Lacey 1993; Roujou de Boubée 2003; Harris, Ryona, and Sacks 2012). Thus, cool ripening conditions can lead to higher MP levels (Lacey et al. 1991; Hashizume and Samuta 1999; Marais, Hunter, and Haasbroek 1999; Hunter et al. 2004; Ryona et al. 2008) and enhance these aromas.

b) Metabolism of fruit aromas

i. Tropical aromas

The characteristic component of tropical fruit notes is volatile thiols, which can be found in large quantities in Sauvignon Blanc but also in wines from different varieties (Coetzee and du Toit 2012, (Jeffery 2016)). Several volatile thiols are known to contribute significantly to the characteristic aroma of wines made from the Sauvignon blanc cultivar (Bouchilloux, Darriet, and Dubourdieu 1998; Darriet et al. 1995; Tominaga, Darriet, and Dubourdieu 1996; Tominaga et al. 1998a; Tominaga et al. 2000). Among them, 3-sulfanylhexanol (3SH, formerly named 3-mercaptohexanol or 3MH), 3-sulfanylhexyl acetate (3SHA, formerly named 3MHA), and 4-methyl-4-sulfanylpentan-2-one (4MSP, formerly named 4MMP) are considered to be the main contributors to the aroma nuances of this wine variety, which exhibits nuances of grapefruit, passion fruit, and box tree (*Buxus sempervirens*), respectively. Due to their low perception thresholds (a few ng/L), they contribute significantly to the aroma profile of many wines (Roland et al. 2011).

The formation of volatile thiols by *Saccharomyces cerevisiae* yeast is now relatively well described. Varietal volatile thiols are released by its metabolism during alcoholic fermentation (AF) by biotransformation of non-odorous precursors present in the grapes (Tominaga, Peyrot Des Gachons, and D. Dubourdieu 1998b; Marullo and Dubourdieu 2010). Tominaga, Peyrot des Gachons, and Dubourdieu (1998b) were the first to demonstrate that the 3-sulfanylhexanol (3SH) was present in musts as S-conjugated cysteine, identifying the S-3-(hexan-1-ol)-L-cysteine (Cys-3SH). Peyrot des Gachons, Tominaga, and Dubourdieu (2002a) showed that during harvest, in Sauvignon Blanc berries, Cys-3SH was present in equal proportions in skin and pulp (Peyrot des Gachons, Tominaga, and Dubourdieu 2002a). In another study, Peyrot des Gachons, Tominaga, and Dubourdieu (2002b) found another precursor: S-3-(hexan-1-ol)-glutathione (Glut-3SH) also present in equal proportions in the skin and pulp of berries (Roland et al. 2011). A new precursor form has recently been found by Thibon et al. (2016): S-3-(hexan-1-

al)-glutathione (Glut-3SH-al), an alternative form of the Glut-3SH. The study of environmental stress on these precursors has been initiated in the last few years (e.g., thermal stress, nutrient, nitrogen, or water status) (Peyrot des Gachons et al. 2005; Choné et al. 2006; Van Leeuwen et al. 2009a,b; Kobayashi et al. 2011; Thibon et al. 2011; Helwi 2015; Helwi et al. 2016). Only Kobayashi et al. (2011) have studied heat stress and they observed that Glut-3SH and Cys-3SH in grapes were enhanced by heat shock (40°C). They also studied the effect of heat shock on the biosynthesis of Glut-3SH and Cys-3SH. In grapes berries, Glut-3SH and cys-3SH followed the same pattern: first an increase for 48 h, and then a rapid decrease. In contrast, glutathione (GSH) decreased in berries exposed to heat stress whereas the transcription of VvGST1, VvGST3, VvGST4, and γ -glutamyl transferase (GGT) enzyme activity in grapevine exposed to UV radiation was up-regulated. Other forms of S-conjugated cysteine were identified in musts (4MSP (4-mercapto-4-methylpentan-2-one)) (Darriet et al. 1995) but no studies have yet been undertaken on the impact of heat or sunlight.

ii. Floral aromas

C13-norisoprenoids are important flavor constituents of many varieties of *Vitis vinifera* including Chardonnay, Cabernet Sauvignon, Syrah, Sauvignon blanc, Chenin blanc, Semillon, and white Riesling (Lee et al. 2007). These compounds typically have low sensory thresholds and can therefore make important contributions to grape and wine aroma even at very low concentrations. The norisoprenoid β -damascenone (mega-stigma-3,5,8-trien-7-one) is one of the most potent odorants known, with a flowery, slightly fruity character (Lee et al. 2007). This compound presents a wide diversity of odor thresholds. The odor threshold of β -damascenone in hydroalcoholic solution is very low, between 10 to 50 ng/L according to several studies, while it was 3 times higher in model white wine, 15–40 times higher in model red wine, and even 140 times higher (almost 10 μ g/L) in red wine (Kotseridis et al. 1998; Pineau et al. 2007). Pineau et al. (2007) suggested that β -damascenone enhances fruity notes and masks herbaceous aromas (such as IBMP). Many other individual norisoprenoids have been identified that also contribute complex aromas to both red and white wines, including eucalyptus or camphoraceous, grassy, tea, lime, honey, oak, and pineapple characteristics (Francis, Sefton, and Williams 1992; Sefton, Francis, and Williams 1994; Lee et al. 2007). The norisoprenoids in grapes can be formed by direct degradation of carotenoids or they can be stored as glycoconjugates, which can then release their volatile aglycone during fermentation via enzymatic and acid hydrolysis processes (Di Stefano et al. 1998).

The exposure of grape clusters to sunlight has frequently been reported to increase C13-norisoprenoids in the resulting wines (Loreto et al. 1998; Marais, Hunter, and Haasbroek 1999; Bruick and McKnight 2001; Loreto and Schnitzler 2010; Gil et al. 2012, 2013; Šuklje et al. 2014). By reason of their overall contribution to wine aroma, several studies have been carried out on carotenoids (Loreto et al. 1998; Bruick and McKnight 2001; Loreto and Schnitzler 2010; Kwasniewski et al. 2010). As we can see, the influence of light has been well described.

However, questions remain as to the role of temperature (Asproudi et al. 2016). No direct link has been established.

c) Dried fruit aromas and markers of premature ageing

Aromatic notes of “dried red fruit,” “jam,” or “cooked fruit” are known to occur when climatic conditions during grape maturation are warmer (e.g., HI > 2400 for 2003 in Europe). Anecdotal evidence and research based on red wines suggest that consumer preferences tend toward wines with fruitier notes rather than those with prominent vegetal characteristics (de Orduña 2010).

Several molecules responsible for these aromas have been identified, such as sotolon (4,5-dimethyl-3-hydroxy-2-(5H)-furanone) in “Vin Doux Naturel” (Natural Sweet Wine) with sensorial descriptors of “cooked fruit,” “nut,” or “prune” (Cutzach, Chatonnet, and Dubourdieu 1998). Secondly, Pons et al. (2008, 2011) and Dubourdieu, Pons, and Lavigne (2013) identified 3-methyl-2,4-nonanedione (with notes of plum-stone), γ -nonalactone (with notes of over-ripe peaches), and massoia lactone (with notes of coconut, cooked peach, and fig) as

elements responsible for prematurely aged aromas (Allamy, Darriet, and Pons 2017; Pons et al. 2017). It has been clearly demonstrated that the concentration in must of (R)-C10-massoia lactone, which is reminiscent of coconut and dried figs, is linked to the intensity of dried fruit flavors. In Merlot and Cabernet Sauvignon musts marked by dried fruit flavors from overripe grapes, the concentration of (R)-10 massoia lactone was above its perception threshold (almost 70 mg/L). In contrast, in wines marked by these flavors, it never exceeded 20 mg/L. During alcoholic fermentation, (R)-10 massoia lactone is reduced to (R)-d-decalactone. In addition, the contribution of growing season temperature on the level in aged red wines of (R)-d-decalactone has been underlined by Pons et al. (2017). Finally, San-Juan et al. (2011) investigated the sensory descriptors of aged premium-quality Spanish wines. It has been demonstrated that 4-ethylphenol, acetic acid, phenylacetaldehyde an methional suppressed fruitiness. Moreover, they were associated with undesirable notes of oxydation and were also observed to be enhanced by high temperatures (Ferreira et al. 2002). Hence untypical advanced ageing aromas threaten the typicity of wines.

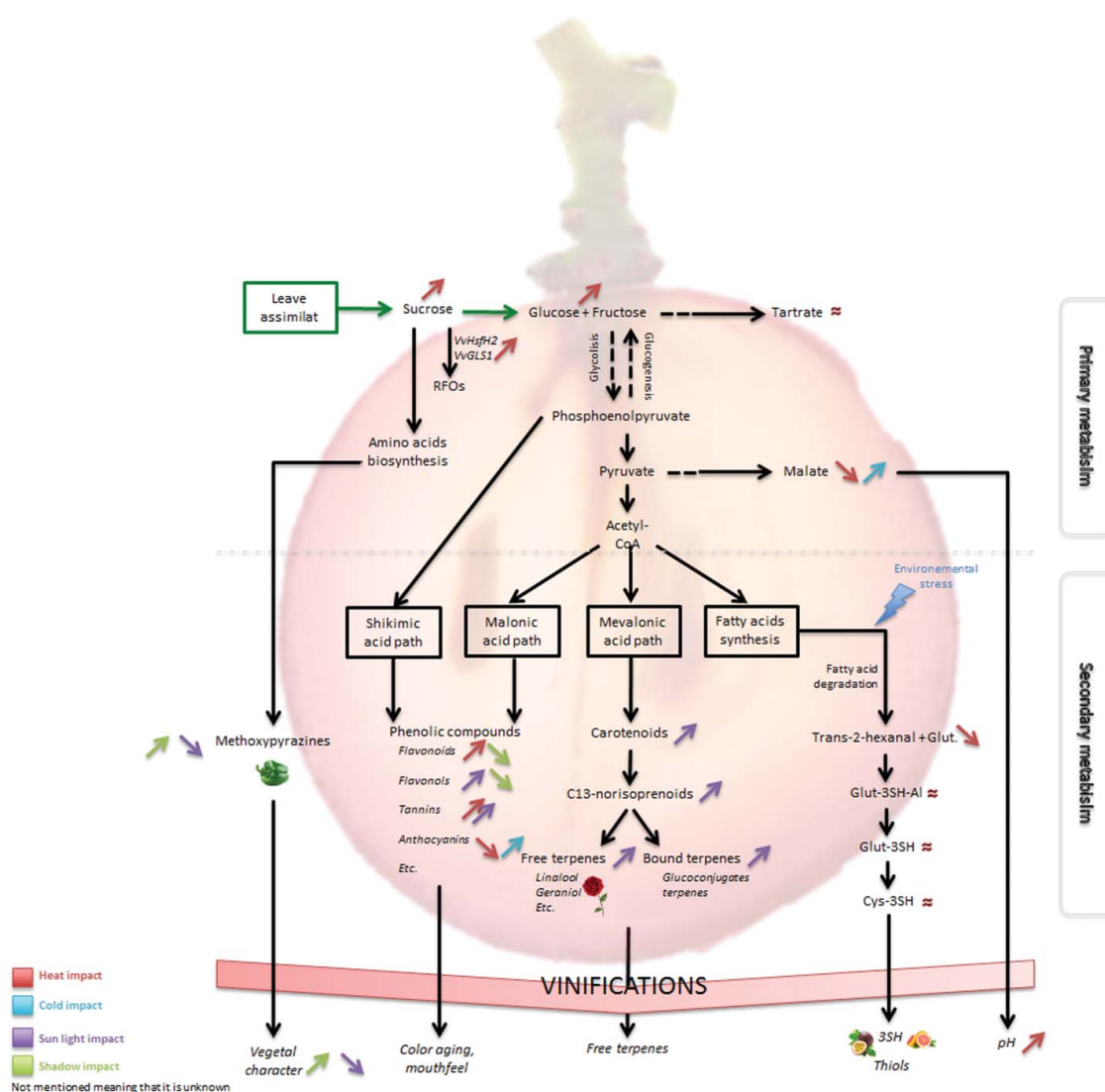


Figure 7. Global pattern of metabolites in grapes related to final wine qualities.

Conclusion

In the future, the effects of climate change on grape quality will pose new challenges for viticulture, vinification, and final wine quality. Extreme conditions have already been experimented in hot winemaking regions and several viticultural regions may become unsuitable for premium wine production in the course of the current century (Jones and Davis 2000). While several European regions may have to rethink current concepts of terroir, regarding cultivar selection and/or winemaking technology, other regions will benefit, but only for a limited time, from changing climatic conditions (White et al. 2006; Seguin 2007; Hannah et al. 2013).

The exceptionally warm 2003 season in Europe provides real insight into what could become normal conditions by the end of the century, leading to the production of what today we would call untypical wines. Moreover, this may lead to a reconsideration of wine classification and certification. To support the previous thought, Tonietto et al. (2014) have investigated the effect of different viticultural climates on wine typicity; red and white wines were well correlated with viticultural climate parameters, the main wine sensory variables affected by viticultural climate being an increase in the perception of alcohol, a decrease in the perception of acidity, accelerated evolution of color, and finally, perturbation of aroma perception (Figure 7). The results can be used to predict the potential impacts of climate change. Of course, further study is needed to assess the nature of the link between wine typicity and the modulation of grape maturation.

Many viticultural practices have been developed to manipulate the grapevine canopy and to improve fruit exposure to sunlight (Dokoozlian and Kliever 1995; Hunter et al. 1995; Bureau, Razungles, and Baumes 2000; Lee et al. 2007). While the effects of these canopy manipulations on basic fruit parameters, such as sugars, pH, and organic acid levels, have frequently been measured, only a few studies have evaluated the effects of canopy microclimate on fruit and wine flavor composition/quality. Therefore the overall impact of these microclimate effects on the sensory properties of the final wines is unclear.

There is a need for research efforts focusing on the differentiation between the effects of temperature and sunlight on grape berry composition. This work is difficult because many of the biochemical pathways are both light- and temperature-sensitive. Important efforts have already been made by several research laboratories worldwide to understand and enhance the effect of temperature on the biology of grapevines and/or on the chemical and sensory attributes of fruit and wine. But nowadays, within sight of future difficulties brought on by climate change, only a few alternatives are proposed to the wine-grower/maker. These avenues of research are still widely open. To adapt to climate change and in order to have a better control over grape quality, maturity, and harvesting, it is reasonable to assume that the development of viticultural techniques (e.g., strategic vine orientation, improved cooling techniques, trellising practices, etc.) to control microclimates at the level of individual grape clusters and/or the selection of new varieties with pleasant sensorial characteristics and improved climate tolerance may be a very useful investment for viticulturists and the wine industry.

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References

- Agasse, A., C. Vignault, C. Kappel, C. Conde, H. Gerós, and S. Delrot. (2009). Sugar transport & sugar sensing in grape. In *Grapevine molecular physiology & biotechnology*, ed. K. A. Roubelakis-Angelakis, 105–39. Dordrecht: Springer Netherlands.
- Allamy, L., P. Darriet, and A. Pons. (2017). Identification and organoleptic contribution of (Z)-1,5-octadien-3-one to the flavor of Vitis vinifera cv. Merlot and Cabernet Sauvignon musts. *Journal of Agricultural and Food Chemistry* 65:1915–23.
- Allen, M. S., and M. J. Lacey. (1993). Methoxypyrazine grape flavour: Influence of climate, cultivar and viticulture. *Vitic. Enol. Sci* 48:211–13.
- Allen, M. S., M. J. Lacey, and S. Boyd. (1994). Determination of methoxypyrazines in red wines by stable isotope dilution gas chromatography-mass spectrometry. *Journal of Agricultural and Food Chemistry* 42 (8):1734–38.
- Asproudi, A., M. Petrozziello, S. Cavalletto, and S. Guidoni. (2016). Grape aroma precursor in Cv. Nebbiolo as affected by vine microclimate. *Food Chemistry* 211:947–56.
- Azuma, A., H. Yakushiji, Y. Koshita, and S. Kobayashi. (2012). Flavonoid biosynthesis-related genes in grape skin are differentially regulated by temperature and light conditions. *Planta* 236 (4):1067–80.
- Belancic, A., and E. Agosin. (2007). Methoxypyrazines in grapes and wines of Vitis vinifera Cv. Carmenere. *American Journal of Enology and Viticulture* 58 (4):462–9.
- Belancic, A., E. Agosin, A. Ibacache, E. Bordeu, R. Baumes, A. Razungles, and C. Bayonove. (1997). Influence of sun exposure on the aromatic composition of Chilean Muscat grape cultivars Moscatel de alejandria and Moscatel Rosada. *American Journal of Enology and Viticulture* 48 (2):181–6.
- Bergqvist, J., N. Dokoozlian, and N. Ebisuda. (2001). Sunlight exposure and temperature effects on berry growth and composition of Cabernet Sauvignon and Grenache in the Central San Joaquin Valley of California. *American Journal of Enology and Viticulture* 52 (1):1–7.
- Bisson, J. (1999). French grapevines classed in phenotypical ecogeogroups essay. *OENO One*, 33(3):105–110.
- Bock, A., T. Sparks, N. Estrella, and A. Menzel. (2011). Changes in the phenology and composition of wine from Franconia, Germany. *Climate Research* 50 (1):69–81.
- Bonada, M. and Sadras, V. O. (2015). critical appraisal of methods to investigate the effect of temperature on grapevine berry composition. *Aust. J. Grape and Wine Res.* 21(1):1–17.
- Bordiga, M., F. Travaglia, M. Locatelli, J. D. Coisson, and M. Arlorio. (2011). Characterisation of polymeric skin and seed proanthocyanidins during ripening in six Vitis vinifera L. Cv. *Food Chemistry* 127 (1):180–87.
- Bouchilloux, P., P. Darriet, and D. Dubourdieu. (1998). Identification of a very odoriferous thiol, 2 methyl-3-furanthiol, in wines. *Vitis* 37:177–80.
- Bruick, R. K., and S. L. McKnight. (2001). A conserved family of Prolyl-4-hydroxylases that modify HIF. *Science* 294 (5545):1337–40.
- Bureau, S. M., A. J. Razungles, and R. L. Baumes. (2000). The aroma of Muscat of Frontignan grapes: Effect of the light environment of vine or bunch on volatiles and glycoconjugates. *Journal of the Science of Food and Agriculture* 80 (14):2012–20.
- Buttrose, M. S., and C. R. Hale. (1971). Effects of temperature on accumulation of starch or lipid in chloroplasts of grapevine. *Planta* 101 (2):166–70.
- Buttrose, M. S., C. R. Hale, and W. M. Kliever. (1971). Effect of temperature on the composition of 'Cabernet Sauvignon' berries. *American Journal of Enology and Viticulture* 22 (2):71–75.

- Chapman, D. M., M. A. Matthews, and J. -X. Guinard. (2004). Sensory attributes of Cabernet Sauvignon wines made from vines with different crop yields. *American Journal of Enology and Viticulture* **55** (4):325.
- Chira, K., G. Schmauch, C. Saucier, S. Fabre, and P.-L. Teissedre. (2009). Grape variety effect on proanthocyanidin composition and sensory perception of skin and seed tannin extracts from Bordeaux wine grapes (Cabernet Sauvignon and Merlot) for two consecutive vintages (2006 and 2007). *Journal of Agricultural and Food Chemistry* **57** (2):545–53.
- Cholet, C., S. Claverol, O. Claisse, A. Rabot, A. Osowsky, V. Dumot, G. Ferrari, and L. GénY. (2016). Tartaric acid pathways in *Vitis vinifera* L. (Cv. Ugni Blanc): A comparative study of two vintages with contrasted climatic conditions. *BMC Plant Biology* **16** (1):144–62.
- Choné, X., V. Lavigne-Cruège, C. van Leeuwen, C. Saucier, and D. Dubourdieu. (2006). Effect of vine nitrogen status on grape aromatic potential: Flavor precursors (S-cysteine conjugates), glutathione and phenolic content in *Vitis vinifera* L. Cv Sauvignon Blanc grape juice. *Journal International Des Sciences de La Vigne et Du Vin* **40** (1):1–6.
- Chuiné, I., P. Yiou, N. Viouy, B. Seguin, V. Daux, and E. Ladurie. (2004). Historical phenology: Grape ripening as a past climate indicator. *Nature* **432** (7015):289–90.
- Coetzee, C., and W. J. du Toit. (2012). A Comprehensive review on Sauvignon Blanc aroma with a focus on certain positive volatile thiols. *Food Research International* **45** (1):287–98.
- Cohen, S. D., J. M. Tarara, G. A. Gambetta, M. A. Matthews, and J. A. Kennedy. (2012). Impact of diurnal temperature variation on grape berry development, proanthocyanidin accumulation, and the expression of flavonoid pathway genes. *Journal of Experimental Botany* **63** (7):2655–65.
- Cohen, S. D., J. M. Tarara, and J. A. Kennedy. (2008). Assessing the impact of temperature on grape phenolic metabolism. *Analytica Chimica Acta* **621** (1):57–67.
- Conde, C., P. Silva, N. Fontes, A. C. P. Dias, R. M. Tavares, M. J. Sousa, A. Agasse, S. Delrot, and H. Geros. (2007). Biochemical changes throughout grape berry development and fruit and wine quality. *Food* **1**:1–22.
- Cook, B. I., and E. M. Wolkovich. (2016). Climate change decouples drought from early wine grape harvests in France. *Nature Climate Change* **6** (7):715–9.
- Coombe, B. G. (1987). Influence of temperature on composition and quality of grape. *Acta Horticulturae* **206**:23–36.
- Coombe, B. G. (1992). Research on development and ripening of the grape berry. *Am. J. Enol. Vitic.* **43**(1):101–110.
- Cozzolino, D., W. U. Cynkar, R. G. Damberg, M. Gishen, and P. Smith. (2010). Grape (*Vitis vinifera*) compositional data spanning ten successive vintages in the context of abiotic growing parameters. *Agriculture, Ecosystems & Environment* **139** (4):565–70.
- Crippen, D. D., and J. C. Morrison. (1986). The effects of sun exposure on the compositional development of Cabernet Sauvignon berries. *American Journal of Enology and Viticulture* **37** (4):235–42.
- Cutzach, I., P. Chatonnet, and D. Dubourdieu. (1998). Rôle Du Sotolon Dans L'arôme Des Vins Doux Naturels, Influence Des Conditions D'élevage et de Vieillessement. *Journal International Des Sciences de La Vigne et Du Vin* **32**:223–33.
- Dai, Z. W., N. Ollat, E. Gomes, S. Decroocq, J.-P. Tandonnet, L. Bordenave, P. Pieri, et al. (2011). Ecophysiological, genetic, and molecular causes of variation in grape berry weight and composition: A review. *American Journal of Enology and Viticulture* **62** (4):413–25.
- Darriet, P., T. Tominaga, V. Lavigne, J. -N. Boidron, and D. Dubourdieu. (1995). Identification of a powerful aromatic component of *Vitis vinifera* L. var. Sauvignon wine: 4-mercapto-4-methylpentan-2-one. *Flavour and Fragrance Journal* **10** (6):385–92.
- del Rio, J. L. P. and Kennedy, J. A. (2006). Development of proanthocyanidins in *Vitis vinifera* L. cv. Pinot noir grapes and extraction into wine. *Am. J. Enol. Vitic.* **57**(2):125–132.
- Deluc, L., Bogs, J., Walker, A. R., Ferrier, T., Decendit, A., Merillon, J. M., ... and Barrieu, F. (2008). The transcription factor VvMYB5b contributes to the regulation of anthocyanin and proanthocyanidin biosynthesis in developing grape berries. *Plant Physiol.* **147**(4): 2041–2053.
- Deluc, L. G., A. Decendit, Y. Papastamoulis, J.M. Merillon, J. C. Cushman, and G. R. Cramer. (2011). Water deficit increases stilbene metabolism in Cabernet Sauvignon berries. *Journal of Agricultural and Food Chemistry* **59** (1):289–97.
- Deluc, L. G., D. R. Quilici, A. Decendit, J. Grimplet, M. D. Wheatley, K. A. Schlauch, J. M. Merillon, J. C. Cushman, and G. R. Cramer. (2009). Water deficit alters differentially metabolic pathways affecting important flavor and quality traits in grape berries of Cabernet Sauvignon and Chardonnay. *BMC Genomics* **10** (1):212–45.
- Demiglio, P., and G. J. Pickering. (2008). The influence of ethanol and pH on the taste and mouthfeel sensations elicited by red wine. *J. Food Agric. Environ* **6** (3–4):143–50.
- Díaz-Maroto, M. C., R. Schneider, and R. Baumes. (2005). Formation pathways of ethyl esters of branched short-chain fatty acids during wine aging. *Journal of Agricultural and Food Chemistry* **53** (9):3503–9.
- Di Stefano, R., Bottero, S., Pigella, R., Borsari, D., Bezzi, G. and Corino, L. (1998). Precursori d'aroma glicosilati presenti nelle uve di alcune cultivar a frutto colorato. *L'Enotecnico* **34**(3):63–74.
- Dokoozlian, N. K., and W. M. Kliever. (1995). The light environment within grapevine canopies. I. Description and seasonal changes during fruit development. *American Journal of Enology and Viticulture* **46** (2):209–18.
- Downey, M. O., N. K. Dokoozlian, and M. P. Krstic. (2006). Cultural practice and environmental impacts on the flavonoid composition of grapes and wine: A review of recent research. *American Journal of Enology and Viticulture* **57** (3):257–68.
- Downey, M. O., J. S. Harvey, and S. P. Robinson. (2004). The effect of bunch shading on berry development and flavonoid accumulation in Shiraz grapes. *Australian Journal of Grape and Wine Research* **10**:55–73.
- Dubourdieu, D., A. Pons, and V. Lavigne. (2013). Le Vieillessement Prématuré de L'arôme Des Vins Rouges. *Revue Des Oenologues* **149**:52–54.
- Duchêne, E., and C. Schneider. (2005). Grapevine and climatic changes: A glance at the situation in Alsace. *Agronomy for Sustainable Development* **25** (1):93–99.
- Dunlevy, J. D., Kalua, C. M., Keyzers, R. A. and Boss, P. K. (2009). The production of flavour & aroma compounds in grape berries. In *Grapevine molecular physiology & biotechnology*, pp. 293–340. Roubelakis-Angelakis, K. A., Ed., Springer Netherlands.
- Dunlevy, J. D., Soole, K. L., Perkins, M. V., Dennis, E. G., Keyzers, R. A., Kalua, C. M. and Boss, P. K. (2010). Two O-methyltransferases involved in the biosynthesis of methoxypyrazines: grape-derived aroma compounds important to wine flavour. *Plant Mol. Biol.* **74**(1–2):77–89.
- Ebeler, S. E., and J. H. Thorngate. (2009). Wine chemistry and flavor: Looking into the crystal glass. *Journal of Agricultural and Food Chemistry* **57** (18):8098–108.
- Erasmus, D., G. Vandermerwe, and H. Vanvuuren. (2003). Genome-wide expression analyses: Metabolic adaptation of to high sugar stress. *FEMS Yeast Research* **3** (4):375–99.
- Escudero, A., E. Campo, L. Fariña, J. Cacho, and V. Ferreira. (2007). Analytical characterization of the aroma of five premium red wines. Insights into the role of odor families and the concept of fruitiness of wines. *Journal of Agricultural and Food Chemistry* **55** (11):4501–10.
- Ewart, A., and W. M. Kliever. (1977). Effects of controlled day and night temperatures and nitrogen on fruit-set, ovule fertility, and fruit composition of several wine grape cultivars. *American Journal of Enology and Viticulture* **28** (2):88–95.
- Falcão, L. D., G. de Revel, M. C. Perello, A. Moutsiou, M. C. Zanús, and M. T. Bordignon-Luiz. (2007). A survey of seasonal temperatures and vineyard altitude influences on 2-methoxy-3-isobutylpyrazine, C₁₃-norisoprenoids, and the sensory profile of Brazilian Cabernet Sauvignon wines. *Journal of Agricultural and Food Chemistry* **55** (9):3605–12.
- Ferreira, A. C. S., P. Guedes de Pinho, P. Rodrigues, and T. Hogg. (2002). Kinetics of oxidative degradation of white wines and how they are affected by selected technological parameters. *Journal of Agricultural and Food Chemistry* **50** (21):5919–24.
- Ferreira, V., R. López, A. Escudero, and J. F. Cacho. (1998). The aroma of Grenache red wine: Hierarchy and nature of its main odorants. *Journal of the Science of Food and Agriculture* **77** (2):259–67.

- Ferreira, M. L. F., S. P. Rius, and P. Casati. (2012). Flavonoids: Biosynthesis, biological functions, and biotechnological applications. *Frontiers in Plant Science* 3.
- Ferrier, T. (2008). Les facteurs de transcription MYB et la régulation de la biosynthèse des flavonoïdes dans la baie de raisin: analyse fonctionnelle et identification de nouveaux candidats (Doctoral dissertation, Bordeaux 1).
- Field, C. B., V. Barros, T. F. Stocker, Q. Dahe, D. Jon Dokken, K. L. Ebi, M. D. Mastrandrea, et al. (2012). *IPCC, 2012: Managing the risks of extreme events and disasters to advance climate change adaptation*. Cambridge, UK, and New York, NY, USA: Cambridge University Press.
- Flint, S. D., P. W. Jordan, and M. M. Caldwell. (1985). Plant protective response to enhanced UV-B radiation under field conditions: Leaf optical properties and photosynthesis. *Photochemistry and Photobiology* 41 (1):95–99.
- Fontoin, H., C. Saucier, P. -L. Teissedre, and Y. Glories. (2008). Effect of pH, ethanol and acidity on astringency and bitterness of grape seed tannin oligomers in model wine solution. *Food Quality and Preference* 19 (3):286–91.
- Forde, C. G., A. Cox, E. R. Williams, and P. K. Boss. (2011). Associations between the sensory attributes and volatile composition of Cabernet Sauvignon wines and the volatile composition of the grapes used for their production. *Journal of Agricultural and Food Chemistry* 59 (6):2573–83.
- Francis, I. L., M. A. Sefton, and P. J. Williams. (1992). Sensory descriptive analysis of the aroma of hydrolysed precursor fractions from Semillon, Chardonnay and Sauvignon Blanc grape juices. *Journal of the Science of Food and Agriculture* 59 (4):511–20.
- Gagné, S., S. Lacampagne, O. Claisse, and L. Génay. (2009). Leucoanthocyanidin reductase and anthocyanidin reductase gene expression and activity in flowers, young berries and skins of *Vitis vinifera* L. Cv. Cabernet-Sauvignon during development. *Plant Physiology and Biochemistry* 47 (4):282–90.
- Gawel, R. (1998). Red wine astringency: A review. *Australian Journal of Grape and Wine Research* 4:74–95.
- Geny, L., C. Saucier, S. Bracco, F. Daviaud, and Y. Glories. (2003). Composition and cellular localization of tannins in grape seeds during maturation. *Journal of Agricultural and Food Chemistry* 51 (27):8051–54.
- Gil, M., R. Bottini, F. Berli, M. Pontin, M. F. Silva, and P. Piccoli. (2013). Volatile organic compounds characterized from grapevine (*Vitis vinifera* L. Cv. Malbec) berries increase at pre-harvest and in response to UV-B radiation. *Phytochemistry* 96:148–57.
- Gil, M., M. Pontin, F. Berli, R. Bottini, and P. Piccoli. (2012). Metabolism of terpenes in the response of grape (*Vitis Vinifera* L.) leaf tissues to UV-B radiation. *Phytochemistry* 77 (May):89–98.
- Goldner, M. C., M. C. Zamora, P. Di Leo Lira, H. Gianninoto, and A. Bandoni. (2009). Effect of ethanol in the perception of aroma attributes and the detection of volatile compounds in red wine. *Journal of Sensory Studies* 24 (2):243–57.
- Gollop, R., S. E. Even, V. Colova-Tsolova, and A. Peri. (2002). Expression of the grape dihydroflavonol reductase gene and analysis of its promoter region. *Journal of Experimental Botany* 53 (373):1397–409.
- Gollop, R., S. Farhi, and A. Perl. (2001). Regulation of the leucoanthocyanidin dioxygenase gene expression in *Vitis vinifera*. *Plant Science* 161 (3):579–88.
- González-Barreiro, C., Rial-Otero, R., Cancho-Grande, B. and Simal-Gándara, J. (2015). Wine aroma compounds in grapes: a critical review. *Crit. Rev. Food Sci. Nutr.* 55(2):202–218.
- Graca da Silveira, M., M. Vitoria San Romao, M. C. Loureiro-Dias, F. M. Rombouts, and T. Abee. (2002). Flow cytometric assessment of membrane integrity of ethanol-stressed *oenococcus oeni* cells. *Applied and Environmental Microbiology* 68 (12):6087–93.
- Gray, J. D. (2002). *The basis of variation in the size and composition of grape berries* (Doctoral dissertation). Australia: The University of Adelaide.
- Green, J. A., W. V. Parr, J. Breitmeyer, D. Valentin, and R. Sherlock. (2011). Sensory and chemical characterisation of Sauvignon Blanc wine: Influence of source of origin. *Food Research International* 44 (9):2788–97.
- Grosch, W. (2001). Evaluation of the key odorants of foods by dilution experiments, aroma models and omission. *Chem. Senses* 26:533–45.
- Guillaumie, S., A. Ilg, S. Rety, M. Brette, C. Trossat-Magnin, S. Decroocq, C. Leon, et al. (2013). Genetic analysis of the biosynthesis of 2-Methoxy-3-Isobutylpyrazine, a major grape-derived aroma compound impacting wine quality. *Plant Physiology* 162 (2):604–15.
- Hannah, L., P. R. Roehrdanz, M. Ikegami, A. V. Shepard, M. R. Shaw, G. Tabor, L. Zhi, P. A. Marquet, and R. J. Hijmans. (2013). Climate change, wine, and conservation. *Proceedings of the National Academy of Sciences* 110 (17):6907–12.
- Harris, S. A., I. Ryona, and G. L. Sacks. (2012). Behavior of 3-isobutyl-2-hydroxypyrazine (IBHP), a key intermediate in 3-isobutyl-2-methoxypyrazine (IBMP) metabolism, in ripening wine grapes. *Journal of Agricultural and Food Chemistry* 60 (48):11901–8.
- Haselgrove, L., D. Botting, R. van Heeswijck, P. B. Hoj, P. R. Dry, C. Ford, and P. G. Iland. (2000). Canopy microclimate and berry composition: The effect of bunch exposure on the phenolic composition of *Vitis vinifera* L. Cv. Shiraz grape berries. *Australian Journal of Grape and Wine Research* 6:141–49.
- Hashizume, K., and T. Samuta. (1999). Grape maturity and light exposure affect berry methoxypyrazine concentration. *American Journal of Enology and Viticulture* 50 (2):194–8.
- Helwi, P. (2015). Effet Du Statut Azoté de La Vigne Sur Le Potentiel Aromatique de La Baie de Raisin et L'arôme Du Vin. PhD, Université de Bordeaux.
- Helwi, P., S. Guillaumie, C. Thibon, C. Keime, A. Habran, G. Hilbert, E. Gomes, P. Darriet, S. Delrot, and C. van Leeuwen. (2016). Vine nitrogen status and volatile thiols and their precursors from plot to transcriptome level. *BMC Plant Biology* 16 (1):173–96.
- Hrazdina, G., and G. F. Parsons. (1982). Induction of flavonoid synthesizing enzymes by light in etiolated pea (*Pisum sativum* Cv. Midfreezer) seedlings. *Plant Physiology* 70 (2):506–10.
- Huglin, P., and C. Schneider. (1998). *Biologie et écologie de la vigne*. 2e édition. Tec & Doc Lavoisier, Paris, FRANCE (Monographie).
- Hunter, J. J., H. P. Ruffner, C. G. Volschenk, and D. J. Le Roux. (1995). Partial defoliation of *Vitis vinifera* L. Cv. Cabernet Sauvignon/99 richter: Effect on root growth, Canopy efficiency; grape composition, and wine quality. *American Journal of Enology and Viticulture* 46 (3):306–14.
- Hunter, J. J., C. G. Volschenk, J. Marais, and G. W. Fouché. (2004). Composition of Sauvignon Blanc Grapes as affected by Pre-Véraison Canopy manipulation and ripeness level. *South African Journal for Enology and Viticulture* 25:13–18.
- IPCC. (2014). *Climate change 2014: Impacts, adaptation, and vulnerability*. International Panel of Climate Change.
- Jackson, D. I., and P. B. Lombard. (1993). Environmental and management practices affecting grape composition and wine quality-a review. *American Journal of Enology and Viticulture* 44 (4):409–30.
- Jeffery, D. W. (2016). Spotlight on varietal thiols and precursors in grapes and wines. *Australian Journal of Chemistry* 69:1323–30.
- Jones, G., and R. Davis. (2000). Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. *American Journal of Enology and Viticulture* 51 (3):249–61.
- Jones, G., E. Duchêne, D. Tomasi, J. Yuste, O. Braslavskaya, H. Schultz, C. Martinez, et al. (2005a). Changes in European winegrape phenology and relationship with climate. XIV International GESCO Viticulture Congress, Geisenheim, Germany.
- Jones, G., and G. Goodrich. (2008). Influence of climate variability on wine regions in the Western USA and on wine quality in the Napa Valley. *Climate Research* 35 (February):241–54.
- Jones, G., N. Snead, and P. Nelson. (2004). Geology and Wine 8. Modeling viticultural landscapes: A GIS analysis of the terroir potential in the Umpqua Valley of Oregon. *Geoscience Canada* 31 (4).
- Jones, G., M. White, O. Cooper, and K. Storchmann. (2005b). Climate change and global wine quality. *Climatic Change* 73 (3):319–43.
- Jones, G. V. (2007). Climate change: observations, projections, and general implications for viticulture and wine production. Economics Department-working paper, (7):14.
- Jones, G. V. (2013). Winegrape phenology. In *Phenology: An integrative environmental science*, ed. M. D. Schwartz, 563–84. Dordrecht: Springer, Netherlands.

- Kataoka, I., A. Sugiura, N. Utsunomiya, and T. Tomana. (1982). Effect of abscisic acid and defoliation on anthocyanin accumulation in Kyoho Grapes (*Vitis vinifera* L. X *V. labruscana* BAILEY). *Vitis* **21**:325–32.
- Keller, M. (2010). Managing grapevines to optimise fruit development in a challenging environment: A climate change primer for viticulturists. *Australian Journal of Grape and Wine Research* **16** (January):56–69.
- Kennedy, J. A. (2008). Grape and wine phenolics: Observations and recent findings. *Ciencia E Investigación Agraria* **35** (2):107–20.
- Kennedy, J. A., C. Saucier, and Y. Glories. (2006). Grape and wine phenolics: History and perspective. *American Journal of Enology and Viticulture* **57** (3):239–48.
- Kim, M. S., S. M. Cho, E. Y. Kang, Y. J. Im, H. Hwangbo, Y. H. Kim, C. -M. Ryu, K. Y. Yang, G. C. Chung, and B. H. Cho. (2008). Galactinol is a signaling component of the induced systemic resistance caused by *Pseudomonas chlororaphis* O6 root colonization. *Molecular Plant-Microbe Interactions* **21** (12):1643–53.
- King, E. S., R. L. Dunn, and H. Heymann. (2013). The influence of alcohol on the sensory perception of red wines. *Food Quality and Preference* **28** (1):235–43.
- Kliwer, W. M. (1965). Changes in the concentration of malates, tartrates, and total free acids in flowers and berries of *Vitis vinifera*. *American Journal of Enology and Viticulture* **16** (2):92–100.
- Kliwer, W. M., and L. A. Lider. (1968). Influence of cluster exposure to the sun on the composition of Thompson seedless fruit. *American Journal of Enology and Viticulture* **19** (3):175–84.
- Kliwer, W. M., and R. E. Torres. (1972). Effect of controlled day and night temperatures on grape coloration. *American Journal of Enology and Viticulture* **23** (2):71–77.
- Kobayashi, H., H. Takase, Y. Suzuki, F. Tanzawa, R. Takata, K. Fujita, M. Kohno, M. Mochizuki, S. Suzuki, and T. Konno. (2011). Environmental stress enhances biosynthesis of flavor precursors, S-3-(hexan-1-ol)-glutathione and S-3-(hexan-1-ol)-L-cysteine, in grapevine through glutathione s-transferase activation. *Journal of Experimental Botany* **62** (3):1325–36.
- Kotseridis, Y., A. A. Beloqui, A. Bertrand, and J. P. Doazan. (1998). An analytical method for studying the volatile compounds of Merlot noir clone wines. *American Journal of Enology and Viticulture* **49** (1):44–48.
- Koyama, K., H. Ikeda, P. R. Poudel, and N. Goto-Yamamoto. (2012). Light quality affects flavonoid biosynthesis in young berries of Cabernet Sauvignon grape. *Phytochemistry* **78** (June):54–64.
- Kriedemann, P., and R. Smart. (1971). Effect of irradiance, temperature and leaf water potential on photosynthesis of vine leaves. *Photosynthetica* **5**:6–15.
- Kuhn, N., L. Guan, Z. W. Dai, B.-H. Wu, V. Lauvergeat, E. Gomes, S.-H. Li, F. Godoy, P. Arce-Johnson, and S. Delrot. (2014). Berry ripening: Recently Heard through the grapevine. *Journal of Experimental Botany* **65** (16):4543–59.
- Kwasniewski, M. T., J. E. Vanden Heuvel, B. S. Pan, and G. L. Sacks. (2010). Timing of cluster light environment manipulation during grape development affects C₁₃ norisoprenoid and carotenoid concentrations in Riesling. *Journal of Agricultural and Food Chemistry* **58** (11):6841–49.
- Lacey, M. J., M. S. Allen, R. L. N. Harris, and W. V. Brown. (1991). Methoxyypyrazines in Sauvignon Blanc grapes and wines. *American Journal of Enology and Viticulture* **42** (2):103–8.
- Lacey, M. J., Brown, M. W., Allen, M. S. and Harris, R. L. N. (1988). Alkyl Methoxyypyrazines and Sauvignon Blanc Character (pp. 344–345). Presented at the Second International Cool Climate Viticulture and Oenology Symposium, Auckland New Zealand.
- Lakso, A. N., and W. M. Kliwer. (1975). The influence of temperature on malic acid metabolism in grape berries I. Enzyme responses. *Plant Physiology* **56** (3):370–2.
- Lakso, A. N., and W. M. Kliwer. (1978). The influence of temperature on malic acid metabolism in grape berries. II. Temperature responses of net dark CO₂ fixation and malic acid pools. *American Journal of Enology and Viticulture* **29** (3):145–9.
- Larronde, F., S. Krisa, A. Decendit, C. Cheze, G. Defieux, and J. M. Mérillon. (1998). Regulation of polyphenol production in *Vitis vinifera* cell suspension cultures by sugars. *Plant Cell Reports* **17** (12):946–50.
- Le Berre, E., B. Atanasova, D. Langlois, P. Etiévant, and T. Thomas-Danguin. (2007). Impact of ethanol on the perception of wine odorant mixtures. *Food Quality and Preference* **18** (6):901–8.
- Lebon, E. (2002). Changements Climatiques: Quelles Conséquences Pour La Viticulture. *CR 6ième Rencontres Rhodaniennes* 31–36.
- Lecourieux, F., C. Kappel, D. Lecourieux, A. Serrano, E. Torres, P. Arce-Johnson, and S. Delrot. (2014). An update on sugar transport and signalling in grapevine. *Journal of Experimental Botany* **65** (3):821–32.
- Lee, S.-H., M.-J. Seo, M. Riu, J. P. Cotta, D. E. Block, N. K. Dokoozlian, and S. E. Ebeler. (2007). Vine microclimate and norisoprenoid concentration in Cabernet Sauvignon grapes and wines. *American Journal of Enology and Viticulture* **58** (3):291–301.
- Loewus, F. (1971). Carbohydrate interconversions. *Annual Review of Plant Physiology* **22**:337–64.
- Loreto, F., A. Förster, M. Dürr, O. Csiky, and G. Siefert. (1998). On the monoterpene emission under heat stress and on the increased thermotolerance of leaves of *Quercus ilex* L. fumigated with selected monoterpenes. *Plant, Cell & Environment* **21**:101–7.
- Loreto, F., and J.-P. Schnitzler. (2010). Abiotic stresses and induced BVOCs. *Trends in Plant Science* **15** (3):154–66.
- Ma, W., A. Guo, Y. Zhang, H. Wang, Y. Liu, and H. Li. (2014). A review on astringency and bitterness perception of tannins in wine. *Trends in Food Science & Technology* **40** (1):6–19.
- Marais, J. (1998). Effect of Grape Temperature, Oxidation and skin contact on Sauvignon Blanc juice and wine composition and wine quality. *South African Journal for Enology and Viticulture* **19**:10–16.
- Marais, J. (2001). Effect of Grape Temperature and Yeast strain on Sauvignon Blanc wine aroma composition and quality. *South African Journal for Enology and Viticulture* **22** (1):47–51.
- Marais, J., J. J. Hunter, and P. D. Haasbroek. (1999). Effect of Canopy microclimate, season and region on Sauvignon Blanc grape composition and wine quality. *South African Journal for Enology and Viticulture* **20**:19–30.
- Marullo, P., and D. Dubourdieu. (2010). Yeast selection for wine flavour modulation. *Managing Wine Quality* **2**:293–345.
- Matus, J. T., R. Loyola, A. Vega, A. Pena-Neira, E. Bordeu, P. Arce-Johnson, and J. A. Alcalde. (2009). Post-Veraison sunlight exposure induces MYB-mediated transcriptional regulation of anthocyanin and flavonol synthesis in berry skins of *Vitis vinifera*. *Journal of Experimental Botany* **60** (3):853–67.
- McIntyre, G. N., L. A. Lider, and N. L. Ferrari. (1982). The chronological classification of grapevine phenology. *American Journal of Enology and Viticulture* **33** (2):80–85.
- Moisselin, J. M., Schneider, M. and Canellas, C. (2002). Les changements climatiques en France au XX^e siècle. Etude des longues séries homogénéisées de données de température et de précipitations. *La météorologie* **38**:45–56.
- Moreno-Arribas, M. V., and M. C. Polo, eds. (2009). *Wine chemistry and biochemistry*. New York, NY: Springer New York.
- Mori, K., N. Goto-Yamamoto, M. Kitayama, and K. Hashizume. (2007). Loss of anthocyanins in red-wine grape under high temperature. *Journal of Experimental Botany* **58** (8):1935–45.
- Mori, K., H. Sato, N. Goto-Yamamoto, M. Kitayama, S. Kobayashi, S. Sugaya, H. Gemma, and K. Hashizume. (2005). Effects of abscisic acid treatment and night temperatures on anthocyanin composition in Pinot noir grapes. *VITIS-Journal of Grapevine Research* **44** (4):161.
- Mori, K., S. Sugaya, and H. Gemma. (2004). Regulatory mechanism of anthocyanin biosynthesis in “Kyoho” grape berries grown under different temperature condition. *Environ. Control in Biol* **42** (1):21–30.
- Mori, K., S. Sugaya, and H. Gemma. (2005). Decreased anthocyanin biosynthesis in grape berries grown under elevated night temperature condition. *Scientia Horticulturae* **105** (3):319–30.
- Mullins, M. G., A. Bouquet, and L. E. Williams. (1992). *Biology of the grapevine*. Cambridge University Press.
- Neethling, E., G. Barbeau, C. Bonnefoy, and H. Quénel. (2012). Change in climate and berry composition for grapevine varieties cultivated in the Loire Valley. *Climate Research* **53** (2):89–101.

- Nurgel, C., and G. Pickering. (2005). Contribution of glycerol, ethanol and sugar to the perception of viscosity and density elicited by model white wines. *Journal of Texture Studies* **36** (3):303–23.
- de Orduña, R. M. (2010). Climate change associated effects on grape and wine quality and production. *Food Research International* **43** (7):1844–55.
- Pachauri, R. K., M. R. Allen, V. R. Barros, J. Broome, W. Cramer, R. Christ, J. A. Church, et al. (2014). Climate change 2014: Synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change.
- Parra, C. S., J. Aguirreolea, M. Sánchez-Díaz, J. J. Irigoyen, and F. Morales. (2010). Effects of climate change scenarios on tempranillo grapevine (*Vitis vinifera* L.) Ripening: Response to a combination of elevated CO₂ and temperature, and moderate drought. *Plant and Soil* **337** (1–2):179–91.
- Petrie, P. R., and V. O. Sadras. (2008). Advancement of grapevine maturity in Australia between 1993 and 2006: Putative causes, magnitude of trends and viticultural consequences. *Australian Journal of Grape and Wine Research* **14** (1):33–45.
- Peynaud, E., and J. Blouin. (2013). *Le Goût Du Vin*. 5e édition. Paris: Dunod.
- Peyrot des Gachons, C., T. Tominaga, and D. Dubourdieu. (2002a). Localization of S-cysteine conjugates in the berry: Effect of skin contact on aromatic potential of *Vitis vinifera* L. Cv. Sauvignon Blanc must. *American Journal of Enology and Viticulture* **53** (2):144–6.
- Peyrot des Gachons, C., T. Tominaga, and D. Dubourdieu. (2002b). Sulfur aroma precursor present in S-glutathione conjugate form: Identification of S-3-(Hexan-1-Ol)-glutathione in must from *Vitis vinifera* L. Cv. Sauvignon Blanc. *Journal of Agricultural and Food Chemistry* **50** (14):4076–79.
- Peyrot des Gachons, C., C. Van Leeuwen, T. Tominaga, J. -P. Soyer, J. -P. Gaudillère, and D. Dubourdieu. (2005). Influence of water and nitrogen deficit on fruit ripening and aroma potential of *Vitis vinifera* L. Cv. Sauvignon Blanc in field conditions. *Journal of the Science of Food and Agriculture* **85** (1):73–85.
- Pickering, G. J. (2000). Low-and reduced-alcohol wine: A review. *Journal of Wine Research* **11** (2):129–44.
- Pieri, P. (2010). Changement climatique et culture de la vigne: l'essentiel des impacts. *Changement climatique, agriculture et forêt en France: simulations d'impacts sur les principales espèces*. Le Livre Vert du projet CLIMATOR (2007–2010), Ademe ed, 213–223.
- Pillet, J. (2011). Impact Du Microclimat Sur Le Métabolisme de La Baie de Raisin (Doctoral dissertation, Bordeaux 2).
- Pillet, J., A. Egert, P. Pieri, F. Lecourieux, C. Kappel, J. Charon, E. Gomes, F. Keller, S. Delrot, and D. Lecourieux. (2012). VvGOLS1 and VvHsfA2 Are involved in the heat stress responses in grapevine berries. *Plant and Cell Physiology* **53** (10):1776–92.
- Pineau, B., J. C. Barbe, C. Van Leeuwen, and D. Dubourdieu. (2007). Which impact for β -damascenone on red wines aroma? *Journal of Agricultural and Food Chemistry* **55**:4103–8.
- Pirie, A., and M. G. Mullins. (1976). Changes in anthocyanin and phenolics content of grapevine leaf and fruit tissues treated with sucrose, nitrate, and abscisic acid. *Plant Physiology* **58**:468–72.
- Pons, A., L. Allamy, V. Lavigne, D. Dubourdieu, and P. Darriet. (2017). Study of the contribution of massoia lactone to the aroma of Merlot and Cabernet Sauvignon musts and wines. *Food Chemistry* **232**:229–36.
- Pons, A., V. Lavigne, P. Darriet, and D. Dubourdieu. (2011). Identification et Impact Organoleptique de La Massoia Lactone Dans Les Moûts et Les Vins Rouges. In 9ème Symposium d'Oenologie, Ed. Bordeaux.
- Pons, A., Lavigne, V., Eric, F., Darriet, P. and Dubourdieu, D. (2008). Identification of volatile compounds responsible for prune aroma in prematurely aged red wines. *J. Agr. Food Chem.* **56**(13):5285–5290.
- Pons, A., V. Lavigne, F. Eric, P. Darriet, and D. Dubourdieu. (2008). Identification of volatile compounds responsible for prune aroma in prematurely aged red wines. *Journal of Agricultural and Food Chemistry* **56** (13):5285–90.
- Price, S. F., P. J. Breen, M. Valladao, and B. T. Watson. (1995). Cluster sun exposure and quercetin in Pinot noir grapes and wine. *American Journal of Enology and Viticulture* **46** (2):187–94.
- Prieur, C., J. Rigaud, V. Cheynier, and M. Moutounet. (1994). Oligomeric and polymeric procyanidins from grape seeds. *Phytochemistry* **36** (3):781–84.
- Ramey, D. D., and C. S. Ough. (1980). Volatile ester hydrolysis or formation during storage of model solutions and wines. *Journal of Agricultural and Food Chemistry* **28** (5):928–34.
- Ramos, M., G. Jones, and J. Martínez-Casasnovas. (2008). Structure and trends in climate parameters affecting winegrape production in North-east Spain. *Climate Research* **38**:1–15.
- Rapp, A. and Mandery, H. (1986). Wine aroma. *Cellular and Mol. Life Sci.* **42**(8):873–884.
- Reay, P. F., and J. E. Lancaster. (2001). Accumulation of anthocyanins and quercetin glycosides in “Gala” and “Royal Gala” apple fruit skin with UV-B-visible irradiation: Modifying effects of fruit maturity, fruit side, and temperature. *Scientia Horticulturae* **90**:57–68.
- Ribéreau-Gayon, P., Glories, Y., Maujean, A. and Dubourdieu, D. (2012). *Traité d'oenologie-Tome 2-6e éd.-Chimie du vin*. Stabilisation et traitements. Dunod.
- Rinaldi, A., M. Jourdes, P. L. Teissedre, and L. Moio. (2014). A preliminary characterization of aglianico (*Vitis vinifera* L. Cv.) grape proanthocyanidins and evaluation of their reactivity towards salivary proteins. *Food Chemistry* **164**:142–49.
- Robinson, A. L., S. E. Ebeler, H. Heymann, P. K. Boss, P. S. Solomon, and R. D. Trengove. (2009). Interactions between wine volatile compounds and grape and wine matrix components influence aroma compound headspace partitioning. *Journal of Agricultural and Food Chemistry* **57** (21):10313–22.
- Roby, G., J. F. Harbertson, D. A. Adams, and M. A. Matthews. (2004). Berry size and vine water deficits as factors in winegrape composition: Anthocyanins and tannins. *Australian Journal of Grape and Wine Research* **10** (2):100–7.
- Roland, A., R. Schneider, F. Charrier, F. Cavelier, M. Rossignol, and A. Razungles. (2011). Distribution of varietal thiol precursors in the skin and the pulp of melon B. and Sauvignon Blanc grapes. *Food Chemistry* **125** (1):139–44.
- Roujou de Boubée, D. (2003). *Research on 2-Methoxy-3-Isobutylpyrazine in grapes and wines*. Bordeaux: Academie Amorim.
- Roujou de Boubée, D., C. Van Leeuwen, and D. Dubourdieu. (2000). Organoleptic impact of 2-methoxy-3-isobutylpyrazine on red Bordeaux and Loire Wines. Effect of environmental conditions on concentrations in grapes during ripening. *Journal of Agricultural and Food Chemistry* **48** (10):4830–34.
- Ruffner, H. P., J. S. Hawker, and C. R. Hale. (1976). Temperature and enzymatic control of malate metabolism in berries of *Vitis vinifera*. *Phytochemistry* **15**:1877–80.
- Ryan, K. G., K. R. Markham, S. J. Bloor, J. M. Bradley, K. A. Mitchell, and B. R. Jordan. (1998). UVB radiation induced increase in quercetin: Kaempferol ratio in wild-type and transgenic lines of Petunia. *Photochemistry and Photobiology* **63** (3):323–30.
- Ryona, I., B. S. Pan, D. S. Intrigliolo, A. N. Lakso, and G. L. Sacks. (2008). Effects of cluster light exposure on 3-isobutyl-2-methoxypyrazine accumulation and degradation patterns in red wine grapes (*Vitis vinifera* L. Cv. Cabernet Franc). *Journal of Agricultural and Food Chemistry* **56** (22):10838–46.
- Sadras, V. O., and M. A. Moran. (2012). Elevated temperature decouples anthocyanins and sugars in berries of Shiraz and Cabernet Franc: Thermal decoupling of anthocyanins and sugars. *Australian Journal of Grape and Wine Research* **18** (2):115–22.
- Sadras, V. O., M. A. Moran, and M. Bonada. (2013). Effects of elevated temperature in grapevine. I Berry sensory traits: Temperature effects on berry traits. *Australian Journal of Grape and Wine Research* **19** (1):95–106.
- Sadras, V. O., and C. J. Soar. (2009). Shiraz vines maintain yield in response to a 2–4°C increase in maximum temperature using an open-top heating system at key phenostages. *European Journal of Agronomy* **31** (4):250–58.
- Saito, K., and Z. Kasai. (1978). Conversion of labeled substrates to sugars, cell wall polysaccharides, and tartaric acid in grape berries. *Plant Physiology* **62** (2):215–9.
- San-Juan, F., V. Ferreira, J. Cacho, and A. Escudero. (2011). Quality and aromatic sensory descriptors (mainly fresh and dry fruit character) of

- Spanish red wines can be predicted from their aroma-active chemical composition. *Journal of Agricultural and Food Chemistry* **59** (14):7916–24.
- Santos, J. A., A. C. Malheiro, M. K. Karremann, and J. G. Pinto. (2010). Statistical modelling of grapevine yield in the port wine region under present and future climate conditions. *International Journal of Biometeorology* **55** (2):119–31.
- Santos, J., A. Malheiro, J. Pinto, and G. Jones. (2012). Macroclimate and viticultural zoning in Europe: Observed trends and atmospheric forcing. *Climate Research* **51** (1):89–103.
- Schultz, H. (2000). Climate change and viticulture: A European perspective on climatology, carbon dioxide and UV-B effects. *Australian Journal of Grape and Wine Research* **6** (1):2–12.
- Schwarz, B., and T. Hofmann. (2008). Is there a direct relationship between oral astringency and human salivary protein binding? *European Food Research and Technology* **227** (6):1693–98.
- Sefton, M. A., I. L. Francis, and P. J. Williams. (1994). Free and bound volatile secondary metabolites of *Vitis vinifera* grape Cv. Sauvignon Blanc. *Journal of Food Science* **59** (1):142–7.
- Seguin, B. (2007). Le Réchauffement Climatique et Ses Conséquences Pour La Viticulture. In *Communication Au Colloque Réchauffement Climatique, Quels Impacts Probables Sur Les Vignobles*.
- Seguin, G. (1983). Influence Des Terroirs Viticoles Sur La Constitution et La Qualité Des Vendanges [Sol, Pédologie, Géologie, Alimentation En Eau]. *Bulletin de l'OIV* **56** (623):3–18.
- Sepúlveda, G. and Kliewer, W. M. (1986). Effect of high temperature on grapevines (*Vitis vinifera* L.). II. Distribution of soluble sugars. *Am. J. Enol. Vitic.* **37**(1):20–25.
- Smekens, S., J. Ma, J. Hanson, and F. Rolland. (2010). Sugar signals and molecular networks controlling plant growth. *Current Opinion in Plant Biology* **13** (3):273–78.
- Smith, G. J., and K. R. Markham. (1998). Tautomerism of flavonol glucosides: Relevance to plant UV protection and flower colour. *Journal of Photochemistry and Photobiology A: Chemistry* **118** (2):99–105.
- Soar, C. J., V. O. Sadras, and P. R. Petrie. (2008). Climate drivers of red wine quality in four contrasting Australian wine regions. *Australian Journal of Grape and Wine Research* **14** (2):78–90.
- Somers, T. C. (1971). The polymeric nature of wine pigments. *Phytochemistry* **10**:2175–86.
- Souquet, J.-M., V. Cheynier, F. Brossaud, and M. Moutounet. (1996). Polymeric proanthocyanidins from grape skins. *Phytochemistry* **43** (2):509–12.
- Spayd, S. E., J. M. Tarara, D. L. Mee, and J. C. Ferguson. (2002). Separation of sunlight and temperature effects on the composition of *Vitis vinifera* Cv. Merlot berries. *American Journal of Enology and Viticulture* **53** (3):171–82.
- Šuklje, K., G. Antalick, Z. Coetzee, L. M. Schmidtke, H. Baša Česnik, J. Brandt, W. J. du Toit, K. Lisjak, and A. Deloire. (2014). Effect of leaf removal and ultraviolet radiation on the composition and sensory perception of *Vitis vinifera* L. Cv. Sauvignon Blanc Wine: Light, ultraviolet radiation and wine composition. *Australian Journal of Grape and Wine Research* **20** (2):223–33.
- Takos, A. M., B. E. Ubi, S. P. Robinson, and A. R. Walker. (2006). Condensed tannin biosynthesis genes are regulated separately from other flavonoid biosynthesis genes in apple fruit skin. *Plant Science* **170** (3):487–99.
- Tanner, G. J., K. T. Francki, S. Abrahams, J. M. Watson, P. J. Larkin, and A. R. Ashton. (2003). Proanthocyanidin biosynthesis in plants: Purification of legume leucoanthocyanidin reductase and molecular cloning of its cDNA. *Journal of Biological Chemistry* **278** (34):31647–56.
- Tarara, J. M., Lee, J., Spayd, S. E. and Scagel, C. F. (2008). Berry temperature and solar radiation alter acylation, proportion, and concentration of anthocyanin in Merlot grapes. *Am. J. Enol. Vitic.* **59**(3):235–247.
- Thibon, C., C. Böcker, S. Shinkaruk, V. Moine, P. Darriet, and D. Dubourdieu. (2016). Identification of S-3-(hexanal)-glutathione and its bisulfite adduct in grape juice from *Vitis vinifera* L. cv. Sauvignon blanc as new potential precursors of 3SH. *Food Chemistry* **199**:711–9.
- Thibon, C., S. Cluzet, J.-M. Mérillon, P. Darriet, and D. Dubourdieu. (2011). 3-Sulfanylnhexanol precursor biogenesis in grapevine cells: The stimulating effect of *Botrytis Cinerea*. *Journal of Agricultural and Food Chemistry* **59** (4):1344–51.
- Tomasi, D., G. Jones, M. Giust, L. Lovat, and F. Gaiotti. (2011). Grapevine phenology and climate change: Relationships and trends in the Veneto region of Italy for 1964–2009. *American Journal of Enology and Viticulture* **62** (3):329–39.
- Tominaga, T., L. Blanchard, P. Darriet, and D. Dubourdieu. (2000). A powerful aromatic volatile thiol, 2-furanmethanethiol, exhibiting roast coffee aroma in wines made from several *Vitis vinifera* grape varieties. *J. Agric. Food Chem* **48**:1799–802.
- Tominaga, T., P. Darriet, and D. Dubourdieu. (1996). Identification of 3-mercaptohexyl acetate in Sauvignon wine, a powerful aromatic compound exhibiting box-tree odor. *Vitis* **35**:207–10.
- Tominaga, T., A. Furrer, R. Henry, and D. Dubourdieu. (1998a). Identification of new volatile thiols in the aroma of *Vitis vinifera* L. var. Sauvignon blanc wines. *Flavour Frag. J* **13**:159–62.
- Tominaga, T., C. Peyrot Des Gachons, and D. Dubourdieu. (1998b). A new type of flavor precursors in *Vitis vinifera* L. cv. Sauvignon blanc: S-cysteine conjugates. *J. Agric. Food Chem* **46**:5215–9.
- Tonietto, J., and A. Carbonneau. (2004). A multicriteria climatic classification system for grape-growing regions worldwide. *Agricultural and Forest Meteorology* **124** (1–2):81–97.
- Tonietto, J., Sotes Ruiz, V., Zanus, M. C., Montes, C., Uliarte, E. M., Bruno, L. A., ... and Kohlberg, E. J. (2014). The Effect of viticultural climate on red and white wine typicity: characterization in Ibero-American grape-growing regions. *Embrapa Semiárido-Artigo em periódico indexado (ALICE)*.
- Tsukaguchi, T., Y. Kawamitsu, H. Takeda, K. Suzuki, and Y. Egawa. (2003). Water status of flower buds and leaves as affected by high temperature in heat-tolerant and heat-sensitive cultivars of snap bean (*Phaseolus vulgaris* L.). *Plant Production Science* **6** (1):24–27.
- Vallarino, J. G., X. A. López-Cortés, J. D. Dunlevy, P. K. Boss, F. D. González-Nilo, and Y. M. Moreno. (2011). Biosynthesis of methoxypyrazines: Elucidating the structural/functional relationship of two *Vitis vinifera* O-methyltransferases capable of catalyzing the putative final step of the biosynthesis of 3-alkyl-2-methoxypyrazine. *Journal of Agricultural and Food Chemistry* **59** (13):7310–16.
- Valluru, R., and W. Van den Ende. (2011). Myo-Inositol and beyond—Emerging networks under stress. *Plant Science* **181** (4):387–400.
- Van Leeuwen, C., P. Friant, X. Chone, O. Tregoat, S. Koundouras, and D. Dubourdieu. (2004). Influence of climate, soil, and cultivar on terroir. *American Journal of Enology and Viticulture* **55** (3):207–17.
- Van Leeuwen, C., and G. Seguin. (2006). The concept of terroir in viticulture. *Journal of Wine Research* **17** (1):1–10.
- Van Leeuwen, C., Bois, B., Cellie, N., Tregoat, O., & Roby, J.-P. (2009a). Les modifications de l'expression du terroir induites par le changement climatique nécessitent une adaptation du matériel végétal et des techniques viticoles. *Revue Française D'oenologie*, (235), 10–14.
- Van Leeuwen, C., O. Tregoat, X. Choné, B. Bois, D. Pernet, and J.-P. Gaudillère. (2009b). Vine water status is a key factor in grape ripening and vintage quality for red Bordeaux wine. How can it be assessed for vineyard management purposes. *J. Int. Sci. Vigne Vin* **43** (3):121–34.
- Van Leeuwen, C., and P. Darriet. (2016). The impact of climate change on viticulture and wine quality. *Journal of Wine Economics* **11** 1675 (01):150–67.
- Vitrac, X., F. Larronde, S. Krisa, A. Decendit, G. Deffieux, and J.-M. Mérillon. (2000). Sugar sensing and Ca²⁺-calmodulin requirement in *Vitis vinifera* cells producing anthocyanins. *Phytochemistry* **53** (6):659–65.
- Webb, L. B., P. H. Whetton, and E. W. R. Barlow. (2007). Modelled impact of future climate change on the phenology of winegrapes in Australia. *Australian Journal of Grape and Wine Research* **13** (3):165–75.
- Webb, L. B., P. H. Whetton, and E. W. R. Barlow. (2008). Climate change and winegrape quality in Australia. *Climate Research* **36**:99–111.
- Webb, L. B., P. H. Whetton, and E. W. R. Barlow. (2011). Observed trends in winegrape maturity in Australia. *Global Change Biology* **17** (8):2707–19.
- White, M. A., N. Diffenbaugh, G. Jones, J. Pal, and F. Giorgi. (2006). Extreme heat reduces and shifts United States premium wine

- production in the 21st century. *Proceedings of the National Academy of Sciences* **103** (30):11217–22.
- Williams, P. J., C. R. Strauss, and B. Wilson. (1980). Hydroxylated linalool derivatives as precursors of volatile monoterpenes of Muscat grapes. *Journal of Agricultural and Food Chemistry* **28** (4):766–71.
- Winkler, A. J., J. Cook, W. Kliewer, and L. Lider. (1974). *General viticulture*. Berkeley: University of California Press.
- Yamane, T., S. T. Jeong, N. Goto-Yamamoto, Y. Koshita, and S. Kobayashi. (2006). Effects of temperature on anthocyanin biosynthesis in grape berry skins. *American Journal of Enology and Viticulture* **57** (1):54–59.
- Zheng, Y., L. Tian, H. Liu, Q. Pan, J. Zhan, and W. Huang. (2009). Sugars induce anthocyanin accumulation and flavanone 3-hydroxylase expression in grape berries. *Plant Growth Regulation* **58** (3):251–60.