# Aromatic maturity is a cornerstone of terroir expression in red wine

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## Abstract

Harvesting grapes at adequate maturity is key to the production of high-quality red wines. Viticulturists, enologists, and wine makers define several types of maturity, including physiological maturity, technological maturity, phenolic maturity, and aromatic maturity. Physiological maturity is a biological concept. Technological maturity and phenolic maturity are relatively well documented in the scientific literature, being linked to quantifiable compounds in grape must. Articles on aromatic maturity are scarcer. This is surprising, because aromatic maturity is, probably, the most important of the four in determining wine quality and typicity, including terroir expression, i.e. the identifiable taste of wine in relation to its origin. Optimal terroir expression can be obtained when technological, phenolic, and aromatic maturity are reached at the same time, or within a short time frame. This is more likely to occur when the ripening takes place under mild temperatures, neither too cool, nor too hot.

Aromatic expression in wine can be driven, in order from low to high maturity, by green, herbal, spicy, floral, fresh fruit, ripe fruit, jammy fruit, dried fruit, candied, or cooked fruit aromas. Green and cooked fruit aromas are not desirable in red wines, while the levels of other aromatic nuances contribute to the typicity of the wine in relation to its place of origin. Wines produced in cool climates, or on cool soils in temperate climates, are likely to express herbal or fresh fruit aromas, while wines produced under warm climates, or on warm soils in temperate climates, may express ripe fruit, jammy fruit, or candied fruit aromas.

This article reviews the state of the art of compounds underpinning the aromas of wines obtained from grapes harvested at different stages of maturity. Advances in the understanding of how aromatic maturity shapes terroir expression and how it can be manipulated by variety choices and management practices, under current and future climatic conditions, are shown. Early ripening varieties perform better in cool climates and late ripening varieties in warm climates. Additionally, maturity can be advanced or delayed by different canopy management practices or training systems. Timing of harvest also impacts aromatic expression of the produced wine. Gaps in the literature are highlighted to guide future directions of research.

**Key words:** *Vitis vinifera*, grapevine, maturity, aroma, terroir, typicity, wine

## Introduction

### 1. Wine typicity, maturity and terroir

Quality and typicity are much valued attributes of wine. Several authors have proposed to define wine typicity (Dubourdieu, 2021; Cadot *et al.*, 2012) although this concept can be difficult to quantify (see Barbe *et al.*, 2021 for a review on the sensory space of wine). Nevertheless, quality and typicity are among the main sources of consumer's willingness to pay, resulting in added value in wine production (Tempère *et al.*, 2019; Souza Gonzaga *et al.*, 2021). Varietal choices, viticultural techniques, and winemaking procedures contribute to crafting quality and typicity (Robinson *et al.*, 2013; Jackson and Lombard, 1992; Ribéreau-Gayon *et al.*, 2006; Ribéreau-Gayon *et al.*, 2021); as does the origin (i.e. the place where the vines grow), which is referred to as the terroir effect (Seguin, 1988; van Leeuwen and Seguin, 2006). According to the international organization of vine and wine (OIV, 2010), *vitivinicultural "terroir" is a concept which refers to an area in which collective knowledge of the interactions between the identifiable physical and biological environment and applied vitivinicultural practices develops, providing distinctive characteristics for the products originating from this area. "Terroir" includes specific soil, topography, climate,* *landscape characteristics and biodiversity features.* In this definition, *the distinctive characteristics for the products origination from this area* refer to wine typicity in relation to its origin. Typicity, as perceived by sensory assessment of wine, is the result of a complex interplay among the numerous molecular compounds present in wine. Wine composition is obviously related to grape composition at the time of harvest. Grape ripening is a dynamic process, from veraison (the onset of ripening) through harvest, during which berry composition dramatically changes, both with respect to primary (sugars, organic acids) as well as secondary metabolites (phenolic compounds, taste-active molecules, aroma precursors, and aromas). The level of maturity at which the grapes are harvested has a major impact on berry components and, as a result, on wine typicity. Maturity is influenced by viticultural management choices and harvest date, but also by the specific combination of variety, soil type, and climatic conditions (i.e. the terroir, van Leeuwen *et al.*, 2004).

## 2. Different types of maturity

Unlike other developmental stages of the vine, for example budburst, flowering, and veraison, maturity is not an easy phenological stage to distinctly define. Viticulturists and winemakers consider different types of maturity: physiological maturity, technological maturity, phenolic maturity, and aromatic maturity. They search for the best possible compromise among these types of maturity according to the style of wine they want to produce.

### 2.1. Physiological maturity

From a reproductive point of view, grapes are mature at veraison, when seeds have become viable for generating new vines (Keller, 2020). Some authors consider that physiological maturity is reached when sugar unloading from the phloem into the berry ceases (Wang *et al.*, 2003; Antalick *et al.*, 2019; Suter *et al.*, 2021). After veraison and during the maturation period, the permeability of grape cell walls increases (Bindon *et al.*, 2012). Berries lose firmness because of modifications in the cell wall structure in the skins (Grotte *et al.*, 2001; Le Moigne *et al.*, 2008a). These parameters influence phenolic maturity (see section 2.3). Sensory traits in grape berries related to quality potential for wine production were positively correlated to cell death (Bonada *et al.*, 2013). The latter was accelerated under high temperatures, in particular when combined with water deficit.

### 2.2. Technological maturity

Technological maturity was defined by Carbonneau *et al.* (1998) as the point when sugar is reaching a plateau and acidity is low (in particular malic acid, Coombe *et al.*, 1992). Sugar to acid ratio was acknowledged in the early 1940s by Amerine and Winkler (1941) as being an indicator of grape maturity. The importance of pH in assessing technological maturity in grapes was emphasizd by Kourakou (1974). Du Plessis (1984) reviewed technological maturity and insisted on the fact that although sugar and acidity are important parameters in grape ripeness, other compounds need to be taken into account to determine optimum date for grape harvesting, such as polysaccharides, phenolics, amino acids and aroma compounds. Grape ripening is generally monitorred by analyzing soluble solids, total acidity, and pH (Jackson and Lombard, 1992). Yeast available nitrogen (YAN) decreases during ripening (Bindon *et al.*, 2013). Excessively low YAN levels may cause sluggish fermentation, which in turn may impact the release of fermentation aromas, such as esters.

### 2.3. Phenolic maturity

Phenolic maturity is considered optimal when the anthocyanin concentration in the skins reaches a maximum and tannin concentrations have decreased from veraison, both in skin and seeds. More important than their quantitative evolution, however, is their structural evolution, leading to trigeminal sensations which are more appreciated by tasters (Blouin and Guimberteau, 2000; Kennedy *et al.*, 2006). Glories was one of the first authors who mentioned the importance of harvesting at phenolic maturity in the early 1990s, although most of his work was not published in international peer reviewed journals (Glories, 1993). Saint Cricq de Gaulejac *et al.* (1998) provided a working definition of phenolic maturity in red grapes, insisting on the need for ease of extractability of phenolic compounds and the quality of tannins perceived by sensory assessment. Extractability of tannins and anthocyanins increases with the loosening of cell walls during grape ripening, which is characterized by a decrease in cell wall material and galactose in cell walls (Ortega-Regules *et al.*, 2008). Rabot *et al.* (2017) proposed a practical method to assess seed maturity based on colour. During a sequential harvest experiment in Australia on Syrah and Cabernet-Sauvignon, anthocyanins and tannins in wines tended to increase with delayed harvest (Šuklje *et al.*, 2019). This was also observed by Bindon *et al.* (2013) on Cabernet-Sauvignon in Langhorne Creek (Australia), while seed tannins decreased during grape ripening. The sensation of astringency in wine is correlated with the concentration in condensed tannins (proanthocyanidins; Robinson *et al.*, 2011). García-Estévez *et al.* (2017) found that « phenolic ripeness » is a complex concept, because wine astringency can be incresaed by carbohydrates and decreased by polysaccharides. Overall, the relationship between grape ripeness and tannin concentration in grapes and wines is complex (Fournand *et al.*, 2006). Ferrer-Gallego *et al.* (2012) developed a method to assess phenolic maturity, where skins and seeds were separated manually and 77 phenolic compounds were analyzed. Although this work gives a better insight in molecular determinants of phenolic ripeness, it does not provide an operational framework for determining phenolic ripeness in production conditions.

### 2.4. Aromatic maturity

Aromas are strong drivers of wine typicity (González-Barreiro *et al.*, 2015). Aromas can be classified according to the chemical family they belong to (Escudero *et al.*, 2007), or alternatively to the level of maturity they can be associated with. As early as 1984, Du Plessis suggested to take into account aroma compounds like methoxypyrazines and terpenes to assess grape maturity. In relation to the level of maturity, wines can be perceived as green, herbal, spicy, floral or fruity (Noble *et al.*, 1984; Heymann and Noble, 1987; Peynaud and Blouin, 2013), with the scale of fruity aromas being very broad, ranging from fresh fruit to cooked fruit (Figure 1). Significant progress has been made over the past decades regarding understanding the molecular basis of aromatic maturity in wines. Some of these compounds are present in grapes and transferred to wine without transformation, e.g., methoxypyrazines (Allen *et al.*, 1991) and (-)-rotundone (Wood *et al.*, 2008), while others are present as odourless precursors and transformed into aroma compounds during the wine making process, e.g., volatile thiols (Darriet *et al.*, 1995). A recent study demonstrated the existence of a predictable aromatic sequence during grape ripening in Australian Syrah and Cabernet-Sauvignon from different meso-climates. Two distinct maturity stages were identified and characterised: i) Fresh Fruit associated with fresh/red fruit attributes appearing 2 weeks after the plateau of sugar accumulation for Syrah and 3 weeks for Cabernet-Sauvignon; and ii) Mature Fruit associated with dark fruit and plum character appearing 3 to 4 weeks after this plateau for Syrah and 6 weeks for Cabernet-Sauvignon) (Antalick *et al.*, 2015; 2021). In the next paragraphs, major aroma compounds identified in wines are presented in an increasing order of perceived maturity. It should be noted that the relation between the concentration of these compounds and the maturity level of the grapes may not always be fully established. Several factors, not linked to the level of maturity, also influence aromatic typicity. These encompass in particular the variety and the conditions of the fermentation (including grape sugar and nitrogen content). Moreover, the molecular basis for some aroma nuances is still under investigation.

### 2.4.1. Green aroma nuances

Undesirable green aroma nuances in wines are reminiscent of tomato leaves and freshly mowed grass. Among these, several volatile compounds as (*Z*)-3-hexenal and (*E*)-2-hexenal were identified in tomato leaves (Buttery *et al.*, 1987). In wine, hexenols ((*Z*-2-and (*Z*)-3-hexenol) were considered as indicators of a lack of ripeness (Ubeda *et al.*, 2017; Poitou *et al.*, 2017). Nevertheless, the sensory contribution of C6 compounds to the green character of wine is limited. Methoxypyrazines constitute another family of aroma compounds associated with green pepper notes in grapes and wines, in particular 2-methoxy-3-isobutylpyrazine (IBMP), and more rarely 2-methoxy-3-isopropylpyrazine, or 2-methoxy-3-secbutylpyrazine (Allen *et al.*, 1991; Allen *et al.*, 1994). Methoxypyrazines are generally considered to be detrimental to red wines' quality, in particular when they are present above the olfactory detection threshold (Allen *et al.*, 1991; Roujou de Boubée *et al.*, 2000; Ryona *et al.*, 2008), while they are not necessarily negatively perceived in white wines, especially in wines from Sauvignon blanc (Marais, 1994). Hedonic preferences of wine sensory attributes, however, are culturally determined (Ristic *et al.*, 2019).

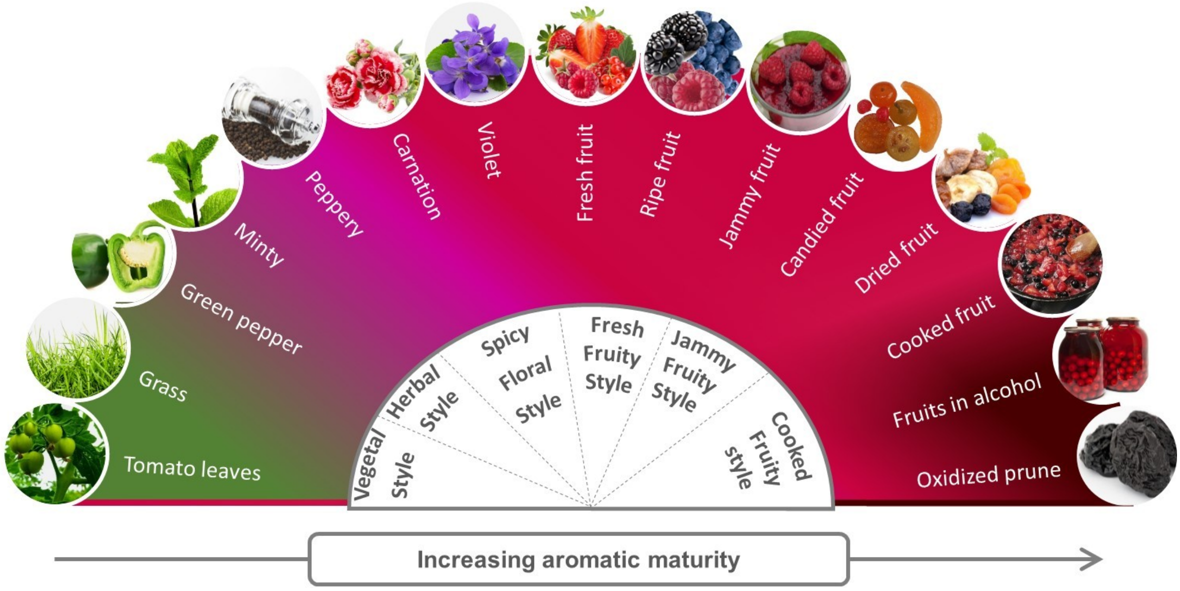


**Figure 1. Aroma wheel with increasing levels of aromatic maturity nuances. It should be noted that aroma expression is not only influenced by the level of maturity at which the grapes are harvested, but also by other factors like the variety and the conditions of the fermentation.**

### 2.4.2. Fresh minty and herbal aroma nuances

1,8-cineole can contribute to fresh green nuances like menthol and eucalyptus in red wines (Capone *et al.*, 2011a ; Antalick *et al.*, 2015 ; Poitou *et al.*, 2017). 1,4-cineole is described as minty, cooling piney, camphoraceous, and eucalyptol-like (Antalick *et al.*, 2015). While these cineoles frequently have an environmental origin and impact in Australian, Chilean and Californian wines, due to the proximity of vineyards to Eucalyptus trees (Capone *et al.*, 2011a), these compounds can also have a varietal orgin as it has been shown for wines from Cabernet (Poitou *et al.*, 2017), Ugni blanc (Trebiano bianco; Thibaud *et al.*, 2020) and Corvina (Slaghenaufi and Ugliano, 2018). They can also be induced by the presence of *Artemisia verlotiorum* in vineyards (Poitou *et al.*, 2017). 1,8-cineole originating from grapes can sometimes be detected in wines at concentrations above its olfactory detection threshold (Poitou *et al.*, 2017; Lisanti *et al.*, 2021). This compound is formed in grapes prior to veraison, before decreasing progressively during ripening, as with IBMP. Its presence is related to less ripe grapes or ripening under cooler conditions. Perceptual interactions have been observed between 1,8-cineole and IBMP, resulting in a reinforcement of green aroma nuances (Poitou *et al.*, 2017). Recently, a series of terpenes resulting from limonene degradation have been identified (Lisanti *et al.*, 2021). These compounds can provide fresh and minty aroma nuances in aged wines. Some lactones can also possibly contribute to fresh minty aroma nuances in aged wines (Picard *et al.*, 2017).

### 2.4.3. Spicy aroma nuances

(-)-rotundone is a sesquiterpene, responsible for peppery notes (Wood *et al.*, 2008). It was first identified in Syrah, but it is also present in several other varieties like Gamay, Duras, and Mourvèdre (a.k.a. Monastrell) (Geffroy *et al.*, 2020). Other linear and cyclic sesquiterpenes can also contribute to balsamic and spicy notes (Slaghenaufi and Ugliano, 2018). Megastigmatrienone (often referred to as tabanone) is a $C_{13}$-norisopreniod with the smell of spices and tobacco (Slaghenaufi *et al.*, 2016). Dimethyl sulfide (DMS) can participate in the expression of truffle and undergrowth nuances at moderate levels of concentration (Picard *et al.*, 2015).

### 2.4.4. Floral aroma nuances

Many compounds contributing to floral nuances in wines have been identified. These compounds may have a varietal origin or may be produced during the alcoholic fermentation due to yeast metabolism. Several monoterpenes such as linalool, geraniol, citronellol, rose-oxide, and nerol are responsible for flowery-muscat-like nuances (Gunata *et al.*, 1985; Noguerol-Pato *et al.*, 2012), while α-Terpineol smells like iris flowers (Schneider *et al.*, 2001; Noguerol-Pato *et al.*, 2012). Among norisoprenoids, β-ionone contributes to violet nuances (Kotseridis *et al.*, 1998) and ß-damascenone to rose-like nuances (Ribéreau-Gayon *et al.*, 2021; Noguerol-Pato *et al.*, 2012). Present in either free volatile forms or as bound glycosides, the concentrations of these compounds in grapes increase during ripening. Nevertheless, different dynamics are observed within the same monoterpene family depending on the compound considered (Costantini *et al.*, 2017; Yue *et al.*, 2020). For example, linalool concentrations increase during ripening, reach a maximum, and then decrease again during further ripening (Costantini *et al.*, 2017). Also, in the register of floral aroma nuances, 2-phenylethyl acetate and 2-phenyethanol are compounds associated with the smell of roses (Campo *et al.*, 2005; Noguerol-Pato *et al.*, 2012). Their concentrations, however, do not depend on the level of maturity of the grapes.

### 2.4.5. Fresh fruit aroma nuances

Monoterpene and C13-norisoprenoids in grapes reach a plateau at the fresh fruit stage (Šuklje *et al.*, 2019). β-damascenone, characterized by fruity-flowery or baked apple nuances, has a very low recognition threshold and improves fruity notes (Kotseridis *et al.*, 1999, Pineau *et al.*, 2007). Fruitiness in wines is also enhanced by several types of esters, including substituted ethyl esters, linear ethyl esters, and isoamyl acetate (Escudero *et al.*, 2007, San-Juan *et al.*, 2011). The effect of substituted esters on fruity nuances is generally observed at concentrations below their individual olfactory detection threshold, through perceptive interactions. This is particularly the case for ethyl 3-hydroxybutanoate and ethyl 2-hydroxy-4-methylpentanoate, involved in red-berry and fresh-fruit perception (Lytra *et al.*, 2012; Lytra *et al.*, 2015). Ethyl butanoate, ethyl hexanoate, ethyl octanoate, and ethyl 3-hydroxybutanoate are associated with red-berry aroma nuances (Pineau *et al.*, 2009). Volatile thiols also participate in fresh fruit aroma nuances in wine (Darriet *et al.*, 2012). DMS can also be involved in the expression of fresh fruity aroma by perceptive interactions, because it can enhance fruitiness in wines at low concentrations (Lytra *et al.*, 2014).

### 2.4.6. Ripe fruit aroma nuances

In red wine, volatile thiols such as 4-methyl-4-sulfanylpentan-2-one (4MSP) 3-sulfanylhexanol (3SH) and 3-(sulfanyl)hexyl acetate (3SHA) can be responsible for blackcurrant aromas (Bouchilloux *et al.*, 1998; Rigou *et al.*, 2014). β-damascenone is described by fruity-flowery or baked apple nuances (Kotseridis *et al.*, 1999, Pineau *et al.*, 2007). Wines from Merlot grapes harvested at high aromatic maturity levels show lower concentrations of fatty acids, ethyl esters, and higher alcohol acetates but higher concentrations of some substituted ethyl esters, such as ethyl 2-hydroxy-4-methylpentanoate, a compound involved in blackberry aroma (Trujillo *et al.*, 2019). Ethyl 2-methylpropanoate and ethyl 2-methylbutanoate are involved in black-berry and blackcurrant aromas (Pineau *et al.*, 2009). 2-methylbutyl acetate can also contribute to black and jammy-fruit nuances through perceptive interaction, even when present in concentrations below its perception threshold (Cameleyre *et al.*, 2017). Sulfur containing compounds, which themselves do not present fruity aromas, may have an important impact on the overall fruity aroma of wine. DMS leads to a significant increase of the perception of fruity characters by modulating black-berry fruit aroma and, more specifically, by enhancing blackcurrant aroma (Lytra *et al.*, 2014; Antalick *et al.*, 2021). Concentrations of DMS in wine increase with the level of ripeness at which grapes are harvested (Dagan *et al.*, 2006; Bindon *et al.*, 2013; Šuklje *et al.*, 2019; Antalick *et al.*, 2021). Furaneol and homofuraneol, which have the aroma of strawberry jam and caramel, are also considered to affect the perception of ripe red fruit notes in red wine (Kotseridis and Baumes, 2000; Ferreira *et al.*, 2016).

### 2.4.7. Dried and cooked fruit aroma nuances

In grape must marked by dried fruit aromas, 3-methyl-2,4-nonanedione (MND), reminiscent of anise and dried plum, and 1,5-octadien-3-one, smelling like geraniums, can be found at high levels (> 100 ng/L; Pons *et al.*, 2008., 2011; Allamy *et al.*, 2017). At a concentration level around 100 ng/L, the latter compound can remind of fig nuances. Compounds involved in dried and cooked fruit aromas in young red wines include massoia lactone (Pons *et al.*, 2017), γ-nonalactone, and furaneol (Pons *et al.*, 2008). γ-nonalactone, reminiscent of coconut and cooked peaches, is also associated with berry shriveling, which happens often when grapes are over-ripe, in particular with Syrah (Chou *et al.*, 2018). (-)-massoia lactone has nuances of dried figs and coconut (Pons *et al.*, 2017). Compounds responsible for caramel notes in wines, namely furaneol (2,5-dimethyl-4-hydroxy-3(2H)-furanone) and homofuraneol (corresponding to keto-enol equilibrium structures of 5-ethyl-4-hydroxy-2-methylfuran-3(2H)-one and 2-ethyl-4-hydroxy-5-methylfuran-3(2H)-one), are also more abundant in wines with dried fruit aromas (Kotseridis *et al.*, 2000 ; Allamy *et al.*, 2018). Perceptive interactions between these latter compounds give rise to the specific “dried fruit” aromas detected in some young red wines. These compounds are often found at higher levels in Merlot wines than Cabernet-Sauvignon wines. Longo *et al.* (2018a) attributes raisin/ prune descriptors to *β*-damascenone.

2.4.8. Oxidized prune aroma nuances

Prune aroma can be detected in grapes, in young wines made from overripe grapes, and in aged red wines. Chemical markers associated with chemical oxidation of precursors have been identified in red wines. The presence of MND in grapes (described above) marks the risk of developing dried-fruit aromas as associated with premature ageing in red wines (Pons *et al.*, 2008). Methional, a carbonyl compound reminiscent of boiled potatoes, as well as other branched carbonyl compounds, are also involved in these aroma nuances, in particular through perceptual interaction (San-Juan *et al.*, 2011). Amino acids are thought to be the precusors of these compounds.

## 3. Terroir influence on aromatic maturity

### 3.1. Evidence of a terroir effect on aromas in grapes and wines

Several articles relate to the terroir effect on aromas in grapes and wines. Herderich *et al.* (2015) report site specific signatures for different aroma compounds, like (-)-rotundone, 3SH and 1,8-cineole. These can have multiple direct origins, like soil type, climate (in particular temperature), surrounding vegetation (like the presence of eucalyptus trees close to vineyards for 1,8-cineole), or plant reactions to pests. The origin can also be indirect and mediated through the effect of environmental factors on vine vigour and related microclimate in the bunch zone. In Côtes du Rhône (France), wines are produced with Grenache from warm, gravel soils with low water holding capacity and from cool, sandy or silty soils, with no gravel and higher water holding capacity. Wines from the warm and dry gravel soils contain more *β*-damascenone and geraniol, while wines from deeper, cooler soils with higher water holding capacity contain more *β*-ionone and cis hex-2-enol (Sabon *et al.*, 2002). In the Nemea region (Peloponesos, Greece), higher levels of bound glycoconjugates of major aroma compounds in wines (in particular terpenols and C13-norisoprenoids) were related to water deficit (Koundouras *et al.*, 2006). Ubeda *et al.* (2017) found for *Vitis vinifera* cv. País in Chile, that the free aroma profile in grapes was more influenced by the degree of ripeness, while the bound aroma (in particular for terpenols) was more impacted by the location. It may be argued, however, that the degree of ripeness at which grapes are harvested is also much impacted by the location (in particular by the air and soil temperature). How location, temperature, and aromatic ripeness are linked was demonstrated by Falcão *et al.*, (2007). In their study investigating aromatic ripeness in Brazilian Cabernet-Sauvignon, IBMP increased significantly with altitude (5 different altitudes tested) due to cooler growing conditions. *α* and *β*-ionone and *β*-damascenone concentrations in wines, however, were not related to altitude. In a study of Cabernet-Sauvignon and Merlot wines from four Chinese winegrowing regions with distinctly different climatic conditions, Jiang *et al.* (2013) found different aroma profiles according to the origin of the wine, in particular for esters. Kontkanen *et al.* (2005) analysed 41 Bordeaux-style blended wines from three different sub-appellations of the Niagara Peninsula in Ontario, Canada. The *Lakeshore* and *Lakeshore plain* sub-appellations were both warmer, with wines of the former showing more dried fruit and less vegetative aromas, while wines from the latter were more vegetative, with the differences attributable to winemaking procedures. Wines from the cooler *Bench* sub-appellation had distinctive spicy notes in the aroma profile.

### 3.2. Compartmentalising the terroir effect in measurable factors

Many studies of the effect of origin (i.e. terroir) on wine typicity, including some of those cited above, found differences in wines produced from different sites. But while such studies may demonstrate that origin has an effect on wine typicity, they may not identify the factors driving these differences. To do so, the terroir effect needs to be broken down in measurable units (van Leeuwen *et al.*, 2018). Major quantifiable factors driving the terroir effect on grape and wine typicity and aroma expression include air and soil temperature, vine water status, solar radiation, and vine nitrogen status (van Leeuwen *et al.*, 2020). Among these factors, air temperature appears to have the strongest impact on grape ripening and aromatic maturity, followed by soil temperature, vine water status, and radiation. Air temperature is highly variable across winegrowing regions worldwide (Gladstones, 2011) and is a clear driver of grape maturity (Coombe, 1992). Soil temperature varies, in particular with soil water content. Soils with high volumetric water content warm up more slowly and are cooler, while dry sandy and gravely soils are warmer (Tesic *et al.*, 2002), with grape ripening on the latter being accelerated (Zelleke and Kliewer, 1979). The impact of air temperature on grape ripening, however, is much greater in magnitude compared to the effect of soil temperature. Vine water status also influences grape ripening (van Leeuwen *et al.*, 2009), as does radiation (Berli *et al.*, 2008). Vine nitrogen status also has a major impact on wine typicity (Peyrot des Gachons *et al.*, 2005; Le Menn *et al.*, 2019), but is less likely to influence the degree of aromatic maturity.

### 3.3. Terroir related factors favouring green, herbal and spicy aroma nuances

High levels of C6 compounds are induced by low sun exposure on grapes (Bureau *et al.*, 2000). UV radiation, however, may have an opposite effect. In a leaf removal trial, the relative-concentration of hexanol and C6 esters (*e.g.*, ethyl *cis*-3-hexenoate, ethyl *trans*-2-hexenoate, *cis*-3-hexenyl and *trans*-2-hexenyl acetate) decreased significantly in a treatment with leaf removal and a UV reducing shield compared to leaf removal alone (Šuklje *et al.*, 2014). Other environmental effects on C6 compounds, like temperature and vine water status, are less well documented in the scientific literature. The sensory impact of these C6 compounds, however, is limited. The abundance of methoxypyrazines in grapes and wines is favoured by low temperatures (Allen *et al.*, 1991; Koch *et al.*, 2012), low radiation (Hashizume and Samuta, 1999 ; Koch *et al.*, 2012) and high water availability (Roujou de Boubée *et al.*, 2000). Antalick *et al.* (2015) report that 1,4-cineole concentrations are higher in Cabernet-Sauvignon from Margaret River (Australia) compared to Cabernet-Sauvignon from Barossa (Australia), which seems to indicate that the concentration of this compound in wine decreases with increasing temperatures and water deficits. Similar observations have been made for 1,8-cineole in French wines by Poitou *et al.* (2017). Capone *et al.* (2012) relate the presence of 1,8-cineole in Australian wines to the proximity of Eucalyptus trees close to the vineyard blocks. However, it remains a matter for debate whether the surrounding vegetation of vineyards, be it natural or not, should be included in the definition of terroir. Higher concentrations of (-)-rotundone are induced by low temperatures (Scarlett *et al.*, 2014; Zhang *et al.*, 2015), high radiation (Homich *et al.*, 2017) and high water availability (Geffroy *et al.*, 2016). Regarding DMS, its precursor is an amino acid derivative (mainly *S*-methylmethionine; Segurel *et al.*, 2004; De Royer Dupré *et al.*, 2014). The concentration of these precursors in must are linked to YAN, and thus impacted by the nitrogen status of the vines. The concentration of DMS in aged wine was shown to be related to both vine water and nitrogen status (Picard *et al.*, 2017; Le Menn *et al.*, 2019).

### 3.4. Terroir related factors favouring floral aroma nuances

Floral nuances in wines are related to several aromatic families, including esters, C13-norisoprenoids and monoterpenes. Monoterpenes in wine increase with vine water deficit (Schüttler *et al.*, 2013). Concentrations in β-ionone increased in grapes from water deficit vines compared to full irrigated control, although the effect was not always statistically significant (Bindon *et al.*, 2007). *β*-ionone was higher in wines from Grenache produced on cool soils with medium to high water holding capacity, compared to those produced on warm soils with low water holding capacity in Côtes du Rhône, France (Sabon *et al.,* 2002). Koundouras *et al.* (2006) found higher levels of C13-norisoprenoids in water deficit vines of Agiorgitiko in Nemea (Greece). Falcão *et al.* (2007) did not find an altitude effect on $\beta$-ionone, indicating that either the concentration of this compound was not dependant on temperature and radiation, or that the effect of lower temperature and higher radiation neutralized each other. C13-norisoprenoids increase with exposure of grapes to sunlight (Marais *et al.*, 1999), probably through an increased induction of their precursors in grapes, which are carotenoids (Kwasniewski *et al.*, 2010).

### 3.5. Terroir related factors favouring fresh fruit aroma nuances

Fresh fruit aroma nuances in wines are linked to a wide range of aroma compounds. Among compounds involved in fruity nuances in wines, esters are of major importance. The relation between the concentration of esters in wines and environmental factors is not easy to establish, because esters are generated during the alcoholic fermentation. Hence, any potential effect of environmental factors is supposed to be indirect. The concentration of esters in wine increases with exposure of vines to water deficit (Chapman *et al.*, 2005) and grapes to radiation (Šuklje *et al.*, 2014), but a possible effect of temperature is not well documented in the literature. The production of esters during alcoholic fermentation is also dependant on must YAN concentration (and thus in relation to vine nitrogen status; Lytra *et al.,* 2020). The impact of vine nitrogen status on the concentration of esters in the resulting wine is not obviously linked to the maturity level of the grapes and beyond the scope of this article.

### 3.6. Terroir related factors favouring ripe and jammy fruit aroma nuances

4MSP and 3SH are volatile thiols linked to black currant aromas in red wine (Bouchilloux *et al.*, 1998; Rigou *et al.*, 2014) and only a few studies have focused on the impact of terroir on their presence in red wines. These compounds result in part from the cleaving of odourless cysteinylated and glutathionylated precursors present in grape and must during alcoholic fermentation (Tominaga *et al.*, 1998, Bonnaffoux *et al.*, 2017). The precursors of the volatile thiol 3SH decrease in grapes with increasing temperatures (investigated for Cabernet-Sauvignon by Wu *et al.*, 2019) and with increasing water deficits (investigated in Sauvignon blanc by Cataldo *et al.*, 2021). The training system, in particular the type of pruning, also influences the amount of 4MSP and 3SH cysteinylated precursors in grapes (Cerreti *et al.*, 2017). 3SH increases in wines produced from grapes exposed to higher levels of radiation (Šuklje *et al.*, 2014; Martin *et al.*, 2016), but decreases when ripening takes place under high temperatures (Paciello *et al.,* 2017). Capone *et al.* (2011b) report that the concentration in precursors of 3MH in grapes depends on their level of maturity. A slow increase after mid-veraison is followed by a sharp increase just prior to commercial harvest. A wide range of esters is also involed in ripe fruit aromas in wine (Pineau *et al.,* 2009). The ripe fruit nuances in red wine attributed to these esters are reinforced by the presence of DMS (Lytra *et al.,* 2014). After aging, the concentrations of DMS in red wine are higher when vines were exposed to high temperatures and water deficits (De Royer Dupré *et al.,* 2014; Le Menn *et al.,* 2019). *β*-damascenone was higher in wines from Grenache produced on dry and warm soils compared to cool soils with higher water holding capacity in Côtes du Rhône (France) (Sabon *et al.,* 2002). In this study, however, the effects of soil temperature and water deficit were not well separated.

### 3.7. Terroir related factors favouring cooked fruit and oxidized prune aroma nuances

Warm temperatures during grape ripening favour dried fruit aromas in wines (Pons *et al.,* 2017; Allamy *et al.,* 2018). Massoia nonalactone is higher in Merlot wines produced from warm vintages in Pomerol (Bordeaux) (Pons *et al.,* 2017). It is likely that this effect is independent of vine water status, because it was observed not only in warm and dry vintages (2003), but also in warm and rainy vintages (2007). Chou *et al.* (2018) and Šuklje *et al.* (2016) found more *γ*-nonalactone in shriveled berries, which may indicate that late water deficit, possibly associated with heat waves (inducing berry dehydration) may increase the concentration of this compound in wine. Bonada *et al.* (2015) investigated interactions between temperature and water deficit and found cooked fruit aromas were increased under high temperature and water deficit, but not under high temperature without water deficit.

### 3.8. General trends in the effect of environmental factors on aromatic maturity

In this article, a classification of aroma nuances in wine is proposed in an increasing order of perceived maturity (Figure 1). Although the molecular basis of these aroma nuances encompasses a wide range of chemical families, general trends in the effect of environmental factors on their abundance in grapes and wines can be observed. The perceived aromatic maturity increases with air and soil temperature. Green, herbal and spicy nuances are favoured by low temperatures, while ripe, dried, or cooked fruit nuances are found more often when grapes ripen under warm conditions. Radiation decreases green nuances in wine due to associated lower levels of methoxypyrazines, while it may increase aroma nuances associated with ripe fruit and, possibly, over-ripe fruit. High radiation may, however, increase fresh peppery notes in wines linked to the abundance of -

(-)rotundone. Vine water deficits lead to a higher degree of perceived maturity in wines. Late water deficit, associated with high temperatures (heat waves) may favour berry shrivelling which induces cooked fruit nuances. A more detailed overview of the impact of temperature, radiation and vine water status on these aroma compounds can be found in van Leeuwen *et al.*, 2020.

## Discussion

### 1. Infuence of the date of harvest on perceived aromatic maturity

Harvest date is obviously an important determinant of aromatic expression in wines. Several references in the literature report on trials for which wines were made from sequential harvest dates, sometimes spanning over several weeks. In Washington State, early harvest of Merlot was associated with fresh vegetable aromas while wines from late harvest exhibited caramel and chocolate aromas (Casassa *et al.*, 2013). On Cabernet-Sauvignon in South Australia, wines from early harvest dates were marked by red fruit or fresh/green aromas, while wines from later harvest dates were characterized by black fruit aromas, bitterness and hotter sensations due to higher ethanol levels (Bindon *et al.*, 2014). Longo *et al.* (2018a) also found that wines from early harvest expressed more herbaceous aromas (Petit Verdot, New South Wales, Australia). Early harvest wines had more intense tomato leaf, green pepper, and red fruit aromas, while wines from late harvest were more intense in dark fruit, black cherry, plum, and black pepper aromas (Longo *et al.*, 2018a). In several of these studies, the molecular basis for the increasing aromatic maturity during grape ripening was investigated.

Most studies found a decrease in compounds associated with vegetative characters in wines the longer grapes ripened. C6 compounds (Hexanol, cis-3-hexenol, trans-2-hexenol and trans-3-hexenol) were associated with early harvest on Syrah in Griffith (New South Wales, Australia, Šuklje *et al.*, 2019). Bindon *et al.* (2013) noted a decrease in C6 compounds and IBMP in Cabernet-Sauvignon wines made from 5 sequential harvest dates in Langhorne Creek (South Australia). However, because their real sensory impact on wines is limited, C6 compounds should rather be considered as markers of the level of maturirty. Roujou de Boubée *et al.* (2000) monitored IBMP in grapes from Merlot and Cabernet-Sauvignon in different vineyards of the Bordeaux area (France) over two vintages and showed a clear decreasing trend over five to seven sampling dates. In a study on Cabernet-Sauvignon in Willunga, South Australia, Kalua and Boss (2009), however, did not observe a decrease of C6 derivatives during grape ripening.

The fruity nuances in wines increase with delayed harvest dates. This was in particular related to an increase in ethyl propanoate and DMS in wines from Syrah in Griffith (Šuklje *et al.*, 2019 ; Antalick *et al.*, 2021). Bindon *et al.* (2013) reported an increase of fatty acid ethyl esters with delayed maturity, which was not confirmed by Antalick *et al.*, 2015 and Šuklje *et al.*, 2019. Substituted acid ethyl esters increased with maturity in wines from Cabernet-Sauvignon and decreased in wines from Syrah (Antalick *et al.*, 2015 and Šuklje *et al.*, 2019). Higher alcohol acetates increase with ripeness, in particular isoamyl acetate, phenylethyl and propyl acetate (Bindon *et al.*, 2013 ; Šuklje *et al.*, 2019). In a trial on Petit Verdot in New South Wales (Australia), Longo *et al.* (2018a) found that increased concentrations of ethyl-2-methyl butanoate and ethyl 3-methyl butanoate in wines from later harvest dates correlated with dark fruit notes, which is consistent with Pineau *et al.* (2009) and Lytra *et al.* (2012). Because esters are products of the alcoholic fermentation, the effect of grape maturity on their concentration in wine is indirect. One hypothesis is that yeast metabolism is enhanced by higher sugar concentrations, resulting in an increase in yeast-derived metabolites, including esters and higher alcohols (Bindon *et al.*, 2013). Nevertheless, esters cannot be considered as just spillover products of sugar metabolism. Trujillo *et al.* (2019) demonstrated that the level of grape maturity (Merlot) strongly impacted ester production during alcoholic fermentation, independently of must sugar and nitrogen compounds concentrations. Fatty acid ethyl esters and higher alcohol acetates concentrations decreased up to 50 % between classical and advanced maturity dates. For other aroma compounds, the impact of the level of maturity is less obvious. $\beta$-damascenone showed no significant differences by harvest date, which was also the case for the monoterpene linalool (Bindon *et al.*, 2013).

## 2. Sensory assessment of grape berries

Grape maturity can be assessed by sensory evaluation of grape berries (Le Moigne *et al.*, 2008a), although this requires intensive training of the panel in order to obtain homogeneous results (Le Moigne *et al.*, 2008b). It works reasonably well for green and cooked fruit aromas, which are both detected in grapes and young wines. Assessment of these descriptors in grapes enables winemakers to predict the intensity of these aromas in the wine to be produced. The aroma impact compounds involved were identified as IBMP for green and MND for cooked fruit aromas, which were transferred from grapes to wines without chemical transformation. Hence, this sensory approach can be completed in tandem with chemical analysis. It has also been shown for Merlot, that the level of over-ripeness of the grapes can be analytically evaluated through the monitoring of MND kinetics during the ripening process (Allamy *et al.*, 2017, Pons *et al.*, 2018). The olfactory detection threshold of MND in must is 62 ng/L, and when MND levels exceed 100 ng/L in must, grapes can be considered as over ripe with aromas reminiscent of prune, figs and dried herbs.

Many aroma compounds, however, are present in grapes in odourless bound forms and released either during the fermentations or during ageing. Other compounds, including esters, are formed during the alcoholic fermentation. Hence, it is not possible to assess the level of aromatic maturity that will be exhibited in the wine by tasting the berries. In order to obtain the desired level of aromatic ripeness, harvest decisions should be based on (i) analysis of primary and, if possible, some key secondary metabolites, (ii) sensory assessment of berries and (iii) experience gathered over previous vintages in the same site of production.

## 3. Achieving technological, phenolic and aromatic maturity simultaneously

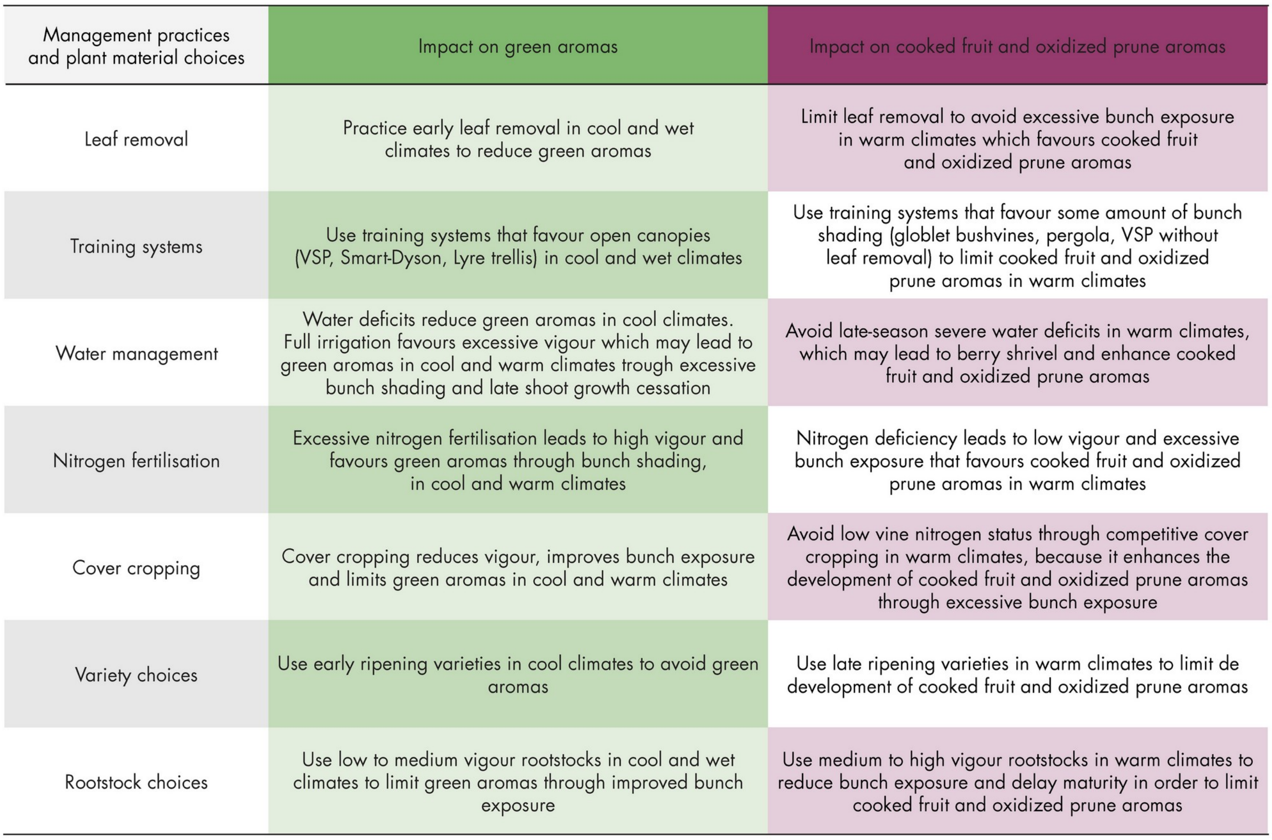
The production of high-quality red wine requires harvesting grapes at optimum maturity. Grape maturity, however, is a phenological stage for which the timing is difficult to assess: the date of optimum maturity depends on the intended wine style, and also on the type of maturity considered (technological, phenolic or aromatic maturity). Grape ripening is highly dependant on environmental conditions and, in particular, temperature. On the one hand, when grapes ripen in very cool conditions, maturity may not be fully achieved. Temperatures decline later in the season and at some point the grapes will no longer continue to ripen. This may result in wines with low alcohol and high acidity, harsh tannins and green aromas. Moderate water deficit and high radiation accelerate grape ripening and can, to a certain point, compensate for low temperatures. On the other hand, when grapes ripen in very warm conditions, the rates of the different types of ripening may be decoupled. This was cleary shown for sugar and anthocyanin accumulation, which are decoupled under high temperatures (Sadras and Moran, 2012; Martinez de Toda and Balda, 2015; Arrizabalaga *et al.*, 2018). It is likely that technological and aromatic maturity are also decoupled under high temperature, although this is less documented in the literature. It means that the simultaneous achievement of technological, phenolic and aromatic maturity, which is a prerequisite for the production of balanced fine wines, is most likely to occur when grape ripening happens under mild conditions, neither too cold, neither too hot. These conditions are most likely to be met when grapes reach full ripeness at the end of the season, in September or early October in the northern hemisphere or in March or early April in the southern hemisphere (van Leeuwen and Seguin, 2006). To a certain extent aromatic maturity can be modulated by adapting the timing of harvest. This adaptation, however, has its limits in extreme temperature conditions. On the one hand, when temperatures are too cold, grapes will never reach full maturity. On the other hand, when temperatures are too hot during grape ripening, technological, phenolic and aromatic maturity are decoupled and it becomes difficult to produce wines with a balanced alcohol/acid ratio and full phenolic ripeness, while avoiding cooked fruit or oxidized prune aromas.

## 4. Grapevine variety selection considering local climate conditions

Temperature, radiation, and water availability are specific to the site where the wine is produced. As such, they are major drivers of terroir expression (van Leeuwen *et al.*, 2004). They also craft the aromatic signature of the wine produced, in relation to its origin (van Leeuwen *et al.*, 2020). When producing wine at a specific site, the temperature regime during grape ripening does not only depend on the local climatic conditions, but also on the phenology of the variety being cultivated. The grower cannot change the temperature regime, but can advance or delay the ripening period by choosing respectively an early or late ripening variety. Hence, it makes sense to cultivate early ripening varieties under cool climatic conditions, where reaching full ripeness is challenging, and late ripening varieties in warm climates, where the decoupling of technological, phenolic and aromatic maturity is a potential risk (Table 1). Temperature requirements for reaching sugar ripeness have recently been published for a wide range of varieties, allowing to fine-tune varietal choices to local temperature summations (Parker *et al.*, 2020). Happ (2000) showed that great wines are produced in conditions where the heat load, expressed in degree.hours over 22 °C during the four weeks prior to harvest, is relatively low. This is the case in cool climate sites, but also in warmer climates when late ripening varieties are grown. Delaying the ripening period later in the season not only exposes the grapes to lower average daily temperatures, but also to a more limited number of hours above 22 °C, due to the shortening of days as the season progresses.

Each variety has its aromatic signature (Robinson *et al.*, 2013; Ilc *et al.*, 2016). This signature, however, is extremely variable depending on the level of aromatic maturity at grape harvest, either because of the timing of harvest, or because of local environmental conditions, in particular temperature. When grapes are harvested under similar temperature conditions there are aromatic similarities among wines from Merlot, Syrah and Cabernet-Sauvignon: exhibiting green, herbal, or spicy nuances when ripened under cool conditions; or jammy or cooked fruit nuances when ripened under very warm conditions. The aromatic signature of each of these varieties, however, can be very different when compared under very cool and very warm ripening conditions, e.g., northern

Côtes du Rhône (French) versus Barossa (Australian) Syrah, or Bordeaux (French) Merlot versus Merlot from Alentejo (southern Portugal).



| Management practices and plant material choices | Impact on green aromas | Impact on cooked fruit and oxidized prune aromas |
|---|---|---|
| Leaf removal | Practice early leaf removal in cool and wet climates to reduce green aromas | Limit leaf removal to avoid excessive bunch exposure in warm climates which favours cooked fruit and oxidized prune aromas |
| Training systems | Use training systems that favour open canopies (VSP, Smart-Dyson, Lyre trellis) in cool and wet climates | Use training systems that favour some amount of bunch shading (globlet bushvines, pergola, VSP without leaf removal) to limit cooked fruit and oxidized prune aromas in warm climates |
| Water management | Water deficits reduce green aromas in cool climates. Full irrigation favours excessive vigour which may lead to green aromas in cool and warm climates trough excessive bunch shading and late shoot growth cessation | Avoid late-season severe water deficits in warm climates, which may lead to berry shrivel and enhance cooked fruit and oxidized prune aromas |
| Nitrogen fertilisation | Excessive nitrogen fertilisation leads to high vigour and favours green aromas through bunch shading, in cool and warm climates | Nitrogen deficiency leads to low vigour and excessive bunch exposure that favours cooked fruit and oxidized prune aromas in warm climates |
| Cover cropping | Cover cropping reduces vigour, improves bunch exposure and limits green aromas in cool and warm climates | Avoid low vine nitrogen status through competitive cover cropping in warm climates, because it enhances the development of cooked fruit and oxidized prune aromas through excessive bunch exposure |
| Variety choices | Use early ripening varieties in cool climates to avoid green aromas | Use late ripening varieties in warm climates to limit de development of cooked fruit and oxidized prune aromas |
| Rootstock choices | Use low to medium vigour rootstocks in cool and wet climates to limit green aromas through improved bunch exposure | Use medium to high vigour rootstocks in warm climates to reduce bunch exposure and delay maturity in order to limit cooked fruit and oxidized prune aromas |

**Table 1. Management practices and plant material choices to avoid green, cooked fruit and oxidized prune aromas in cool and warm climates.**

## 5. Infuence of management practices on perceived aromatic maturity

Each site offers a particular combination of resources to the vines (temperature, light, water, nutrients), and based on the concept of terroir, explains why wines produced at different sites have specific sensory attributes (van Leeuwen *et al.*, 2018). These resources can, to a certain extent, be manipulated through management practices. Canopy management can modulate light and temperature in the fruit zone (Smart and Robinson, 1991) and water availability can be managed through irrigation practices (Dry *et al.*, 2001). These and other management practices can be adapted to local environmental conditions. The water use characteristics of a vineyard can also be affected by decisions regarding planting densities or vine architecture (Lebon *et al.*, 2003; van Leeuwen *et al.*, 2019a). When excessively cool ripening conditions induce the risk of green aroma nuances, improving bunch exposure by leaf thinning may increase radiation and temperature, and hence improve aromatic maturity (Koch *et al.*, 2012) (Table 1). Under these conditions water deficits can also help avoid green aroma nuances. Conversely, under warm temperatures, canopy management that results in partial shading of grape bunches may limit the risk of cooked fruit and oxidized prune aromas. Moderately low vine nitrogen status and cover cropping limit green aromas in cool and wet climates through reduced vigour and improved bunch exposure (van Leeuwen *et al.*, 2020). Nitrogen deficiency and excessively competitive cover cropping should be avoided in warm climates, because these practices favour bunch exposure, which enhances the development of cooked fruit and oxidized prune aromas (Table 1).

## 6. Unexpected outcomes of aromatic maturity

Major drivers of aromatic maturity are temperature, radiation and water availability. In general, cool sites tend to have lower levels of radiation and higher water availability. Warm sites tend to be more exposed to high radiation and drought. Hence, the former are expected to produce wines with lower aromatic maturity, while the latter produce wines with higher aromatic maturity. In some situations, however, environmental drivers of terroir expression (temperature, light and water availability) are combined in a different way. A particular example are high altitude vineyards, where low temperatures may be combined with high radiation and, possibly, water deficits. In this situation, the aromatic maturity can be greater than expected on the basis of the temperature regime alone. Falcão *et al.* (2007) addresses the issue of the effect of altitude on methoxypyrazine concentrations in wines, but more research is needed on the effect of altitude with a better separation of the effect of temperature and radiation. In heavily irrigated vineyards in warm climates, which can result in dense vine canopies, high temperatures may be associated with low levels of radiation in the bunch zone and no water deficit. In a worst case scenario, this could result in wines having both vegetal and cooked fruit aromas.

## 7. Trends in the management of harvest dates

Viticulturists and winemakers are generally keen to improve phenolic ripeness. There is a common belief among winemakers that delaying harvest can increase fruity characters, mouth feel and colour in wine, although scientific evidence is limited and mostly anecdotal (Bindon *et al.*, 2014). Phenolic ripeness is very difficult, if not impossible, to measure in production conditions. Le Moigne *et al.* (2008b) describes a methodology for the evaluation of grape berry ripeness by sensory assessment, although, Rabot *et al.* (2017) consider that this technique remains subjective. The trend in increasing alcohol levels in wines worldwide (Mira de Orduña, 2010; van Leeuwen *et al.*, 2019b) is partly due to changing climatic conditions (Webb *et al.*, 2012; Alston *et al.*, 2015), but also to increased « hang time » (i.e. the delay between veraison and harvest ; van Leeuwen and Destrac-Irvine, 2017). At the same time, however, consumers are tending to prefer wines with lower alcohol levels (Saliba *et al.*, 2013). Delayed harvest also increases aromatic maturity (Casassa *et al.*, 2013; Bindon *et al.*, 2013, 2014; Longo *et al.*, 2018a, Longo *et al.*, 2018b; Šuklje *et al.*, 2019). When delaying harvest to improve (poorly defined) phenolic ripeness, there is a clear risk that grapes are picked not only at unbalanced technological maturity (excessively high sugar levels and pH), but also at an undesirable level of aromatic maturity where cooked fruit and oxidative prune aroma nuances become predominant. Conversely, the willingness to decrease the alcohol level and to preserve freshness could lead to excessively early harvests, giving wines with unbalanced tastes and textures.

## 8. Effect of climate change

Wine styles are changing worldwide in most production areas under the effect of climate change. Trends in increasing alcohol levels and pH are well documented (van Leeuwen *et al.*, 2019b). Modifications in aromatic maturity due to climate change are less well documented in the scientific literature, but largely acknowledged in the professional press (Goode, 2017; Cukierman *et al.*, 2021). Given the proven effect of temperature and water deficit on aromatic maturity, these modifications are not surprising. Climate change not only increases tempertures, but also shifts phenology. Hence, grape ripening is taking place earlier in the season, when temperatures are higher. The combined effect of higher temperatures and shifted phenology can double the temperature increase during grape ripening compared to the effect of increased temperures alone (Molitor and Junk, 2019). Hence, when no adaptations are implemented, aromatic maturity in grapes and wines will increase under climate change. To maintain wine typicity in production areas, grape ripening must be delayed and maintained, if possible, at the end of the season (September or early October in the northern hemisphere or March or early April in the southern hemisphere). This can be achieved by modifying training systems, decreasing leaf area/fruit weight ratio, performing late pruning, or planting later ripening clones and varieties (Friend and Trought, 2007; van Leeuwen and Destrac, 2017; Naulleau *et al.*, 2021; Gutiérrez-Gamboa *et al.*, 2021). The most drastic, but also one of the most effective adaptations is a change in the grapevine variety. Growers and consumers sometimes fear that this may change aromatic typicity of the produced wines. However, there is probably less difference in aromatic typicity between wines from two different varieties (e.g., Cabernet-Sauvignon versus Merlot) produced in similar growing conditions, than between wines from one of those varieties produced under very different growing conditions.

## Concluding remarks

Terroir expression is driven by the influence of locally available resources (temperature, light, water, and nutrients) on wine quality and typicity, with aroma expression being a particularly important facet of wine typicity. Aroma nuances in wines can be classified according to the aromatic maturity at which the grapes are harvested (Figure 1). Hence, aromatic maturity is a cornerstone of terroir expression. Excessively green aromas (e.g., tomato leaves, freshly cut grass) are not desirable in red wines, nor are excessively ripe aromas (e.g., cooked fruit or oxidative prune nuances). In between these extremes, aroma nuances ranging from herbal, spicy, floral, fruity, to jammy induce aromatic typicity and give identity to the wine in relation to its place of origin. Selection of grapevine varieties should take into account their thermal requirements in relation to local temperature summations, such that grape ripening occurs at the end of the season when temperatures are not too cool or hot. If temperatures during grape ripening end up being excessively cool or hot, management practices can help by advancing or delaying aromatic maturity, in order to avoid green, cooked fruit, or oxidative prune aromas in the produced wines.

Some aroma compounds, like methoxypyrazines, are present in similar form in grapes and wines. Others, like volatile thiols, are present in grapes as precursors. Analytical procedures need to be improved to facilitate the monitoring of these compounds during grape ripening. Easy access to their dynamics would optimize targeting harvest dates for desired aromatic maturity in wines. Furthermore, investigations need to be conducted for identifying additional markers of aromatic maturity in grapes, in particular those related to cooked fruit aromas.

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