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Recent advancements in understanding the terroir effect on aromas in grapes and wines

Cornelis van Leeuwen[1*], Jean-Christophe Barbe[2], Philippe Darriet[2], Olivier Geffroy[3], Eric Gomès[1], Sabine Guillaumie[1], Pierre Helwi[4], Justine Laboyrie[2], Georgia Lytra[2], Nicolas Le Menn[2], Stéphanie Marchand[2], Magali Picard[2,5], Alexandre Pons[2,6], Armin Schüttler[2,7] and Cécile Thibon[2]

[1]EGFV, Université de Bordeaux, Bordeaux Sciences Agro, Inrae, ISVV, 33882 Villenave d'Ornon, France
[2]Unité de Recherche Œnologie, EA 4577, USC 1366 INRA, ISVV, Université de Bordeaux, 33882 Villenave d'Ornon France
[3]PPGV, Université de Toulouse, INP-PURPAN, 75 voie du TOEC, F-31076 Toulouse Cedex 3, France
[4]Texas A&M AgriLife Extension Service, TAMU, Lubbock 79403, Texas, United States
[5]Demptos Research Center, CESAMO, Institut des Sciences Moléculaires, Univ. Bordeaux, 351 Cours de la Libération, F-33405 Talence, France
[6]Tonnellerie Seguin-Moreau, ZI Merpins, 16103 Cognac
[7]Hochschule Geisenheim Unversity, Von-Lade-Strasse 1, 65366 Geisenheim, Germany

*corresponding author: vanleeuwen@agro-bordeaux.fr

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ABSTRACT

Terroir is about the link between wine and its origin. It has long been understood by sensory evaluation that the taste of wine from a given variety can be related to its origins. Specific organoleptic characteristics of wine are influenced by environmental factors such as soil and climate. By deconstructing the effect of measurable soil and climate parameters on grape and wine aroma compounds, the terroir effect on wine typicity can be better understood. Climate influences on vine development and grape ripening are mainly associated with temperature, radiation and rainfall, while soil influences are primarily associated with water availability and nitrogen supply. Significant advances have been made over recent years in understanding wine aromas and their molecular basis and influences of climate and soil on a wide range of molecules responsible for wine aroma expression. This article aims to review these recent research advances to obtain a more comprehensive understanding of how terroir influences wine typicity. The effect of terroir on wine quality and typicity is sometimes considered intangible and difficult to explain on a scientific basis. By combining agronomic, analytical and sensory approaches, however, this review shows that the terroir effect is mediated by measurable factors that can easily be monitored in the vineyard. Assessment of the results compiled by this review allows the suggestion that terroir expression at specific sites might be maximized by choosing appropriate plant material in relation to soil and climate, by acting on manageable parameters like vine water and nitrogen status, or by implementing canopy management to modify microclimate in the bunch zone.

KEYWORDS

Terroir, soil, climate, temperature, radiation, water balance, nitrogen, vine, wine, aroma, typicity

INTRODUCTION

1. Understanding the effect of terroir on wine typicity

The quality and style of wine are influenced by the place where the vines grow (Jackson and Lombard, 1993). It is acknowledged that particular local soil and climate conditions have a major influence on wine sensory attributes (Seguin, 1988; van Leeuwen *et al.,* 2004). The winegrower is also of importance in shaping this so-called terroir effect by choosing plant material and vineyard management practices adapted to local soil and climate conditions (van Leeuwen and Seguin, 2006) and the winemaker needs to translate berry composition into optimum wine quality by the use of appropriate winemaking techniques. Climate has long been considered as a major factor in wine production (Winkler, 1965; Jones and Davis, 2000). The influence of soil on grape ripening and wine quality has been investigated by many authors (Seguin, 1969; Bodin and Morlat, 2006; Morlat and Bodin, 2006; Renouf *et al.,* 2010; van Leeuwen *et al.,* 2018). However, to go beyond a descriptive link between wine typicity, soil and climate, it is necessary to break these down into measurable parameters (van Leeuwen *et al.*, 2018). The climate acts primarily through the influence of air temperatures, rainfall and radiation. Temperature acts on phenology (Duchêne and Schneider, 2005; Parker *et al.,* 2011) and grape ripening (Coombe, 1986). Solar radiation influences photosynthesis (Zufferey *et al.,* 2000) and secondary metabolites in grapes (Spayd *et al.,* 2002; Alonso *et al.,* 2016). Soil provides nutrients to the vines. Among these, nitrogen (N) is of major importance, because it influences yield, vigour and grape composition at ripeness (Spayd *et al.,* 1993; Hilbert *et al.,* 2003; Trégoat *et al.,* 2002). Vine water status is determined both by soil type and rooting depth (through their effect on soil water holding capacity) and climate (through rainfall and reference evapotranspiration). Vine water status influences shoot development (Pellegrino *et al.,* 2005), yield (Matthews and Anderson, 1989), grape ripening (van Leeuwen *et al.,* 2009) and fruit composition (Matthews and Anderson, 1988). Hence, the terroir effect can be assessed through the measurement of air temperatures, radiation, rainfall, soil water holding capacity and vine nitrogen status. Comprehensive databases are published on air temperatures in winegrowing regions (Gladstones, 2011) and temperature zoning within winegrowing regions is accessible at an increasingly finer scale (Santos *et al.,* 2012; Bois *et al.,* 2018; de Rességuier *et al.,* 2020). Radiation can be easily quantified as well (Smart, 1986). Many indicators have been validated to assess vine nitrogen status (Spayd *et al.,* 1993; van Leeuwen *et al.,* 2000; Hilbert *et al.,* 2003) and vine water status (Cifre *et al.,* 2005; van Leeuwen *et al.,* 2009; Rienth and Scholasch, 2019). Today, major parameters determining terroir expression can be quantified and even spatialized at vineyard scale (van Leeuwen *et al.,* 2018; de Rességuier *et al.,* 2020).

2. Aromas in grapes and wines

Aroma expression in wine is of major importance (Peynaud and Blouin, 2013) and aromas can be classified as primary (produced during grape ripening), secondary (produced during fermentation) and tertiary (produced during wine ageing) (Ribéreau-Gayon *et al.,* 2020). The odorous compounds associated with primary aromas can either be free (volatile compounds) or bound (conjugated) initially to other molecules in grapes and revealed later, during fermentation, or ageing (Rapp, 1988). Although classified as secondary aromas, ester compounds produced during fermentation are more or less abundant depending on wine composition. Hundreds of odorous compounds have been identified in wines and these can be grouped in specific families (Ferreira, 2010; Ribéreau-Gayon *et al.,* 2020).

2.1. Green and peppery flavours

One family includes several compounds involved in green aromas. Major contributors are methoxypyrazines, in particular 2-methoxy-3-isobutylpyrazine (IBMP) (Allen *et al.,* 1991; Lacey *et al.*, 1991). IBMP is responsible for the odour of green (bell) pepper. C6 compounds are also involved in green aromas (González-Barreiro *et al.,* 2015). The abundance of C6 compounds in wines is modulated by winemaking processes (Ferreira *et al.,* 1995a). The literature is, however, scarce about a possible impact of environmental factors on their presence in grapes and wines. 1,8-cineole is a monoterpene providing minty flavours to wine (Capone *et al.,* 2011; Poitou *et al.,* 2017). (-)-rotundone is a sesquiterpene that is an important aroma compound of Syrah and some other varieties, responsible for peppery notes (Wood *et al.,* 2008).

2.2. Other monoterpenes

Terpenes are an important family of grape and wine aromas that can be found as free compounds or glycosidated forms in grapes (Marais, 1983). They have been identified for their involvement in the Muscat aromas of many grapevine varieties (Muscat, Gewürztraminer, Riesling) (Park and Noble, 1993).

2.3. Volatile thiols and C_{13}-norisoprenoids

Volatile thiols are an aroma family first identified in Sauvignon blanc but also present in numerous other varieties (Darriet *et al.,* 2012). They are present in grapes as non-odorant glutathione or cysteine bound precursors that are released during alcoholic fermentation by the yeast (Peyrot des Gachons *et al.,* 2000). The most important volatile thiols are 3-sulfanylhexanol (3SH, grapefruit), 3-Sulfanylhexyl acetate (3SHA, passion fruit) and 4-methyl-4-sulfanylpentan-2-one (4MSP, boxwood) (Tominaga *et al.,* 1998). C_{13}-norisoprenoids, are another family of major compounds involved in wine aroma (Lee *et al.,* 2007). Among these, β-damascenone is described by fruity-flowery or baked apple nuances (Kotseridis *et al.,* 1999, Pineau *et al.,* 2007), while 1,1,6-trimethyl-1,2-dihydronaphtalene (TDN) recalls kerosene-like notes (Marais *et al.,* 1992). The latter is particularly present in older Riesling wines (Simpson*,* 1978; Simpson*,* 1979; Sacks *et al.,* 2012; Ziegler *et al.,* 2019). Megastigmatrienone is a C_{13}-norisopreniod with the smell of spices and tobacco (Slaghenaufi *et al.,* 2016). Hence, this compound is often referred to as "tabanone".

2.4. Dried fruit aromas

Recently, several compounds involved in dried fruit aromas in must and red wines have been identified, including massoia lactone (Pons *et al.,* 2017a), γ-nonalactone and furaneol (Pons *et al.,* 2008), 3-methyl-2,4-nonanedione (MND, Pons *et al.,* 2011) and (Z)-1, 5-octadien-3-one (Allamy *et al.,* 2017). The aromatic expression of this family of compounds is specific to the phenomenon of over-ripening in grapes and is detected in wines resulting from their vinification.

2.5. Substitutes esters and qualitative fruit aromas

Substituted esters are another important family of compounds with several studies demonstrating their particular sensory impact on fruity expression in red wines, even when these compounds were present at concentrations below their olfactory thresholds. Numerous synergistic effects between fruity compounds have been described in the past, highlighting the fact that these esters increased the perception of fruity aromas (Cameleyre *et al.,* 2015).

2.6. Other aroma compounds and complementary observations

Dimethyl sulphide (DMS) is an aroma compound in wine reminiscent of blackcurrant at low concentration, truffle or undergrowth at medium concentration and green olive or asparagus at high concentration (Spedding and Raut, 1982; Anocibar-Beloqui *et al.,* 1996). DMS concentration is positively correlated to ageing bouquet complexity of great Bordeaux red wines (Picard *et al.,* 2015). Although DMS does not present fruity aromas, it has an indirect impact on fruity aroma expression, enhancing, at low concentrations, blackcurrant aroma (Lytra *et al.,* 2014). Aromatic *N,S*-heterocycles form a large family of compounds involved in wine aroma with a broad spectrum of odours from meat to cooked potatoes, roasted coffee or hazelnut (Marchand *et al.,* 2000). Finally, o-aminoacetophenone (AAP) is associated with the untypical ageing flavour in white wines, in particular from Riesling (Rapp *et al.,* 1993). Wines with high levels of AAP recall naphthalene, floor polish, acacia blossom or mothballs and displaying a metallic bitterness on the palate (Schneider, 2014).

Volatile odorous compounds are not variety specific, but rather their concentration generally varies with the cultivar. For instance, Riesling wines contain more TDN compared to wines from Chardonnay or Gewürztraminer (Sacks *et al.,* 2012) and wines from Cabernet-Sauvignon or Carmenère contain more IBMP than wines from Merlot (Roujou de Boubée *et al.,* 2000). Aroma compounds in wine can also vary to a large extent with environmental conditions like soil or climate (Dunlevy *et al.,* 2009; Pons *et al.,* 2017b). The influence of variety, soil and climatic conditions on the taste of wine is referred to as the "terroir effect" (van Leeuwen and Seguin, 2006). To quantify the effect of soil and climate, they need to be broken down into measurable parameters, such as air temperature, radiation, vine water status and vine nitrogen status (van Leeuwen *et al.,* 2018). This article aims to review the impact of these soil and climate parameters on major aroma compounds expressed in wine, to better understand how terroir shapes wine typicity. The interplay between climate, soil, grapevine variety and management techniques (including winemaking) is, however, complex and wine typicity cannot be totally predicted beforehand. Additionally, this review highlights gaps in the existing literature where more research is needed to improve our understanding of the terroir effect.

EFFECT OF MAJOR TERROIR FACTORS ON AROMA EXPRESSION IN GRAPES AND WINES

1. Effect of air temperature

1.1. Green and peppery flavours

Methoxypyrazines are particularly odorant green flavours in grapes and wines. They are present as free aromas in grapes and their concentration does not vary during wine ageing (Roujou de Boubée *et al.,* 2000). IBMP is the most impacting methoxypyrazine in wine, mainly present in Sauvignon blanc or Cabernet-Sauvignon wines. During maturation, methoxypyrazines, and in particular, IBMP, decrease in grapes with increasing temperatures. This decrease is similar in magnitude compared to the effect of light (Koch *et al.,* 2012). Falcão *et al.* (2007) showed that IBMP increased with the altitude of the vineyard, which can be attributed to lower temperatures. This observation is important because at higher altitudes light intensity is generally higher compared to low altitudes, which shows that in this study the effect of temperature is independent of the effect of light. In most studies where leaf removal is considered, the effect of temperature and sunlight cannot be separated (Roujou de Boubée *et al.,* 2000). In an experiment where grapes were heated by 1.5 °C average over the season without modifying radiation, Cabernet-Sauvignon contained less IBMP at bunch closure while at this stage there was no difference with the control in Sauvignon blanc grapes (Wu *et al.,* 2019). 1,8-cineole is a monoterpene with a menthol/eucalyptus flavour, particularly present in wines from Cabernet-Sauvignon. Its concentration decreases with temperature (Antalick *et al.,* 2015; Poitou *et al.,* 2017). However, in these studies, the effect of temperature and vine water status were not totally differentiated: vintages with lower 1,8-cineole content in wines were also dryer. Rotundone is a peppery flavour present in grapes and wines from Syrah and some other varieties. It has been highlighted that cool vintages were favourable to obtaining high levels of (-)-rotundone in wines (Caputi *et al.,* 2011). Notably, high temperatures during the ripening period, expressed in degree hours above 25 °C or 30 °C, decrease (-)-rotundone in grapes and wines (Zhang *et al.,* 2015a; Zhang *et al.*, 2015b; Harner *et al.,* 2019). Delayed fruit ripening by pre-véraison treatment of Syrah grapes with 1-naphthaleneacetic acid (NAA) increased (-)-rotundone in grapes and wines (Davies *et al.,* 2015).

1.2. Other monoterpenes

Contradictory results are reported about the effect of temperature on terpenols. A negative effect of higher temperatures was shown on monoterpene concentrations and in particular linalool and geraniol (Duchêne *et al.,* 2016). This decrease was correlated with a decrease of linalool synthase gene expression. Belancic *et al.* (1997) also suggested that high berry temperature negatively affects monoterpene concentrations in berries. Conversely, other studies showed a positive effect of increased growing degree days on monoterpenes, and in particular linalool, in Riesling and other varieties (Marais *et al.,* 1992; Reynolds *et al.,* 1995; Schüttler *et al.,* 2013). The distribution pattern of single monoterpenes is temperature-dependant (Marais *et al.,* 1992). All of these studies did not allow, however, to decouple the effect of sun-exposure/radiation from temperature.

1.3. Volatile thiols and C13-norisoprenoids

The impact of temperature on volatile thiols is not fully understood, although 4MSP seems to decrease under high temperatures in wines from Sauvignon blanc (Darriet *et al.,* 2019). In a field experiment where grapes were heated by 1.5 °C on average without modifying incoming radiation, the aldehydic glutathionylated precursor of 3SH (Glut-3SH-Al) was much lower in grapes from Cabernet-Sauvignon and Sauvignon blanc compared to the control (Wu *et al.,* 2019). Marais *et al.* (1992) showed that cool climate Riesling from Germany contained less TDN compared to warm-climate Riesling from South-Africa. In leaf removal trials, warmer grapes produce wines with higher TDN levels, although these experimental designs do not allow separating the effect of temperature from the effect of sunlight (Kwasniewski *et al.,* 2010). No relation was found with altitude (temperature) for α-ionone, β-ionone and β-damascenone (Falcão *et al.,* 2007). Tabanone levels are higher in Bordeaux wines produced from warmer vintages (Le Menn *et al.,* 2019). This observation, however, does not exclude possible interference of other factors like water deficit, because warm vintages are often (but not always) dryer vintages.

1.4. Dried fruit aromas

There is a clear effect of temperature on compounds involved in dried fruit aromas. The concentration of aroma-impact compounds like γ-nonalactone (coconut, cooked peaches) (Pons *et al.,* 2008), massoia lactone (dried figs), furaneol (caramel) or MND (anis, fruit pit) (Pons *et al.,* 2017a) were higher is must and wine samples marked by this aroma. Field experiments as well as those conducted in the laboratory demonstrated that Merlot was much more likely to develop these aroma compounds than Cabernet-Sauvignon. It is also worth mentioning that (Z)-1,5-octadien-3-one, reminiscent of dried figs at low concentrations (< 100 ng/L), increased in dried grapes in a warm incubator (Allamy *et al.,* 2018). Precursors of these compounds were not clearly identified, but high temperatures at the end of maturation likely enhance in situ oxidation mechanisms leading to fatty acid family cleavage as well as to Maillard chemical reactions, which explains the formation of these compounds in grapes. It is likely that the temperature effect is independent of vine water status because γ-nonalactone and massoia lactone content in wines from a Pomerol estate (Bordeaux) were high in warm vintages, whether they were dry (2003) or wet (2007) (Pons *et al.,* 2017a).

1.5. Other aroma compounds and complementary observations

Le Menn *et al.* (2019) observed particularly high DMS levels in Bordeaux wines of the very warm 2003 vintage, perhaps due to either a high production of the precursors of DMS (pDMS) in the berries or to the increased transformation of pDMS into DMS associated with high yeast-available nitrogen as reported by De Royer Dupré *et al.* (2014). Le Menn *et al.* (2019) also observed that aromatic heterocycles seemed to be higher in aged wines from warm vintages. Several hypotheses, such as production in the berries by Maillard-like reactions, presence of high cysteine concentrations in wine acting like a precursor, or high pH need to be explored. Although not an aroma compound, glutathione is of particular importance in aroma expression in wines, because it acts as a preserving agent for white and rosé wine aromas (in particular for volatile thiols) during wine production and ageing. Wines produced in the Bordeaux area showed lower levels of glutathione in warm years, but this effect was not independent of a possible effect of water deficit (Pons *et al.,* 2015; Pons *et al.,* 2017). There is, however, scientific evidence for a temperature effect on glutathione, whereby antioxidant compounds like glutathione and ascorbate tend to decrease in plants under high temperatures (Szymańska *et al.,* 2017). Moreover, such grapes contain higher levels of polyphenols, which increases their sensitivity to oxidation mechanisms, resulting in a quick decrease of glutathione in grape must during crushing and pressing (Nikolantonaki *et al.,* 2012). An in-depth review on the effect of temperature on wine composition, including aroma compounds was published by Drappier *et al.* (2017).

2. Effect of radiation

2.1. Green and peppery flavours

Hashizume and Samuta (1999) observed lower levels of IBMP in grapes under high radiation. Most studies on the impact of light on methoxypyrazines are conducted in leaf removal trials, where the effect of sunlight and temperature cannot be separated (Ryona *et al.,* 2008). In one of the rare studies where light and temperature could be separated, Koch *et al.* (2012) concluded that the effect of light in decreasing IBMP concentrations in grapes acts prior to véraison. Varying light conditions after véraison did not modify IBMP content in grape berries. These authors showed that the depressing effect of high temperature and high light intensity on methoxypyrazines was similar in magnitude. There seems to be no impact of UV-B intensity on IBMP (Gregan *et al.,* 2012). C6 compounds are lower in sun-exposed bunches compared to shaded bunches (Bureau *et al.,* 2000). The effect of light on (-)-rotundone has not been formally investigated but there is evidence suggesting a stimulating effect. Indeed, mean irradiation, hours of sunshine and cumulative solar exposure (CSEv) over the maturation showed a positive contribution to prediction models for (-)-rotundone concentrations in wine (Geffroy *et al*., 2019a; Harner *et al.,* 2019). These observations are in accordance with studies showing that defoliation can enhance (-)-rotundone when implemented in cool-climate vineyards, where the increasing effect on berry surface temperature is limited (Homich *et al.,* 2017, Geffroy *et al.,* 2019b).

2.2. Other monoterpenes

Terpenols were decreased in artificially shaded bunches of Muscat de Frontignan compared to the control, while they were not in naturally shaded bunches. This could be, however, an indirect effect, because the temperature was higher in artificially shaded bunches, but much lower in naturally shaded bunches compared to the control (Bureau *et al.,* 2000). Exposure to full sunlight increased terpenol content in Traminette (Skinkis *et al.,* 2010). In an experiment where the effect of light and temperature were well separated, Friedel *et al.* (2016) showed that exposure to light increased monoterpenes in Riesling grape berries. Terpene synthase genes responded positively to light. Total substituted esters slightly increased with higher radiation, while linalool increased with exposure to light and UV-B (Šuklje *et al.,* 2014). However, in this research project, an interference with temperature cannot be excluded, the light-exposed treatments being slightly warmer.

2.3. Volatile thiols and C_{13}-norisoprenoids

3SH increases with the exposure to sunlight and UV-B, while 3SHA increases with the exposure to sunlight, but not with UV-B (Šuklje et *al.,* 2014). In this leaf removal experiment, the effect of sunlight was, however, not well separated from the effect of temperature. The effect of UV-B on 3SH is consistent with Kobayashi *et al.* (2011), who showed that UV-B radiation increases the production of precursors of this thiol. C_{13}-norisoprenoids increase under higher sunlight (Marais *et al.,* 1999), probably because of an increase in their precursors, which are carotenoids (Kwasniewski *et al.,* 2010). Schultz *et al.* (1998) demonstrated that carotenoid levels in Riesling decreased by eliminating UV-B radiation at controlled temperatures. Kwasniewski *et al.* (2010), Schüttler *et al.* (2013) and Schüttler *et al.* (2016) showed higher TDN levels in Riesling wines from sun-exposed grapes, with greater impact of early leaf removal (Schüttler *et al.,* 2013), but in this trial, the effect of light and temperature were not well separated. In another leaf removal experiment, Riesling grapes shaded by cloth showed lower TDN concentrations than naturally shaded grapes (Gerdes *et al.,* 2001), indicating the importance of radiation quality. Schüttler *et al.* (2013) showed that sun exposure on grapes increased TDN levels in young wines (12 months after bottling), but this effect disappeared after 22 months of ageing.

2.4. Dried fruit aromas

Dried fruit aromas (furaneol, homofuraneol and γ-nonalactone) increased post-harvest under light exposure but not carbonyl compounds such as MND and (Z)-1,5-octadien-3-one (Allamy *et al.,* 2018). Regarding the latter, it is not excluded that under the experimental conditions the effect of dehydration overruled a possible radiation effect.

2.5. Other aroma compounds and complementary observations

High UV-B levels are associated with increased AAP content in white wines (Hühn *et al.,* 1999; Schultz, 2000). Under high radiation antioxidant compounds like glutathione and ascorbate tend to decrease in plants (Szymańska *et al.,* 2017). Total phenolics increase with exposure of grapes to light (Alonso *et al.,* 2016) and UV-B (Gregan *et al.,* 2012), which may negatively impact volatile thiols in white wine production during pre-fermentation processes.

3. Effect of vine nitrogen status

3.1. Green and peppery flavours

Many studies found an increase of IBMP in wine produced from vines with high nitrogen status. Nitrogen status does not, however, directly affect IBMP content in grapes but does so indirectly. High N vines are often vigorous and more prone to bunch shading, which decreases both the temperature of the grapes and their exposure to sunlight (Mendez-Costabel *et al.,* 2014). In an experiment where vine N status was decoupled from vine water status and where no marked differences in vigour were recorded between the control and vines with high N status, IBMP content in grapes was not affected (Helwi *et al.,* 2015). It can thus be concluded that high nitrogen status does not affect directly IBMP content in grapes but indirectly, through an altered bunch microclimate. In a nitrogen fertilization trial (30 vs. 60 kg N/ha/year), Mendez-Costabel *et al.* (2014) found no effect on C6 compounds. No research was found studying the effect of vine nitrogen status on (-)-rotundone. However, as with IBMP, an indirect increase bunch microclimate as a consequence of higher plant vigour can be expected.

3.2. Other monoterpenes

Few studies are dedicated to the effect of vine nitrogen status on monoterpenes. Terpenes are reported to decrease with nitrogen fertilisation (Garde-Cerdán *et al.,* 2015).

3.3. Volatile thiols and C_{13}-norisoprenoids

Many studies report a consistent effect of vine nitrogen status on volatile thiols. Volatile thiols are higher in wines produced from vines which are naturally high in nitrogen (due to soil type and climatic condition, Peyrot des Gachons *et al.,* 2005) In a fertilisation trial, Choné *et al.* (2006) managed to produce grapes with much-increased content in volatile thiol precursors due to fertilisation with 60 kg N/ha/year. Nitrogen was applied to the soil around bloom, to limit a possible impact on vine vigour. Similar results were obtained by Lacroux *et al.* (2008). In their experiment nitrogen fertilisation was also applied late in the season, through foliar applications. They observed that the addition of sulphur to the foliar nitrogen application increased the effect on volatile thiols. Helwi *et al.* (2016) showed a positive effect of nitrogen on the glutathionylated precursor of 3SH (glut-3SH), while it did not affect the cysteinylated precursor (cys-3SH). TDN was shown to decrease in Riesling wines with high nitrogen fertilization in a long-term trial, while other C_{13}-norisoprenoids were not affected (Linsenmeier and Löhnertz, 2007). In another nitrogen fertilisation experiment performed on Pinot noir, Yuan *et al.* (2018) observed that low nitrogen status was associated with low β-damascenone content in wine.

3.4. Dried fruit aromas

To the knowledge of the authors, there is no evidence of any effect of vine nitrogen status on dried fruit aromas in wines.

3.5. Substituted esters and qualitative fruit aromas

Nitrogen levels in must are related to vine nitrogen status (Bell and Henschke, 2005). The effect of yeast-available nitrogen and amino acid content in must on substituted esters and their corresponding acids formation during alcoholic fermentation has been the subject of several studies. Foliar N fertilisation increased the levels of ethyl hexanoate and ethyl octanoate in Tempranillo, while it decreased the concentration of isoamyl acetate (Ancín-Azpilicueta *et al.,* 2013). A recent study assessed the influence of must yeast-available nitrogen content on fruity aroma variation during alcoholic and malolactic fermentation in red wine (Lytra *et al.,* 2020). Higher yeast-available nitrogen content significantly increased concentrations of short- and substituted alkyl fatty acid ethyl esters produced during alcoholic fermentation (up to a 67 % increase in samples with the highest nitrogen content) and hydroxycarboxylic acid ethyl esters generated during malolactic fermentation (up to a 58 % increase in samples with the highest nitrogen content). Sensory profiles showed that malolactic fermentation led to a significant increase in black-berry and jammy-fruit notes, thus revealing the role of substituted esters as natural fruity-note enhancers.

3.6. Other aroma compounds and complementary observations

DMS potential in grapes (pDMS) increases with vine nitrogen status (De Royer Dupré *et al.,* 2014). In this research, however, the effect of nitrogen cannot clearly be separated from the effect of vine water status: vines with high yeast-available amino acids had also undergone more severe water deficits. However, an effect of vine nitrogen status on DMS content in wine is highly likely, because the formation of pDMS in berries is related to the abundance of amino acids, in particular *S*-methylmethionine (Segurel *et al.,* 2005). Similarly, the levels of several *N,S*-heterocycles are positively correlated with the amount of amino acids in aged Champagne reserve wines (Le Menn *et al.,* 2017), which is in agreement with the fact that amino acids are precursors of heterocycles (Marchand *et al.,* 2000). In red wine only three *N,S*-heterocycles were reported to be correlated to vine nitrogen status (Le Menn *et al*., 2019).

Low vine nitrogen status is associated with higher levels of AAP in white wines (Hühn *et al.,* 1999; Schneider, 2014).

Low vine N-status increases the levels of skin polyphenols and decreases glutathione content in grapes (Choné *et al.,* 2006; Pons *et al.,* 2017b). During pre-fermentation manipulations of grapes, polyphenols are transformed into quinones which are highly reactive with the precursors of volatile thiols, while glutathione acts as a preservative of these compounds. Hence, vines with low nitrogen status produce wine with low levels of volatile thiols, not only because grapes contain less precursors but also because the high concentrations in polyphenols and low concentrations in glutathione provoke increased loss of these precursors.

4. Effect of vine water status

4.1. Green and peppery flavours

Deficit irrigation decreases IBMP content in wines (Chapman *et al.,* 2005; Mendez-Costabel *et al.,* 2014). However, this effect may be, indirect because of an increased bunch shading in fully irrigated vines which are generally more vigorous. Roujou de Boubée *et al.* (2000) reported an effect of water deficit on decreasing IBMP content in wines independently from radiation. No effect of irrigation treatment on C6 compounds was reported by Mendez-Costabel *et al.* (2014). 1,8-cineole was lower in wines produced from vines which had undergone water deficits, although this effect was not completely independent from a possible temperature effect (Antalick *et al.,* 2015; Poitou *et al.,* 2017). Wines made from vines irrigated just prior to véraison had a greater (-)-rotundone concentration than those made from non-irrigated vines (Geffroy *et al.,* 2014; Geffroy *et al.,* 2016). As no differences in berry surface temperature were observed between the two treatments (Geffroy *et al.,* 2016), the effect induced by irrigation is likely to be direct rather than indirect through a modification of bunch microclimate (Geffroy *et al.,* 2016). The importance of water supply was also emphasized in another study showing that calcium concentration in leaf petioles, a variable that correlated with $\delta^{13}C$, had a strong influence on (-)-rotundone accumulation (Harner *et al.*, 2019). At an intra-block scale, a similar correlation was observed between $\delta^{13}C$ measured on grape sugar at harvest and (-)-rotundone concentrations in wine (Geffroy *et al.,* 2014).

4.2. Other monoterpenes

Monoterpene concentrations were found to increase with the intensity of water deficits (Schüttler *et al.,* 2013; Savoi *et al.,* 2016) while Giordano *et al.* (2013) reported higher terpineol levels in irrigated vines compared to the dry control.

4.3. Volatile thiols and C_{13}-norisoprenoids

Volatile thiols increase under mild water deficit and decrease under severe water deficit (Peyrot des Gachons *et al.,* 2005; Schüttler *et al.,* 2013). Schüttler *et al.* (2013) observed a tendency toward lower TDN levels in wines from vines facing strong water deficits. Water deficit increased tabanones in wines after ageing (Le Menn *et al.,* 2019), with wines from severely water-stressed vines showing remarkably high tabanone content after several years of bottle ageing. In a study conducted in Nemea on Agiorgitiko (Peloponesos, Geece) C_{13}-norisoprenoids were high in wines produced by microvinification from parcels where vines were facing water deficits (Koundouras *et al.,* 2006). This is also consistent with results from an irrigation trial reported by Bindon *et al.* (2007), where water deficit induced by partial rootzone drying (PRD) caused increases in the concentration of hydrolytically released C_{13}-norisoprenoids β-damascenone, β-ionone, and TDN. This study also found carotenoids, which are precursors of C_{13}-norisoprenoids, increased in PRD grapes when the fruit approached maturity.

4.4. Dried fruit aromas

There is no clear evidence of an effect of water deficit on dried fruit aromas when it occurs at the beginning of the ripening process. However, when severe water deficit during the last days before harvest triggers dehydration, there can be a profound effect on berry composition. A threshold of 10 % desiccation was determined, above which dried fruit aromas begin to appear (Allamy *et al.,* 2018).

4.5. Other aroma compounds and complementary observations

De Royer Dupré *et al.* (2014) reported increased pDMS in water deficit vines, but no clear separation could be established from a possible nitrogen effect, due to water deficit vines also having higher yeast-available amino acids. This observation is consistent with Picard *et al.* (2017) who observed enhanced ageing bouquet in wines produced from water deficit vines. DMS plays a direct role in the ageing bouquet of wine by producing intense truffle-like aromas (Picard *et al.,* 2015) and an indirect role by enhancing fruity flavours (Lytra *et al.,* 2016). In the study of Picard *et al.* (2017), the ageing bouquet of matured red Bordeaux wines was compared against the water status of the vines as assessed by $\delta^{13}C$ measured on wine (Guyon *et al.,* 2015). Ageing bouquet typicity was significantly correlated to $\delta^{13}C$ (Figure 1). Another study found water deficit increased fruity characters in wine and reduced green flavours (Chapman *et al.,* 2005). In this study, the increased fruity character in deficit irrigated vines was attributed to esters, although no aroma compounds were measured. It is not clear either whether the

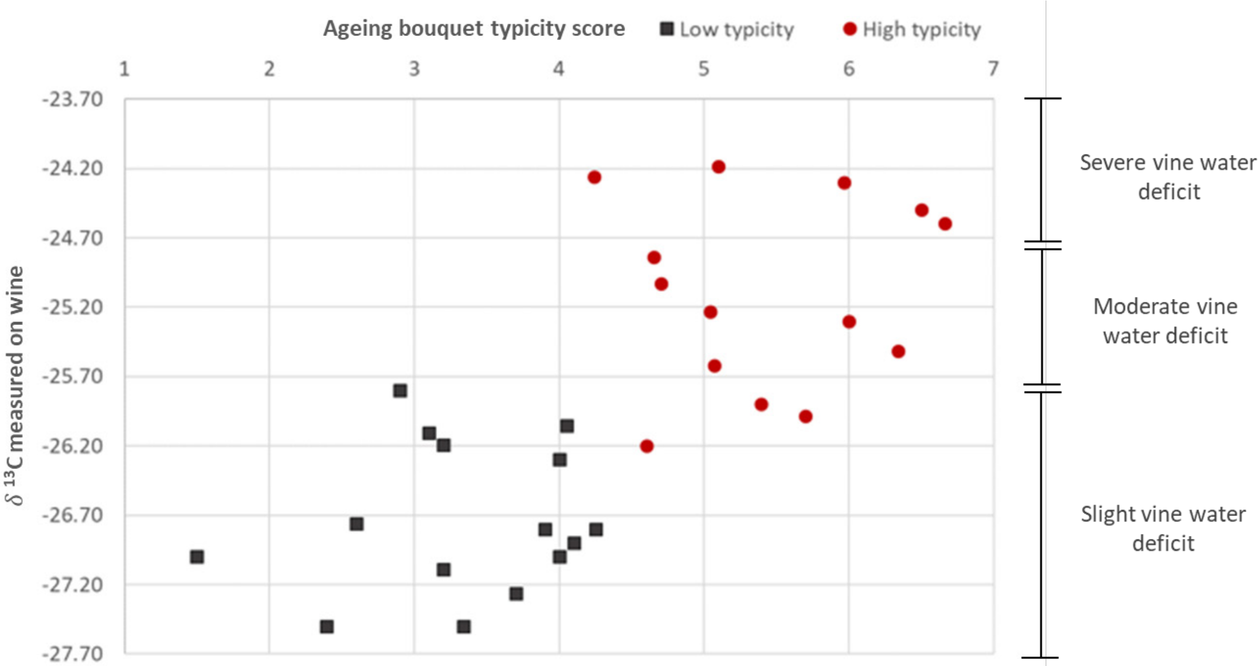

FIGURE 1. Ageing bouquet typicity score as a function of $\delta^{13}C$ measured on wine representing vine water status.

Sensory and chemical analyses were performed on a series of 29 red Bordeaux wines, which were subsequently classified according to their ageing bouquet representativeness (i.e., low typicity in black squares; high typicity in red circles).

differences were due to a direct effect of water deficit or an indirect effect through differences in bunch microclimate (vigour) or yield. Water stress in vines is associated with higher levels of AAP in white wines (*Hühn et al.,* 1999), especially in combination with low vine nitrogen status (Schneider, 2014). Levels of glutathione in wines from the Bordeaux area were lower in dry years, but this effect was not independent of a possible effect of temperature, because dry years were also warm years in this study (Pons *et al.,* 2015; 2017). Water deficit increases polyphenols in grapes and wines. These may react with volatile thiol precursors during pre-fermentation operation and reduce subsequent thiol expression in wine (Pons *et al.,* 2017b).

HOW TERROIR SHAPES THE AROMA PROFILE OF GRAPES AND WINES

1. Hierarchy of terroir factors and variety choice

Predominant terroir factors are climate, soil and the grapevine variety (van Leeuwen *et al.,* 2004). It can be considered that the influence of climate and soil is expressed through the grapevine variety. Although there are some general trends across varieties, each one has a specific aromatic composition. Hence, the terroir effect needs to be considered for each variety separately, with the focus in this article on some major varieties: Cabernet-Sauvignon, Merlot, Syrah, Sauvignon blanc and Riesling. Cabernet-Sauvignon is the most widely planted red variety in the world followed by Merlot, while Syrah is fourth (Anderson and Aryal, 2013). Sauvignon blanc is the third most widely planted white variety while Riesling is number six. The compounds responsible for the aromatic expression of these varieties are well known. Other major varieties in terms of planted acreage according to Anderson and Ayral (2013) were discarded in this analysis, either because their aroma structure is less well known (Tempranillo and Chardonnay), because they are only of local importance (Aíren, Rkatsitelli), or because they are mainly used for spirit production (Trebbiano, also called Ugni blanc).

2. The climate component: temperature and radiation

The temperature regime during grape ripening is of major importance in aroma typicity in wine. Temperature can be considered at a broad scale with winegrowing regions characterized from cool to warm by means of agroclimatic indicators (Winkler, 1965; Gladstones, 2011). Recently, the temperature structure inside winegrowing regions was explored, showing that considerable variability in temperature can exist at the mesoscale (Bois *et al.,* 2018) or even at the microscale (de

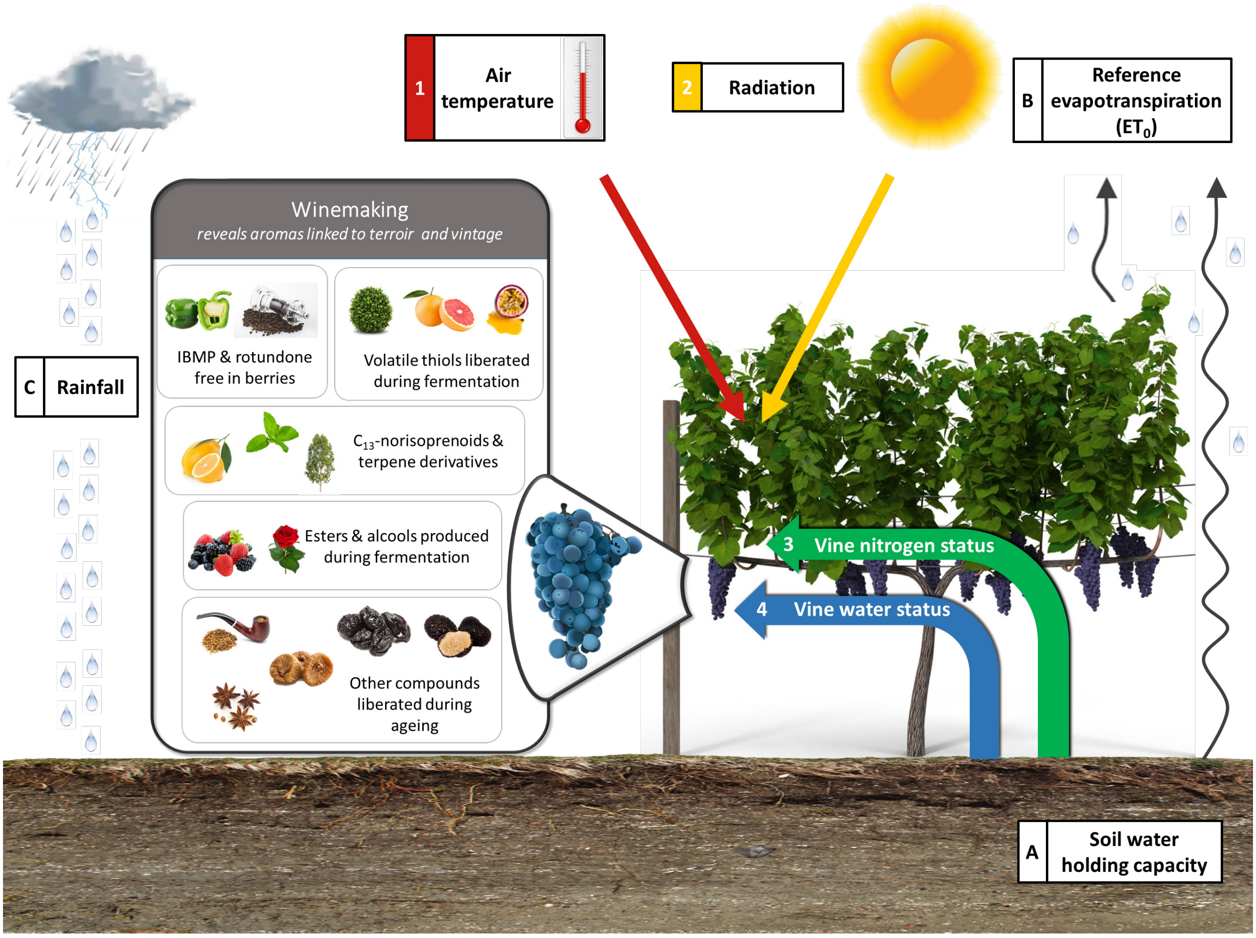

FIGURE 2. Overview of the terroir effect on aromas in grapes and wines.
Terroir expression is mainly mediated through (1) air temperature (climate), (2) radiation (climate), (3) vine nitrogen status (4) and vine water status which results from (A) soil water holding capacity (soil), (B) reference evapotranspiration (climate) and (C) rainfall (climate). These four components related to soil and climate impact aroma composition and expression in grapes and wines. By connecting recent advances in the understanding of the impact of environmental factors on aroma expression, wine typicity in relation to terroir can be better understood.

Rességuier *et al.,* 2020). Radiation varies with cloud cover and increases with altitude. High radiation levels are received in vineyards planted in the Andes of Argentina, where the effect of low cloud cover is combined with the effect of high altitude. The temperature during grape ripening is impacted by the phenology, with early phenology causing grapes to ripen during the warmest part of the summer. At a given location, temperature and radiation vary from year-to-year (so-called "vintage-effect") and, as a result of climate change, may be increasing in most winegrowing regions over time (Garcia de Cortazar *et al.,* 2017).

Cool temperatures during grape ripening will increase green flavours, like IBMP or 1,8-cineole (Falcão *et al.*, 2007; Koch *et al.,* 2012; Poitou *et al.,* 2017). Excessive levels of IBMP are detrimental to red wine quality, but concentrations close to the perception threshold presumably provide freshness, as does the presence of 1,8-cineole. In Sauvignon blanc, IBMP is important for the perceived freshness, and the finest wines from this variety are obtained when the presence of IBMP and volatile thiols is balanced. High radiation has a similar effect to temperature in decreasing IBMP levels in grapes and wines. Low temperatures induce higher levels of (-)-rotundone in Syrah, which is generally an appreciated character of this variety (Zhang *et al.,* 2015a, Zhang *et al.*, 2015b; Caputi *et al.,* 2011). High temperatures increase dried fruit aromas in red wine which may lead to decreased aroma complexity and premature ageing (Pons *et al.,* 2017a; Pons *et al.,* 2017b), in particular for Merlot (Allamy *et al.,* 2017; 2018). Some compounds which play an important role in the ageing bouquet of fine red wines, such as DMS and possibly tabanones, are more abundant in wines from Cabernet-Sauvignon and Merlot when grapes ripen in warm conditions (Le Menn *et al.,* 2019). Sauvignon blanc produced in warm locations express more tropical fruit aromas and less asparagus and boxwood aromas. Riesling produced in warm climates is more prone to express kerosene-like and ripe fruit flavours induced by the presence of TDN and rearrangement of linalool towards oxide forms or α-terpineol (Marais *et al.,* 1992; Ziegler *et al.,* 2020).

Aroma expression in grapes and wines is positively related to radiation. High radiation reduces green flavours (methoxypyrzaines and C6 compounds; Koch *et al.,* 2012) and increases fruity flavours induced by monoterpenes (Friedel *et al.,* 2016), volatile thiols, esters (Šuklje *et al.,* 2014), C_{13}-norisoprenoids (Marais *et al.,* 1999) and peppery notes from (-)-rotundone (Geffroy *et al.,* 2019a, Geffroy *et al.,* 2019b).

3. The soil component: vine nitrogen status

Among nutrients that vines assimilate from the soil, nitrogen (N) has the greatest impact on vine development, yield and fruit composition (Bell and Henschke, 2005). The soil effect in terroir expression is partly mediated through soil nitrogen availability (van Leeuwen *et al.,* 2018). The latter depends on soil organic matter content and several factors involved in its turnover by soil microorganisms (soil temperature, humidity, aeration, pH, lime content, organic matter and C/N content) (van Leeuwen *et al.,* 2000). Vine nitrogen status has a major impact on aroma compounds in grapes and wines. This effect can be either direct or indirect. The indirect effect is mediated through increased vigour, which alters the microclimate in the bunch zone, making it cooler, and less exposed to radiation. High vine nitrogen status increases often green flavours particularly IBMP in Sauvignon blanc, Cabernet-Sauvignon and, to a lesser extent Merlot wines. However, Helwi *et al.* (2015) have shown that this effect is indirect and induced by higher vigour and more shaded microclimate in the bunch zone. A strong, direct effect of nitrogen has been shown on volatile thiols, or more precisely their precursors (Choné *et al.,* 2006; Helwi *et al.,* 2016). Volatile thiols are involved in the fruity character of Cabernet-Sauvignon wines and the boxwood/tropical fruit aromas of Sauvignon blanc. They are also involved in the typicity of Riesling wine (Schüttler *et al.,* 2015). In Sauvignon blanc, high N status increases glutathione content in grapes and wines and reduces the amount of phenolic compounds in berry skin, leading to better conservation of thiol derived aromas. A moderately high N status can be considered as favourable to the typicity of Sauvignon blanc wines because for this variety the combination of volatile thiols and IBMP is appreciated by consumers. Excessively high vine N-status can reduce the quality of wines from Cabernet-Sauvignon due to an excess of green aromas, while high N-status contributes to lower TDN levels in Riesling wines (Linsenmeier and Löhnertz, 2007). A balanced nitrogen status of the vines is considered being preventive against the formation of undesirable AAP (Schneider, 2014). In aged Merlot and Cabernet-Sauvignon wines, unlimited nitrogen uptake by the vines favours the development of DMS during ageing, which is a positive contributor to the bouquet appreciated by wine experts (Le Menn *et al.,* 2019).

4. The combined effect of soil and climate: vine water status

Vine water status is a major driver of terroir expression (Seguin, 1969). It depends on climatic conditions (rainfall and reference evapotranspiration) and soil type (soil water holding capacity, SWHC) (van Leeuwen *et al.,* 2009). Wine aromatic typicity is much impacted by vine water status.

The wines produced from vines which undergo water deficit, may present a reduction in green aromas (Cabernet-Sauvignon, Merlot, Sauvignon blanc) and contain less (-)-rotundone (Syrah). It is not well established if this effect is direct, or indirect, as mediated by lower vigour and more exposed fruit to sunlight (Chapman *et al.,* 2005; Mendez-Costabel *et al.,* 2014). Wines from water deficit vines are more fruity (Chapman *et al.,* 2005) and contain more C_{13}-norisoprenoids (Koundouras *et al.,* 2006; Bindon *et al.,* 2007). After bottle ageing, these wines contain more DMS (De Royer Dupré *et al.,* 2014) and display an improved ageing bouquet (Picard *et al.,* 2017). Mild water deficit increases thiol expression in Sauvignon blanc, although this becomes detrimental with severe water deficit (Peyrot des Gachons *et al.,* 2005). Riesling wines from grapes grown under water deficit are more prone to develop AAP during bottle ageing (Schneider, 2014).

5. Predicting aroma typicity from different terroirs

Major drivers of terroir expression are air temperature, radiation, vine water status and vine nitrogen status. Temperature and radiation can be measured in a classical weather station. Vine water status can be assessed by measuring stem

TABLE 1. Effect of four terroir factors (air temperature, radiation, vine nitrogen status, vine water deficit) on aroma compounds in grapes and wines.

		Terroir factor			
	Aroma compound or family	**Air temperature**	**Radiation**	**Vine nitrogen status**	**Vine water deficit**
Green and peppery flavours	**Methoxypyrazines**	**Koch *et al.*, 2012; Falçao *et al.*, 2007; Wu *et al.*, 2919**	**Hashizume and Samuta, 1999;** Ryona *et al.*, 2008; **Koch *et al.*, 2012**	**Helwi *et al.*, 2015**	Roujou de Boubée *et al.*, 2000; Mendez-Costabel *et al.*, 2014
	C6 compounds		Bureau *et al.*, 2000	Mendez-Costabel *et al.*, 2014	Mendez-Costabel *et al.*, 2014
	1,8-cineole	Antalick *et al.*, 2015; Poitou *et al.*, 2017			Antalick *et al.*, 2015; Poitou *et al.*, 2017
	(-)-rotundone	Caputi *et al.*, 2011, Zhang *et al.*, 2015a et **2015b**; Harner *et al.*, 2019	Homich *et al.*, 2017; Geffroy *et al.*, 2019a et b; Harner *et al.*, 2019	Not investigated but indirect increase expected	Geffroy *et al.*, 2014; **2016;** Harner *et al.*, 2019
Other monoterpenes	**Other monoterpenes**	Marais *et al.*, 1992; Reynolds *et al.*, 1995; Belancic *et al.*, 1997; Schüttler *et al.*, 2013; Duchêne *et al.*, 2016	Bureau *et al.*, 2000; Skinkis *et al.*, 2010; Šuklje *et al.*, 2014; **Friedel *et al.*, 2016**	Garde-Cerdan *et al.*, 2015	Schüttler et *al.*, 2013; Giordano *et al.*, 2013; Savoi *et al.*, 2016
Volatile thiols and C_{13}-norisoprenoids	**Volatile thiols**	Darriet *et al.*, 2019; Wu *et al.*, 2019	Šuklje *et al.*, 2014	Peyrot des Gachons *et al.*, 2005; **Choné *et al.*, 2006; Lacroux *et al.*, 208; Helwi *et al.*, 2016**	Peyrot des Gachons *et al.*, 2005; Schüttler *et al.*, 2013
	TDN	Marais *et al.*, 1992; Kwasniewsky *et al.*, 2010; Ziegler *et al.*, 2019	Schultz *et al.*, 1998; Gerdes *et al.*, 2001 ; Kwasniewsky *et al.*, 2010	Linsenmeier *et al.*, 2007	Bindon *et al.*, 2007; Schüttler *et al.*, 2013
	Tabanones	Le Menn *et al.*, 2019			**Le Menn *et al.*, 2019**
	Other C_{13}-norisoprenoids	Falçao *et al.*, 2007	Marais *et al.*, 1999	**Yuan *et al.*, 2018 (β-damascenone)**	Koundouras *et al.*, 2006
Dried fruit aromas	**Dried fruit aromas**	**Pons *et al.*, 2008; Pons *et al.*, 2017a; Pons *et al.*, 217b; Allamy *et al.*, 2018**	**Allamy *et al.*, 2018**		Possible increasing effect when late water deficit leads to dehydration
Esters	**Esters**		Šuklje *et al.*, 2014	**Ancín-Azpilicueta *et al.*, 2013; Lytra *et al.*, 2020**	Chapman *et al.*, 2005
Orher compounds	**DMS**	Le Menn *et al.*, 2019		Le Menn *et al.*, 2019	De Royer Dupré *et al.*, 2014
	Red wine aging bouquet				**Picard *et al.*, 2017**
	Aromatic heterocycles	Le Menn *et al.*, 2019		Le Menn *et al.*, 2017	
	o-aminoacetophenone		Hühn *et al.*, 1999; **Schultz *et al.*, 2000**	Hühn *et al.*, 1999	Hühn *et al.*, 1999
	Glutatione	Pons *et al.*, 2015; 2017; **Szymańska *et al.*, 2017**	Szymanski *et al.*, 2017	**Choné *et al.*, 2006; Pons *et al.*, 2017**	Pons *et al.*, 2017b
	Tanins		Alonso *et al.*, 2016	**Choné *et al.*, 2006**	Pons *et al.*, 2015

Key to table
Increase with increase of terroir factor
Decrease with increase of terroir factor
No effect of terroir factor
Contradictory results in literature
Increase followed by decrease with increase of terroir factor
Black bold reference when terroir factor was analysed without interference from other factors

◄ Red colour indicates that the aroma compound (or family) increases with increasing terroir factor, blue colour that aroma compound (or family) decreases with increasing terroir factor. Grey colour indicates no effect was shown. In references in bold the terroir factor was investigated without interference from other factors. In references not printed in bold the effect of several factors cannot be easily disentangled (e.g., light and temperature in a leaf removal trial).

water potential or $\delta^{13}C$ (van Leeuwen *et al.,* 2009). Vine nitrogen status can be assessed by measuring yeast-available nitrogen in grapes (van Leeuwen *et al.,* 2018). Once these four terroir factors are adequately characterized, aroma expression can be predicted (Figure 2) using published data from the literature (Table 1). The interplay between environmental factors (climate and soil) plant material (in particular the grapevine variety), management practices and winemaking techniques is, however, complex and more research is needed to obtain a complete understanding of flavour typicity in relation to terroir. In many experiments, terroir factors (in particular light and temperature, but also vine water and nitrogen status) are not well separated. References in which the impact of one terroir factor on a specific aroma compound or family was investigated without possible interference of other factors are mentioned in bold in Table 1. Unfortunately, they are a minority among the studies consulted for this review. White cells in Table 1 highlight topics where more research is needed. It appears that the effect of water deficit on aroma compounds is relatively well understood, but that progress can be made on the understanding of the effects of vine nitrogen status, for instance on 1,8 cineole, (-)-rotundone or dried fruit aromas. This should be relatively easy to do, because several reliable plant-based indicators, like yeast-available nitrogen, or petiole nitrogen content, are available to assess vine N status.

6. Examples of typical aroma profiles related to specific terroirs

Sauvignon blanc is grown under a wide range of climatic conditions and soil types. Typical cool climate Sauvignon blanc is produced in Marlborough, New Zealand, and Sancerre, France. In brief, the typical aroma of cool climate Sauvignon blanc is shaped by a delicate balance between green aromas (bell pepper induced by IBMP and boxwood by 4MSP) and fruity aromas (grapefruit induced by 3SH and passion fruit by 3SHA). In very cool climates, like the Awatere Valley in New Zealand (a sub-region of Marlborough), the green aromas of asparagus and bell pepper can dominate the fruity character related to varietal odorous thiols. However, sensory perception is a complex, multi-odour component blend and these observations can sometimes be modulated by the abundance of other volatile compounds. Examples of warm climate Sauvignon blanc can be found in the USA, Australia and Chili. The aroma profile of these is dominated by passion fruit. Bordeaux is a major winegrowing area for Sauvignon blanc where the climate is temperate. The most expressive Sauvignon blanc is produced in the cooler parts of the Bordeaux area, on soils with medium to high water holding capacity and medium to high in nitrogen supply due to moderately high organic matter content. Severe water deficits and low vine nitrogen status are factors which are clearly negatively impacting aromatic typicity of Sauvignon blanc wines. High radiation reduces IBMP in Sauvignon blanc grapes and increases volatile thiols.

Merlot and Cabernet-Sauvignon grown in cool climates, or with low radiation, can be green, because of the presence of IBMP, although this is fairly rare for Merlot, which is more early ripening. An excess of IBMP is generally not appreciated, although some green aromas, like 1,8-cineole, can provide some minty freshness in the aroma expression. Merlot and Cabernet-Sauvignon grown in temperate climates express fruity flavours and develop a complex ageing bouquet after a few years of bottle storage. These positive characters are induced by a wide range of compounds, including substituted esters, volatile thiols (in particular 3SH) and DMS. Aroma expression after bottle ageing is enhanced when wines are produced by vines facing water deficits. It has been shown that these wines contain more DMS and tabanones. Under warm climates, wines from the above mentioned varieties can express dried fruit aromas, in particular when produced from Merlot. Some of the finest wines from Cabernet-Sauvignon are produced in Margaux, Saint-Julien, Pauillac and Saint-Estèphe (Bordeaux, France). In the Bordeaux area, Cabernet-Sauvignon ripens late in the season, when temperatures are decreasing, eliminating any possible risk of dried fruit aromas. The gravel soils of these appellations induce an interesting combination of moderate to severe water deficit and unlimited nitrogen supply to the vines. This combination of cool climate, water deficit, and unlimited nitrogen can shape beautiful ageing bouquets.

Syrah can express different typicities depending on the climate. In cool climate vineyards, such as those from the northern Rhone valley in France, the Victoria's Grampians region in Australia, or the Hawke's Bay area is New Zealand, Syrah expresses very intense peppery aromas, induced by the presence of (-)-rotundone. The combination of cool temperatures and high light is positive for (-)-rotundone expression in Syrah grapes and wines. In warmer climates (i.e., Languedoc area or southern Rhone valley in France, Barossa valley in Australia), Syrah is rather marked by the expression of ripe and dried fruit, and black olive aromas. DMS has been identified as a major contributor to these notes (Segurel *et al.,* 2004).

The typicity of Riesling wines is shaped by various aromatic nuances, which reflect growing conditions, in particular temperature and vine water status. Typical cool climate Riesling wines, as they are grown in Europe (e.g., Germany, Alsace, Austria), are marked by the fruity aromas induced by volatile thiols and terpenols. These fruity aromas can range from fresh citrus, green apple, pear, peach and apricot, to ripe and sweet fruit character accompanied by floral, mineral, spicy and honey like aroma (Schüttler *et al.,* 2015). They are enhanced under high light (Friedel *et al.,* 2016). Wines from steep slope vineyards with low water holding capacity often show distinctive floral nuances and lack citrus or grapefruit character in years with water deficit, caused by elevated linalool concentrations and lower volatile thiol concentrations. Bottle aged bouquet, especially in Riesling wines from warmer climates, like Australia or South Africa, but also from United States, Canada or New Zealand contains more kerosene-like aromas as a result of the presence of TDN (Ziegler *et al.,* 2019). Riesling wines from warmer climatic zones also tend to be characterised more by ripe fruit aromas, which can be related to a change in monoterpene pattern through acidic catalyzed rearrangements of terpenols towards their oxide forms or a-terpineol (Marais *et al.,* 1992). When Riesling vines face severe stress (high UV-B radiation, water stress or nitrogen deficiency) AAP can develop in the wine and give yield to untypical (premature) ageing.

7. Managing aromatic typicity related to terroirs

Terroir factors (temperature, radiation, water, nitrogen) induce specific aromatic typicities. The choice of plant material and management factors can, however, modulate this expression. The excessive presence of green aromas is generally not appreciated in red wines. They are often the result of low temperatures during grape ripening, low light intensity, unlimited water supply and/or unlimited nitrogen supply. The presence of green flavours can be reduced by planting early ripening varieties (Merlot instead of Cabernet-Sauvignon). Another option is reducing nitrogen availability by planting cover crop or increasing exposure to light by leaf removal (which will also increase the temperature in the bunch zone). It should be mentioned that 1,8 cineole in grapes and wines can be induced by the presence of the invasive plant *Artemisia verlotiorum* in vineyards (Poitou *et al.,* 2017). Under warm climates there is a risk to produce red wines that are excessively marked by overriding and "trivial" dried fruit aromas, which reduces freshness and aromatic complexity. These can be limited by planting later ripening varieties (Cabernet-Sauvignon instead of Merlot). Other options are earlier harvest dates or increased vigour to expose bunches to less direct sunlight. In Sauvignon blanc grape fruit expression can easily be enhanced by nitrogen fertilization (when soil N supply is limited). In warm climates, or on soils inducing moderate to severe water deficits, red varieties should be preferred over Sauvignon blanc for the production of high-quality wines. Berry temperature and light can be manipulated through canopy management and leaf removal. An extensive review on the effect of management practices on aroma compounds in grapes and wines can be found in Alem *et al.,* 2019. The effect of plant material (rootstock and clone) on aroma compounds in Riesling is addressed in Ziegler *et al.,* 2020.

8. The impact of winemaking

Fermentation (alcoholic and malolactic) and ageing have a major impact on wine aromas (Lytra *et al.,* 2020). Many wine flavours are either not detectable or present as non-odorous bound precursors in grapes and are shaped during the fermentation process. Among others, this applies to β-damanscenone (Lloyd *et al.,* 2011), floral aromas including β-ionone (Loscos *et al.,* 2007), volatile thiols (Murat *et al.,* 2001), esters (Ferreira *et al.,* 1995b; Lytra *et al.,* 2020) and monoterpenes (Park and Noble, 1993). Other flavour compounds may increase wine ageing, like tabanones (Slaghenaufi and Ugliano, 2018) or barrel ageing (Cameleyre *et al.,* 2020). Aroma compounds can also be lost during winemaking. Volatile thiols are reported to be particularly sensitive to oxidation during pre-fermentation processes (Blanchard *et al.,* 2004). In contrast to substituted esters accumulated during ageing, most linear fatty acid esters produced during alcoholic fermentation decline with age (Lytra *et al.,* 2020). It is obvious that winemaking techniques also have a major impact on aroma expression in wines. It is, however, out of the scope of this article to review these in detail.

CONCLUSIONS

Wine typicity in relation to terroir is largely shaped by odorous compounds. Over the past decades, a wide body of literature is published on the molecular basis of wine aromas. Many of these studies relate cultivar specific aroma profiles and how these are influenced by environmental factors and management practices. The effect of several environmental factors in these studies is, unfortunately, often not easy to disentangle. Many studies on the effect of light on aroma compounds are conducted by means of leaf removal trials, where generally bunch temperature is increased in the bunches exposed to more sunlight. In irrigation or nitrogen fertilisation trials vigour is often increased. In such situations, it is hard to know if the observed effect from the treatment is direct or indirect (i.e., mediated by modified bunch microclimate). There is clearly a need for improved experimental design, where the effect of each factor can be studied without interference with other factors. Major effects of terroir expression are air temperature, radiation, water supply to the vines and vine nitrogen status. In this article, the effect of these factors on aroma compounds is reviewed, to provide a better understanding of how terroir shapes aromatic typicity.

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