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Soil-related terroir factors: a review

Cornelis van Leeuwen*, Jean-Philippe Roby and Laure de Rességuier

EGFV, Bordeaux Sciences Agro, INRA, Univ. Bordeaux, ISVV, 33883 Villenave d'Ornon, Francex

Abstract

A "terroir" is a cultivated ecosystem in which the vine interacts with the soil and the climate. The soil influences vine development and grape ripening through soil temperature, water supply and mineral supply. Soil temperature has a significant effect on vine phenology. Limited water supply to the vines restricts shoot and berry growth, which is critical for reaching a suitable grape composition to produce high-quality red wines. Secondary metabolites, like polyphenols (anthocyanins, tannins) and aroma compounds or their precursors, are impacted in particular by vine water status. Among nutrients vines pick up from the soil, nitrogen plays a key role. Nitrogen influences vine vigor, yield, berry size and grape composition. Low nitrogen supply stimulates the synthesis of polyphenols, while it can negatively impact certain aroma compounds in grapes and wines, like volatile thiols. Over the past decades, tools have been developed to quantify terroir parameters. Vine water status can be assessed by means of carbon isotope discrimination measured on grape sugar (so-called $\delta^{13}C$). Vine nitrogen status can be assessed with the measurement of Yeast Available Nitrogen (YAN) in grape must. In this way, terroir parameters can not only be measured but also mapped. Ideally, vineyards should be established in areas where soil temperature (relative to air temperature), soil water holding capacity (relative to rainfall and potential evapotranspiration) and soil nitrogen availability are optimum for the type of wine which is intended to be produced. Terroir expression can, however, be optimized by choosing appropriate plant material, and via vineyard floor management, fertilization and other management techniques.

Key words: terroir, soil, vine, *Vitis vinifera*, water status, nitrogen status, soil temperature

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*Corresponding author : vanleeuwen@agro-bordeaux.fr

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Terroir expression in winegrowing and the specific role of the soil

In wine production, quality and style are considered to be impacted by the place where the vines grow. This relation between the sensory attributes of a wine and its origin is referred to as "terroir", a French word which cannot easily be translated into English. The official definition according to the International Organization of Vine and Wine (OIV, 2010) is that « 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 ». A more condensed definition is provided by Seguin (1988), who considers terroir « as an interactive ecosystem, in a given place, including climate, soil and the vine ». Human factors should also be considered when referring to "terroir", because terroir expression implies, at a minimum, a history of winegrowing in a given place and also the intervention of men to optimize terroir expression (van Leeuwen and Seguin, 2006). Many factors are involved in terroir expression. Among these, climate, soil, and cultivar obviously are of major importance. All of these factors interact, which makes it impossible to consider the optimum for each factor when taken separately (van Leeuwen, 2010). It is, for instance, not possible to refer to the ideal climate for producing high-quality wines, without taking into account the local soil type and cultivar. Because so many factors are involved, it makes sense to propose a hierarchy of their influence on vine phenology, vine development, and grape composition. In a trial where 37 variables were measured on nine parcels with three soils, and three grapevine varieties over five consecutive vintages (climate effect), van Leeuwen *et al.* (2004) investigated for each variable the percentage of the total variance attributable respectively to the climate, soil and temperature effect. Vine development and phenology were predominantly driven by the climate, except total shoot length and ripening speed (Figure 1a). Yield parameters were equally impacted by the soil and the climate, with cluster number being more impacted by the climate and cluster weight by the soil (Figure 1b). Berry composition was mainly driven by the climate, in particular all components linked to acidity. Berry nitrogen and total anthocyanins were mostly influenced by the soil type. Berry sugar was equally impacted by the soil and the cultivar (Figure 1c). Vine mineral status was predominantly determined by the soil type (Figure 1d) while all parameters linked to vine water status were equally impacted by the soil and the climate (Figure 1e). Note that all parcels were dry-farmed. In sum, soil and climate determine water and nitrogen supply to the vines which, in turn, controls vegetative and reproductive development.

Soil and terroir expression

1. Vineyard soils are diverse and soil type impacts wine quality

Great wines are produced on a wide diversity of soils, including gravelly soil on Quaternary alluvium (in Pauillac, Bordeaux, Table 1a), clayey lime-rich soil on Jurassic limestone (in Mazis-Chambertin, Burgundy, Table 1b) and heavy clay soil on Paleogene substratum (in Saint-Emilion, Bordeaux, Table 1c).

It is surprising how diverse these soils are, although they are all located in highly prestigious estates. High-quality potential vineyard soils may be coarse (Table 1a) or fine textured (Table 1b and 1c), have high (Table 1b) or low pH (Table 1a), and may be rich (Table 1a) or poor in organic matter content (Table 1c). It is obvious from these examples that no straight forward relationship can be established between soil composition and wine quality. Vineyard soils are also often modified by human intervention. The high copper content, in particular in the soil from the Bordeaux area (Table 1c), is the result of copper sprayings to protect the vines against downy mildew.

There is, however, proof that soil type influences wine quality, as shown by Trégoat (2003) and Renouf *et al.* (2010). These authors mapped the soils of seven of the most prestigious estates of the Bordeaux area at high resolution (between 1/1000th and 1/5000th), covering 400 ha of vineyards. Soils were classified according to the French "Référentiel pédologique" classification (Baize and Girard, 1995). Predominant soil type was identified for each parcel. These estates produce generally three wines, according to three levels of quality. Grapes are fermented separately by the parcel of origin and only the best lots of wine are blended into the 1st quality wine, which is the only one being marketed with the full name of the estate. A quality index was constructed, based on the frequency with which the wine from a given parcel integrated the 1st quality and a rating was accordingly attributed to each parcel and averaged over a five year period. Nine major soil types were identified (Figure 2), with PEYROSOL (gravelly soil on Quaternary alluvium) being the predominant soil type. Highest quality was produced on PLANOSOL

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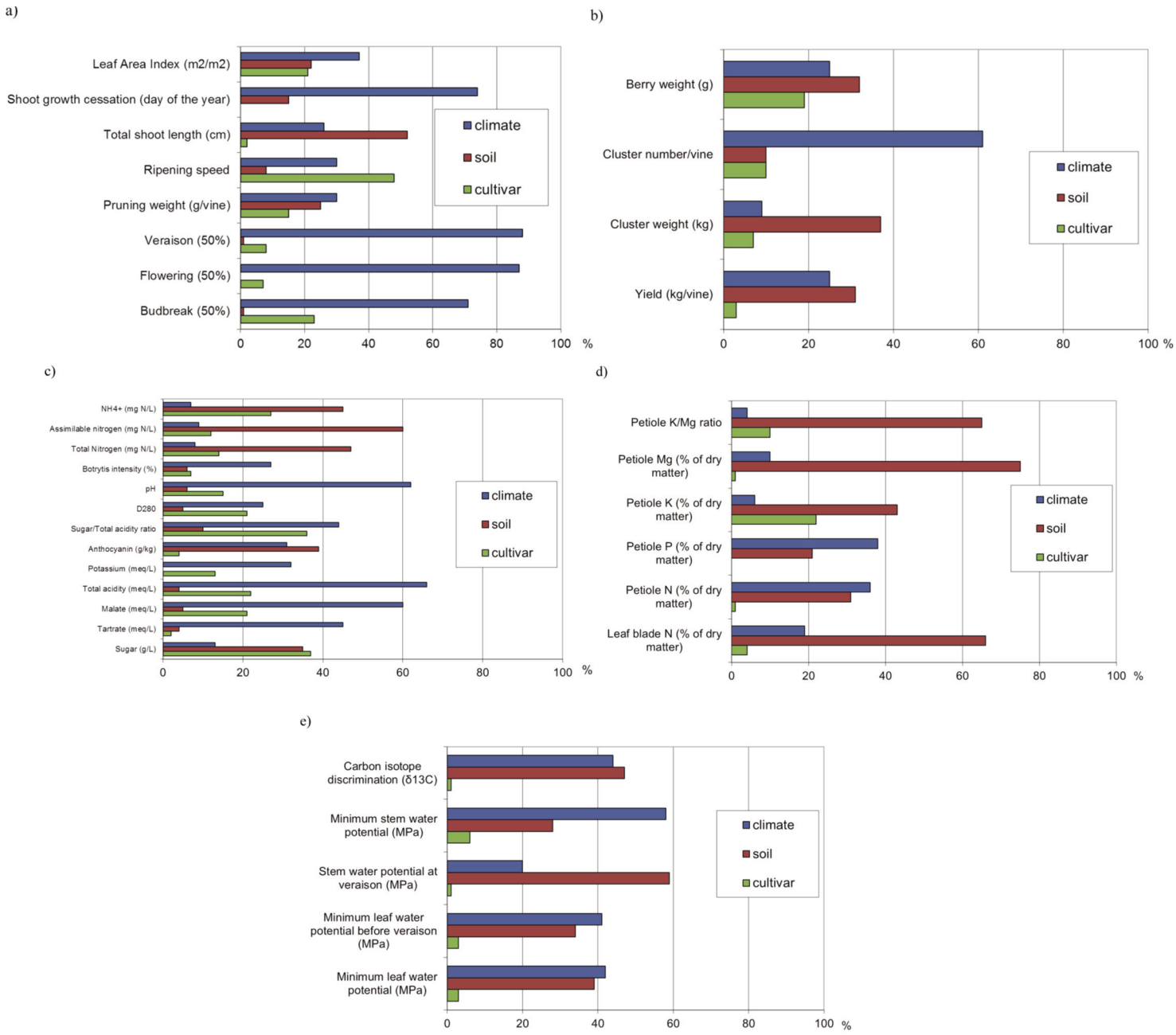


Figure 1. Percentage of variance attributable to climate, soil, and cultivar effect for a) vine development and phenology, b) yield components, c) grape composition, d) vine mineral status and e) vine water status (computed from van Leeuwen *et al.*, 2004). All parcels located in Saint-Emilion (Bordeaux area), vintages spanning the period 1996-2000.

(soil with heavy clay subsoil of Tertiary origin), ARENOSOL (sandy soil of Quaternary aeolian origin), BRUNISOL (sandy-gravel soil on Quaternary alluvial terraces) and PEYROSOL (gravelly soil on Quaternary alluvial terraces) (Figure 3). Quality was lowest on COLLUVIOSOL (deep sandy soil on colluvium from Quaternary substratum), LUVISOL (leached sandy clay soil on Quaternary alluvium) and REDUCTISOL (sandy soil with permanent water table, located in talwegs on Quaternary substratum). This study shows that wine quality varies significantly according to soil type, although it does not explain which mechanisms are involved.

2. Different approaches to study vineyard soils

Experts from different scientific backgrounds study vineyard soils, resulting in a diversity of approaches. Geologists study the parent material (Wilson, 1998)

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Table 1. Soil composition in three famous vineyards located on a) gravelly soil developed on Quaternary alluvium in Pauillac, Bordeaux, b) clayey lime-rich soil developed on Jurassic limestone in Mazis-Chambertin, Burgundy and c) heavy clay soil on Paleogene substratum in Saint-Émilion, Bordeaux.

a)

	Layer 1	Layer 2
DEPTH (cm)	0 - 50	50 - 100
COARSE ELEMENTS %	35%	70%
FINE EARTH (%)	65%	30%
Coase sand	55%	85%
Fine sand	16%	8%
Coarse silt	7%	1%
Fine silt	10%	2%
Clay	12%	4%
TEXTURE (fine earth)	Sandy	Sandy
ORGANIC MATTER (%)	4.20	0.24
ORGANIC CARBON (%)	2.44	0.14
TOTAL NITROGEN (%)	0.24	-
C/N ratio	10.2	-
pH (water)	6.2	6.2
CATION EXCHANGE COMPLEX		
K^+ $cmol^+/kg$	0.25	0.09
Mg^{2+} $cmol^+/kg$	0.78	1.65
Ca^{2+} $cmol^+/kg$	7.57	0.68
S (sum of cationes)	8.6	++
% base saturation	95%	Sat.
Cation Exchange Capacity ($cmol^+/kg$)	9.1	1.8
Total lime (%)	0	0
Active lime (%)	0	0
IPC (chlorosis index)	-	-
Phosphorus P_2O_5 mg/kg (OLSEN method)	0.13	<0.02
TRACE ELEMENTS		
Cu mg/kg	4.8	-
Mn mg/kg	1.8	-

b)

Layer 1
0 - 55
10%
90%
3%
4%
21%
28%
45%
Clay
1.79
1.04
0.13
8,0
8.2
0.48
0.67
++
++
Sat.
23.1
3.0
0
-
0.031
-
-

c)

Layer 1	Layer 2	Layer 3
0 - 40	40 - 80	80 - 110
2%	0%	0%
98%	100%	100%
55%	15%	4%
13%	10%	3%
11%	7%	9%
11%	14%	20%
9%	53%	64%
Sandy clay	Clay	Heavy clay
0.86	0.35	0.35
0.50	0.20	0.20
0.037	-	-
13.4	7.7	7.4
7.6	7.9	8.4
0.26	0.59	0.56
1.28	8.80	12.26
5.32	9.78	++
++	++	++
Sat.	Sat.	Sat.
6.7	18.9	18.9
0	0	0
0	0	0
-	-	-
0.124	0.015	0.015
105.7	1.4	1.1
29.1	1.1	12.7

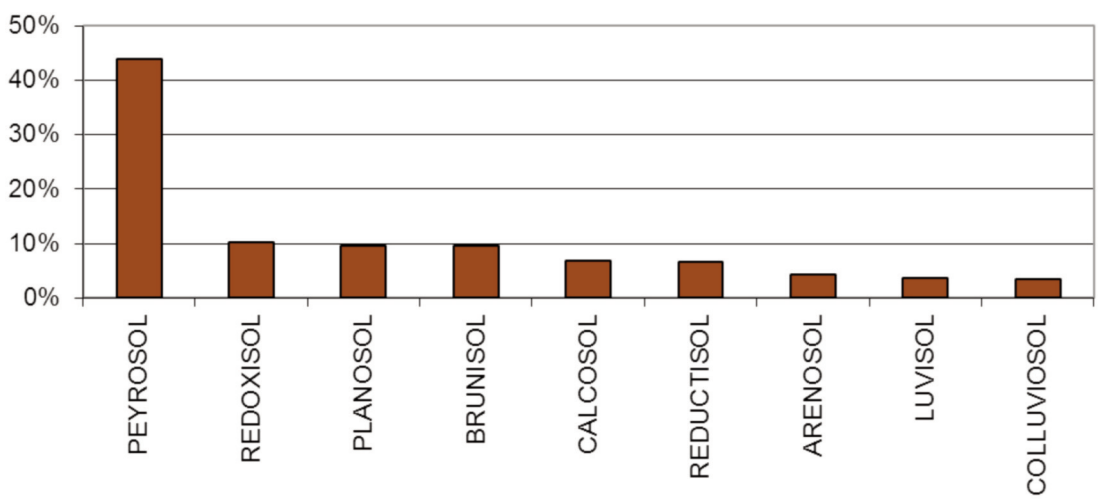


Figure 2. Frequency of soil types identified in seven highly prestigious Bordeaux estates.

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and geomorphologists the topography (Fanet, 2001). Soil scientists map vineyard soils (van Leeuwen *et al.*, 1989) and agronomists study soil physical and chemical composition (Seguin, 1986). Soil microbiologists analyze the microbial community of vineyard soils (Bokulich *et al.*, 2014; Gilbert *et al.*, 2014). All these approaches provide useful information, but generally remain highly descriptive. Another drawback is that most scientists stick to the tools they are familiar with and in a sense "are prisoners of their own discipline" (Moran, 2001). Yet, there are many factors involved in terroir expression, which implies that terroir studies have to be multi-disciplinary. If the soil has an impact on grape composition and wine quality, it is necessarily mediated through the vine. In order to *explain* the effect of terroir on wine composition, interactions between the soil and the vine (and possibly the climate) need to be taken into account. This paper deals with the soil effect in terroir expression, through its impact on vine physiology. The soil provides anchorage to the vine, minerals, water and a specific temperature regime in the root zone. Hence, the understanding of its effect on terroir needs to be focused on the effect of soil temperature, soil water supply, and soil mineral supply on vine development, phenology and grape ripening dynamics. Moreover, contrary to geological outcrops or soil types, these variables can be quantified.

Major soil-related parameters in terroir expression that can potentially be quantified: temperature in the root zone, soil mineral supply, and soil water supply

1. Soil temperature in the root zone

The timing of ripeness is critical in the production of wines offering specific characteristics in relation to their origin. If grapes ripen too early in the season in warm conditions, those grapes are high in sugar and low in organic acids. Wines produced from such grapes are unbalanced and lack freshness. Moreover, aromatic complexity is reduced in warm ripening conditions (Pons *et al.*, 2017). If grapes ripen too late in the season, they may not reach full ripeness, with the resulting wines tending to be acidic and showing an excess of green flavors. The ideal window for reaching ripeness is roughly situated between the 10th of September and the 15th of October in the Northern Hemisphere, or March in the Southern Hemisphere (van Leeuwen and Seguin, 2006). The timing of phenology (budburst, flowering and veraison) is mainly driven by air temperature (Parker *et al.*, 2011) and the specific temperature requirements of the grapevine variety (Parker *et al.*, 2013). To remain within the ideal ripening window, growers who are looking for optimal terroir expression adapt their choice of the grapevine variety to local climatic conditions so as to plant early ripening varieties in cool climates and late ripening varieties in warm climates (van Leeuwen and Seguin, 2006). Soil temperature in the root zone also impacts phenology, but does so in a less decisive way compared to air temperature. Soil temperature depends on energy balance, which is related to soil color and albedo (proportion of sunlight reflected on the soil), slope steepness and direction. It is also highly impacted by water content, because water has a high specific caloric capacity: wet soils warm up more slowly compared to dry soils (Tesic *et al.*, 2002). Soil temperature is also related to soil structure. According to Steenwerth and Belina (2008), soil

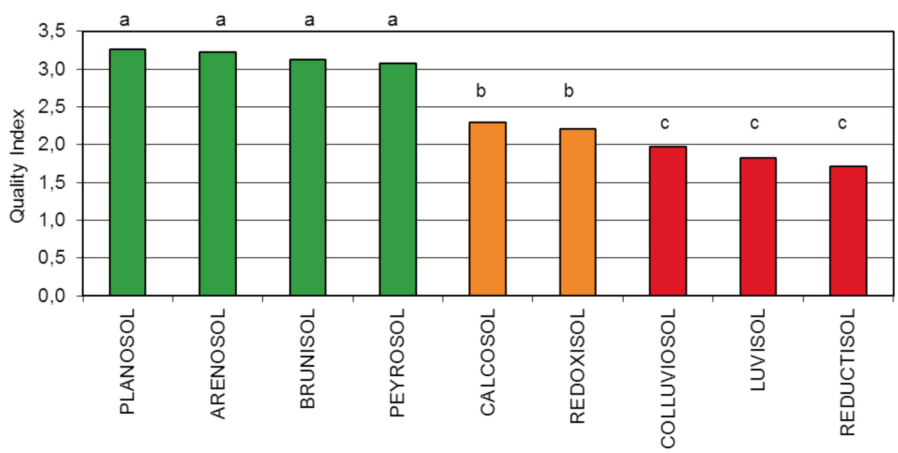


Figure 3. Quality potential index, based on the frequency with which the wine produced on a given soil type is blended into the highest quality wine, for the nine major soil types identified in seven highly prestigious Bordeaux winegrowing estates.

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management (cover crop versus tillage) does not have a major impact on soil temperature.

In vineyards where the combination of local climatic conditions and the precocity of the major grapevine variety results in ripening late in the ideal calendar window, a warm soil in the root zone (either because of low water content or shallow rooting) generally results in better wines. This is clearly the case with Cabernet franc in the Loire Valley (Bodin and Morlat, 2006), Cabernet-Sauvignon in the Bordeaux area (van Leeuwen, 2001) and Cabernet-Sauvignon in Hawke's Bay, New Zealand (Tesic *et al.*, 2002). For these varieties in these locations, soil temperature is critical to produce high-quality wines. For varieties ripening in the middle of the ideal ripening window (e.g. Merlot in Bordeaux or Cabernet-Sauvignon in Napa, California), soil temperature has little impact on quality performance. Cool soils may be an advantage in warm climates because they can slightly delay ripeness, although this aspect is poorly documented.

2. Soil mineral supply (except nitrogen)

Soil supplies vines with minerals, including major elements (N, P, K, Mg, Ca) and trace elements (Fe, Bo, Mn, Zn, among others). Except for nitrogen, which will be addressed in the next section, there is little evidence that soil minerals are major drivers of terroir expression. In popular wine books, terroir expression is repeatedly attributed to « deep roots picking up trace elements » but no demonstration is provided on how these elements could possibly be transformed into aroma compounds or other sensory attributes of wines (Moran, 2001; Maltman, 2013). Seguin (1986) found no close relation between soil minerals and wine quality, and this was confirmed by van Leeuwen *et al.* (2004). This does not mean that soil minerals have no impact whatsoever. Excess in available soil potassium can possibly increase pH in must and wines (Morris *et al.*, 1983; Soyer and Molot, 1993). High potassium levels are found in soils derived from specific rocks containing large amounts of feldspar, illite and mica (volcanic rocks, slate or shale; Huggett, 2006) or can be the result of excessive fertilization (Dundon *et al.*, 1984). Many famous winegrowing sites are developed on parent material containing limestone, inducing the presence of high available soil calcium (Champagne, Burgundy, Saint-Émilion, Loire Valley in France, Tuscany in Italy, la Rioja in Spain and Coonawarra in Australia) (Wilson, 1998; Fanet, 2001). However, high soil calcium is not a prerequisite for good vineyard soil, because some of the world's most renowned wines are produced on acidic soils developed on Quaternary alluvium, with low calcium content (Table 1a; Seguin, 1986). The depicted positive effect of calcium may be indirect. High calcium improves soil structure (White, 2003), which in turn improves root penetration, speeds up soil warming in the spring and improves internal drainage. The presence of active lime also reduces soil organic matter turnover, limiting the availability of mineral nitrogen (Duchaufour, 2001).

3. Soil nitrogen supply

Nitrogen is a highly important nutrient in all agricultural crops, including grapevines. The level of nitrogen supply influences vine vigor, crop level, berry size, and impacts both major metabolites of the grape (sugar, organic acids) and secondary metabolites (phenolic compounds, aromas and aroma precursors) (Keller, 2010). The soil availability of nitrogen to the vine is not easy to estimate, because the vast majority of nitrogen in the soil is in organic form, which is not directly accessible to the vines. The organic matter first has to be turned into mineral nitrogen by soil microorganisms (including *Nitrosomonas* and *Nitrobacter*) before it can be absorbed by the vines, predominantly as NO_3^-. This is a complex and dynamic process, which depends on many factors: soil aeration, soil temperature, soil humidity, soil pH, and the type of organic matter, in particular its C/N ratio (van Leeuwen *et al.*, 2000). The amount of available mineral nitrogen is clearly linked to the soil type and, thus, makes it part of the "terroir" effect (van Leeuwen, 2010), although it can obviously also be manipulated through fertilization practices (Spayd *et al.*, 1993, 1994) and vineyard cover crop management.

In the production of red table wines, moderate nitrogen supply is an important quality-enhancing factor. Vine vigor is related to nitrogen supply (Figure 4). Low nitrogen supply limits berry size and berry malic acid content, and it increases sugar content and phenolic content (Tregoat *et al.*, 2002). 3-Isobutyl-2-methoxypyrazine (IBMP), a major green flavor in grapes and wines, considered detrimental in red wines, is not directly impacted by vine nitrogen status (Helwi *et al.*, 2015). However, high vigor induced by high nitrogen supply potentially increases bunch shading, which may increase berry IBMP content. In white wine production, the desired level of nitrogen supply is higher in comparison with red wine production. In Sauvignon blanc, nitrogen increases the synthesis of volatile thiol precursors (volatile thiols are major aroma compounds in many grapevine varieties, including Sauvignon blanc, generally considered being positively associated with

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wine quality). Because nitrogen also stimulates the synthesis of glutathione (a compound that preserves aroma compounds in musts and wines) and limits the production of tannins (that are involved in volatile thiol degradation), moderately high nitrogen supply to the vines is desired in white wine production, at least for those varieties dependent on volatile thiols for their aromatic signature (Choné *et al.*, 2006; Helwi *et al.*, 2016). Excessive nitrogen supply is not desired either, because it increases susceptibility of grapes to grey rot (*Botrytis cinerea*; Mundy, 2008). It is important to note that optimum nitrogen supply is different in red and white wine production. This observation explains, at least partially, why some soils are better for the production of high-quality white wines and others for the production of high-quality red wines.

Some authors have attributed a major role to soil microorganisms in terroir expression, although they remain relatively vague about the mechanisms involved in this potentially beneficial effect (Bourguignon, 1995). It is true that a healthy soil should have at least some minimum level of microbiological activity, because soil microorganisms play a major role in the transformation of organic nitrogen into mineral nitrogen. Without this process, vines would not survive because of severe nitrogen deficiency. Microbial interactions in vineyard soils are, however, highly complex, and our current state of knowledge provides no evidence that higher microbiological activity induces higher quality and enhances terroir expression. Very high microbiological activity in the soil would simply result in excessive nitrogen release, which is often detrimental to wine quality, in particular in red wine production (Choné *et al.*, 2001). Soil microbiology has recently received increased attention because it has been shown that the soil microbiome is terroir-specific (Bokulich *et al.*, 2014; Gilbert *et al.*, 2014). However, the study by Bokulich *et al.* (2014) does not clearly show a functional impact of diverse microbiological communities across geographical origins on grape composition, or wine sensory attributes. The study of vine health and longevity supported by healthy biomes are additional areas of research which need further investigation.

4. Soil water supply

Vine water status depends on climatic parameters (rainfall and reference evapotranspiration), the capacity of the soil to store water, the transpiration rate of the vines, rooting depth, and, when applied, irrigation practices. The impact of soil and climate on vine water status is similar in magnitude (van Leeuwen *et al.*, 2004; Figure 1e). Depletion of soil water reserves can be simulated with a water balance model (Lebon *et al.*, 2003). Soil water is stored in soil porosity. Except for water-logged soils, water is drained out of the large soil pores (>10 µm in diameter). Water located in extremely small pores (<0.2 µm in diameter) cannot be extracted by vine roots. Pores within the 0.2 µm to 10 µm range can store water against deep drainage and progressively release it to the vines. The percentage of total soil volume within this range of pore size varies with soil texture: approximately 5% in a very sandy soil, 10% in a very clayey soil, and 20% in a very silty soil (Saxton *et al.*, 1986). Hence, soil texture has a major impact on soil water holding capacity (SWHC). It is also extremely dependent on rooting depth and percentage of coarse elements. SWHC of vineyards is highly variable, covering a range from 50 mm in very shallow soils with a sandy texture and having a high percentage of coarse elements, to over 350 mm in silty soils, which allow deep rooting (van Leeuwen *et al.*, 2009). When a water table is present within the

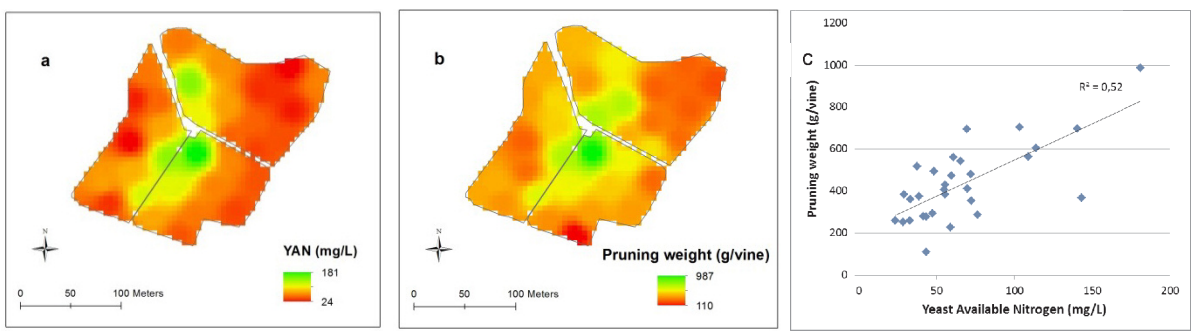


Figure 4. Relations between vine nitrogen status and vigor in a Bordeaux vineyard (Château Fombrauge, Saint-Emilion) in 2016: a) Vine nitrogen status, assessed by the measurement of Yeast Available Nitrogen (YAN) at harvest; b) Vine vigor, assessed by the measurement of winter pruning weight; and c) correlation between YAN and pruning weight. Maps were obtained by Inverse Distance Weighting (IDW) interpolation from results from 10 samples/ha.

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Table 2. Correlation coefficients between vine water status (as assessed by water potential measurements), and veraison (day of the year), shoot growth, yield parameters, and grape composition. Compiled from van Leeuwen and Seguin, 1994; Trégoat *et al.*, 2002; van Leeuwen *et al.*, 2004; Koundouras *et al.*, 2006; and van Leeuwen *et al.*, 2009. Note that water potentials are negative and become more negative with increasing water deficit; hence, positive correlations indicate a decrease with water deficit and negative correlations an increase.

Location	**Saint-Emilion (Bordeaux)**	**Saint-Emilion (Bordeaux area)**	**Nemea (Greece)**	**Bordeaux**	**Saint-Emilion (Bordeaux)**
Cultivars	Cabernet franc	Merlot, Cabernet franc and Cabernet-Sauvignon	Agiorgitiko	Merlot	Merlot
Years	1990	1996, 1997, 1998 1999, 2000	1997, 1998	2000	2004, 2005, 2006, 2007
Number of observations	8	72	6	10	48
Reference	van Leeuwen and Seguin, 1994	van Leeuwen *et al.*, 2004	Koundouras *et al.*, 2006	Trégoat *et al.*, 2002	van Leeuwen *et al.*, 2009
Indicator of water deficit	average pre-dawn leaf water potential veraison - harvest	minimum pre-dawn leaf water potential veraison - harvest	average pre-dawn leaf water potential veraison - harvest	pre-dawn leaf water potential at ripeness	minimum stem water potential over the season
Shoot growth cessation (Day of the Year)	0.95***	0.66***	0.94**		0.71***
Total shoot length (cm)		0.63**	0.83*		
Veraison (Day of the Year)		-0.04NS	0.94**		
Berry weight (g)	0.71*	0.44***	0.54NS	0.79**	0.77***
Yield (kg/vine)			0.45NS	0.69*	
Grape sugar (g/L)	-0.68NS	-0.25*	-0.93**	-0.16NS	
Total acidity (g tartrate/L)	0.58NS	0.53***	0.74NS		
pH		-0,58***			
Malic acid (g/L)	0.85**	0.51***	0.87*	0.55NS	0.83***
Tartaric acid (g/L)		0.04NS	-0.94		
Sugar/Acid ratio		-0.52***			
Grape anthocyanins (mg/L)	-0.78*		-67NS	-0.92***	
Wine anthocyanins (mg/L)					0.51***
Total phenolics (index)	-0.84**		-0.64NS	-0.90***	
Ripening speed	-0.54NS	-0.48***	-0.98***		
Global wine quality (rating)			-0.99***		

Significance: *, **, *** represents significance at p< 0,05, 0,01 and 0,001 respectively; NS: non significant

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reach of the roots (in the case of water-logged soils), SWHC can be considered infinite, because water consumed by the vines will be replaced through lateral soil-water movements.

Vine water status has a major impact on vegetative and reproductive growth, fruit composition and wine quality. Evidence that regular, but limited, water supply to the vines is a major factor explaining the terroir effect was first published in the 1960s (Seguin, 1969) and confirmed many times since (Duteau, 1987; van Leeuwen and Seguin, 1994; Trégoat *et al.*, 2002; van Leeuwen *et al.*, 2004; Storchi *et al.*, 2005; Bodin and Morlat, 2006; Koundouras *et al.*, 2006; de Andrès-de-Prado *et al.*, 2007; van Leeuwen *et al.*, 2009; Tramontini *et al.*, 2013; Picard *et al.*, 2017). Limited water supply leads to shoot growth cessation (Table 2; van Leeuwen and Seguin, 1994; Pellegrino *et al.*, 2005) and restrains berry growth, in particular when water deficits occur pre-veraison (Table 2; Ojeda *et al.*, 2001; van Leeuwen *et al.*, 2004). Water deficit also reduces berry malic acid content (Table 2; van Leeuwen and Seguin, 1994). The impact of water deficit on berry sugar content is non-linear: grape sugar is increased under mild water deficit because of reduced carbon allocation to shoots, but grape sugar is reduced under severe water deficit because of restrained photosynthesis (van Leeuwen *et al.*, 2009). Water deficit increases skin phenolics, in particular anthocyanins (Table 2; Duteau *et al.*, 1981; Ojeda *et al.*, 2002; Trégoat *et al.*, 2002; Ollé *et al.*, 2011), which is a major asset in the production of high-quality red wines. Limited water supply to the vines increases glycoconjugates of major aromas in red grapes (Koundouras *et al.*, 2006) and improves the aging bouquet of fine red wines (Picard *et al.*, 2017) and their global quality (Table 2; Koundouras *et al.*, 2006). Severe water deficit stress, however, can impair red wine quality. Vine water deficit is not necessarily a major driver of white wine quality, because their aromas may be negatively impacted (Peyrot des Gachons *et al.*, 2005; Pons *et al.*, 2017). Strong water deficit negatively impacts aromas from the volatile thiol family and thus depreciates the quality of white wines produced from Sauvignon blanc and, probably, of all varieties which depend on volatile thiols for their aromatic typicity (Peyrot des Gachons *et al.*, 2005).

5. Terroir expression and irrigation

One of the major driving factors behind terroir expression is the occurrence of moderate water deficits, in particular for red wines. Hence, full irrigation is not compatible with terroir expression. In very dry areas, excessive water stress can impair yields and possibly grape quality potential. In the Mediterranean basin, growers have developed over the past millenniums training systems and selected plant material which allows grape production in extremely dry conditions. In New World production areas, irrigation is frequently implemented to obtain economically sustainable yields and avoid major damage to vines and grapes under dry conditions. It is striking though that some of the most famous wines in the New World are grown in dry-farmed vineyards (Hill of Grace in Australia, Dominus Estate in Napa, California, Montebello Ridge in the Santa Cruz Mountains, California). When necessary, irrigation should be maintained at a minimum, to allow water deficits to develop over the season. It is not easy to mimic moderate water deficits by means of controlled irrigation the same way that they may occur in dry-farmed vineyards. The positive effect of water deficit is mediated through abscisic acid (ABA) synthesis in the roots, which is best induced during long drying cycles. In irrigated vineyards, vine rooting is often shallow and the water supply to the vines is not buffered, meaning water becomes suddenly available immediately following an irrigation event, to become quickly reduced again, once the applied water is consumed. This drawback can be partly overcome when irrigation events are applied less frequently. Regulated deficit irrigation (RDI) and partial root zone drying (PRD) are also interesting irrigation strategies by which root ABA synthesis can be enhanced in irrigated vineyards (RDI: McCarthy, 1997; Dry *et al.*, 2001; and PRD: Stoll *et al.*, 2000).

Integrative indicators in terroir studies

1. Soil depth

Soil depth has a slightly different meaning for soil scientists and viticulturists. For soil scientists, soil depth represents the weathered layer above the parent rock. When vines are established, this layer is generally explored by the root system. For viticulturists, however, soil depth corresponds to rooting depth, which can extend beyond the weathered soil layer when parent material is either soft or contains cracks. The role of soil depth in terroir expression is often erroneously interpreted in many popular wine books, in which the terroir effect is attributed to deep rooting vines. The first vineyard soils to be studied on a scientific basis were from the Médoc area, Bordeaux (Seguin, 1969). In these sandy soils with high gravel content, the capacity of the soil to store water was so low that deep rooting was necessary to prevent vines from facing excessive water stress in dry summers. In a very popular wine

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atlas, Hugh Johnson (1979) published a soil profile from Seguin's study but, unfortunately, from which many wine writers subsequently concluded that deep rooting is *always* a critical factor for terroir expression. In fact, in most situations, the relationship between rooting depth and wine quality is rather the opposite. When soils are not extremely poor, deep rooting provides access to unlimited water and possibly nitrogen, which increases vine vigor and yield. This then decreases the quality attributes of the grapes, in particular for red wine making, like anthocyanins and tannins. The effect of soil depth on grape quality was investigated by Morlat and Bodin (2006) and by Bodin and Morlat (2006) in the Loire Valley (France). These authors compared phenology, yield parameters and grape composition for three groups of vineyard soils with increasing depth: Weakly Weathered Rock (WWR), Moderately Weathered Rock (MWR) and Strongly Weathered Rock (SWR). The highest grape quality potential was obtained from WWR soils with limited depth and soil water availability. These conditions tended to make the soil temperature in the root zone higher, thereby enhancing precociousness of subsequent phenological stages and grape ripening curves. Similar results were obtained by Coipel *et al.* (2006) in the Rhône Valley, where highest quality potential for Grenache was obtained in shallow soils where nitrogen and water were more limited. For sites on hillsides, erosion is a key driver of soil depth (Brenot *et al.*, 2008), shallow soils being located upslope and deeper colluvial soils distributed closer to and at the bottom. This is the case in Burgundy where the highest quality wines are produced at the middle and top parts of the slopes (Wilson, 1998). On the richer soils at the bottom of the slopes, lower quality wines are produced. Because vine performance is often closely related to soil depth it can be used as an integrative parameter in terroir studies. In some situations, soil depth can be mapped with electrical resistivity tomography (André *et al.*, 2012).

It is not desirable, however, to have roots located in the top 20 cm of the soil, because this zone is generally too rich in nitrogen. Roots close to the soil surface may also pick up water from rainfall events close to the harvest date, with possible dilution of grape components. Managing the vineyard floor with the use of cover crops or mechanical weed destruction (tillage) tends to prevent roots from colonizing the layer close to the soil surface. Weed control with herbicides, on the other hand, can promote shallow root growth (Soyer *et al.*, 1984).

2. Vine vigor

Vine vigor is driven by plant material (in particular the rootstock) and soil fertility. When plant material is homogeneous over a given area, vigor can be used as an indicator of the effect of environmental factors on the vine. Vigor can be easily mapped by means of remote sensing and used as a zoning tool, as

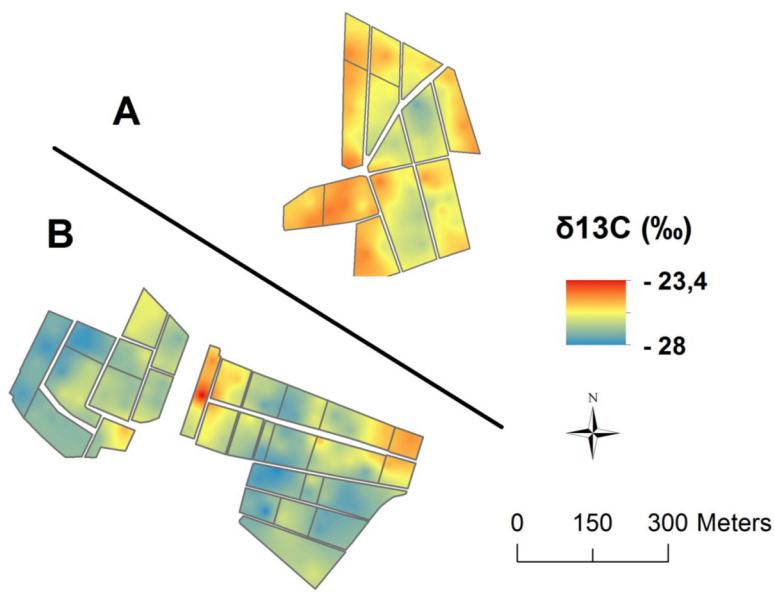


Figure 5. Vine water status assessed by $\delta^{13}C$ measured on grape sugar at harvest in a Bordeaux winegrowing estate in 2015 (Château La Tour Carnet). Map was obtained by Inverse Distance Weighting (IDW) interpolation from results from 10 samples/ha. A and B refer to vineyard blocks where A is located north of B.

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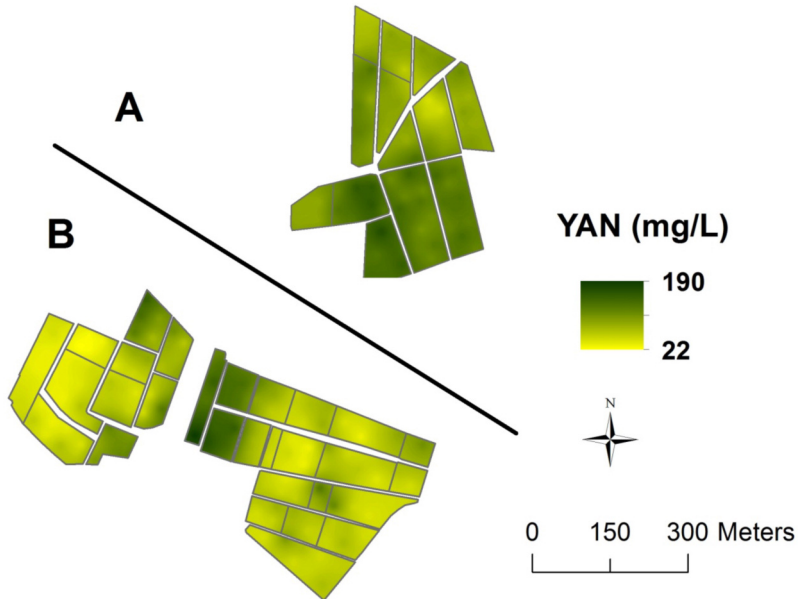


Figure 6. Vine nitrogen status assessed by grape juice Yeast Available Nitrogen measured at harvest in a Bordeaux winegrowing estate in 2015 (Château La Tour Carnet, Haut-Médoc). Map was obtained by Inverse Distance Weighting (IDW) interpolation from results from 10 samples/ha. A and B refer to vineyard blocks where A north of B.

described by Hall *et al.* (2003) and Bramley *et al.* (2011).

Management of terroir

1. Human factors in terroir expression

Seguin (1988) defined terroir as a cultivated ecosystem in which the vine interacts with factors from the natural environment, principally soil and climate. Because this ecosystem is cultivated, man plays a major role in terroir expression. He or she can orientate terroir expression through the choice of plant material and management practices. In this way, it is possible to manage terroir in order to maximize terroir expression in each location (van Leeuwen *et al.*, 2016).

2. Indicators of major terroir parameters

Major soil-related terroir parameters are water and nitrogen supply to the vines as well as soil temperature. Many indicators of vine water and nitrogen status have been developed over the past decades (see Cifre *et al.*, 2005 and van Leeuwen *et al.*, 2009 for a review on indicators of vine water status and van Leeuwen *et al.*, 2000 for a review on indicators of vine nitrogen status). Among these indicators, $\delta^{13}C$ measured in grape juice is a convenient tool for assessing vine water status (Gaudillère *et al.*, 2002; van Leeuwen *et al.*, 2009) and Yeast Available Nitrogen (YAN) for assessing vine nitrogen status at high throughput (van Leeuwen *et al.*, 2016). By means of these tools, vine water status (Figure 5) and vine nitrogen status (Figure 6) can be mapped at high resolution. In the latter example (from Château La Tour Carnet, appellation Haut-Médoc), the soils are gravelly-sandy and are rich in organic matter in the northern block, explaining greater water deficit and higher vine nitrogen status compared to the southern part, where soils are more clayey and lower in organic matter. Soil temperature can be measured, but because it is variable both spatially and temporally it is not easy to compute a relevant indicator. Warm and cool soils can be identified by expertise, as warm soils tend to be coarse textured and high in coarse elements. Because the relevant factor for soil temperature is the temperature *in the root zone*, shallow rooting soils can also be considered as warm soils.

3. Management of vine water status

The production of high-quality red wines requires moderate water deficits. Frequently red wine grapes are negatively affected because of insufficient water deficits. There are no clear vine symptoms for this, so it can easily be overlooked by growers. In situations of excess vine water, the selection of soils with low SWHC and the implementation of training systems that increase transpiration (e.g. high planting density, high leaf area per hectare) may help to reach water deficit levels that promote wine quality. White

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varieties generally perform better in soils with high SWHC than red varieties (van Leeuwen, 2001). Installation of drainage tiles is only a partial solution, because they only allow evacuating water stored in macropores. In soils with high SWHC, large amounts of water are stored in micropores and drainage tiles have little effect. In dry climates, where excessive water stress may negatively impact yields and jeopardize wine quality, vineyard soils should have at least a medium SWHC. The choice of plant material is a powerful tool to adapt vineyards to drought, through the combination of drought-resistant rootstocks (Ollat *et al.*, 2015) and drought-resistant cultivars (Schultz, 2003). Another possible adaptation to dry conditions is the use of the Mediterranean bush vine training system (also called the "gobelet"; Santesteban *et al.*, 2017). When such adaptations still do not result in high-quality wines with economically sustainable yields, irrigation can be considered if there are adequate water resources available. Only deficit irrigation (when water supply does not meet climatic water demand), however, is compatible with terroir expression.

4. Management of vine nitrogen status

Vine nitrogen status is a terroir parameter easy to manage. When vine nitrogen status is very low, yield and vine vigor may be overly impacted. Red wine quality potential is rarely negatively impacted by low nitrogen availability, but important white wine aromas can be jeopardized. When vine nitrogen status is too low, it can be adjusted by organic or mineral fertilizers. If the vine nitrogen status is too high, it may provoke excessive vigor, thereby negatively impacting red wine quality potential and increasing susceptibility to grey rot (*Botrytis cinerea*). Cover crops can be an easy-to-implement solution to decrease vine vigor by acting as competitors for available nitrogen (Wheeler *et al.*, 2005).

5. Management of soil temperature

Optimal terroir expression is closely related to the timing of ripeness of the grapes at the end of the season, avoiding high temperatures if too early and cool temperatures if too late (van Leeuwen and Seguin, 2006). The timing of ripeness is mainly driven by air temperature, but is also impacted by soil temperature, slope and aspect. When, in a given region, grapes tend to ripen too early, ripeness can be delayed by using later ripening varieties and long vegetative cycle rootstocks or by planting on north-facing slopes (south-facing slopes in the Southern Hemisphere). When grapes tend to ripen too late, the use of early ripening varieties and short cycle rootstocks may help to achieve full grape ripeness more regularly. When an important variety for a given region reaches ripeness at the end of the ripening window, planting in warm soils or on south-facing slopes (north-facing slopes in the Southern Hemisphere) should be preferred to reach full ripeness more easily.

Conclusion

The relationship between the sensory attributes of a wine and its origin is referred to as the "terroir" effect. Soil is a major factor in terroir expression, with its effect being mediated through the vine. Hence, soil-vine interactions have to be taken into account when studying the effect of soil on terroir expression. The soil effect has to be broken down into quantifiable components so as to measure its impact on grape composition and wine quality. Soil mainly influences grapevine phenology, vegetative and reproductive development, and grape composition through its effect on temperature in the root zone, as well as through its impact on vine water and nitrogen status. Over the past decades, tools have been developed to quantify these effects, both temporally and spatially. Once the major terroir parameters are quantified, growers can adapt their plant material and management practices accordingly so as to optimize terroir expression in their particular vineyard site.

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