



# The Value of Soil Knowledge in Understanding Wine Terroir

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There is an extensive literature on the role of soil physicochemical factors such as rate of water supply, N supply and soil temperature in wine terroir expression, especially for dry-grown vines. Other recent literature invokes the possibility of unique strains of the natural yeast *Saccharomyces cerevisiae* influencing must fermentations to produce distinctive aroma profiles in wines. Others suggest that the composition of the soil microbiome at particular sites can influence vine growth, fruit composition and wine characteristics to create a microbial terroir. Because terroir is a multifactor concept, no general quantitative relationships between one or more soil properties and the distinctive characteristics of wine from a particular site have been identified; rather a unique combination of soil factor values interacts with local climate, grape variety, vintage, canopy management, and winemaker technique to determine a site's terroir. However, with modern methods of sensing spatially referenced values of environmental and other variables at high resolution, terroirs can be mapped. This provides a platform for monitoring terroirs over time and recording how they respond to changes in environmental factors or to manipulations in the vineyard and winery.

**Keywords:** soil physics, soil chemistry, soil microbiome, soil variability, climate change, wine terroir

## INTRODUCTION

Wine terroir is a multifaceted concept that is recognized as embodying three broad categories of factors (Barham, 2003):

1. Natural factors that are associated with the environment (sometimes called "endowments").
2. Human factors – involving the use of techniques in the vineyard and winery that are confined to a particular region (sometimes referred to as "technologies").
3. Historical factors – reflecting widespread public knowledge of the wine coming from a region and recognition that this has been a long tradition.

Because terroir is such a broad concept, in this article I shall restrict my comments to the first category of factors. This is consistent with the view of van Leeuwen et al. (2016) that terroir is an ecosystem concept primarily incorporating the vine's interaction with its environment, a view shared by many scientists (e.g., Matthews, 2016) and respected wine writers (e.g., Goode, 2014; Hunt, 2015). With respect to the natural resources of a site, van Leeuwen and Seguin (2006) identified climate, soil and vine cultivar as the key factors that interact to determine the terroir. Although van Leeuwen et al. (2004) concluded, from a multi-season study in Bordeaux vineyards, that climate had the most significant effect on grape properties, van Leeuwen and de Rességuier (2018) acknowledged a specific effect of soil in terroir expression. While recognizing the

complexity of the interactions determining terroir, in this article I aim to update my review of the soil component (White et al., 2007), focusing on soil properties as they affect vine phenology and the consequential effects on the composition of grapes that are converted into wine. In so doing, I argue, along with van Leeuwen and de Ressaiguier (2018), that the recognition of terroir must be based on a wine's sensory characteristics that are consistently evident over a considerable period of time. Note that this requirement implicitly embraces the other two terroir categories suggested by Barham (2003); that is, an historical tradition that rests not only on consumer perceptions but also on the consistency of winemaking techniques.

## CONCEPTS OF TERROIR

Amongst soil scientists, the concept of terroir most commonly accepted is that championed by the Bordeaux school (the Institut des Sciences de la Vigne et du Vin) (e.g., Seguin, 1986; van Leeuwen et al., 2004; van Leeuwen and Seguin, 2006; van Leeuwen and de Ressaiguier, 2018). In this, terroir is identified as an ecophysiological concept whereby a wine's sensory characteristics are related to the geographical origin of the wine. Two important consequences flow from this concept – first, that the appreciation of a wine's terroir depends on the consumers of the wine, whether they be experienced tasters or individuals not concerned with the origin of the product, only its enjoyment. Secondly, as Seguin (*ibid.*) explained, the geographical “fingerprint” of a wine explicitly or implicitly invokes the influence of many factors, which he listed as:

- Climatic conditions.
- The heat and light conditions of the vine's microclimate resulting from the particular training system.
- The cultivar and rootstock.
- The yield.
- Topography.
- Soil properties, including the water supply and mineral nutrition, especially of nitrogen (N).
- The “ecogeopedological milieu.”

To this, Seguin (*ibid.*) added technological factors relating to winemaking techniques and conservation of the wines. Aside from the technological factors, this long list of ecophysiological factors is a fertile field for researchers to investigate which, if any, of these factors alone or in combination is definitive in determining the terroir of a wine from within a vineyard block, or an individual vineyard, or a region. Seguin did not mention soil biological factors, except as may be covered by the term “ecogeopedological milieu.” However, the influence of the soil microbiome leading to the concept of a microbial terroir has received considerable attention in recent years, as is discussed later (Gilbert et al., 2014).

At the time of writing, Seguin (*ibid.*) discussed wine produced from vineyards in Bordeaux appellations with little reference to the scale at which resource factors might vary. However, the issue of scale became important as the terroir concept was extended to other French regions, and globally. For example, Vaudour

et al. (2015) reviewed the tools available for rapid proximal- and remote-sensing of soil properties, coupled with the storage and manipulative power of geographic information systems, to map viticultural terroirs at a range of scales. Proffitt et al. (2006) demonstrated how the systematic analysis of spatial variability within Australian vineyards could be used not only to define terroirs, if that was a vigneron's objective, but also how this knowledge could be used to direct soil and canopy management, pest and disease control and selective harvesting. van Leeuwen et al. (2010), in describing methods for viticultural zoning based on soil properties, emphasized the importance of having clear objectives whether they be the demarcation of production areas, or adaptation of management practices to soil type, or protection of viticultural landscapes. Predictably, the precision of zoning and hence the reliability of the information provided increases with scale, but so does the cost. Nevertheless, as Vaudour et al. (2015) have noted, terroir maps at an appropriate scale can be updated and hence used to monitor changes in the underlying variables in response, for example, to climate change. The information provided can then inform changes in viticultural management practices to offset or at least ameliorate the effects of such change.

## PHYSICOCHEMICAL FACTORS – WATER, NITROGEN AND TEMPERATURE

van Leeuwen and de Ressaiguier (2018) have argued, from many detailed studies in dry-grown French vineyards, that water and nitrogen supply to the vines, as well as soil temperature, are the major soil determinants of the terroir effect. These authors discuss how moderate soil water deficits are necessary to produce high quality wines, especially for red varieties. They describe how this condition can be achieved through under-drainage in wet clay soils, by appropriate choice of variety/rootstock, or choice of vine training system in dry regions, or by deficit irrigation where irrigation is practised. Also discussed is how a controlled N supply prevents excessive vegetative growth, but that sufficient N must be supplied to generate adequate Yeast Available N in the fruit and promote the synthesis of flavor and aroma compounds (especially in white wines) (Choné et al., 2001). With respect to soil temperature, the authors state that optimal terroir expression depends on the timing of grape ripeness toward the end of a season. Although the timing of ripeness is mainly driven by air temperature, they argue that soil temperature, which can be affected by the nature of the soil surface, as well as land slope and aspect, is also important.

The implicit conclusion to be drawn from this analysis is that the action of these factors, singly or in combination, is sufficiently different among different sites for the wines produced at any one site to express a distinctive terroir. Van Leeuwen and de Ressaiguier's (*ibid.*) stated that once the key soil factors have been quantified, vignerons can choose their planting material and management practices accordingly, to optimize the terroir expression of a site. Among the management practices identified, they acknowledged that irrigation may be necessary in dry areas

to obtain economically sustainable yields, but stated that “only deficit irrigation . . . is compatible with terroir expression.” However, this opinion reflects the Bordeaux school’s emphasis on soil water deficits and the rate of water supply as the predominant factors in a terroir effect, which is not necessarily borne out by research in irrigated vineyards. For example, Bramley et al. (2011) studied the grape and wine characteristics of a Cabernet Sauvignon vineyard in the Murray Valley, Australia (mean annual rainfall 289 mm), which received up to 5 ML/ha/year of irrigation from 2004 to 2007. In this vineyard of 8.2 ha, which was not deficit-irrigated, zones of high and low yield were consistently identified that produced wines with different sensory properties (color and phenolics), the causes of which could not be established. However, the authors deemed that these differences could reflect a terroir difference due to biophysical characteristics of the site other than water supply. A similar conclusion was reached in a study of irrigated Shiraz vines in the Grampians region, Victoria, Australia, as discussed below (Bramley et al., 2017).

Many vigneronns have an empirical knowledge of the robustness, or otherwise, of the relationships between particular soil properties at a site and the composition of the grapes produced and wines made: what is lacking in most cases is a quantitative understanding of these relationships. For both dry-grown and irrigated vineyards, key questions to be asked are:

- What is the critical soil water content (or water potential) corresponding to a desirable stress level in the vines – at what point in the vine’s phenology and for how long is this applicable and how are these criteria affected by soil water-holding capacity and depth?
- Can the optimum soil N supply during growth be defined in terms of soil mineral N available in the whole soil profile at bud burst, or in terms of soil organic N, or potentially mineralizable N (measured by laboratory incubation), which is found to be correlated with soil organic N (White et al., 2008)?
- What is the optimum range for soil temperature to express a site’s terroir? Although van Leeuwen and de Ressaiguier (ibid.) cited the “ideal window” for ripeness to be March in the southern hemisphere and between 10 September and 15 October in the northern hemisphere, they gave no soil temperature criteria.
- Are there specific soil chemical or biological properties responsible for a terroir effect at a given site?

Because soil properties interact with many other environmental properties to determine vine growth and fruit composition, it is likely there is no generally applicable answer to these questions: rather the critical combination of factor values will depend on the grape variety (sometimes the clone) and vintage (Bodin and Morlat, 2006), canopy management (Kliewer and Weaver, 1971), and soil type (van Leeuwen et al., 2009), and therefore be different from site to site. This conclusion reinforces the concept that a distinctive wine terroir reflects the uniqueness of the interaction of variables at a given site.

## PHYSICO-CHEMICAL FACTORS – SOIL NUTRIENTS

In his seminal 1986 paper, Seguin wrote at the time that “it is impossible to establish any correlation between wine quality and the soil content of any nutrient element.” (Seguin believed that the expression of terroir and wine quality were interdependent). van Leeuwen and de Ressaiguier (2018) reiterated this view. Nevertheless, Seguin (ibid.) also offered the somewhat contradictory notion that soils of the Premier Grand Cru Classé (First Growths) in Bordeaux were generally nutritionally “richer” than soils producing lesser wines, not because they were naturally that way, but because the vineyard owners had nurtured these soils over many years.

Subsequent to Seguin’s statement about the role of nutrients, a range of sophisticated analytical techniques have been developed for measuring the content of nutrient elements and many non-essential elements in soil. Vaudour et al. (2015) reviewed examples of the use of selected methods for relating wine composition to soil or parent rock composition, from which it may be concluded that these methods have value for determining the provenance of a wine. However, even though in many cases authors invoked the concept of terroir (e.g., Imre et al., 2012; Tarr et al., 2013), their results did not reveal any relationship between a wine of distinctive character and the supply of an element in soil, whether it be an essential nutrient or otherwise. In the context of vine uptake, three main problems persist for the successful quantification of such a relationship:

- Variations in the bio-availability of a nutrient, as controlled by soil processes such as precipitation/dissolution, sorption/desorption, buffering, mass flow (influenced by water flow), diffusion and microbiological transformations.
- Variations in the demand for a nutrient created by the growing vine and the selectivity for individual elements imposed at the absorbing root surface and in translocation within the plant.
- The influence of local climate fluctuations on the aforesaid bio-availability and demand factors.

## OTHER QUESTIONS

In addition to the questions raised above, arising from our lack of quantitative knowledge of soil property–terroir relationships, Seguin’s comment about Bordeaux First Growths begs the question – to what extent can the many variations in vineyard management modify a site’s terroir (this is discussed further under ‘Microbiological factors’)? Moreover, assuming one or more quantitative soil–terroir relationships can be demonstrated for a given site, how independent are such relationships of vintage variations caused by climatic variations from one season to another? A study of the distinctive character of Shiraz grapes in the Grampians region of Victoria provides a partial answer to this question. Although not specifically focused on soil properties, Scarlett et al. (2014) and Bramley et al. (2017) found that the variation within a single vineyard in the concentration of

rotundone, a grape compound responsible for the pepper aroma of some Shiraz wines (Jeffery et al., 2009), was spatially structured and closely related to the topography of the land. This effect was most likely due to the influence of aspect and slope on variations in ambient temperature and/or the amount of incident solar radiation received (Zhang et al., 2015). The pattern of variation was the same for three consecutive vintages, even though the mean rotundone concentration differed 40-fold between vintages. Thus, the terroir effect in the studied vineyard appeared to be temporally stable. Gupta et al. (2019) have investigated this vineyard further to determine whether differences in any soil properties, especially the structural composition of the microbiome, might be associated with the rotundone variations, as discussed later.

Finally, there is the question of how climate change might affect the recognized terroir of many famous vineyards in iconic wine-growing regions. Hannah et al. (2013) derived ensemble mean temperature projections for the year 2050 for world wine regions, based on 17 Global Circulation Models and two Representative Concentration Pathways. They forecast that the suitability of current viticultural areas would decrease by 17–85%, depending on the region. van Leeuwen et al. (2013) disputed this forecast, citing examples of premier regions in France and Germany that were sustaining high-quality viticulture in spite of higher temperatures. They pointed to methodological flaws in the climate modeling, which used uncapped Growing Degree Days (GDD), underestimated varietal tolerances of higher temperatures and relied on a monthly time-step in calculating GDD. Irrespective of questions about the modeling, the projected decreases in suitable area in some regions were so large that some viticultural changes must occur, even though as van Leeuwen et al. (ibid.) stated, growers are adapting through changed management to higher temperatures and greater water stress. However, these authors also referred to the “evolution of consumer’s preferences,” which suggests that terroir expression is as much in the nose and taste of the consumer as it is in the natural endowments of a vineyard.

## MICROBIOLOGICAL FACTORS

Microbial terroir is a recent concept based on the idea there is a unique composition of the microbial population (the soil microbiome) at a site. The existence of diverse populations of microorganisms associated with grapevines in the rhizosphere and as endophytes and epiphytes has been known for some time, and the possible influence of particular populations on wine metabolites has been explored (reviewed by Liu et al., 2019). However, with the development of advanced genetic-based techniques, such as next generation sequencing, the focus of the research has been on (1) the uniqueness of the natural yeast population present in the soil and on various plant parts, and how this influences the array of compounds synthesized during fermentation, and (2) the uniqueness of the suite of microorganisms found in the soil and also on plant parts, which influence the sensory properties of the fruit and wine.

Noting that strains of *Saccharomyces cerevisiae* outcompeted other yeast strains during the later stages of alcoholic fermentation, Goddard (2010) reported that the natural populations of *S. cerevisiae* in New Zealand soils were genetically distinct from those found internationally. Subsequently, Knight et al. (2015) identified sub-populations of these organisms residing in each of six major New Zealand wine regions. They used a representative genotype from each regional sub-population to ferment Sauvignon Blanc juice and found there were differences in the aroma and flavor of the wines produced. The authors argued that their results showed there was a quantifiable microbial contribution to terroir, acknowledging that they could not say anything about the temporal stability of these results. The latter proviso is important because, given the potential transfer of the organisms through insects, for example, the suite of *S. cerevisiae* strains in a vineyard or sub-region in any 1 year may differ from that in other years. This requires further study to confirm the significance of a yeast contribution to microbial terroir.

The research of Bokulich et al. (2013) and others supports the hypothesis that soil microbial composition and activity are linked with wine terroir. For example, Burns et al. (2015) studied the structure of the soil microbial communities in 19 vineyards selected from sub-appellations of the Napa Valley American Viticultural Area (AVA). These sub-appellations, originally delineated by qualitative assessment of climatic, topographic and edaphic features (including soil), were found to have different soil microbial communities. However, the authors were undecided as to whether the differences were merely correlated with the AVA features, or the microbiota had a direct effect on vine growth and fruit properties. Similarly, Zarraonaindia et al. (2015) showed that the majority of bacterial communities associated with vine parts (leaves, flowers, fruit, and roots) were highly localized and reflective of the corresponding soil populations. Bokulich et al. (2016) provided a further link in the chain by showing that the microbial “fingerprint” derived from the vineyard and winery was reflected in the fermentations and correlated with the chemical composition of the finished wines. Nevertheless, as the authors indicate, correlation is not causation and more research is needed to link one or more functional characteristics of the soil microbiome to a specific sensory property of the finished wines. Gupta et al. (2019) (ibid.) reached a similar conclusion after they found distinct differences in the microbial communities in soils supporting high and low rotundone concentrations in the Grampians, Victoria; however, they could not assign any specific function to the few microbial taxa/groups that accounted for these differences.

Another group of soil microorganisms that have been extensively studied is the arbuscular mycorrhizal fungi (AMF), common symbionts with grapevines. Although much is known about the effect of AMF on nutrient uptake, especially phosphorus, zinc and copper (Schreiner, 2005), little is known about the creation of a recognized wine terroir through an AMF–vine cultivar symbiosis. For example, based on experiments with a specific clone of Tempranillo inoculated with a commercial AMF inoculum (a mixture of five species), Torres et al. (2019) speculated that infection with AMF might enhance the amino



acid content of the grapes, which may in turn affect the aromatic characteristics of the wine.

## CONCLUSION

Although factors influencing terroir such as soil water supply, N availability and soil temperature have been extensively reported in the literature, we still lack quantitative information on these relationships for individual grape cultivars at individual sites. Similarly, whereas the relationships between an existing soil microbiome, including the yeast *S. cerevisiae*, and vine phenology and grape composition have been explored in a variety of environments, quantitative relationships between a species or group of microorganisms and wine sensory properties have yet to be revealed. Gilbert et al. (2014) (ibid.) speculated that, with the modern genomic tools of microbial ecology, we may develop a mechanistic understanding of the practices that vigneronns have used for centuries, even to the point where the soil microbiome could be manipulated to improve soil quality and wine terroir. Similarly, looking to the future, Vaudour et al. (2015) suggested that knowledge of the microbial genome could indicate how a soil could be manipulated by probiotics designed to select suitable bacterial species, which could improve soil quality and crop productivity. Echoing this speculation, Gupta et al. (2019) (ibid.) suggested that with such an understanding, a vineyard could be managed to achieve specific grape and wine attributes, for example, by inoculation with specific organisms and/or by particular management practices. Perhaps in the future a test of this speculation might involve characterizing the soil

microbiome of long-established biodynamic vineyards compared with organic and conventional-managed vineyards in the same environment, to determine whether (a) significant differences existed and if so, were they stable over time, and (b) were any differences reflected in the character of the wine. Given that our knowledge of the quantitative relationships between any of a site's natural endowments – physicochemical or microbiological above or below ground – and wine terroir is still in an exploratory stage, wine writers, sommeliers and vigneronns will continue to rely on historical tradition and their sensory perceptions to define a wine's "sense of place." Nevertheless, as Ballantyne et al. (2019) pointed out, based on the views of experienced winemakers in three regions of the world, terroir is not a fixed concept, but is evolving under the influence of consumer preferences (van Leeuwen et al., 2013) and the impact of climate change on the functioning of the natural site and regional endowments.

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The author confirms being the sole contributor of this work and has approved it for publication.

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## REFERENCES

- Ballantyne, D., Terblanche, N. S., Lecat, B., and Chapuis, C. (2019). Old world and new world wine concepts of terroir and wine: perspectives of three renowned wine makers. *J. Wine Res.* 30, 122–143. doi: 10.1080/09571264.2019.1602031
- Barham, E. (2003). Translating terroir: the global challenge of the French AOC labelling. *J. Rural Stud.* 19, 127–138. doi: 10.1016/s0743-0167(02)00052-9
- Bodin, F., and Morlat, R. (2006). Characterization of viticultural terroirs using a simple field model based on soil depth I. Validation of the water supply regime, phenology and vine vigour in the Anjou vineyard (France). *Plant Soil* 281, 37–54. doi: 10.1007/s11104-005-3768-0
- Bokulich, N. A., Collins, T. S., Masarweh, C., Allen, G., Heymann, H., Ebeler, S. E., et al. (2016). Associations among wine grape microbiome, metabolome, and fermentation behavior suggest microbial contribution to regional wine characteristics. *mBio* 7, 1–12. doi: 10.1128/mBio.00631-16
- Bokulich, N. A., Thorngate, J. H., Richardson, P. M., and Mills, D. A. (2013). Microbial biogeography of wine grapes is conditioned by cultivar, vintage, and climate. *Proc. Natl. Acad. Sci. U.S.A.* 111, E139–E148. doi: 10.1073/pnas.1317377110
- Bramley, R. G. V., Ouzman, J., and Boss, P. K. (2011). Variation in vine vigour, grape yield and vineyard soils and topography as indicators of variation in the chemical composition of grapes, wine and wine sensory attributes. *Austral. J. Grape Wine Res.* 17, 217–229. doi: 10.1111/j.1755-0238.2011.00136.x
- Bramley, R. G. V., Siebert, T. E., Herderich, M. J., and Krstic, M. P. (2017). Patterns of within-vineyard spatial variation in the 'pepper' compound rotundone are temporally stable from year to year. *Austral. J. Grape Wine Res.* 23, 42–47. doi: 10.1111/ajgw.12245
- Burns, K. N., Kluepfel, D. A., Strauss, S. L., Bokulich, N. A., Cantu, D., and Steenwerth, K. L. (2015). Vineyard soil bacterial diversity and composition revealed by 16S rRNA genes: differentiation by geographic features. *Soil Biol. Biochem.* 91, 232–247. doi: 10.1016/j.soilbio.2015.09.002
- Choné, X., van Leeuwen, C., Cherry, P., and Ribereau-Gayon, P. (2001). Terroir influence on water status and nitrogen status of non-irrigated Cabernet Sauvignon (*Vitis vinifera*): vegetative development, must and wine composition. *S. Afr. J. Enol. Vitic.* 22, 8–15.
- Gilbert, J. A., van der Lelie, D., and Zorraonaindia, I. (2014). Microbial terroir for wine grapes. *Proc. Natl. Acad. Sci. U.S.A.* 111, 5–6. doi: 10.1073/pnas.1320471110
- Goddard, M. (2010). Australasian Science. *Microb. Terror.*
- Goode, J. (2014). *The Science of Wine: From Vine to Glass*, 2nd Edn. Berkeley: University of California Press.
- Gupta, V. V. S. R., Bramley, R. G. V., Greenfield, P., Yu, J., and Herderich, M. J. (2019). Vineyard soil microbiome composition related to rotundone concentration in Australian cool climate 'peppery' Shiraz grapes. *Front. Microbiol.* 10:1607. doi: 10.3389/fmicb.2019.01607
- Hannah, L., Roehrdanz, P. R., Ikegami, M., Shepard, A. V., Shaw, M. R., Tabor, G., et al. (2013). Climate change, wine, and conservation. *Proc. Natl. Acad. Sci. U.S.A.* 110, 6907–6912. doi: 10.1073/pnas.1210127110
- Hunt, M. (2015). 'Rebellion and the Meaning of Terroir', *Jancis Robinson Purple*. Available at: <http://www.jancisrobinson.com> (accessed July 9, 2015).
- Imre, S. P., Kilmartin, P. A., Rutan, T., Mauk, J. L., and Nicolau, L. (2012). Influence of soil geochemistry on the chemical and aroma profiles of Pinot noir wines. *J. Food Agric. Environ.* 10, 280–288.
- Jeffery, D. W., Siebert, T. E., Capone, D. L., Pardon, K. H., van Leeuwen, K. A., and Solomon, M. R. (2009). Grape and wine pepper aroma – analytically challenging but we sniff it out in the end. *Tech. Rev.* 180, 11–16.

- Kliewer, W. M., and Weaver, R. J. (1971). Effect of crop level and leaf area on growth, composition, and coloration of 'Tokay' grapes. *Am. J. Enol. Vitic.* 22, 172–177.
- Knight, S., Klaere, S., Fedrizzi, B., and Goddard, M. R. (2015). Regional microbial signatures positively correlate with wine phenotypes: evidence for a microbial aspect to terroir. *Sci. Rep.* 5, 1–10. doi: 10.1038/srep14233
- Liu, D., Zhang, P., Chen, D., and Howell, K. (2019). From vineyard to the winery: how microbial ecology drives regional distinctiveness of wine. *Front. Microbiol.* 10:2679. doi: 10.3389/fmicb.2019.02679
- Matthews, M. A. (2016). *Terroir and Other Myths of Winegrowing*. Berkeley: University of California Press.
- Proffitt, T., Bramley, R., Lamb, D., and Winter, E. (2006). *Precision Viticulture: A New Era in Vineyard Management and Wine Production*. Adelaide: Winetitles.
- Scarlett, N. J., Bramley, R. G. V., and Siebert, T. E. (2014). Within-vineyard variation in the 'pepper' compound rotundone is spatially structured and related to variation in the land underlying the vineyard. *Austral. J. Grape Wine Res.* 20, 214–222. doi: 10.1111/ajgw.12075
- Schreiner, R. P. (2005). "Mycorrhizas and mineral acquisition in grape vines," in *Soil Environment and Vine Mineral Nutrition*, eds L. P. Christensen, and D. R. Smart, (Davis CA: American Society of Enology and Viticulture), 49–60.
- Seguin, G. (1986). 'Terroirs' and pedology of wine growing. *Experientia* 42, 861–873. doi: 10.1007/bf01941763
- Tarr, P. T., Dreyer, M. L., Athanas, M., Shahgholi, M., Saarloos, K., and Second, T. P. (2013). A metabolomics based approach for understanding the influence of terroir in *Vitis vinifera* L. *Metabolomics* 9, S170–S177.
- Torres, N., Hilbert, G., Antolín, M. C., and Goicoechea, N. (2019). Amino acids and flavonoids profiling in Tempranillo berries can be modulated by the arbuscular mycorrhizal fungi. *Plants* 8, 400–415. doi: 10.3390/plants8100400
- van Leeuwen, C., and de Ressaiguier, L. (2018). Major soil-related factors in terroir and vineyard siting. *Elements* 14, 159–165. doi: 10.2138/gselements.14.3.159
- van Leeuwen, C., Friant, P., Choné, X., Tregoat, O., Koundouras, S., and Dubourdieu, D. (2004). Influence of climate, soil and cultivar on terroir. *Am. J. Enol. Vitic.* 55, 207–217.
- van Leeuwen, C., Roby, J.-P., and de Ressaiguier, L. (2016). "Understanding and managing wine production from different terroirs," in *Proceedings of the 11th International Terroir Congress*, eds G. V. Jones, and N. Doran, (Ashland: Southern Oregon University), 388–393.
- van Leeuwen, C., Roby, J.-P., Pernet, D., and Bois, B. (2010). Methodology of soil-based zoning for viticultural terroirs. *Bull. l'OIV* 83, 13–29.
- van Leeuwen, C., Schultz, H. R., de Cortazar-Atauri, I. G., Duchêne, E., Olat, N., Pieri, P., et al. (2013). Why climate change will not dramatically decrease viticultural suitability in main wine producing areas by 2050. *Proc. Natl. Acad. Sci. U.S.A.* 110, E3051–E3052.
- van Leeuwen, C., and Seguin, G. (2006). The concept of terroir in viticulture. *J. Wine Res.* 17, 1–10. doi: 10.1080/09571260600633135
- van Leeuwen, C., Tregoat, O., Choné, X., Bois, B., Pernet, D., and Gaudillère, J.-P. (2009). Vine water status is a key factor in grape ripening and vintage quality for red bordeaux wine. How can it be assessed for vineyard management purposes? *J. Int. Sci. Vigne Vin* 43, 121–134.
- Vaudour, E., Costantini, E., Jones, G. V., and Mocali, S. (2015). An overview of the recent approaches to terroir functional modelling, footprinting and zoning. *Soil* 1, 287–312. doi: 10.5194/soil-1-287-2015
- White, R. E., Balachandra, L., Edis, R., and Chen, D. (2007). The soil component of terroir. *J. Int. Sci. Vigne Vin* 41, 9–18.
- White, R. E., Balachandra, L., Edis, R., and Chen, D. (2008). "Grapevine vigour is correlated with N-mineralization potential of soil from selected cool climate vineyards," in *Proceedings VIIIth International Terroir Congress*, (Nyons: Agroscope Changins-Wädenswil).
- Zarraonaindia, I., Owens, S. M., Weisenhorn, P., West, K., Hampton-Marcell, J., Lax, S., et al. (2015). The soil microbiome influences grapevine associated microbiota. *mBio* 6, 1–10.
- Zhang, P., Barlow, S., Krstic, M., Herderich, M., Fuentes, S., and Howell, K. (2015). Within-vineyard, within-vine, and within-bunch variability of the rotundone concentration in berries of *Vitis vinifera* L. cv. Shiraz. *J. Agric. Food Chem.* 63, 4276–4283. doi: 10.1021/acs.jafc.5b00590

**Conflict of Interest:** The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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