Terroir analysis and its complexity

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ABSTRACT

Terroir is not just a geographical site, but also a complex concept aiming to express the “collective knowledge of the interactions” between the environment and the vines mediated through human action, “providing distinctive characteristics” to the final product (OIV 2010).

In the popular press, it is often treated and communicated without a proper understanding of the mechanistic relationships between the wine characteristics and the site. These relationships are primarily rooted in the physical environment, particularly in the interactions between the soil-plant and atmosphere system, affecting grapevine physiology, grape composition and wine. Comprehension of the phenomena starts with viticulture zoning techniques, a crucial first step in mapping, describing and further studying terroirs. Viticulture zoning can be carried out with diverse empiricism and expertise and achieving different level of details in describing complex biophysical processes. Spatial and temporal scales can vary across studies, and not all of them have been able to capture the multidisciplinary nature of the terroir.

The scientific understanding of the mechanisms ruling vineyard variability and grape composition is one of the most critical scientific focuses of terroir research. This knowledge can contribute to the analysis of climate change impacts on terroir resilience, the identification of new suitable land for viticulture, and the precise management of vineyards to reach a specific oenological goal.

This article gives an overview of the latest approaches to terroir studies and of new zoning technology, with particular attention to their importance in supporting terroir resilience to climate change.

KEYWORDS: terroir, viticultural zoning, precision viticulture, climate change, soil-plant-atmosphere system, digital viticulture

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INTRODUCTION

Terroir has gained much importance in the European Union (Wilson, 1998) and beyond (Kontkanen et al., 2005) in featured viticultural areas, in terms of geographical indications and designation of origins, the suitability of grape cultivars for a particular region, and the appropriateness of winemaking styles.

According to OIV (Resolution OIV/VITI 333/2010), “terroir is a concept that refers to an area in which collective knowledge of the interactions between the identifiable physical and biological environment and applied viticultural and enological practices develops, providing distinctive characteristics for the products originating from this area. Terroir includes specific soil, topography, climate, landscape characteristics, and biodiversity features”.

Variability between vineyard sites significantly affects grapevine development and berry composition. Therefore, terroir is accepted as a critical aspect in determining wine characteristics and similarity with the general traits of wines produced in a given region; i.e., typicity (van Leeuwen et al., 2004). The definition of the typical characteristics of wine at a regional scale requires a general agreement between producers on which variety, cultural practices and winemaking styles are most suitable to the area. Such an agreement can be harder to find in new producing regions, where producers are more experimental, while climate change threatens the typicity and geographical recognition across generations of people in old producing countries. The concept of terroir is dynamic by nature. Although social recognition is an essential component of the French vision of the idea (Vaudour, 2002; Vaudour, 2003), this is not a field of the natural sciences and does not bring further understanding to the study of physical-biological concepts.

As reported in Figure 1, the terroir is based on the interaction of three main components: (i) the physical environment (climate, topography, geology and pedology), (ii) the biological material (e.g., rootstock, variety and soil biodiversity), and (iii) the cultural (tradition), social-economical and even political issues on which human activities (viticultural practices and winemaking style) act to achieve the expression of terroir. Human activities have a strong influence on the characteristics of wine, but these are themselves ultimately dependent upon the local environment (van Leeuwen and Seguin, 2006) and can also modify the environmental system (e.g., soil characteristics).

As an example of the effect of the physical environment on grapevine physiology and grape composition, Scarlett et al. (2014) and Bramley et al. (2017) highlighted the influence of soil and topography on temperature variability at the vineyard scale, and its implication as a key driver of spatial variability of rotundone concentration in grapes, a sesquiterpene responsible for pepper aroma in wines. Furthermore, Brillante et al. (2017) and Brillante et al. (2020) showed how the spatial variability of plant water status affects spatial variability in sugars, anthocyanins and flavonoid concentration. What is obvious in this context is that soil is

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**FIGURE 1.** The main components of terroir and their declination.
critical, and in particular, the hydrological properties of soil play a fundamental role in determining the water status of the plant and the qualitative response of the berries. As shown by Bonfante et al. (2015) and Bonfante et al. (2017) under the same climate in a vineyard, two very different soils can produce very different wines.

Soil type, land reshaping and soil preparation influence vine development and grape composition through their impact on vine water and nitrogen status (van Leeuwen et al., 2018) and then the expression of terroir. It is easily understood that any human action that directly acts on soil in a vineyard (e.g., the pre-planting preparation) can profoundly modify plant-environment relationships and generate negative or positive effects on achieving the winemaking goals. Figure 2 shows an example of the negative impacts of human activity on the environmental functionality of the vineyard Soil-Plant and Atmosphere (SPA) system. In Figure 2, the reshaping of the slope to facilitate mechanical operations (2014) was obtained through invasive bulldozing and soil movements with profound modification of the physical characteristics of soil horizons in the root zone, such as their vertical sequence and thickness, ultimately leading to a loss of the original soil identity. The result (2021) of this human action is the creation of artificial variability and an important differentiation in plant responses, which are hard to manage, and which negatively affect the oenological objective. Conversely, an example of a positive effect of human action in vineyard preparation can be found in some areas of the northern Médoc region (Bordeaux, France), where the installation of drainage (perforated agricultural pipes) to draw down the water table, has improved the expression of those terroirs (White and Krstic, 2019). It is also worth considering that all modifications to land characteristics that cannot be easily reverted may change properties in a way that may become unsuitable in the long term because of climate change. It is important to stress that the environmental component dominates crop responses by placing limits on the ability of humans to mitigate any adverse conditions of anthropogenic or environmental nature.

Although there is no reference to wine quality in the description of the terroir concept (OIV, 2010), single-vineyard wines are often perceived by consumers and treated by winemakers as high-end products obtained from certain grapes that have flavours better expressed when they are not blended but processed in specific programmes. In old wine regions, geographical recognition is often based on the history and culture of the area, and it is not necessarily understood in terms of its mechanics (Brillante et al., 2021).

The study of terroirs is therefore necessarily a posteriori as this is a relatively new scientific field compared to the establishment of vineyards in these areas. History, traditions and culture are crucial to the recognition and future development of wine, but they are not adequate for informing management and ensuring resilience to changing conditions. Their relevance can be lost over time if not supported by scientific understanding. In new areas, where history and traditions have a shorter time span, the study of terroirs becomes even more significant as it helps growers make more informed decisions and directly contribute to the development of new practices. At the same time, a lack of data for the purposes of comparison and emerging social acceptance can complicate terroir studies in new regions.

In this paper, the complexity of analysing terroir will be discussed from a vineyard perspective and by considering the current technological possibilities in viticultural zoning approaches.

**FIGURE 2.** Detrimental human action on the soil functionality in a vineyard due to preplanting vineyard preparation. Zone 1 and 2 show the different vine development and NDVI in June 2021, following invasive pre-planting modifications.
VINEYARD COMPLEXITY

The vineyard is a complex composite Soil-Plant-Atmosphere system (SPA) under human management, which is characterised by strong spatial variability (Figure 3). The latter is strictly related to the local variability of soil and climate that influences the spatial structure of yield variability and sensory characteristics of the end product.

It is a complex puzzle that cannot be excessively simplified; all the pieces are connected logically and must be treated considering each aspect in-depth to understand their functionality. Moreover, it is a multidisciplinary system that needs different scientific expertise and interdisciplinary approaches to study the terroir expression and face current and future global issues that weigh on the vineyard and jeopardise the resilience of the terroir. For example, soil characteristics affect plant water availability and, consequently, grape composition. However, standard chemical and physical analyses cannot explain the relationships between, and processes involved in soil and plant water availability. Soils that are classified with the same textural class can have very different horizons in terms of thickness, vertical distribution and hydraulic properties, leading to different plant water statuses under similar climate conditions. An example of this was reported for an Aglianico vineyard located in southern Italy by Bonfante et al. (2015) and Bonfante et al. (2017), where two soils (Calcisol and Cambisol) had very different hydraulic properties although they belonged to the same textural class (clay loam). Grapevines showed specific plant water status on each of the two soils, with related effects on grape and must quality. Furthermore, in the same experimental site, Basile et al. (2020) studied the relative contribution of soil hydraulic properties and slope gradient on grapevine water status. These authors concluded that in the study conditions the soil hydraulic properties can drive plant water status more than the morphology of slope.

Similarly, Brillante et al. (2016a) found that in two Cambisols the amount of rock fragments rather than differences in textural properties generates significant differences in plant-soil water relationships over very short distances. These examples show that given the complexity of plant-soil relationships, the professional competences of soil scientists (pedologists, soil physicists and hydropedologists, etc.) is needed to avoid coming to erroneous conclusions in the evaluation of vineyard behaviour and the analysis of terroirs.

Water status is often considered a key factor in the variability of plant response in different terroirs (van Leeuwen et al., 2010). Variability of soil attributes can drive grapevine water status and grape composition in all vineyards (van Leeuwen et al., 2009; Acevedo-Opazo et al., 2010; Intrigliolo and Castel, 2011; Bonfante et al., 2015; Bonfante et al., 2017), independently of irrigation (Brillante et al., 2017; Yu et al., 2020). This has a strong physiological impact, as water is a primary driver of plant physiology and grape ripening (e.g., Castellari et al., 2007).

As well as soil, climate also has a strong impact on vine growth and wine characteristics, which is well documented in the literature (Saayman, 1977; Saayman and Kleynhans, 1978; De Villiers et al., 1996; Carey, 2001; Roux, 2005; van Leeuwen et al., 2010, among others).

When climate micro-variability in vineyards is considered, the most important effects are linked to frost risk, plant diseases and pests, and grape composition.

The complexity of vineyards can be approached using precision viticulture methods, making it possible for site-specific viticultural management to improve the efficiency of production (Bramley et al., 2011; Tardaguila et al., 2011; Bramley, 2020; Yu et al., 2020) and to emphasise the product’s peculiarities derived by environmental site characteristics through the optimisation
of agricultural decisions (Brillante et al., 2020). However, an effort must be made to move from the “black box” view of the vineyard system to the “gray/white box” view, thereby improving knowledge of system processes, which are often influenced by site-specific conditions.

It is therefore possible to conclude that the basis for improving terroir knowledge is the analysis of the SPA system. This analysis cannot rely only on traditional and social recognition but must be elucidated in its casual relationships.

**TERROIR ANALYSIS COMPLEXITY**

Interest in site characterisation originates from two different agricultural objectives: one is related to management and the ability to maximise quality of production per unit of land, and the other is related to communication and the ability to explain to consumers the characteristics of the final products and the rationale behind production choices.

The identification, characterisation and mapping of agricultural sites with similar physical characteristics, also called zoning, is a crucial component of terroir studies and it is also of major importance in precision and sustainable viticulture. In the literature, there is a large variation in the complexity and scale at which these studies are carried out. Furthermore, the availability of spatial-temporal data obtained through new technologies is increasing the ability to delineate within-field variability with unprecedented resolution at reduced cost, and we can expect in the near future to also have the ability to take advantage of this information for operational management at a variable rate in space and time.

The study of terroir has moved from a largely descriptive analysis of geographical variability in land characteristics to a finer elucidation of the relationships between the plant and the environment, which are influenced by agricultural practices, thus opening the door to site-specific management. While descriptive studies have a role in depicting large scale variability and allow macroareas to be compared, they are often limited in scope and not suited to guiding management practices. They are based on the idea that areas with similar geology, soil unit and climate will produce similar responses in terms of grapevine physiology (Gómez-Miguel and Sotés, 2003). These areas are thought to produce grapes with similar characteristics that will result in the production of wines that could be recognised as belonging to the same origin. Carried out at a relatively coarse scale, these studies necessarily reduce the detail of investigation, and cannot elucidate finer relationships between the plant and the environment, which may have a very strong impact on the local scale. New technologies such as remote sensing (Delezir and Guy, 1987; Bramley and Hamilton, 2007; Vaudour, 2002; Vaudour, 2003) and geophysics (Acevedo-Opazo et al., 2008; Brillante et al., 2015; Brillante et al., 2016b), multivariate statistics, geostatistics (Bramley and Gardiner, 2021) and machine-learning (Brillante et al., 2016c) are increasing our ability to characterise large surfaces in detail. However, several important characteristics, in particular those related to soil hydrology, are hard to spatialise, yet they are major drivers of plant responses to the environment.

At a regional scale, the zoning of terroirs starts with mapping the physical environment including climate, geology, geomorphology, topography and soil (Fregoni, 1999; Deloire et al., 2005; van Leeuwen et al., 2010). The second step is the delineation of zones with homogeneous characteristics followed by the analysis of plant material (variety, clones, rootstock) and cultivation techniques in reference vineyards in each zone, and quantitative and qualitative analysis of grapes and wines (Fregoni, 1999; Vaudour, 2003; Deloire et al., 2005; Costantini and Barbetti, 2008; Gaiotti et al., 2010). Finally, homogeneous zones are classified within a relational system in terms of wine specificity. This can be performed using capability classes derived from a series of quantitative and environmental criteria (Sotés and Gómez-Miguel, 1992; Sotés et al., 1994).

Climatology studies based on agroclimatic indices have been one of the most popular approaches to the regional description of terroirs. They have the advantage of generally offering readily available data and can be easily scaled-up. Agro-climatic indices are designed to be more strictly linked to grapevine development than individual atmospheric variables, such as mean temperatures, radiation or precipitation. Most commonly used agroclimatic indices are based on temperature, such as the popular Winkler (Amerine and Winkler, 1944) and Huglin (Huglin and Schneider, 1998) indexes. A modern take is the use of modelling approaches instead of indexes, such as the Grapevine Flowering Veraison model (Parker et al., 2011) and the Grapevine Sugar Ripeness model (Parker et al., 2020). These are also based on temperature and can be used directly to predict phenology and sugar ripeness of different varieties. In the context of terroir studies, they can be applied spatially to understand the suitability of a given region or site for viticulture or for a specific variety (Tonietto and Carbonneau, 2004; Santos et al., 2020). They can be used to understand climate effects on grape ripening, berry composition and possible impacts of climate change scenarios. These approaches tend to only consider the climate, which is of course limiting as its effects on plants are modulated by soil conditions and in particular by soil hydraulic properties and water availability.

To move from a descriptive approach (the black box in Figure 4) toward a more mechanistic understanding of the terroir system (the grey box in Figure 4), terroir studies should take into account the interactions between some of the components of the physical environment; i.e., the atmosphere, lithosphere, hydrosphere with the biosphere, and possibly the anthroposphere. For example Bois, et al. (2020) measured rainfall amounts over short scale and input the information into soil water balance models to understand potential impacts of precipitation variability on simulated soil scenarios, differentiated by their available water holding capacity. Tesci et al. (2002) proposed the use of a quantitative site index which resulted from an empirical formula, using climate and soil parameters. Bodin and Morlat (2006) used
a simple field model based on soil depth, clay content and degree of parent rock weathering, delineated functional units and verified effects of soil on plant physiology. Jones et al. (2004) assessed the suitability of topography, soil, land use and climate in the Umpqua Valley (Oregon, USA) to identify “the best terroirs of the region”. Vaudour et al. (1998) used a somewhat similar approach in the Côtes du Rhône (France), and sampled Grenache fruit to demonstrate grape compositional differences between four of a set of identified terroirs. More robust quantitative methods have emerged in recent years thanks to advances in geographical information systems (GIS) and digital mapping (Bramley et al., 2021 among others), a review of which can be found in Vaudour et al. (2015). These studies need to be completed to move in the direction of a more complete understanding of the relationships between the grapevine and the environment that could help growers make informed management decisions. Of course, there is no limit to learning, and the complete mechanistic understanding of viticulture systems is a moving target (the white box in Figure 4). Moreover, while an enhanced understanding can be obtained locally at the block or farm level, it can be difficult to scale it in its entirety to new conditions. We can aim to achieve a simplified and straightforward zoning approach that can provide as much information as possible on the impact of the environment on plant physiology and thus on grape composition with a high resolution and in a short timeframe.

Currently, there is no unique approach to viticultural zoning able to take into account all processes involved in the vineyard in their totality. Modelling approaches can help standardise analyses and help simulate adaptation to climate change scenarios, while capturing some non-linear interaction between climate and vine (Brillante et al., 2016c; Bonfante et al., 2018). Mechanistic integrated approaches are almost non-existent, which is unfortunate, because mechanistic models are well known for enabling a better adaptation to spatial applications (Leenhardt et al., 1995), even if they require a higher amount of basic data parameters and are more expensive (Manna et al., 2009). A review of mechanistic modelling approaches in grapevine is given in Moriondo et al., 2015.

**IDENTIFICATION AND CLASSIFICATION OF TERROIR**

The previous section explored terroir analyses involving different scales and approaches characterised by different complexity levels. In this section, the classification of terroir will be discussed, considering current possibilities in terms of terroir components and spatial scale. This classification leads to a demarcation that involves the development and use of a zoning methodology. The complexity of the approach depends on the available information layers that describe terroir components and resolution.

Figure 5 shows an example of a framework of components involved in terroir classification (climate, grapevine, geomorphology and soil), their information source (e.g., remote sensing), and spatial resolution (e.g., raster information 20x20 m or 2x2 cm; shapefile) at different spatial scales (regional and local). In terroir zoning, each component is represented by different layers that are used to classify the target area according to zone. Therefore, at the regional scale, the applied information is generally at a lower resolution compared to the corresponding information applied at the local scale. For example, the study of geomorphology based on classifying landscape shape from a digital terrain model (DTM) information layer in a GIS environment to identify micro-topographic variability will be more accurate at the local scale if realised with DTM built from UAV measurements (orthogonal flight with RGB camera or LiDAR camera). It should be highlighted that the resolution...
of this information at the local scale is important, because it helps to understand how the vineyard is placed and supports the analysis of soil spatial distribution. Therefore, it must not be too coarse (because information on processes affecting at microscale the plant behaviour can be lost) or too fine (as it can create too much information and macro processes at a local scale may not be well identified). The final resolution depends, of course, on the scale at which environmental variability needs to be understood and ultimately managed.

Discrete or spatially continuous grapevine information referring to plant status (e.g., vigour and water status) or production (grape yield and composition) can be used in zoning procedures. Plant status can be measured in vivo (discrete info) or estimated (spatial info) using ancillary variables, such as remotely sensed spectral reflectance. The visible (500-700 nm) and red-edge (700-800 nm) domains allows the concentration of pigments in leaves to be highlighted, particularly chlorophyll (Main et al., 2011; Matese and di Gennaro, 2015), which may be linked to water availability in the plant (Tilling et al., 2007; Ballester et al., 2017; Rapaport et al., 2015). The red-edge domain has been used to detect water stress at the canopy scale (Rossini et al., 2013). The near-infrared (800-1000 nm) domain provides information on leaf morphology and cell structure (Kim et al., 2015; Maimaitiyiming et al., 2017), which can also be affected by water content (Poblete et al., 2017). However, the wavelengths directly correlated with the water content of the vegetation belong to the short-wave infrared domain, SWIR, in particular the spectral range within 1000-2000 nm (Cecatto et al., 2001; Seelig et al., 2008; Rapaport et al., 2015; Das et al., 2018; Zovko et al., 2019). The use of vegetation indices (VIs) from remotely sensed sources has become a mainstream approach for monitoring, analysing and spatially mapping variations in vegetation structure and the variability of numerous biophysical parameters in a short time and at a large scale (e.g., Hashimoto et al., 2019).

Grapevine spatial information can be obtained from multispectral satellite images or from multispectral or hyperspectral cameras installed on unmanned aerial vehicles (UAV aka drones). Spectral space-borne data can be collected using different satellite platforms with different costs (Sentinel, Landsat, Proba, PlanetScope, Venüs, WorldView, etc.), which vary in spatial resolution (1 km to sub-meter resolution) and spectral configurations (bands across visible VIS, near-infrared NIR, short-wave infrared SWIR and thermal infrared TIR regions), and which have regular time intervals (monthly to daily). However, the principal

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**FIGURE 5.** Framework for terroir classification at different spatial scales and resolutions of the involved datasets.
limitation of the use of satellite-based remote sensing data for agricultural applications is related to meteorological conditions and their spatial resolution. Moreover, their application in the viticultural sector shows a critical limitation in describing the vineyard structure, a complex scene characterised by grapevine rows, bare soil and weeds. The use of drone applications results in improved spatial resolution and vineyard structure description, with data collected in various spectral configurations and images obtained across UV-SWIR and TIR regions through true colour cameras (RGB) and multispectral, hyperspectral and thermal sensors at a shorter distance from the crop. Nevertheless, the obtained information is limited in terms of the area covered. A continuous temporal data collection at regular time intervals (preferably days) is not available, as the acquisition is not yet automatic. Mainstream commercial sensors are currently limited to the acquisition of VIS-NIR reflectance data, while the UV and SWIR, as well as fluorescence information, are less readily available. Moreover, the vegetation/canopy water content cannot be accurately assessed without the SWIR absorption features (Laroche-Pinel, 2021). Since canopy water content is a product of leaf area index (LAI) and leaf water content (e.g., Momen et al., 2017), it can be estimated by NIR-SWIR VIs that are sensitive to both LAI and leaf water content (e.g., the normalised difference infrared index (NDII) and the normalised difference water index (NDWI)), as well by using models developed from a combination of the individual bands.

For the above reasons, satellite images are more oriented towards terroir classification at regional scale than at local scale in macro viticultural zoning and in areas where block surfaces are large. However, the advantages of using satellite images comprise their historical time series, automatic acquisition at defined intervals (from daily to monthly), spectral range and cost. UAV information supports local scale terroir classification and the development of new sensing systems and models. Satellite and UAV imagery can be integrated; for example, recent studies have applied convolutional neural networks to space-borne remote sensing data for multiscale pan-sharpening (e.g., Zhao et al., 2017; Ghamisi et al., 2018), and a methodology has been developed to improve Sentinel 2A image resolution in the vineyard (Brook et al., 2020) for improved description of vineyard complexity.

Discrete grapevine data collection in vineyards refers to different types of data that can be monitored continuously or not. Although expensive to run, sensors can be applied directly on plant leaves or within the plant stem to continuously monitor the plant status (e.g., the operative sap-flow sensors (Rienth and Scholasch, 2019) or the Bioristor sensors, not yet commercially available for vines (Janni et al., 2019; Janni et al., 2021). The use of the Scholander pressure chamber (Scholander et al., 1965) is a traditional method for assessing plant water status in grapevine and many other species. It is based on measuring the tension of water in plant xylem (the water potential) through equilibration within an enclosed chamber under pressure. Carbon isotope discrimination of grape juice, $\delta^{13}$C, (Gaudillère et al., 2002; Brillante et al., 2018) offers an easily accessible alternative to traditional water status measurements (pressure chamber, porometers). In combination with geostatistic approaches, $\delta^{13}$C can be used to map average water status during ripening at a low cost (van Leeuwen et al., 2009). Large surfaces can be mapped, as sample acquisition is not strictly time-sensitive, and only one sampling time point per season is needed. The $\delta^{13}$C can be used to validate sensor maps from a physiological point of view (Brillante et al., 2020) and for the alternative testing of machine-learning performances to predict plant water status (Brillante et al., 2016c).

As well as water status, all types of data can be collected in the vineyard with a precise geographical reference, allowing the information to be spatialised through geostatistics (e.g., kriging), thus creating an information layer with a resolution that agrees with the density of the spatial data collection. It is important to stress that some data are discontinuous in space and time. Therefore, their ability to express average plant conditions can be questioned spatially when their location is biased, and temporally when the weather is not stable during the growing season and the measurements are not randomised in time during the day or across the season. The measurement of water potentials to assess plant water status is a good example of this; it is common to select this information on sunny days, thus maximising the relative difference between sites, and to only measure these values at midday (in such conditions, the plant water potential is more strictly linked to the atmosphere). Furthermore, when the time interval between consecutive measurements is too long, a discrete measurement may entail the loss of relevant information (for example, the effect of a precipitation event distant in time from the actual measurement) and may not be adequately representative of average plant conditions during the growing season. The information of a time discrete data source can be extended through the use of modelling approaches using continuous predictors; for example, predicting water potentials from weather data. Machine learning offers a powerful solution to this issue (Brillante et al., 2016c). Alternative modelling approaches are physically based simulation models of SPA which have been previously tested or applied in the target area. They have a mechanistic basis and allow the SPA system to be described continuously over the years at a reduced cost (e.g., Bonfante et al., 2011; Bonfante et al., 2017; Bonfante et al., 2018).

Crop load and leaf area to fruit weight ratio are other crucial aspects for understanding variability in plant physiology in space and time. Although it is currently possible to map yield at harvest (Taylor et al., 2016; Sams et al., 2017) when mechanical harvesters are used, it is not yet possible to map yield during the season with an adequate enough precision for informing variable-rate crop load management (Tardaguila et al., 2021). Machine-vision technology is promising in this sense (Nuske et al., 2014; Íñiguez et al., 2021 among others), although it has the disadvantage of being affected by occlusion and being potentially usable
only in a system with sparse and well-trained canopy vegetation. Unmanned ground vehicles equipped with scales are a possibility for providing yield maps in hand-harvested vineyards, as developed by Ampatzidis et al., 2016 for cherry, blueberry and apple.

Point data collection in vineyards can be used not only for plants but also for soil and weather data obtained with sensor networks. The ability to spatialise this information through geostatistical approaches depends on the parameters under consideration, the resolution and the required accuracy. In the case of weather, temperature can be accurately spatialised from point sources and topographical information derived from DTM (de Rességuier et al., 2020 as an example), and it can also be combined with remotely-sensed raster data (MODIS, Landsat) to correct spatial patterns with ground-based information (Morin et al., 2020). Solar radiation can also be spatialized with similar approaches (Bois et al., 2008). Conversely, precipitation is hard to predict in space at a high resolution. It is also variable over short distances, strongly influencing plant-soil relationships and creating variable responses between closely located vineyard blocks (Bois et al., 2020). In the case of soil, the vertical heterogeneity and variation in rooting depth further complicates the mapping of soil properties, while soil is also strongly variable over very short distances. Soil water monitoring is generally carried out at different depths with probes (e.g., TDR probes and tensiometers) placed at defined depths and sometimes according to the distribution of soil horizons. Soil measurements can be used to create an information layer, which may be useful for terroir classification or not. For example, soil matrix potential and soil water content (SWC) can be spatialised and can produce operational information. However, while the spatialised soil matrix potential information can be directly used, because it is directly related to the plant water status (plant water status in the field), the spatial SWC information must be interpreted with the use of soil map information and, in order to be operative, must be converted to soil matrix potential information by means of soil water release curves (soil hydraulic properties). A continuous ancillary variable is needed for spatialisation. Moreover, SWC alone does not explain plant water status (and thus the expected plant behaviour or spatial differentiation), because different pressure head values can correspond to the same SWC in agreement with the specific soil release curve. Hence, the SWC information layer, if not translated in light of hydraulic properties in the pressure head, cannot be considered as valuable data for SPA system analyses and terroir expression classification. Furthermore, grapevine physiology is not directly affected by the amount of SWC, but by the soil water potential dependent on the relative amount of plant-available soil water present in the soil. Lebon et al. (2003) expressed this in terms of the fraction of transpirable soil water (FTSW) and showed that grapevine does not respond to change in available soil water until only 40% of the FTSW is left. However, mapping FTSW across an area is very difficult, because variability in rooting depth needs to be known, which is generally not the case. A promising approach to analysing the spatial behaviour of vineyard soil is combining discrete soil measurements with spatial soil information based on soil electrical conductivity or resistivity derived from geophysical surveys (Brillante et al., 2015; Brillante et al., 2016a; Yu et al., 2021).

The information about soil spatial variability applied in the classification procedure is of critical importance. Soil spatial distribution (soil description and chemical and physical data of each soil horizon) can be identified through pedological surveys that can be oriented by the results of the landforms study (regional scale) and supported by the use of spatial information related to soil physical or chemical characteristics (local scale). At the local scale, standard spatial information derived by non-invasive survey techniques and used to drive soil surveys is electrical resistivity (ER), which can be obtained from a geophysical survey carried out by geophysical sensors, such as electromagnetic induction (EMI) or direct current sensors (Doolittle and Brevik, 2014). The ER varies in space and its variability can be strongly correlated to soil physical properties, such as the amount of rock fragments (Brillante et al., 2014), soil texture - particularly clay (Morari et al., 2009, Brillante et al., 2014), soil depth (Saey et al., 2009), water content (Cousin et al., 2009; Lück et al., 2009; Tromp-van Meerveld and McDonnell, 2009, Brillante et al., 2014, 2016a), water salinity (Doolittle et al., 2001 among others) and carbon content (Martinez et al., 2009; Brillante et al., 2014 among others).

At the regional scale, the result of a pedological survey is a soil map in which information about soil variability inside the soil unit is not reported (although it may be described and evaluated by a pedologist during the soil survey) and cannot be taken into account in the classification procedure. Currently, new soil spatial information can be applied to classify and validate terroir zones characterised by a much higher resolution than was previously available. Higher resolution can support data-driven approaches, enabling the identification of new consistent units of distinct wine styles and/or challenging the robustness of existing units derived from historic and heuristic assessment (Bramley et al., 2020).

This high resolution information can be obtained from direct measurements with sensors (e.g., ER), but new digital resources are also becoming readily available. For example, the ‘GlobalSoilMap.net’ project (https://www.isric.org/projects/globalsoilmapnet) makes soil property information available globally at a resolution of approximately 100 m, which is in marked contrast to a conventional soil or land resource survey at a scale of 1:50,000 (e.g., Hall et al., 2009). While this new information helps us-understand part of the spatial variability of the soil on the one hand, it cannot be used to evaluate the processes involved in the SPA systems in the vineyard for which a complete description of the soil vertical complexity is necessary (e.g., soil taxonomy) on the other hand. Moreover, its spatial resolution is currently still too coarse to properly address soil spatial variability in most vineyards. Only the soil type derived by pedological surveys can be used to model and explore the possible future effects of climate change on the SPA system (Bonfante et al., 2020),
having a “carrier of information” or a “class–pedotransfer” function (Bouma, 1989). At the local scale, the spatial resolution of this new digital information is still not sufficient for carrying out a local classification or for studying the SPA system relationship. An increase in resolution through direct measurements on the ground is needed to understand the processes driving plan performances and the result in terms of wine quality and typicity.

Each approach applied to identify and classify the terroirs of a target region in space, will produce a classification map (shape1 or raster2 file, Figure 5). At a regional scale, the type of compartment data and their resolution will lead to the identification of the UTB/VTU’s (basic terroir unit; Salette et al., 1998; Morlat, 1989;) or the VTU’s (viticultural terroir unit; Carbonneau, 2001), while at local scale, the high resolution of data applied in the zoning procedure will lead to the delineation of the homogeneous zones (HZs), functional HZs (fHZs) (Bonfante et al., 2015) or a clustering data layer (Bramley et al., 2020).

The approach of functional homogeneous zones is more in-depth compared to the other approaches, because it classifies the recognised HZs of a vineyard based on their functionality for a specific target. The HZs of a vineyard consist of zones/units in which different plant responses are expected depending on the spatial variability of intrinsic environmental characteristics and where the precision agriculture principles can be applied. Because the relationships within the SPA system are not linear, different HZs can produce similar effects on plant response. In this last case, the evaluation of HZ’s functionality in relation to plant behaviour is necessary to improve local scale zoning. In viticulture, the term fHZs was first reported by Bonfante et al. (2015) to express the different capacities of HZs to produce a specific level of plant water stress (dynamic information). This kind of classification can also be obtained by studying the plant behaviours in the delineated HZs through high-resolution multitemporal satellite information, dendro sciences and plant hydraulics approaches (De Micco et al., 2018), or by using simulation modeling approaches (Bonfante et al., 2017). When simulation modeling is applied, soil type and soil hydraulic properties must be known, and long-term simulation runs can be run, which include the effect of climate change (Bonfante et al., 2017).

CONCLUSION

The complexity of terroir can be analysed in different ways and at different resolutions depending on the spatial scale and the quality and quantity of available data. The expression of terroir, however, can only be correctly described at the SPA scale and when studying the involved processes. Current and new global challenges require multidisciplinary approaches to preserve the current terroirs and identify new opportunities. For example, the impact of climate change on terroir expression cannot be addressed if the relationship between a specific grapevine variety and environmental changes is not well described.

Changes should not be treated individually for each singular compartment but at the system level. Simulation modeling can help to describe in a dynamic way the impacts of climate change on vineyards, opening new horizons for viticultural zoning (“dynamic viticultural zoning”). Increased knowledge about the functioning of the terroir SPA systems will help to define short-, mid- and long-term adaptation strategies. Cultural practices comprise short-term adaptation, which can be applied within a grapevine growing season. More structured actions, such as changes in training systems, varieties, clones and rootstocks, are examples of long-term adaptations. The ultimate form of adaptation is vineyard relocation, with significant local socio-economic impacts.

More sophisticated approaches require a more significant financial investment in the characterisation of some sectors involved in the classification procedures, such as the spatial characterisation of the soil. This is essential to describe the functionality in the vineyard system correctly. No less significant are investments in the development of in vivo measurements and the monitoring of the vine, which have higher costs than the use of remote sensing, but are essential for reading, calibrating and understanding the information derived from remote measurements.

Deepening the study and knowledge of terroir is necessary, bringing it to a process level, since the reproduction of terroir in another place is not possible. Even though with current technology it is possible to identify environmental characteristics, ensuring the adaptation and production of specific vines, the terroir expression also encompasses other non-physical components (culture, history and society) that cannot be easily transferred. The social aspect is as important as the relationships with the consumers; a terroir must be not only characterised, but also recognized. In the future, even though climate change will impose modifications of the current practices, new or established terroirs will achieve high-quality viticulture and continue to produce wine that reflects their origin thanks to the use of adaptation strategies based on precision and digital viticultural methods. In this way, wine producers will continue to meet consumer preferences.

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