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ORIGINAL RESEARCH ARTICLE

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

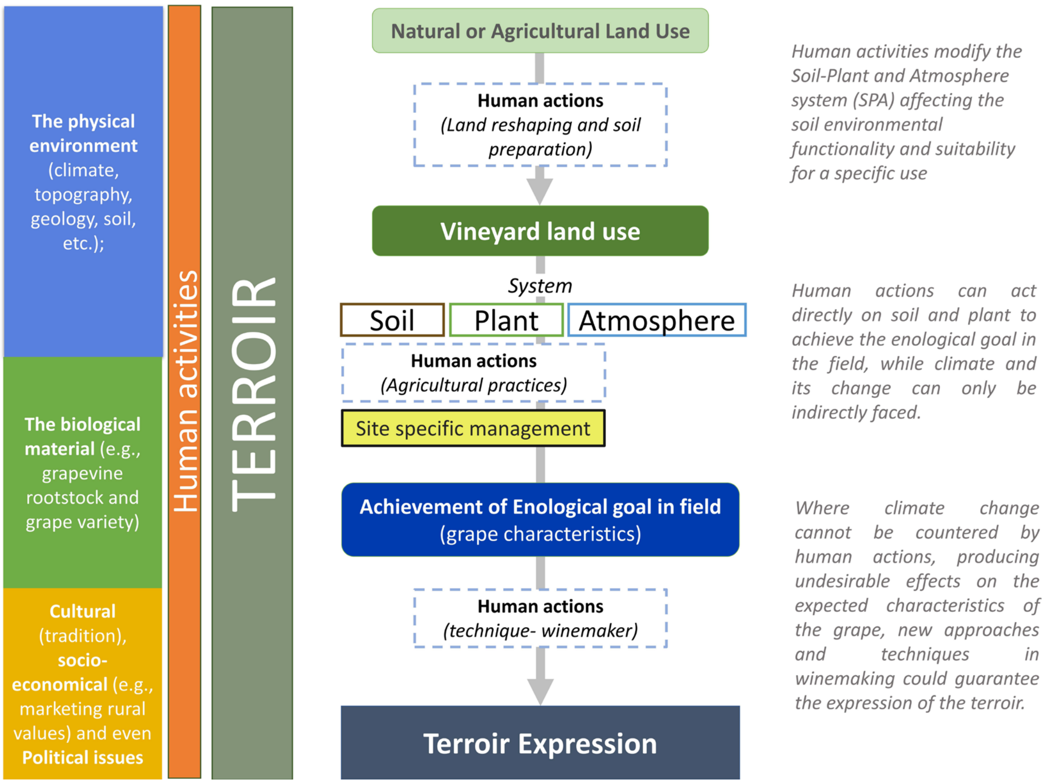
Terroir has gained much importance in the European Union (Wilson, 1998) and beyond (Kontkanen *et al*., 2005) in featured viticultural areas, in terms of geographical indications and designation of origins, the suitability of grape cultivars for a particular region, and the appropriateness of winemaking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



Human activities modify the Soil-Plant and Atmosphere system (SPA) affecting the soil environmental functionality and suitability for a specific use

Human actions can act directly on soil and plant to achieve the enological goal in the field, while climate and its change can only be indirectly faced.

Where climate change cannot be countered by human actions, producing undesirable effects on the expected characteristics of the grape, new approaches and techniques in winemaking could guarantee the expression of the terroir.

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., Castellarin *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

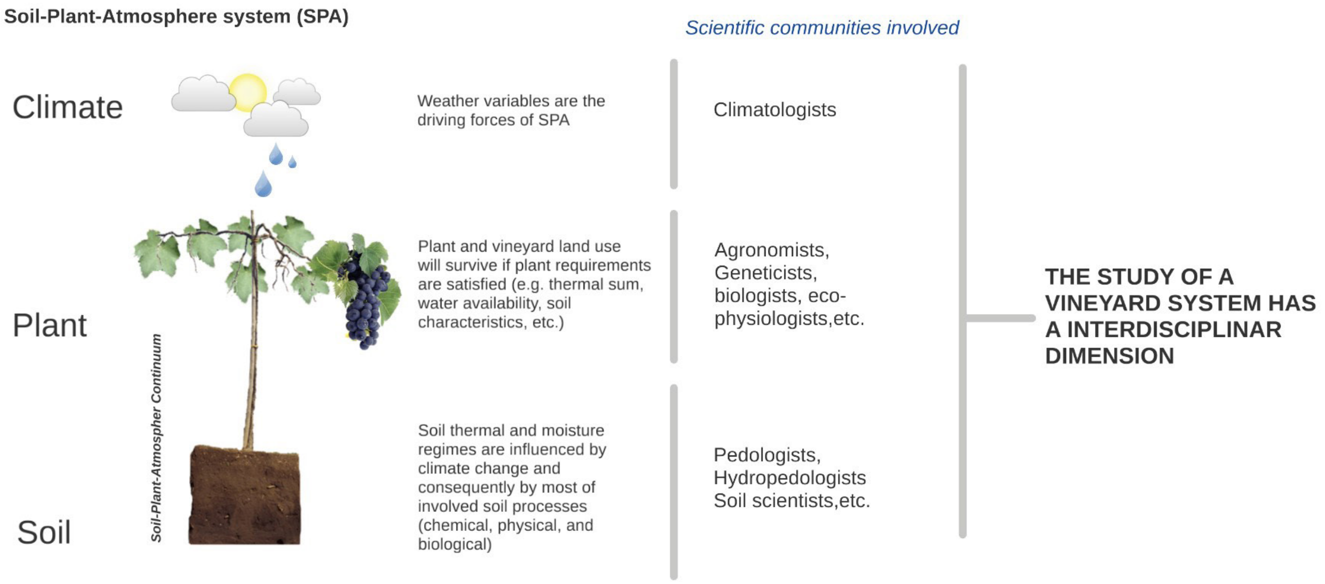


FIGURE 3. The interdisciplinary dimension of the Soil-Plant-Atmosphere (SPA) system.

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. Tesic *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

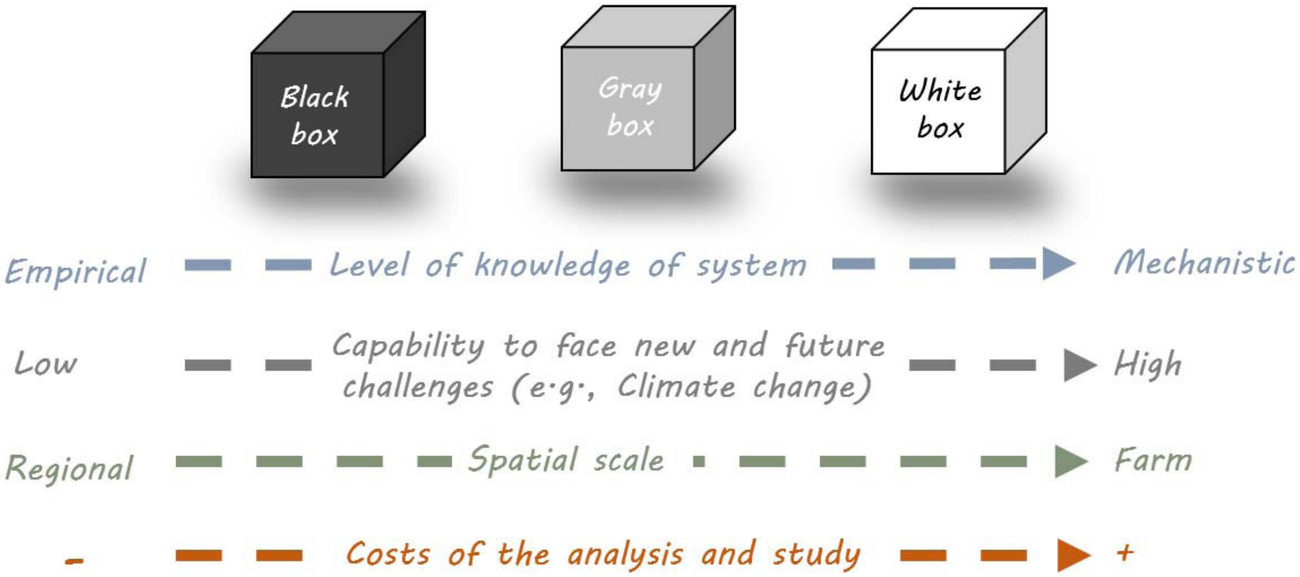


FIGURE 4. The complexity of terroir analysis.

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

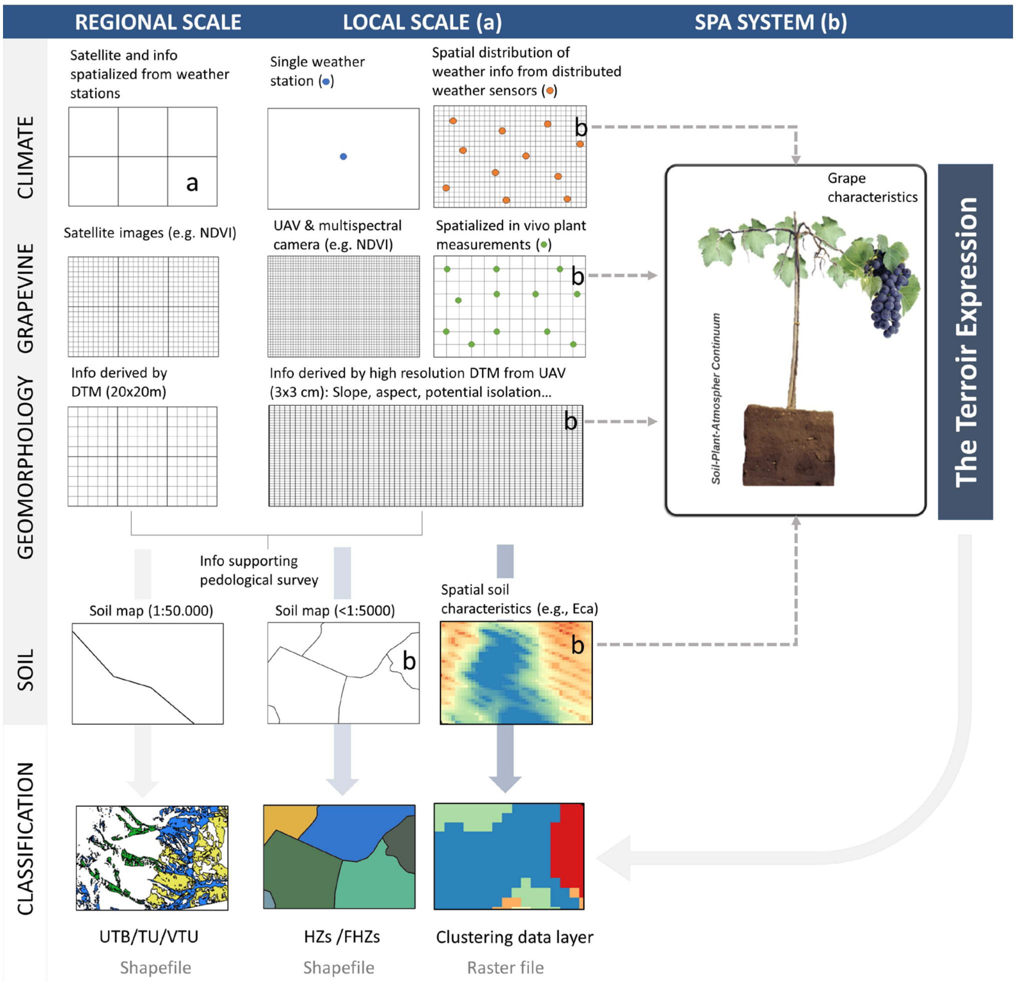


FIGURE 5. Framework for terroir classification at different spatial scales and resolutions of the involved datasets.

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 (Ceccato *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, Venμs, 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 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 matric 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 survey 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 usunderstand 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 (shape[1] or raster[2] file, Figure 5). At a regional scale, the type of compartment data and their resolution will lead to the identification of the UTB/BTU'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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To friendship and freedom. There are no just wars. KTM group (Knowledge of Terroir Matters).

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[1] A shapefile is a simple, nontopological format for storing the geometric location and attribute information of geographic features. Geographic features in a shapefile can be represented by points, lines, or polygons (areas). The workspace containing shapefiles may also contain dBASE tables, which can store additional attributes that can be joined to a shapefile's features.

[2] Raster (or bitmap) images are described by an array or map of bits within a rectangular grid of pixels or dots.

REFERENCES

Acevedo-Opazo, C., Tisseyre, B., Ojeda, H., Ortega-Farias, S., & Guillaume, S. (2008). Is it possible to assess the spatial variability of vine water status? *Journal International des Sciences de la Vigne et du Vin*, 42(4), 203-219. https://doi.org/10.20870/oeno-one.2008.42.4.811

Acevedo-Opazo, C., Ortega-Farias, S., & Fuentes, S. (2010). Effects of grapevine (*Vitis vinifera* L.) water status on water consumption, vegetative growth and grape quality: An irrigation scheduling application to achieve regulated deficit irrigation. *Agricultural Water Management*, 97(7), 956–964. https://doi.org/10.1016/j.agwat.2010.01.025

Amerine, M. A., & Winkler, A. J. (1944). Composition and quality of must and wines of California grapes. *Hilgardia*, 15(6), 493–675. https://doi.org/10.3733/hilg.v15n06p493

Ampatzidis, Y., Tan, L., Haley, R., & Whiting, M. D. (2016). Cloud-based harvest management information system for hand-harvested specialty crops. *Computers and Electronics in Agriculture*, 122, 161-167. https://doi.org/10.1016/j.compag.2016.01.032

Basile, A., Albrizio, R., Autovino, D., Bonfante, A., De Mascellis, R., Terribile, F., & Giorio, P. (2020). A modelling approach to discriminate contributions of soil hydrological properties and slope gradient to water stress in Mediterranean vineyards. *Agricultural Water Management*, 241, 106338. https://doi.org/10.1016/j.agwat.2020.106338

Ballester, C., Zarco-Tejada, P. J., Nicolás, E., Alarcón, J. J., Fereres, E., Intrigliolo, D. S., & Gonzalez-Dugo, V. (2017). Evaluating the performance of xanthophyll, chlorophyll and structure-sensitive spectral indices to detect water stress in five fruit tree species. *Precision Agriculture*, 1–16. https://doi.org/10.1007/s11119-017-9512-y

Bodin, F., & 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 and soil*, 281(1), 37-54. https://doi.org/10.1007/s11104-005-3768-0

Bois, B., Wald, L., Pieri, P., van Leeuwen, C., Commagnac, L., Chery, P., Christen, M., Gaudillère, J. P., & Saur, É. (2008). Estimating spatial and temporal variations in solar radiation within bordeaux winegrowing region using remotely sensed data. *Journal International des Sciences de la Vigne et du Vin*, 42(1), 15–25. https://doi.org/10.20870/oeno-one.2008.42.1.829

Bois, B., Pauthier, B., Brillante, L., Mathieu, O., Leveque, J., van Leeuwen, C., et al. (2020). Sensitivity of grapevine soil-water balance to rainfall spatial variability at local scale level. *Frontiers in Environmental Science*. 8, 110. https://doi.org/10.3389/fenvs.2020.00110

Bonfante, A., Agrillo, A., Albrizio, R., Basile, A., Buonomo, R., De Mascellis, R., Gambuti, A., Giorio, P., Guida, G., Langella, G., Manna, P., Minieri, L., Moio, L., Siani, T., & Terribile, F. (2015). Functional homogeneous zones (fHZs) in viticultural zoning procedure: an Italian case study on Aglianico vine. *Soil*, 1, 427–441. https://doi.org/10.5194/soil-1-427-2015

Bonfante, A., Alfieri, S. M., Albrizio, R., Basile, A., De Mascellis, R., Gambuti, A., Giorio, P., Langella, G., Manna, P., Monaco, E., Moio, L., & Terribile, F. (2017). Evaluation of the effects of future climate change on grape quality through a physically based model application: a case study for the Aglianico grapevine in Campania region, Italy. *Agricultural Systems*, 152. https://doi.org/10.1016/j.agsy.2016.12.009

Bonfante, A., Basile, A., & Bouma, J. (2020). Targeting the soil quality and soil health concepts when aiming for the United Nations Sustainable Development Goals and the EU Green Deal. *SOIL*, 6(2). https://doi.org/10.5194/soil-6-453-2020

Bonfante, A., Basile, A., Langella, G., Manna, P., & Terribile, F. (2011). A physically oriented approach to analysis and mapping of terroirs. *Geoderma*, 167–168, 103–117. https://doi.org/10.1016/j.geoderma.2011.08.004

Bonfante, A., Monaco, E., Langella, G., Mercogliano, P., Bucchignani, E., Manna, P., & Terribile, F. (2018). A dynamic viticultural zoning to explore the resilience of terroir concept under climate change. *Science of the Total Environment*, 624. https://doi.org/10.1016/j.scitotenv.2017.12.035

Bouma, J. (1989). Using Soil Survey Data for Quantitative Land Evaluation (pp. 177–213). *Springer*, New York, NY. https://doi.org/10.1007/978-1-4612-3532-3_4

Bramley, R. G., & Hamilton, R. P. (2007). Terroir and precision viticulture: Are they compatible? *Journal International des Sciences*, 41(1), 1-8. https://doi.org/10.20870/oeno-one.2007.41.1.855

Bramley, R. G.V., Ouzman, J., & 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. *Australian Journal of Grape and Wine Research*, 17(2), 217–229. https://doi.org/10.1111/j.1755-0238.2011.00136.x

Bramley, R. G.V., Siebert, T. E., Herderich, M. J., & Krstic, M. P. (2017). Patterns of within-vineyard spatial variation in the 'pepper' compound rotundone are temporally stable from year to year. *Australian Journal of Grape and Wine Research*, 23(1), 42–47. https://doi.org/10.1111/ajgw.12245

Bramley, Robert G.V., Ouzman, J., & Trought, M. C. T. (2020). Making sense of a sense of place: precision viticulture approaches to the analysis of terroir at different scales. *OENO One*, 54(4), 903–917. https://doi.org/10.20870/oeno-one.2020.54.4.3858

Bramley, R. G. V., & Gardiner, P. S. (2021). Underpinning terroir with data: a quantitative analysis of biophysical variation in the Margaret River region of Western Australia. *Australian Journal of Grape and Wine Research*, 27(4), 420-430. https://doi.org/10.1111/ajgw.12491

Brillante, L., Bois, B., Mathieu, O., Bichet, V., Michot, D., Lévêque, J. (2014) Monitoring soil volume wetness in heterogeneous soils by electrical resistivity. A field-based pedotransfer function, *Journal of Hydrology*, 516, 56-66, https://doi.org/10.1016/j.jhydrol.2014.01.052

Brillante, L., Mathieu, O., Bois, B., van Leeuwen, C., & Lévêque, J. (2015). The use of soil electrical resistivity to monitor plant and soil water relationships in vineyards. *Soil*, 1(1), 273–286. https://doi.org/10.5194/soil-1-273-2015

Brillante, L., Bois, B., Lévêque, J., Mathieu O. (2016a). Variations in soil-water use by grapevine according to plant water status and soil physical-chemical characteristics-A 3D spatio-temporal analysis. *European Journal of Agronomy*, 77, 122–135. https://doi.org/10.1016/j.eja.2016.04.004

Brillante, L., Bois, B., Mathieu, O., Lévêque, J. (2016b). Electrical imaging of soil water availability to grapevine: a benchmark experiment of several machine-learning techniques. *Precision Agriculture* 17 (6), 637-658. https://doi.org/10.1007/s11119-016-9441-1

Brillante, L., Mathieu, O., Lévêque, J., Bois, B. (2016c) Ecophysiological modeling of grapevine water stress in Burgundy terroirs by a machine-learning approach. *Frontiers in Plant Science*, 7 (796). https://doi.org/10.3389/fpls.2016.00796

Brillante, Luca, Martínez-Luscher, J., Yu, R., Plank, C. M., Sanchez, L., Bates, T. L., Brenneman, C., Oberholster, A., & Kurtural, S. K. (2017). Assessing Spatial Variability of Grape Skin Flavonoids at the Vineyard Scale Based on Plant Water Status Mapping. *Journal of Agricultural and Food Chemistry*, 65(26), 5255–5265. https://doi.org/10.1021/acs.jafc.7b01749

Brillante, L., Mathieu, O., Lévêque, J., van Leeuwen, C., & Bois, B. (2018). Water status and must composition in grapevine cv. Chardonnay with different soils and topography and a mini meta-analysis of the δ13C/water potentials correlation. *Journal of the Science of Food and Agriculture*, 98 (2), 691-697

Brillante, Luca, Bonfante, A., Bramley, R. G. V., Tardaguila, J., & Priori, S. (2020). Unbiased Scientific Approaches to the Study of Terroir Are Needed! *Frontiers in Earth Science*, 8, 493. https://doi.org/10.3389/feart.2020.539377

Brook, A., De Micco, V., Battipaglia, G., Erbaggio, A., Ludeno, G., Catapano, I., & Bonfante, A. (2020). A smart multiple spatial and temporal resolution system to support precision agriculture from satellite images: Proof of concept on Aglianico vineyard. *Remote Sensing of Environment*, 240. https://doi.org/10.1016/j.rse.2020.111679

Carbonneau, A. (2001). Concepts "terroir." Proc. XIIèmes Journées du GESCO, 3–7.

Carey, V. A. (2001). Spatial characterisation of natural terroir units for viticulture in the Bottelaryberg-Simonsberg-Helderberg winegrowing area. Thesis (MScAgric) Stellenbosch: Stellenbosch University (https://scholar.sun.ac.za/handle/10019.1/52459).

Castellarin, S. D., Matthews, M. A., Di Gaspero, G., and Gambetta, G. A. (2007). Water deficits accelerate ripening and induce changes in gene expression regulating flavonoid biosynthesis in grape berries. *Planta*, 227, 101–112. https://doi.org/10.1007/s00425-007-0598-8

Ceccato, P., Flasse, S., Tarantola, S., Jacquemoud, S., & Grégoire, J.-M. (2001). Detecting vegetation leaf water content using reflectance in the optical domain. *Remote Sensing of Environment*, 77(1), 22–33. https://doi.org/10.1016/S0034-4257(01)00191-2

Costantini, E. A., & Barbetti, R. (2008). Environmental and visual impact analysis of viticulture and olive tree cultivation in the province of Siena (Italy). *European Journal of Agronomy*, 28(3), 412-426. https://doi.org/10.1016/j.eja.2007.11.012

Cousin, I., Besson, A., Bourennane, H., Pasquier, C., Nicoullaud, B., King, D., & Richard, G. (2009). From spatial-continuous electrical resistivity measurements to the soil hydraulic functioning at the field scale. Comptes Rendus *Geoscience*, 341(10–11), 859–867. https://doi.org/10.1016/j.crte.2009.07.011

Das, B., Mahajan, G. R., & Singh, R. (2018). Hyperspectral Remote Sensing: Use in Detecting Abiotic Stresses in Agriculture. In Advances in Crop Environment Interaction (pp. 317–335). *Springer Singapore*. https://doi.org/10.1007/978-981-13-1861-0_12

Delezir, J., Guy, M. (1987). Essai d'inventaire de la vigne par images Spot Obliques. Spot 1, utilisation des images, bilan, resultats, Paris, novembre 1987. CNES, Toulouse, 327–331

Deloire, A., Vaudour, E., Carey, V. A., Bonnardot, V., & van Leeuwen, C. (2005). Grapevine responses to terroir: a global approach. *Journal International des Sciences de la Vigne et du Vin*, 39(4), 149-162. https://doi.org/10.20870/oeno-one.2005.39.4.888

De Micco, V., Zalloni, E., Battipaglia, G., Erbaggio, A., Scognamiglio, P., Caputo, R., & Cirillo, C. (2018). Rootstock effect on tree-ring traits in grapevine under a climate change scenario. *IAWA Journal*. https://doi.org/10.1163/22941932-20170199

de Rességuier, L., Mary, S., Le Roux, R., Petitjean, T., Quénol, H., & van Leeuwen, C. (2020). Temperature variability at local scale in the Bordeaux area relations with environmental factors and impact on vine phenology. *Frontiers in Plant Science*, 11, 515. https://doi.org/10.3389/fpls.2020.00515

De Villiers, F.S., Schmidt, A., Theron, J.C.D., Taljaard, R. (1996). Onderverdeling van Wes-Kaapse wynbougebiede volgens bestaande klimaatskriteria. Wynbou Tegnies, 78, 10–12.

Doolittle, J. A., & Brevik, E. C. (2014). The use of electromagnetic induction techniques in soils studies. In Geoderma (Vols. 223–225, Issue 1, pp. 33–45). *Elsevier*. https://doi.org/10.1016/j.geoderma.2014.01.027

Doolittle, J., Petersen, M., & Wheeler, T. (2001). Comparison of two electromagnetic induction tools in salinity appraisals. *Journal of Soil and Water Conservation*. 56 (3), 257-262.

Fregoni, M. (1999). Viticoltura di qualità. L'informatore agrario. s.r.l.-Lungadige Galtarossa, 23/E-37133 Verona (IT).

Gaiotti, F., Marcuzzo, P., Battista, F., Lovat, L., Tomasi, D. (2010). Storia del prosecco e del suo territorio di produzione: un percorso di studi in continuo progresso. VIII International Terroir Congress, june 14th–18th, Soave (VR) Italy: Proceedings, vol. 1. 1, 22–30.

Gaudillère, J. P., van Leeuwen, C., & Ollat, N. (2002). Carbon isotope composition of sugars in grapevine, an integrated indicator of vineyard water status. *Journal of Experimental Botany*, 53(369), 757-763.

Ghamisi, P., Member, S., Rasti, B., Yokoya, N., Wang, Q., Höfle, B., Bruzzone, L., Bovolo, F., Chi, M., Anders, K., Gloaguen, R., Atkinson, P. M., & Atli Benediktsson, J. (2018). Multisource and Multitemporal Data Fusion in Remote Sensing. Retrieved from https://arxiv.org/abs/1812.08287v1

Hall, J. A. S., Maschmedt, D. J., & Billing, N. B. (2009). The soils of Southern South Australia, The South Australian Land and Soil Book Series, Volume 1: Geological Survey of South Australia. Bulletin, 56, 188.

Hashimoto, N., Saito, Y., Maki, M., & Homma, K. (2019). Simulation of Reflectance and Vegetation Indices for Unmanned Aerial Vehicle (UAV) Monitoring of Paddy Fields. *Remote Sensing* 2019, Vol. 11, Page 2119, 11(18), 2119. https://doi.org/10.3390/rs11182119

Huglin, P., & Schneider, C. (1998). Biologie et Écologie de la vigne, 2nd ed. Lavoisier, Paris.

Íñiguez, R.; Palacios, F.; Barrio, I.; Hernández, I.; Gutiérrez, S.; Tardaguila, J. (2021) Impact of leaf occlusions on yield assessment by computer vision in commercial vineyards. *Agronomy* 2021, 11, 1003. https://doi.org/10.3390/agronomy11051003

Intrigliolo, D. S., & Castel, J. R. (2011). Interactive effects of deficit irrigation and shoot and cluster thinning on grapevine cv. Tempranillo. Water relations, vine performance and berry and wine composition. *Irrigation Science*, 29(6), 443–454. https://doi.org/10.1007/s00271-010-0252-2

Janni, M., Coppede, N., Bettelli, M., Briglia, N., Petrozza, A., Summerer, S., Vurro, F., Danzi, D., Cellini, F., Marmiroli, N., Pignone, D., Iannotta, S., & Zappettini, A. (2019). In Vivo Phenotyping for the Early Detection of Drought Stress in Tomato. *Plant Phenomics*, 2019. https://doi.org/10.34133/2019/6168209

Janni, M., Claudia, C., Federico, B., Sara, P., Filippo, V., Nicola, C., Manuele, B., Davide, C., Loreto, F., & Zappettini, A. (2021). Real-time monitoring of Arundo donax response to saline stress through the application of in vivo sensing technology. *Scientific Reports*, 11(1), 18598. https://doi.org/10.1038/s41598-021-97872-6

Jones, G., Snead, N., & Nelson, P. (2004). Geology and wine 8. Modeling viticultural landscapes: A GIS analysis of the terroir potential in the Umpqua Valley of Oregon. *Geoscience Canada*, 31(4), 167-178.

Kim, D. M., Zhang, H., Zhou, H., Du, T., Wu, Q., Mockler, T. C., & Berezin, M. Y. (2015). Highly sensitive image-derived indices of water-stressed plants using hyperspectral imaging in SWIR and histogram analysis. *Scientific Reports*, 5(1), 15919. https://doi.org/10.1038/srep15919

Kontkanen, D., Reynolds, A. G., Cliff, M. A., & King, M. (2005). Canadian terroir: sensory characterization of Bordeaux-style red wine varieties in the Niagara Peninsula. *Food Research International*, 38(4), 417–425. https://doi.org/10.1016/j.foodres.2004.10.010

Laroche-Pinel, E., Duthoit, S., Albughdadi, M., Costard, A.D., Rousseau, J., Chéret, V., & Clenet, H. (2021). Towards vine water status monitoring on a large scale using sentinel-2 images. *Remote Sensing*, 13(9):1837. https://doi.org/10.3390/rs13091837

Lebon, E., Dumas, V., Pieri, P., Schultz, H.R. (2003). Modelling the seasonal dynamics of the soil water balance of vineyards. *Functional Plant Biology*, 30 (2003), pp. 699-710. https://doi.org/10.1071/FP02222

Leenhardt, D., Voltz, M., & Rambal, S. (1995). A survey of several agroclimatic soil water balance models with reference to their spatial application. *European journal of agronomy*, 4(1), 1-14. https://doi.org/10.1016/S1161-0301(14)80012-9

Lück, E., Gebbers, R., Ruehlmann, J., & Spangenberg, U. (2009). Electrical conductivity mapping for precision farming. Near Surface Geophysics. https://doi.org/10.3997/1873-0604.2008031

Maimaitiyiming, M., Ghulam, A., Bozzolo, A., Wilkins, J. L., & Kwasniewski, M. T. (2017). Early detection of plant physiological responses to different levels of water stress using reflectance spectroscopy. *Remote Sensing*, 9(7), 1–23. https://doi.org/10.3390/rs9070745

Main, R., Cho, M. A., Mathieu, R., O'Kennedy, M. M., Ramoelo, A., & Koch, S. (2011). An investigation into robust spectral indices for leaf chlorophyll estimation. ISPRS *Journal of Photogrammetry and Remote Sensing*, 66(6), 751–761. https://doi.org/10.1016/j.isprsjprs.2011.08.001

Manna, P., Basile, A., Bonfante, A., De Mascellis, R., & Terribile, F. (2009). Comparative Land Evaluation approaches: An itinerary from FAO framework to simulation modelling. Geoderma, 150(3-4), 367-378. https://doi.org/10.1016/j.geoderma.2009.02.020

Martinez, G., Vanderlinden, K., Ordóñez, R., Muriel, J.L. (2009). Can apparent electrical conductivity improve the spatial characterization of soil organic carbon? Vadose Zone J. 8 (3), 586–593. https://doi.org/10.2136/vzj2008.0123

Matese, A., & di Gennaro, S. F. (2015). Technology in precision viticulture: a state of the art review. *International Journal of Wine Research*, 69. https://doi.org/10.2147/IJWR.S69405

Momen, M., Wood, J. D., Novick, K. A., Pangle, R., Pockman, W. T., McDowell, N. G., & Konings, A. G. (2017). Interacting Effects of Leaf Water Potential and Biomass on Vegetation Optical Depth. *Journal of Geophysical Research: Biogeosciences*, 122(11), 3031–3046. https://doi.org/10.1002/2017JG004145

Morari, F., Castrignanò, A., & Pagliarin, C. (2009). Application of multivariate geostatistics in delineating management zones within a gravelly vineyard using geo-electrical sensors. *Computers and Electronics in Agriculture*. https://doi.org/10.1016/j.compag.2009.05.003

Moriondo, M., Ferrise, R., Trombi, G., Brilli, L., Dibari, C., & Bindi, M. (2015). Modelling olive trees and grapevines in a changing climate. *Environmental Modelling & Software*, 72, 387-401. https://doi.org/10.1016/j.envsoft.2014.12.016

Morlat, R. (1989). Le terroir viticole : contribution à l'étude de sa caractérisation et de son influence sur les vins : application aux vignobles rouges de moyenne vallée de la Loire. Revue Française d'oenologie, 32(139), S6–S13. Retrieved from http://www.theses.fr/1989BOR22019

Morin, G., Le Roux, R., Lemasle, P., & Quénol, H. (2020). Mapping Bioclimatic Indices by Downscaling MODIS Land Surface Temperature: Case Study of the Saint-Emilion Area. *Remote Sensing* 2021, 13, 4. https://dx.doi.org/10.3390/rs13010004

Nuske, S., Wilshusen, K., Achar, S., Yoder, L., Narasimhan, S., Singh, S. (2014) Automated Visual Yield Estimation in Vineyards. J. Field Robot. 31, 837–860. https://doi.org/10.1002/rob.21541

OIV (2010) Definition of vitivinicultural "terroir". The International Organization of Vine and Wine, Resolution OIV/VITI 333/2010.

Parker, A.K., De Cortázar-Atauri, I.G., van Leeuwen, C., Chuine, I. (2011) General phenological model to characterise the timing of flowering and veraison of *Vitis vinifera* L. *Australian Journal of Grape and Wine Research*, 17 (2) (2011), pp. 206-216. https://doi.org/10.1111/j.1755-0238.2011.00140.x

Parker, A. K., García de Cortázar-Atauri, I., Gény, L., Spring, J.-L., Destrac, A., Schultz, H., Molitor, D., Lacombe, T., Graça, A., Monamy, C., Stoll, M., Storchi, P., Trought, M. C. T., Hofmann, R. W., & van Leeuwen, C. (2020). Temperature based grapevine sugar ripeness modelling for a wide range of *Vitis vinifera* L. cultivars. *Agricultural and Forest Meteorology*, 285–286, 107902. https://doi.org/10.1016/j.agrformet.2020.107902

Poblete, T., Ortega-Farías, S., Moreno, M., & Bardeen, M. (2017). Artificial Neural Network to Predict Vine Water Status Spatial Variability Using Multispectral Information Obtained from an Unmanned Aerial Vehicle (UAV). *Sensors*, 17(2488), 1–17. https://doi.org/10.3390/s17112488

Rapaport, T., Hochberg, U., Shoshany, M., Karnieli, A., & Rachmilevitch, S. (2015). Combining leaf physiology, hyperspectral imaging and partial least squares-regression (PLS-R) for grapevine water status assessment. ISPRS *Journal of Photogrammetry and Remote Sensing*, 109, 88–97. https://doi.org/10.1016/j.isprsjprs.2015.09.003

Rienth, M., & Scholasch, T. (2019). State-of-the-art of tools and methods to assess vine water status. *OENO One*, 53(4) 619-637. https://doi.org/10.20870/oeno-one.2019.53.4.2403

Roux, F. A. (2005). Die Invloed van Spesifieke Grond en Klimaats Parameters op Wingerdprestasie, Wynkwaliteit en Karakter. MSc Agric thesis. Stellenbosch University, Stellenbosch.

Rossini, M., Fava, F., Cogliati, S., Meroni, M., Marchesi, A., Panigada, C., Giardino, C., Busetto, L., Migliavacca, M., Amaducci, S., & Colombo, R. (2013). Assessing canopy PRI from airborne imagery to map water stress in maize. ISPRS *Journal of Photogrammetry and Remote Sensing*, 86, 168–177. https://doi.org/10.1016/j.isprsjprs.2013.10.002

Saayman, D. (1977). The effect of soil and climate on wine quality. In: Proc. Int. Symp. Quality of the Vintage, February 1977, Cape Town, South Africa. 197-208.

Saayman, D., & Kleynhans, P. H. (1978). The effect of soil type on wine quality. In:South African Society for Enology and Viticulture Congress (SASEV), October 1978, Stellenbosch, South Africa. 105–119.

Saey, T., Simpson, D., Vermeersch, H., Cockx, L., & Van Meirvenne, M. (2009). Comparing the EM38DD and DUALEM-21S Sensors for Depth-to-Clay Mapping. Soil Science *Society of America Journal*, 73(1), 7. https://doi.org/10.2136/sssaj2008.0079

Salette, J., Asselin, C., & Morlat, R. (1998). Le lien du terroir au produit : Analyse du système terroir-vigne-vin ; possibilité d'application à d'autres produits. *Sciences des Aliments*, 18(3), 251–265. Retrieved from https://hal.inrae.fr/hal-02692348

Sams, B., Litchfield, C., Sanchez, L., & Dokoozlian, N (2017). Two methods for processing yield maps from multiple sensors in large vineyards in California. Adv. Anim. Biosci. 8, 530–533. https://doi.org/10.1017/S2040470017000516

Santos, J. A., Grätsch, S. D., Karremann, M. K., Jones, G. V, & Pinto, J. G. (2013). Ensemble projections for wine production in the Douro Valley of Portugal. *Climatic Change*, 117(1–2), 211–225.

Scarlett, N. J., Bramley, R. G. V., & 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. *Australian Journal of Grape and Wine Research*, 20(2), 214–222. doi: 10.1111/AJGW.12075

Scholander, P. F., Bradstreet, E. D., Hemmingsen, E. A., & Hammel, H. T. (1965). Sap Pressure in Vascular Plants: Negative hydrostatic pressure can be measured in plants. *Science*, 148(3668), 339-346. https://doi.org/10.1126/science.148.3668.339

Seelig, H.-D., Hoehn, A., Stodieck, L. S., Klaus, D. M., Adams III, W. W., & Emery, W. J. (2008). The assessment of leaf water content using leaf reflectance ratios in the visible, near-, and short-wave-infrared. *International Journal of Remote Sensing*, 29(13), 3701–3713. https://doi.org/10.1080/01431160701772500

Sotés, V., & Gómez-Miguel, V. (1992). Criterios de diferenciación y delimitación de comarcas y regiones vitivinícolas. Examen de los factores naturales y humanos que concurren. *Vitivinicultura*, 5, 29-39.

Sotés, V., Gómez-Sanchez, P., Laya, H., & Gómez-Miguel, V. (1994). Cuantificación de las variables implicadas en la delimitación y caracterización de zonas vitícolas en la DO Ribera del Duero. 7th GESCO, 21-23.

Gómez-Miguel, V., & Sotés, V. (2003). Zonificación del terroir en España. Terroir-Zonazione-Viticoltura: trattato internazionale Phytoline, 187-226.

Tardaguila, J., Baluja, J., Arpon, L., Balda, P., & Oliveira, M. (2011). Variations of soil properties affect the vegetative growth and yield components of "Tempranillo" grapevines. *Precision Agriculture* 2011 12:5, 12(5), 762–773. https://doi.org/10.1007/s11119-011-9219-4

Tardaguila, J., Stoll, M., Gutiérrez, S., Proffitt, T., & Diago, M. P. (2021). Smart applications and digital technologies in viticulture: A review. *Smart Agricultural Technology*, 1, 100005. https://doi.org/10.1016/j.atech.2021.100005

Taylor, J.A.; Sanchez, L.; Sams, B.; Haggerty, L.; Jakubowski, R.; Djafour, S.; Bates, T.R. (2016) Evaluation of a commercial grape yield monitor for use mid-season and at-harvest. *OENO One* 2016, 50, 57–63. https://doi.org/10.20870/oeno-one.2016.50.2.784

Tesic, D., Woolley, D. J., Hewett, E. W., & Martin, D. J. (2002). Environmental effects on cv Cabernet Sauvignon (*Vitis vinifera* L.) grown in Hawke's Bay, New Zealand.: 2. Development of a site index. *Australian Journal of Grape and Wine Research*, 8(1), 27-35. https://doi.org/10.1111/j.1755-0238.2002.tb00208.x

Tilling, A. K., O'Leary, G. J., Ferwerda, J. G., Jones, S. D., Fitzgerald, G. J., Rodriguez, D., & Belford, R. (2007). Remote sensing of nitrogen and water stress in wheat. *Field Crops Research*, 104(1–3), 77–85. https://doi.org/10.1016/j.fcr.2007.03.023

Tonietto, J., & Carbonneau, A. (2004). A multicriteria climatic classification system for grape-growing regions worldwide. *Agricultural and forest meteorology*, 124(1-2), 81-97. https://doi.org/10.1016/j.agrformet.2003.06.001

Tromp-van Meerveld, H. J., & McDonnell, J. J. (2009). Assessment of multi-frequency electromagnetic induction for determining soil moisture patterns at the hillslope scale. *Journal of Hydrology*, 368(1–4), 56–67. https://doi.org/10.1016/j.jhydrol.2009.01.037

van Leeuwen, C., Friant, P., Choné, X., Tregoat, O., Koundouras, S., & Dubourdieu, D. (2004). Influence of Climate, Soil, and Cultivar on Terroir. *American Journal of Enology and Viticulture*, 55(3).

van Leeuwen, C., & Seguin, G. (2006). The concept of terroir in viticulture. *Journal of Wine Research*, 17(1), 1–10. https://doi.org/10.1080/09571260600633135

van Leeuwen, C., Roby, J.-P., Pernet, D., & Bois, B. (2010). Methodology of soil-based zoning for viticultural terroirs. Bulletin de l'OIV, 83(947/948/949), 13–29.

van Leeuwen, C., Roby, J. P., & de Rességuier, L. (2018). Soil-related terroir factors: a review. *OENO One*, 52(2), 173–188. https://doi.org/10.20870/oeno-one.2018.52.2.2208

van Leeuwen, C., Tregoat, O., Choné, X., Bois, B., Pernet, D., Gaudillère, J.-P., & others. (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. *Journal International des Sciences de la Vigne et du Vin*, 43(3), 121–134. https://doi.org/10.20870/oeno-one.2009.43.3.798

Vaudour, E., Girard, M. C., Brémond, L. M., & Lurton, L. (1998). Caracterisation spatiale des terroirs et constitution des raisins en AOC Cotes-du-Rhone meridionales (Bassin de Nyons-Valreas). *Journal International des Sciences de la Vigne et du Vin*, 32(4), 169-182.

Vaudour, E. (2002). The quality of grapes and wine in relation to geography: Notions of terroir at various scales. *Journal of Wine Research*, 13(2), 117–141. https://doi.org/10.1080/0957126022000017981

Vaudour, E. (2003). Les terroirs viticoles. Dunod, Paris.

Vaudour, E., Costantini, E., Jones, G. V., & Mocali, S. (2015). An overview of the recent approaches to terroir functional modelling, footprinting and zoning. *Soil*, 1(1), 287-312. https://doi.org/10.5194/soil-1-287-2015

Yu, R., Brillante, L., Martínez-Lüscher, J., Kurtural, S.K. (2020). Spatial variability of soil and plant water status and their cascading effects on grapevine physiology are linked to berry and wine chemistry. *Frontiers in Plant Science* 11, 790 https://doi.org/10.3389/fpls.2020.00790

Yu, R., Zaccaria, D., Kisekka, I., Kurtural, S.K. (2021). Soil apparent electrical conductivity and must carbon isotope ratio provide indication of plant water status in wine grape vineyards. *Precision Agriculture* 22, 1333–1352 (2021). https://doi.org/10.1007/s11119-021-09787-x

White, R., & Krstic, M. (2019). Healthy Soils for Healthy Vines. In Healthy Soils for Healthy Vines. https://doi.org/10.1071/9781486307395

Wilson, J. E. (1998). Terroir: The role of geology, climate and culture in the making of French wines. University of California Press.

Zhao, W., Jiao, L., Ma, W., Zhao, J., Zhao, J., Liu, H., Cao, X., & Yang, S. (2017). Superpixel-based multiple local CNN for panchromatic and multispectral image classification. *IEEE Transactions on Geoscience and Remote Sensing*, 55(7), 4141–4156. https://doi.org/10.1109/TGRS.2017.2689018

Zovko, M., Zibrat, U., Knapic, M., Bubalo Kovacic, M., & Romic, D. (2019). Hyperspectral remote sensing of grapevine drought stress. *Precision Agriculture*, 20(2), 335–347. https://doi.org/10.1007/s11119-019-09640-2.