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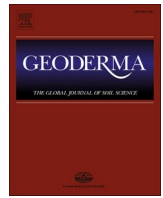
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Systematic review and meta-analysis

The contribution of near surface geophysics to measure soil related terroir factors in viticulture: A review

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ABSTRACT

Wine quality is affected by environmental factors in the location where the vines are cultivated, in particular the soil and the climate. Major soil-related factors influencing vine development, yield, and berry composition (and thus wine quality) include soil water availability, soil temperature, and soil nutrients, particularly nitrogen. These can be impacted by soil depth and soil compaction. Mapping these factors with classical field-based methods is constraining and expensive. Near surface geophysics (NSG) can be useful in increasing the resolution of data acquisition and, possibly, its cost. Among these techniques, many are already commercially available, but some of them, including Magnetic Resonance Sounding, Induced Polarization and Spectral Analysis of Surface Waves, require a high degree of expertise for acquisition and processing. These should be further developed in order to enlarge the application possibilities. This article reviews soil-related parameters relevant to terroir expression in vineyards and how these can be measured with NSG techniques.

1. Introduction

1.1. Specificities of grape growing

Grapes are a major crop worldwide (Anderson and Aryal, 2013). The grapevine is a deep rooting, perennial species, adapted to warm and dry climates. Grapes can be used either for direct consumption (table grapes), as dried fruit (raisins), or in wine making (Keller, 2020). Distillation can also follow the winemaking process to produce spirits, e. g. Armagnac and Cognac (Bertrand, 2003). Although the physiology of the vine is not fundamentally different from other fruit trees, the transformation of grapes into wine and spirits presents additional challenges for viticulture as an agricultural activity. While yield and production costs are major factors affecting profitability in viticulture, the revenue generated is also highly dependent on the selling price of the crop, which is related to perceived wine quality and reputation (van Leeuwen and Seguin, 2006). Basic table wine can be sold for less than 0.5€ per litre, while high quality wines from renowned areas can retail for hundreds of euros per bottle of 0.75 L. Because there is no objective measurement of wine quality, it is not easy to disentangle the effect of wine quality and reputation on the retail price of wine, even though they

are obviously related (Ashenfelter, 2008).

1.2. Quality factors in wine production

Because of its effect on the retail price of wine, many studies have focused on the viticultural factors affecting wine quality. These factors encompass (1) the selection of plant materials, like the variety (Robinson et al., 2013), the clone (van Leeuwen et al., 2013) or the rootstock (Ollat et al., 2015), (2) viticultural techniques, including trellising systems (Reynolds and Vanden Heuvel, 2009), canopy management (Smart, 1985) and vineyard floor management (Tescic et al., 2007; Vanden Heuvel and Centinari, 2021), (3) wine making and ageing techniques (Ribéreau-Gayon et al., 2006), and (4) the natural environment where the grapes are grown, including soil and climate. The complex interplay between soil, climate and the vine is referred to as the *terroir effect* (van Leeuwen and Seguin, 2006). According to the International Organization of Vine and Wine (OIV, 2010), « *vitivinicultural "terroir" is a concept which refers to an area in which collective knowledge of the interactions between the identifiable physical and biological environment and applied vitivinicultural practices develops, providing distinctive characteristics for the products originating from this area* ». Hence, terroir links the

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quality and the typicality of wine to the site where it is produced.

1.3. Terroir studies

Given its importance to understanding wine quality and its ability in creating added value in wine production, terroir has been studied for over half a century. A precursor in this area was Seguin and his early work still stands as a benchmark (Seguin, 1969). The terroir effect has been addressed in the scientific literature with a wide range of methodologies, resulting in an increasing number of references. Many authors have published on terroir taking into account only one single discipline, generally their own, e.g., climatology (Tonietto and Carbonneau, 2004), geology (Wilson, 1998), geomorphology (Fanet, 2001; Rouvelac, 2006), pedology (van Leeuwen et al., 1989; Lévêque et al., 2006) or soil microbiology (Bourguignon, 1995; Bokulich et al., 2014). Although it is useful to highlight one single factor of terroir, this sort of approach remains descriptive and does not lead to a greater understanding of how terroir influences wine quality and style. Particularly in terroir studies, ‘(researchers are) victims of their own discipline’ (Moran, 2001) and often fail to take into account other disciplines and interactions between various terroir factors. Moreover, it is important to consider that any possible effect of the natural environment on wine quality is necessarily mediated through the vine. Hence, it is critical to address soil-vine interactions and climate-vine interactions. When considering the natural environment in terroir studies, one should focus on those factors which can possibly influence vine phenology, physiology, vigour, yield and/or grape ripening dynamics and grape composition at ripeness.

1.4. Near surface geophysics

The soil on which the vines grow has a major impact on terroir (van Leeuwen et al., 2004). To quantify the effect of the soil on the grapevine, it is necessary to break it down into measurable parameters (van Leeuwen et al., 2018), which can be addressed with a wide range of methodologies, either in the laboratory, or in the field. Many of these methods are, however, costly and time consuming. Moreover, they generally yield point data, which cannot be easily spatialized. Over the past decades, Near Surface Geophysics (NSG) techniques have been developed to assess soil composition or properties in field conditions (Rubin and Hubbard, 2005). The tremendous advantage over classical soil measurements is that they can yield information on soil composition and properties in the form of a transect (x, z), a map (x, y) or a three dimensional block diagram (x, y, z). Because terroir has a spatial dimension, these technologies potentially contribute to terroir studies. The aim of this article is (1) to review which soil related parameters are of interest in terroir studies and (2) if and how these can be addressed by NSG techniques. It is specified which of these techniques are already commercially available for vineyard management purposes and which are promising but need further development.

2. Major soil-related parameters of interest in terroir studies

2.1. Soil water availability

The availability of water in the soil influences shoot growth, yield, and grape composition (Matthews and Anderson, 1988). Soil water deficits restrict photosynthesis (Flexas et al., 1988) and berry growth (Ojeda et al., 2001), while promoting the production of phenolic compounds in skins (Ojeda et al., 2002) and grape aromas (van Leeuwen et al., 2020). Soil water deficits benefit grape quality potential, restricting shoot growth more than photosynthesis, hence limiting competition for carbohydrates with berry ripening (Pellegriano et al., 2005; van Leeuwen et al., 2009). Severe water stress is, however, detrimental to wine quality, in particular for white wine (Peyrot des Gachons et al., 2005).

Soil water is located in the porosity of the soil. The availability of soil water depends on the pore size in which the water is contained: the smaller the pores, the greater the matrix potential plants have to overcome to extract the water. In water-logged soils, free water (i.e., water with a matrix potential close to 0 J/kg) is mostly stored in macropores greater than 10 µm in diameter (Luxmoore, 1981). Water logging can be permanent or temporary. In the latter case, free water is present only in a part of the season, generally in the winter and the spring, but disappears when the conditions become dryer because of reduced rainfall and/or increased evapotranspiration. If water logging is present close to the surface, it can harm the vines due to anoxia in the rootzone. If free water is present beyond approximately one meter in depth, but still in contact with the rootzone, it provides unrestricted water supply to the vines, which may result in excess vigour and yield, as well as altered grape composition. Water contained in pores between 0.2 and 10 µm in diameter (or -30 to -1500 J/kg) is less subject to gravity (i.e. it will not drain out of the soil profile) and thus available to plants. The volume of soil porosity in this pore size range over the rooting depth is referred to as the soil water holding capacity (SWHC). SWHC depends on texture, proportion of coarse elements and rooting depth (Saxton et al., 1986). Water contained in pores smaller than 0.2 µm is not available to plants (Luxmoore, 1981). It is also called “constitutional water”. To relate soil water to vine development and physiology, it is not only necessary to assess the volumetric soil water content, but also to assess the percentage of the water contained in each range of pore size (i.e. < 0.2 µm, between 0.2 and 10 µm and > 10 µm) or potential (above -30 J/kg, between -30 and -1500 J/kg or below -1500 J/kg).

2.2. Soil temperature

Air and soil temperature impact phenology, (i.e. the timing of major developmental stages during the growing season). Air temperature is the strongest driver of phenology and major phenological stages can be predicted with models based on air temperatures (Parker et al., 2011). On a more limited scale, soil temperature also affects phenology, with low-temperature soils delaying grape ripening and high temperature hastening it (Morlat, 2010). For quality wine production, the timing of ripeness is important as grape composition is more balanced when temperatures during the ripening period are neither too low (resulting in green and acidic wines), nor too high (resulting in high alcohol wines with cooked fruit aromas). The ideal period for harvest is either the end of September, or early October (in the Northern Hemisphere), when temperatures are close to the required optimum in most wine production regions (van Leeuwen and Seguin, 2006). The grapevine variety also influences the timing of ripeness, with early and late ripening varieties requiring low and high temperature summations, respectively, to reach proper ripeness (Parker et al., 2020). As a result, early ripening varieties give the best results in cool climates while late ripening varieties are better suited to warm climates. Assessment of soil temperature allows for the fine-tuning of the choice of the optimum grapevine varieties, in terms of precocity, for a specific location (van Leeuwen, 2001).

2.3. Soil nutrients

Major soil nutrients like calcium, magnesium and potassium are adsorbed on soil colloids like clay and organic matter, with the storage capacity of the soil for these cations referred to as the cation exchange capacity (CEC) (Rhoades, 1983). Surprisingly, famous vineyard soils can be either high or low in CEC and major soil minerals (K⁺, Mg⁺⁺ and Ca⁺⁺) and these do not seem to have a decisive impact on wine quality as long as they are not present in the soil in clear excess or severe deficiency (Seguin, 1986; van Leeuwen et al., 2018). The same is true for trace elements (Seguin, 1986). One soil nutrient which does matter when considering wine quality is nitrogen: vine nitrogen status impacts vine vigour (Verdenal et al., 2021), yield (Choné et al., 2001), phenolic compounds in grape skins (Choné et al., 2001) and aroma compounds in

grapes and wines (van Leeuwen et al., 2020). Nitrogen is stored in soil organic matter, but is not available to plants in this form. It must first be turned into mineral nitrogen (preferably NO_3^-) by soil microorganisms, before it can be assimilated by the vine roots (Verdenal et al., 2021). Vine nitrogen status depends on soil organic matter (OM) content and OM turnover. The latter is related to OM C/N ratio, soil aeration, pH, humidity, temperature and lime content (Verdenal et al., 2021). Optimum vine nitrogen status depends on the production aims of the grower. If profitability is based on high yields, moderately high N-status is required, but when it is based on high quality (and related high retail prices), a more restricted nitrogen supply is preferred. It also depends on the colour of the produced wine. Red wine quality relies on phenolic compounds, in particular anthocyanins. Grapes contain more phenolic compounds when vine nitrogen status is moderately low (Chone et al., 2001). White wine production requires a higher vine nitrogen status, because it promotes aroma expression (van Leeuwen et al., 2020). Sodium (Na^+), when present in vineyard soils, can reduce yield (Shani and Ben-Gal, 2005).

2.4. Soil depth and soil compaction

Soil depth is usually governed by the depth of the unaltered parent material below. Soils are less deep over hard bed-rock and soil depth can be further reduced on slopes by erosion (Tesfa et al., 2009; Novara et al., 2018; Chevigny et al., 2014). Rooting depth is, in general, related to soil depth, although the roots of young vines may not have fully explored the total soil profile, or the roots of older vines may extend beyond the soil profile into non-consolidated parent material below. Vineyard sites with high quality potential often have shallow soils, as these tend to be lower in water and nitrogen, which restrict vine vigour and productivity, leading to increased grape quality potential (Morlat and Bodin, 2006). When vines are irrigated, irrigation strategy also influences rooting depth (Ma et al., 2020).

Soil compaction can be related to the texture of the soil and the passage of heavy agro-equipment on wet soils (Shah et al., 2017). Near-surface soil compaction limits soil aeration and can have an adverse effect on soil microbiological activity, hence reducing mineral nitrogen availability (Verdenal et al., 2021). In this way, soil compaction close to the surface can lead to irregular vine development and yield losses. Soil compaction in deeper layers, linked to specific soil textures or bedrocks, can restrict root growth (Unger and Kaspar, 1994). This limits the SWHC, which may lead to desired water deficits and improve wine quality, particularly in dry-farmed vineyards. Soil compaction in deeper layers does not affect the availability of mineral nitrogen, because these layers do not contain a significant amount of OM.

2.5. Parameters of interest

Taking into account the way soil influences terroir expression in grapevine, the following soil related factors are of major interest in terroir studies:

- Presence of free water in the root zone;
- Soil water holding capacity (SWHC) and all parameters necessary for its calculation, i.e., soil texture, coarse elements content and rooting depth; SWHC can also be estimated from two volumetric soil moisture measurements: a first measurement at field capacity (early in the season) and a second measurement at wilting points (at the end of a dry season);
- Soil temperature;
- Soil depth;
- Soil compaction close to the surface (having potentially negative effects on vine development) or in deeper layers (with generally positive effects on wine quality);
- Soil mineral nitrogen content or, alternatively, variables necessary to estimate it: soil organic matter (OM) content and all parameters

related to soil OM turn-over, i.e., OM C/N ratio, soil aeration, pH, humidity, temperature and lime content.

3. Classical field-based soil surveys and scale issues

3.1. Addressing specific soil related parameters

A wide range of methodologies has been developed to study soil-related parameters of interest in terroir studies, in field conditions, or in the laboratory. Free water can be assessed with a piezometer (Faulkner et al., 1989), volumetric soil water can be measured in the field with a neutron moisture probe (Visvalingam and Tandy, 1972; Kodikara et al., 2014) or frequency domain sensors, soil matrix potential with a tensiometer (Bittelli, 2010), soil nutrients can be measured in the field (Kim et al., 2009) or in the laboratory (Okalebo et al., 2002) and soil temperature assessed by thermocouples (Popiel et al., 2001). Although relevant, these methods are, however, costly and time-consuming. Moreover, they yield point data and need to be replicated in many locations in order to spatialize the results with appropriate geostatistics.

3.2. Soil mapping

Classical methodology for soil mapping is based on a preliminary study of the local geology and geomorphology to identify the appropriate locations for hand auger samples (approximately 1 m in depth) and soil pits (1 to 1.5 m in depth), with an ideal ratio of auger samples to soil pits being around 10. The number of samples is highly dependent on the scale of the map, with the cost of producing the map increasing rapidly with resolution (scale). Approximately four auger samples per hectare are needed to publish a map at a resolution of 1/5,000th, such as for a wine estate, while one auger sample for every 10 ha is the rule for maps at a scale of 1/25,000th, such as for an entire wine producing area (van Leeuwen et al. 2010). At farm scale, the local topography has often been modified by pre-planting levelling of the land, making the choice of the locations for augering and soil pits difficult. Using proximal sensors can help to optimise these locations, possibly reducing their number. The key to good soil maps is proper classification of soil types. However, many different classifications for soil types exist worldwide, making it difficult to directly relate the soil type in a given region to the quality-potential of those soils for wine production. Hence, identifying (and mapping) soil-related factors, like water, temperature and nitrogen that affect vine phenology, physiology, and berry ripening dynamics for understanding terroir expression is more important than mapping soil types.

4. Contribution of near surface geophysics (NSG) techniques to terroir studies

4.1. The challenge of spatialization

Near surface geophysics (NSG) can yield useful information in terroir studies, complementary to classical soil surveys. Output of NSG can be in the form of a transect (2D), a map 2D, or a soil volume (3D). While a transect can help characterize soil distribution (e.g. down a slope), maps are more useful to understand variability in vine behaviour within a vineyard. 3D studies allow the most complete representation for understanding soil-vine interactions. Unlike classical soil surveys, NSG technology generally yields continuous or near-continuous information, which greatly contributes to the precision of the maps or block diagrams being produced.

4.2. The challenge of repeated measurement

Some soil related parameters, like soil texture, hardly vary over time, and can be characterized by one single measurement. For other

parameters, repeated measurements may provide useful insight in the dynamics of the considered parameter (e.g., measurement of volumetric soil water content to assess vine water consumption over a given period of time). This requires implementation of subsequent sessions of data acquisition, which may interfere with day-to-day vineyard management and creates challenges in terms of cost.

4.3. Scale issues

Vines are planted with a density of 1,000 to 10,000 plants.ha⁻¹. The smallest relevant unit to study soil-vine interactions is one vine, i.e. an area of 1 to 10 m², depending on the planting density. Parcels of vines encompass a fraction of one hectare to several hectares. Assessing intra-parcel variability of soil related terroir factors is of interest, because they can be addressed with specific management techniques (so-called precision viticulture; Bramley and Hamilton, 2007). A wine growing estate is made-up out of several parcels. Characterizing soil variability across parcels can help to adapt plant material (variety and rootstock) and management practices (fertilization, vineyard floor management) to soil type (van Leeuwen et al., 2018). A quantitative analysis of soil properties in a production area can assist terroir zoning of sub-regions (Bramley and Gardiner, 2020). Hence, terroir studies are of interest at various scales, ranging from 1/1,000th (intra-parcel) to 1/5,000th (inter-parcel, estate) or 1/25,000th (winegrowing region).

5. Survey of major ground geophysical methods for investigations in vineyard

A very abundant literature exists to describe the principles of geophysical methods. Nevertheless, only a few references are addressing advanced developments that would be suited to potential commercial applications in agriculture. Most geophysical methods are described by Rubin and Hubbard (2005) and Garré et al. (2022), from Direct Current Resistivity (DCR) to Geo Penetrating Radar (GPR), including seismic methods. A more exhaustive description of Resistivity and Induced Polarization is provided by Binley and Kemna (2005) and Binley and Slater (2020). A general issue for all geophysical methods is the non-uniqueness solution after the inversion process. Hence, a range of possible values is generally generated, called equivalences, impacting on the existence of a range of possible values of the retrieved parameters (e.g., water content). Available methods being discussed in this review paper are presented in Table 1 and a specific mention is made for the tools that are already used by service providers to assist commercial wine producing estates in their management choices. Others are commercially available for applications in civil engineering, but are cost prohibitive for vineyard management (mentioned “BCP” in Table 1). In the following paragraphs of this section, a very short description of the NSG methods will be given. For more details, the readers should refer to the references mentioned.

5.1. Low frequency geoelectrical methods: Apparent Resistivity Profiling (ARP), Electrical Resistivity Tomography (ERT), Induced Polarization (IP) and ElectroMagnetics by Induction (EMI)

All these three methods are based on electrical conductivity parameters, with some significant differences: Electrical Resistivity (ER) acquires only electrical resistivity, while ElectroMagnetic by Induction (EMI) and Induced Polarization (IP) also acquire additional parameters. Moreover, ER and IP require galvanic contact with the soil, which is not necessary for EMI.

5.1.1. Electrical Resistivity (ER) and Induced Polarization (IP)

ER and IP allow, respectively, the determination of the spatial distribution of the low-frequency resistive and capacitive characteristics of the soil. ER and IP are deployed in a similar manner. It should be noted that IP is a derivative method from ER. ER is founded on Direct Current

Table 1
Summary of major geophysical methods with potential applications in vineyard. V*: Vertical; H*: Horizontal. **: for applications in vineyards. BCP: But Cost is Prohibitive for studies in vineyards. Zonation accessible: plate (1 m²) = A; intraparcel (1 m x 50–100 m = B; parcel part (100 to 5000 m²) = C; parcel (0.5 to 10 ha) = D; vineyard (10 to 100 ha) = E; small area (> 100 ha) = F. The geophysical methods abbreviations correspond to: Electrical Resistivity Tomography = ERT; Apparent Resistivity Profiling = ARP; ElectroMagnetic by Induction = EMI; Induced Polarization = IP; GeoPenetrating Radar = GPR; Spectral Analysis of Surface Waves = SASW; Surface Nuclear Magnetic Resonance = SNMR.

Method	Parameter	Vineyard objectives	Vertical resolution (meters)	Depth of survey (meters) **	Horizontal mesh (meters)	Acquisition duration (zonation type)	Results representation	Implementation, acquisition, processing	Technique commercialized by provider
ERT	ρ	Layer thickness, lithology	0.1 to 10	1 to 50	0.1 to 100	1 h/profile (A, B)	V*- 2D or 3D	Quite easy	Yes, BCP
ARP	ρ_a	Soil textural map	Not relevant	0.5 to 1.7	0.1 along profile	10 to 15 km/h (C, D, E)	H*-2D	Very easy	Yes
EMI	σ_a, σ_t InPhase	Soil textural, soil physico-chemical properties map	If σ_a , not relevant If σ_t , 0.5 to 10	0.25 to 10	0.1 in continuous mode along profile	1 ha/day (C, D, E)	H-2D	Very easy	Yes
IP	ρ, φ, M_n	Water content, CEC, textural zones	0.5 to 10	1 to 50	0.5 to 100	1-2 profiles/day (A, B)	V-2D	Difficult	Yes, BCP
GPR	ϵ	Soil interfaces, water content (if soil not saturated)	0.1 to 10	1 to 50	0.1 to 100	2 ha/day (A, B, C, D, E, F)	V-2D or 3D	Not easy	Yes, BCP
Seismic refraction	V_p	Soil interfaces, water table	0.5 to 10	1 to 50	1 to 100	1 h/profile (A, B)	V-2D	Quite easy	Yes, BCP
SASW	V_s	Soil interfaces	0.5 to 10	1 to 50	1 to 100	1-2 profiles/day (A, B)	V-2D	Not easy	Yes, BCP
SNMR	E_0, T^{*2}	Water content	0.5 to 10	1 to 50	1 to 10	1-2 soundings/day (A, B)	V-1D or 2D	Difficult	No

(DC) resistivity methods that use artificial sources of current to produce an electrical potential field in the ground. A current is injected into the ground through point injection electrodes and the potential field is measured using two other electrodes (the potential electrodes).

There are two main applications suited to viticulture in terms of scale and purpose. The first system acquires apparent resistivities along several profiles keeping the same quadrupole size (the fastest system is towed by an agricultural engine and is called Apparent Resistivity Profiling or ARP), and the second system is Electrical Resistivity Tomography (ERT). The first one yields 2D apparent resistivity maps (horizontal), while the second produces 2D vertical images of true resistivity from the surface (vertical). Both are complementary but not equivalent. Where apparent resistivity maps from ARP allows to produce a map of the laterally variability of soil features, the resistivity tomographies from ERT determines the precise lateral and vertical true resistivity distribution.

The ARP system is widely used in agriculture and viticulture (Dabas, 2006; André et al., 2012; Andrenelli et al., 2013). It allows to acquire at one measurement point three different depths of investigations (through three channels), at moderate acquisition velocity (classically around 6 km/h until maximum 15 km/h) within the vine rows and data density (each 10 cm on the three channels in parallel along a studied profile). This system leads to the production of 3 apparent resistivity maps corresponding to three different depths of investigation. These measurements are commercially available, allowing fast acquisition of shallow apparent resistivities. The data acquired are, however, apparent resistivities, and cannot be directly related to quantitative vertical soil information.

The vertical distribution of “true” resistivities can only be obtained after a so-called inversion process, whose objective is to convert the apparent measured resistivities to “true” resistivities based on physical laws (Loke and Barker, 1996). The number of required data (or apparent ER) to run a proper inversion are linked to the complexity of the medium (number of layers). Generally, data are acquired on at least 8–10 measurements for increasing quadrupole spacings. After the 2D inversion process, 2D vertical images of surface versus the real depth of the true resistivity are provided, called “Electrical Resistivity Tomography” (ERT). The model obtained is not unique and contains uncertainties linked to the discrepancy between measured and predicted data, and inherent equivalences (Sharma and Kaikkonen, 1999).

ERT is implemented using multi-electrodes and multi-channel devices, which are commercially available. Depending on the equipment, between 48 and 192 electrodes are deployed, all connected through linking cables allowing to number each electrode. The chosen electrode spacing is the result of a compromise of the inversely correlated resolution (lateral / vertical) and the objectives regarding the depth of investigation (Oldenburg and Li, 1999). The fastest system is easy to implement and allows to acquire a tomography in less than one hour.

The ER parameter variation is linked to both water quantity (in relation to porosity and saturation) and/or water quality (mineralization, clay content, metallic minerals content). For this reason, to assess quantitative physico-chemical parameters, the IP method is more appropriate than ER, because the capacitive properties determined from IP methods are quantitatively linked to water and clay content, in relation to Cation Exchange Capacity and permeability (Revil et al., 2021) as well as metallic minerals content (Revil et al., 2015, 2018).

Induced Polarization (IP) methods can be deployed in the time domain (TIP) and in the frequency domain, also referred to as Spectral Induced Polarization (SIP). TIP corresponds to the voltage decay after excitation by a current pulse is measured. Recording spectra in the time domain is achieved by measuring the voltage transient at a number of instants after the current pulse has been switched off. With SIP, the measured parameters are the amplitude $|Z|$ (in ohm) of the electrical impedance of the soil and the phase lag φ (in mrad) between the current and the voltage, following the injection of the alternating current. It should be noted that, in the Electrical Resistivity (ER) mode, only one

amplitude of the electrical impedance at one frequency (e.g., 1 Hz) is used to determine the DC electrical resistivity ρ_a . In the spectral induced polarization (SIP) mode, both the amplitude and the impedance phase are analysed, over the whole frequency range (1 mHz–1000 Hz generally).

IP Tomography is implemented in the same way as ERT (same device, same cables). However, many specificities about electrodes, cables layout and sequences must be considered to obtain usable data quality (Blondel et al., 2014). For IP, the DOI and resolution follow the same rule as for ERT. IP devices are commercially available, but the tomography implementation and the processing requires a high level of expertise, as it is cumbersome to obtain good data quality (Schmutz et al., 2014; Flores Orozco et al., 2021). The processing tool requires specific skills (Olson et al., 2016) and the physical and chemical interpretation of induced polarization parameters has not yet been validated in a broad number of field situations. In vineyards, metallic posts and wires from the trellising system can possibly interfere with the signal. Hence, IP is very promising but not easy to implement to retrieve soil physical and chemical parameters.

5.1.2. Electromagnetics by Induction

While ER and IP are galvanic methods which require a contact of electrodes with the ground, electromagnetic methods do not. The Controlled Source ElectroMagnetism (CSEM) method of geophysical prospecting is founded on Maxwell's equations that govern electromagnetic phenomena (e.g., Kaufman and Keller, 1983).

Among existing CSEM Frequency Domain ElectroMagnetic (FDEM) systems, the one often used for soil zonation in vineyards is the ElectroMagnetic in Low Induction Number (LIN), also called ElectroMagnetism by Induction (EMI). This system is particularly interesting for soil mapping, as the effective penetration depth is mainly linked to the Receiver-Transmitter distance (L) for a given frequency f of the device and medium resistivity (or its inverse, the conductivity σ). This feature is of particular interest, allowing the same depth of investigation for all apparent conductivity data acquired with the same system (same frequency, and receiver-transmitter length). Using the device with the right assumptions (Signal/Noise, Low Induction Number condition), the EMI techniques measure the quadrature-phase component of the induced magnetic field. This component of the magnetic field is linearly related to the ground apparent electrical conductivity (Eca). The depth of investigation is a function of the Transmitter-Receiver distance and coil orientation. The sensitivity curves of each coil orientation differ and are complementary (McNeill, 1980).

One additional advantage of this technique, is the possibility to use the apparent InPhase component of the induced magnetic field that is linked to magnetic susceptibility thus to metal content (in the ionic form of metal or native form) (McNeill, 1980). EMI-based studies have used in-phase components in order to characterize archaeological features (e.g., McNeill, 2012; Benech et al., 2016), or engineered structures and utilities (e.g., Huang and Won, 2002; Saey et al., 2016) and to detect metal content variability (e.g., copper, iron) in a vineyard soil (McLachlan et al., 2022).

The technique is commercially available, easy to use, and apparent conductivity maps can be produced at reduced cost. The main point of vigilance is the potential effect of metallic posts and wires from the vineyard trellis on data acquisition (Lamb et al., 2005). To achieve optimal results for soil Eca mapping in vineyards, the studied parcels should be free from metallic trellises or planted with wide row spacing. These conditions allow for covering 20 to 40 ha per day with a resolution of approximately 1 m by 6–10 m between rows. However, in trellised vineyards with narrow row spacing, or when inverted EC parameters are needed, the mapping speed must be reduced. This reduction is due to several factors, such as the need to carefully navigate around the vines and the requirement to cover the parcel 2 to 3 times with geophysical tools to achieve up to 8 different depths of investigation. In these cases, in continuous mode (one measurement per second), an area of 1 ha can

be covered in a day, achieving a longitudinal resolution of 10 cm and a lateral resolution of 4–5 m, with data collected from eight different depths. This method has many advantages, including fast acquisition and the possibility to acquire data at different DOIs, allowing to run the inversion process and retrieve physical and chemical parameters.

5.1.3. Comparison between ER and EMI sensors

ER sensors require contact with the soil, whereas EMI sensors do not. ER sensors can operate in static and on-the-go modes: statically with the ERT system or on-the-go with the ARP system. The ERT system is, however, significantly more time-consuming than the ARP system, requiring approximately 1.5 h per ERT profile, compared to about 1 h per hectare for ARP (at a speed of ~ 5–6 km/h).

EMI sensors are exclusively used on-the-go. They can be deployed by a human operator, towed by an agricultural engine, or mounted on a drone. However, in vineyards, the presence of a trellising system and the need for high sensitivity requires that sensors should be positioned close to the ground. Additionally, the short spacing between vine rows imposes sensors to move at low speed (≤ 6 km/h), to avoid damaging the plants.

As a result, in vineyards, both systems (ARP and EMI) progress at similar speeds. Moreover, the ARP and EMI maps, for similar depths of investigation, are equivalent: they display apparent conductivity which is not equivalent to “true” conductivity. Hence, they are of limited use for transforming the signal into physical and chemical soil properties, which can only be correctly retrieved from true electrical resistivity.

ARP maps are produced with 3 different depths of investigation, whereas EMI maps, obtained with various devices, are offering multiple depths of investigations (up to 8). With data from multiple depths, it becomes possible to run the inversion process, allowing to retrieve real (or inverted) electrical resistivity.

5.2. High frequency geoelectrical methods: Ground Penetrating Radar (GPR)

The principle of GPR is founded on the ElectroMagnetic (EM) theory, based on Maxwell’s equations. Combined with constitutive relationships, both provide the basis for the quantitative description of the GPR signal, based on the propagation and reflection of electromagnetic waves ranging from 20 MHz to 3 GHz (Annan, 2005). It is sensitive to variations in the electromagnetic properties of the medium (electrical permittivity, electrical conductivity and magnetic susceptibility).

A map can be obtained after the concatenation of a number of parallel profiles. Each profile is composed of a radargram that corresponds to a 2D vertical image of surface distance versus double time of wave velocity and is composed of a high number of traces (amplitude of wave propagation versus time).

GPR devices are commercially available, but acquisition and processing require specific skills. For ground-based GPR a theoretical acquisition speed of 70 km/h can be reached on a paved road, but on irregular surfaces as soils, the acquisition speed is limited because of the required contact of the antenna with the soil. In the continuous mode, the required time is about 0.5 day to cover a surface of 1 ha in a vineyard setting (longitudinal resolution of 10 cm and lateral resolution of 4–5 m). In spite of its sensitivity to EM interferences, GPR is generally not affected by metallic wires and posts of vineyard trellises. New airborne-based GPR methods look promising, because they have the advantages of high data acquisition speed and do not require contact with the ground (Klotzsche et al., 2024). The antennas used are small (25*25 cm for 400 MHz) and shielded, and can thus be maintained out of the influence zone of the trellis.

5.3. Surface Nuclear Magnetic Resonance (SNMR)

Nuclear Magnetic Resonance (NMR) is the only geophysical method that can detect hydrogen directly, and thus has an interesting potential

to measure water content (Legtchenko et al., 2002). The principle of Surface Nuclear Magnetic Resonance (SNMR) is based on nuclear magnetic resonance (NMR). Magnetic resonance sounding assumes that the soil contains a proton-containing liquid (e.g., water). A wire coil is used as a transmitting/receiving antenna.

SNMR devices are commercially available, but the implementation and the data processing require a high level of expertise, even for geophysicists. To date, this technique is not implemented routinely, and measurements are carried out with 1D sounding, and each sounding lasts around several hours (2.5 to 4 h). A 2D vertical section would be obtained by juxtaposition of 1D soundings, and would require a high number of implementations. An important drawback of SNMR is its high sensitivity to EM noise, which makes it not suited inside a vineyard plot containing metallic wires and posts of the vineyard trellis. Taking into account the required level of specialization to run this technique properly, it is not likely to be widely deployed in vineyards, but it can be complementary to other methods. Additionally, its implementation is limited to unplanted parcels.

5.4. Shallow seismic: Refraction seismic and Spectral Analysis of Surface Waves (SASW)

Seismic methods are based on the principle of wave propagation (deformation of the medium) in an elastic medium. Seismic waves propagate in materials as particle deformation patterns through materials with velocities that depend on their elastic properties and densities. The seismic methods suited to viticultural purposes are mainly refraction seismic and SASW.

The seismic refraction method is based on the propagation of the compression waves (also called primary wave, V_p) (Haeni, 1986).

SASW is a seismic method used to determine shear wave velocity (also called secondary wave, V_s) models (e.g., Nazarian and Stokoe, 1989). The main principle of the method is based on the dispersive properties of surface-waves (Park et al., 2000). Because the dispersion effects can be measured in seismic data, the V_s model – V_s variations with depth – that produced them can be estimated using the seismic data inversion theory.

Commercial devices do exist, both for seismic refraction and for SASW techniques. Refraction seismic is easy to implement, acquire and process. SASW requires specific skills to acquire and process. Refraction seismic profile acquisition time is comparable to ERT, whereas SASW profiles require a longer acquisition time (~the same order of duration as IP tomographies). One of the main drawbacks of seismic methods is the risk of soil compaction induced by a repetition of wave generation by hammering onto the soil. These methods can be used as a complement to geoelectrical methods, at some specific locations.

6. How can NSG help to measure the parameters of interest?

The main parameters of soil characterization in viticulture are the presence of free water, soil water holding capacity, soil texture, rooting depth, soil temperature, soil depth, soil compaction, soil carbon, soil mineral nitrogen content and salinization. The main geophysical methods able to reach these objectives are summarized in the Table 2.

6.1. Estimation of soil water content in the root zone

As indicated in Table 1, many geophysical and geo-electrical methods are sensitive to water content: Electrical Resistivity Tomography (ERT), ElectroMagnetic by Induction (EMI), Induced Polarization (IP), Ground-Penetrating Radar (GPR) and Surface Nuclear Magnetic Resonance (SNMR). Two different approaches may be employed: instantaneous measurements with one or several geophysical methods or repeated measurements. The latter has the advantage capturing parameters changing over time (e.g., water content), while reducing the impact of the stable ones (e.g., texture). The drawback of this system is

Table 2

Summary of geophysical methods to measure viticultural parameters of interest. With Surface Nuclear Magnetic Resonance = SNMR; Spectral Induced Polarization = SIP; Ground Penetrating Radar = GPR; Electrical Resistivity Tomography = ERT; ElectroMagnetic by Induction = EMI; Induced Polarization = IP; Apparent Resistivity Profiling = ARP; Mise-à-la-Masse = MALM; Spectral Analysis of Surface Waves = SASW. *:this method might be useful to define the free water, indirectly.

Mapping objective	Method used	References
Presence of free water	SNMR, (SIP*)	Costabel and Günther, 2014 (SNMR); Legchenko et al., 2020 (SNMR); Ghorbani et al., 2008 (SIP)
Soil water holding capacity	Monitoring of GPR, ERT, EMI, IP, ARP	Abdu et al. 2008 (EMI)
Soil texture	EMI, ARP, ERT, IP, GPR	Hubbard et al., 2003 (GPR); André et al., 2012 (ARP); Hubbard et al., 2021 (EMI and ERT); Revil et al., 2022 (IP)
Rooting depth imaging	Combination of various ER methods, IP, GPR	Zenone et al., 2008; Paglis, 2013 (root distribution and biomass estimation – ER); Weigand and Kemna, 2017, 2019 (functional properties of root systems – SIP); Mary et al., 2019 (vine rooting depth – ERT)
Soil temperature	Directly none Indirectly ERT, EMI, ARP	Cheviron et al., 2004; Tabbagh et al., 2017 (soil temperature profile sensors)
Soil depth	ERT, IP, GPR, Seismic (refraction and SASW)	Courjault-Radé et al., 2010 (ER); Revil et al., 2021 (SIP); Zajíčková and Chuman, 2019 (GPR); Choo et al., 2018 (seismic); Inman et al., 2002 (GPR, EMI); Coulouma et al., 2012 (seismic + ERT)
Soil compaction	ERT, ARP, EMI, seismic (refraction and SASW)	André et al., 2012; Iwasaki et al., 2020 (GPR); Donohue et al., 2013, Romero-Ruiz et al., 2021 (seismic); Besson et al., 2004; Rossi et al., 2013 (ERT); Blanchy et al., 2020 (ERT and EMI); Petersen et al., 2005 (GPR, EMI, and refraction seismic)
Soil mineral nitrogen content	ERT, EMI+calibration points	Korsaeth, 2005, Rentschler et al., 2020 (EMI); de Benedetto et al., 2022 (EMI and GPR); Klotzsche et al., 2024 (ERT, EMI and GPR); Lavaud et al., (2024 submitted) (EMI, ERT)
Soil salinization	ERT, EMI	Zarai et al., 2022 (EMI); Greggio et al., 2018, Lech et al., 2016 (ERT); Mohammed et al., 2022 (ERT and EMI)

the requirement to repeat the surveys over time (Martini et al., 2017).

One effective method for determining volumetric water content is GPR, supported by various field studies. These include purely water content measurements (Hubbard et al., 2002; Grote et al., 2003) and tracking water movements and moisture migration (Hubbard et al., 1997; Eppstein and Dougherty, 1998; Kuroda et al., 2009). Hubbard et al. (2002) successfully estimated soil water content at shallow depths (10–15 cm) in a Californian vineyard using GPR ground waves with 900 MHz and 450 MHz antenna frequencies. Grote et al. (2003), in the same site and campaign, used reflected waves to estimate soil water content at greater depths (30–40 cm), achieving reasonable accuracy despite more complex data processing requirements.

Lunt et al. (2005) further explored GPR reflection travel times in the same vineyard to estimate soil water content changes up to 3 m depth, using a low-frequency 100 MHz antenna. They achieved low RMS-errors in volumetric water content estimates, contingent on borehole control and sufficient reflection strength. However, GPR performance can be

hindered by signal attenuation in water-saturated or thick clay layers. Additionally, Wu and Lambot (2024) demonstrated the potential of drone-borne GPR for Digital Soil Mapping to retrieve soil moisture information.

To allow investigation of soil moisture over the whole rooting depth, required investigation depth might be greater than 3 m, which is approximately the limit of the GPR technology in a vineyard setting. The advantage of electrical based methods is the ability to provide deeper information (as the depth of investigation is a function of electrode spacing for a given sequence), and not to be impeached by clay layers. Thus, soil water content estimation has also naturally been studied since decades by electrical resistivity, in particular Electrical Resistivity Tomography (ERT) and ElectroMagnetic by Induction (EMI) methods (Fig. 1, ERT 3D).

Regarding the conversion of real (or inverted) electrical resistivity parameters into water content, a long history of petrophysical relationship determinations, linking soil water content to electrical resistivity is available in the published literature. A good state of the art was published by Brillante et al. (2015), from pure empirical models, totally site dependent, to semi-empirical models (the most well-known is Archie, 1942).

At field scale, the spatial analysis of electrical resistivity alone is shown to be inadequate for characterizing soil water content variability (e.g., Besson et al., 2010), because of the influence of multiple other soil parameters. To overcome this issue, it is possible to implement ERT combined with temperature measurements, Induced Polarization, or monitoring of one of both previous suggested approaches. Similarly EMI sensors allow to effectively map spatiotemporal soil moisture variations, through the definition of a relationship between water content and true electrical conductivity, to create time-lapse images of soil (e.g., Huang et al., 2017). In other studies, water variation in the root zone were retrieved from EMI monitoring, based on calibration of water content with punctual data (e.g., Murad et al., 2022). Revil et al. (2021) applied the SIP method in a Bordeaux vineyard and provided a 2D vertical soil water content image between 0 and 3 m depth, which was validated by punctual soil water content measurements.

The techniques described here above allow for determining the total volumetric soil water content. However, the access of the vine to this water, and its consequences on the physiology of the vine, are related to the pore size in which the water is stored. It is of particular important to access plant available water, which is stored in pored between 0.2 and 10 μm .

6.2. Estimation of free water in the root zone

In geophysics, several concepts are used with regards to free water: volumetric water content, water saturation (partial or total) or aquifer characterization. From an agronomic perspective, the most relevant parameter in reference to the functioning of plants, is the quantification of water stored in pores $> 10 \mu\text{m}$ in diameter (*macro-* and *meso-*porosity, water with a matrix potential close to 0 J/kg). To date, no published study addresses the issue whether GPR or ERT techniques can be used to determine specifically the water stored in pores $> 10 \mu\text{m}$ in diameter (free water). In a field and lab experiment with an original set-up, Ghorbani et al. (2008), showed the indirect capacity of SIP to provide information linked to water stored in specific pore sizes. The study was based on the coupled acquisition of tensiometer data and SIP spectra during an infiltration event created by an artificial rainfall event at a constant rate. The experiment confirms the existence of a significant phase drop in the high-frequency domain during the first infiltration cycles. The interpretation of the tensiometer and SIP data shows that this phase drop is correlated with the water filling of pores in the [30–85] μm diameter range. The results of this study strongly suggest that the SIP method can be used to monitor the water filling of structural or draining pores in the field. Nevertheless, these results need to be validated in other sites, and suggests that the sensitivity may not be totally suited to

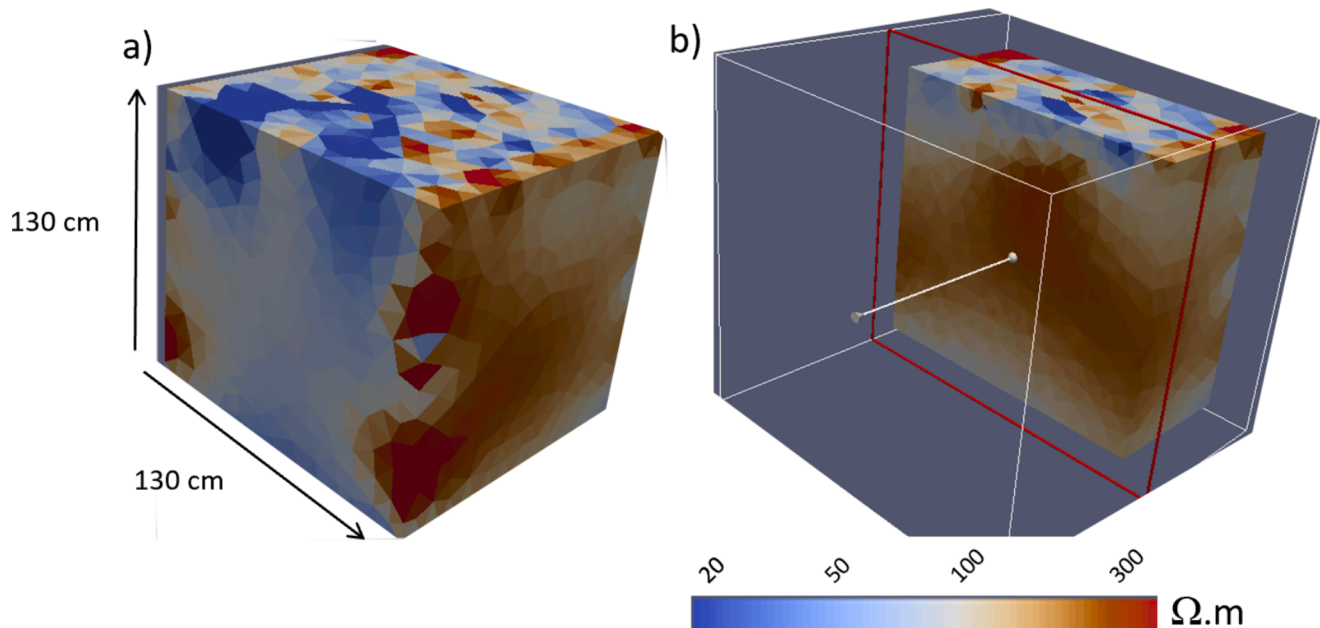


Fig. 1. Soil 3D Electrical Resistivity Tomography (ERT) around a vine plant. a) 3D inverted resistivity block diagram. b) extraction of a slice in plan of a vine. (Schmutz, Boaga, Cassiani, unpublished data).

the one required to obtain the complete signal of free water ($>10 \mu\text{m}$ required vs. $30\text{--}85 \mu\text{m}$ measured).

The only geophysical method that is able to characterize the free water content in the soil is SNMR, as the relaxation time of the measured signal is directly linked to the pore space. Whereas most of the SNMR case studies in the literature are related to the saturated zone, few studies focus on specific vadose zone characteristics and the corresponding water dynamics (Costabel and Günther, 2014; Legchenko et al., 2020).

More recently, near surface SNMR approaches for water content characterization in the vadose zone have been developed (Hiller et al., 2020; de Pasquale and Mohnke, 2014; Hiller et al., 2021). Hiller et al. (2020) show that even if SNMR-PrePolarization (SNMR-PP) is able to measure the water content in the uppermost meter, it still suffers from relatively poor data quality. Nevertheless, in conjunction with TDR probes that investigate the upper 0.25 m, semi-mobile pointwise application can be imagined. Thus, the application for irrigation monitoring is possible and yields water content estimations also at depths that are not easily accessible to TDR. Finally, this SNMR technique requires a high degree of expertise, and the presence of trellis wires interfering with the measurement may be a critical barrier, that might limit the use of the NMR method to unplanted vineyard parcels.

To conclude, none of the ground geophysical techniques are able to provide routinely the free soil water content at date. To achieve this objective, an approach combining punctual (e.g., TDR) and geophysical techniques (SIP, SNMR-PP) is required.

6.3. Estimation of soil water holding capacity (SWHC)

Soil Water Holding Capacity (SWHC) or Available Water Capacity (AWC) refers to the amount of water accessible to plants, stored in pores between 0.2 and $10 \mu\text{m}$ in diameter at field capacity. It corresponds to the volumetric water content between Field Capacity (~ 33 KPa) and Wilting Point (~ 1500 KPa). When soils contain free water (water logged soils, with water present in pores $> 10 \mu\text{m}$ in diameter), the concept of SWHC does not apply.

Cousin et al., (2022) provide a review about methods used to estimate AWC. They are very diverse, including laboratory measurements of soil samples, field monitoring, use of pedotransfer functions, and inverse

modeling of soil-vegetation models. Among all these approaches, AWC can be derived using various geophysical methods, primarily based on EC and ECa measurements. EC (or ECa) maps can be converted into texture maps, which are then transformed into AWC using pedotransfer functions (PTFs; Abdu et al. 2008; Fortes et al. 2015), by combining ECa-delineated homogeneous zones with direct laboratory measurements and through direct regression analyses between ECa and laboratory measurements (Ortuani et al. 2016, Jiang et al. 2007). Due to EC's sensitivity to water content, it can also be used as a proxy for water content at full capacity, producing AWC maps by combining field and laboratory measurements (e.g., Lo et al. 2017). However, the relationship between ECa and AWC can weaken at greater soil depths, leading to inconsistent patterns (Ortuani et al. 2016). This variability is influenced by the season of measurement, the depth and sensitivity of the geophysical method, and the vertical arrangement of soil layers.

Finally, as a number of geophysical methods and approaches, like GPR, ERT, EMI and SIP, are sensitive to soil texture (see the dedicated paragraph) or rooting depth (see dedicated paragraph), it would be possible to use these outputs to determine indirectly the SWHC by a pedotransfer function.

6.4. Assessment of soil texture

This soil parameter is probably one of the most widely studied by geophysical means in vineyards, as attested by the numerous studies on the topic. The geophysical family that most contributed to vineyard soil texture studies is based on geoelectrical methods, and more specifically on ECa measurements. Due to its easy implementation, ARP and EMI methods have been most widely deployed to explore the relationship between ECa and soil texture (among others, see, Doolittle et al., 1994; Triantafyllis and Lesch, 2005; Rossi et al., 2013; Priori et al., 2010). It appears that the majority of studies that demonstrated a good correlation between vineyard soil ECa and soil texture were performed using the EM38 system or first ARP channel and soil samples, each one sampling the upper ~ 30 cm of the soil profile (e.g., Rodríguez-Pérez et al., 2011; Bonfante et al., 2015). Other studies (see review in Hubbard et al., 2021) have found poor relationships that they attributed to interference with agro-equipment (trellis, underground infrastructure) or local parameters (soil compaction, presence of a specific crop). Soil texture

refers to particles < 2 mm in diameter (sand, silt and clay). Several authors show that the defined relationships between ECa and EMI sensors are also valid for coarse sediments (gravel) (Morari et al., 2009; Hubbard et al., 2021).

Beside EMI measurements, the GPR method has proven its ability to provide soil textural information in vineyards with high spatial resolution. Grote et al. (2010) showed how time-lapse GPR soil moisture information can be used to estimate shallow vineyard soil texture. They showed that geophysically-derived estimates of soil water content obtained with GPR can be used to improve spatial estimation of soil texture. Lastly, the SIP method has also proven its ability to provide soil textural information on vineyard in a 2D vertical section (Revil et al., 2021). Also, Schmutz et al. (2011) showed the capacity of the IP method to distinguish between clay and other types of soil texture. However, more research is needed to confirm if SIP can be an operational method to determine soil texture. The data processing required to extract relevant information from GPR and SIP can be challenging, while the EMI approach is easy to use and can be implemented over large areas in vineyards.

It is critical to characterize soil texture over the whole rooting depth. As suggested by Hubbard et al. (2021), plant vigor can be linked to soil texture over the rooting depth, and thus soil texture profiles extracted from ECa need to be compatible with that depth. The same is true when soil texture is used to obtain SWHC by means of pedotransfer functions.

6.5. Assessment of rooting depth and root distribution

Additionally to state variables (e.g. soil moisture, salt concentration) and soil properties characterization (e.g. clay content, cation exchange capacity), geophysical properties can be related to root properties. Vanderborgh et al. (2013) provided an overview of geophysical methods for field-scale imaging of root zone properties and processes. The main geophysical methods used are based on electromagnetic signals (GPR, ERT and IP), which are sensitive to conduction and polarization processes necessary for root investigations (root architecture, distribution and density).

More specifically, rooting imaging can be studied through (i) root water uptake characterization (e.g. Garré et al., 2011; Cassiani et al., 2015; Mary et al., 2019), (ii) root distribution and biomass estimation (e.g., Zenone et al., 2008; Petersen and Al-Hagrey, 2009; Paglis, 2013), and (iii) functional properties of root systems (more specifically of IP methods, see Dalton, 1995; Vanderborgh et al., 2013; Weigand and Kemna, 2017, 2019).

Nevertheless, to our knowledge, only one field study addresses the characterization of vine rooting depth (Mary et al., 2019). It is based on a vineyard infiltration experiment determining the root water uptake, using the electrical resistivity methods.

As the requirements (i.e., root diameter, root length, lignified vs. non-wooded roots) and preferred techniques (GPR vs. ERT) depend on crop species, studies implemented on other crops will not be addressed in this Review, but some essential features are highlighted.

The GPR signal has been used for root detection and biomass estimation (i.e., Hruska et al., 1999; Hirano et al., 2009), coarse root imaging (i.e., Guo et al., 2013) and, more recently, for studying patterns of associated soil-root-processes (Klotzsche et al., 2024). Zajčová and Chuman (2019) provided an overview of the application of GPR in soil surveys, including root detection. It appears that successful GPR-based coarse root investigation is site specific. It is suited to well-drained and electrically-resistive soils under dry conditions. Moreover, inherently to any GPR study, the signal can be affected by numerous factors (i.e., local soil conditions) that can affect the reliability and accuracy of GPR detection and quantification of coarse roots.

Beside, GPR, ERT and Electrical Impedance Tomography (EIT, close to IP) are increasingly used in plant-soil interaction studies, in spite of a decrease in resolution with depth inherent to ERT/EIT. Furman et al. (2013) published an overview of the use of ERT to study the root zone,

and Cimpoiașu et al. (2020) reviewed advantages and limitations of geoelectrical methods for root zone structure and processes monitoring.

In summary, GPR is mainly capable of distinguishing coarse individual roots and is not able to perform vine root architecture imaging. ERT provides useful information about the root zone biomass, but its efficiency needs to be increased under time-lapse monitoring and/or water deficit measurements. IP shows an important potential for root detection, but has not yet been deployed in the field for this purpose, as some challenges still need to be overcome. Most likely, a combination of methods will have to be considered for investigations in the field (GPR, ERT and/or IP), and an important prerequisite is to precisely define objective to be reached: (i) what is the predominant rooting depth, (ii) what is the rooting depth of the deepest root, or (iii) is the target to identify active or lignified roots?

6.6. Soil temperature

The diffusion of heat in the soil is provided mainly by the phenomenon of conduction, but the percolation of water (convection) can also modify the temperature distribution (Cheviron, 2004). The only geophysical property that can be linked to temperature is electrical resistivity (or linked properties, as those derived from IP). As soon as temperature increases, electrical resistivity decreases because of the increase in ionic mobility.

Even if temperature is a factor influencing electrical conductivity, geophysical methods are not often used for its estimation. Hence, in order to characterize temperature, geophysicists use dedicated temperature sensors, at one or multiple depths and locations to define a soil temperature profile (Cheviron et al., 2004; Tabbagh et al., 2017) associated to the geophysical measurements. These temperature sensors are limited to providing a temperature variation map, as the information is punctual and potentially destructive.

A recently developed approach consists of installing low-cost temperature sensors at high spatial density (i.e., Tabbagh et al., 2017; Dafflon et al., 2022) to better apprehend the soil temperature variability. As an example, high precision temperature measurements could be tested to distinguish between the different types of liquid water flows in soils, typically in micro- and macro-porosity (Vogel et al., 2011).

ERT can also be used as a proxy to distinguish between cool and warm soils, as cool soils are generally fine textured and conductive, while warm soils are frequently coarse textured and resistive (Fig. 2; van Leeuwen, 2021).

6.7. Soil depth/thickness

While maps are generated by horizontal spatial geophysical investigations, the determination of soil depth needs to consider the vertical component as well. It is obtained with the so-called “tomography” technique. This approach is one of the most common tools used by geophysicists, whatever the geophysical method implemented (ERT, multiple depths EMI, IP, surface waves seismic), given that sufficiently contrasted medium properties (e.g., moisture, texture, compaction, permeability) between the soil and the underlying rock do exist. Many applied geophysical publications address the characterization of the vertical distribution of soil layers. Nevertheless, few of such studies have been carried out in vineyards (i.e., Courjault-Radé et al., 2010; Revil et al., 2021; Hubbard et al., 2021). The ability of geophysical methods to provide reliable estimations of bedrock depth is known to depend greatly on local site characteristics (Coulouma et al., 2012).

Zajčová and Chuman (2019) reviewed GPR applications for soil characterization, concluding that GPR is effective for detecting soil or peat stratigraphy and estimating layer thickness. In vineyards, Grote et al. (2003) and Lunt et al. (2005) produced GPR tomograms reflecting spatial soil thickness variation, calibrated with wave velocity from known interfaces. Liu et al. (2021) and Sucre et al. (2011) successfully used GPR to detect soil thickness. Sucre et al. (2011) even found that

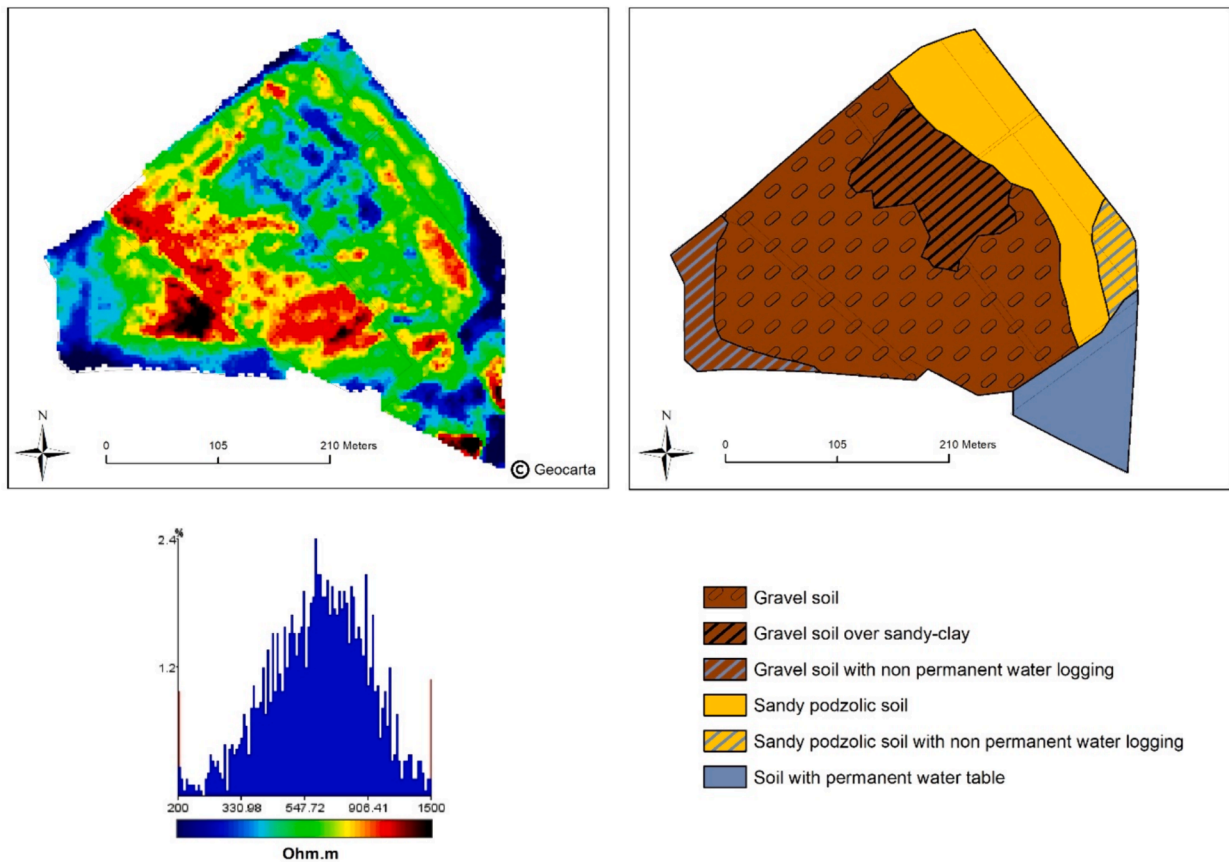


Fig. 2. Soil resistivity map and soil map of a winegrowing estate in Bordeaux acquired with ARP. Red and black on the resistivity map indicate coarse textured warm soils, blue corresponds to cooler soils with higher clay content or water logging.

GPR provided better soil depth estimates than soil augers. Optimal conditions for GPR-based soil layer thickness estimation are dry, coarse-textured soils, low in expandable clays, above the water table (Doolittle and Collins, 1995; Smith and Jol, 1995).

ERT is another method for studying soil thickness and depth (Fig. 3: Schmutz, personal communication). Courjault-Radé et al. (2010) used 2D ERT to establish soil layer depths in a vineyard, and Wisen et al. (2006) found both 2D and 3D ERT produced reliable soil depth models when compared with geotechnical data. However, Besson et al. (2004) observed that very-high resolution ERT maps were consistent with morphological descriptions but not with pedological soil layers, likely due to resistivity heterogeneity. EMI methods, typically limited in

investigation depths, are used for lateral soil texture extension rather than soil depth characterization (Hubbard et al., 2021; André et al., 2012). New joint inversion approaches combining ERT and EMI are being developed to improve soil depth estimation (Lopane et al., 2024; Lavaud et al., 2024 submitted).

IP can also provide detailed soil texture information and vertical profiles, as shown by Revil et al. (2021) in a Bordeaux vineyard. Seismic methods, particularly SASW, have been used to estimate soil depth, with Choo et al. (2018) successfully comparing their method with dynamic cone penetration tests.

Combining multiple geophysical methods can improve soil depth estimates, as demonstrated by Inman et al. (2002), who found a strong

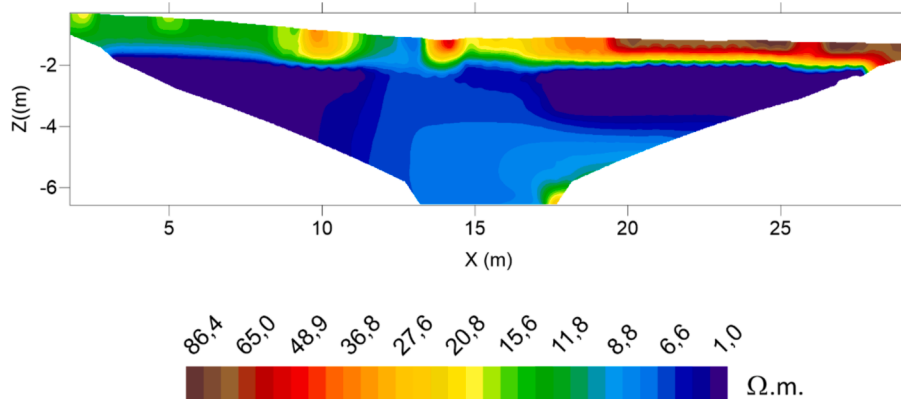


Fig. 3. Electrical Resistivity Tomography (ERT) acquired in a Bordeaux vineyard (Schmutz, 2023: non-published personal data). The blue dotted line corresponds to the limit of the saturated field.

agreement between GPR data and soil morphology and physical data. [Coulouma et al. \(2012\)](#) combined seismic and ERT methods to predict bedrock depth, finding variable performances depending on groundwater presence. Their study established an estimator of bedrock depth, favouring ERT in the upper hillslope and SASW in the lower hillslope. This combination of geophysical methods enhances the accuracy of soil property estimates when prediction uncertainties vary with the methods used.

In summary, GPR may be used alone under favourable conditions to provide soil depth (above clay and water table), whereas EMI and ERT methods may require validation data, or complementary geophysical investigations by GPR and/or SASW.

6.8. Soil compaction

Vineyard soils can be compacted near the surface by trafficking or in deeper layers by specific soil textures or bedrock properties. Soil compaction affects soil structure (porosity, permeability) and soil moisture (free water varies with soil compaction). It has an influence on EM waves, soil dielectric constant, electrical resistivity and mechanical seismic waves, generally increasing these parameters in comparison with similar but not compacted soil layers.

Several references dedicated to controlled laboratory experiments indicate that GPR signals ([Wang et al., 2016](#); [di Matteo et al., 2013](#)) and seismic waves ([Lu et al., 2004](#)) are modified by soil compaction. Moreover, in their review about geophysical methods for soil structure characterization, [Romero-Ruiz et al. \(2018\)](#) report that compacted soil layers induce observable GPR signals ([André et al., 2012](#); [Muñiz et al., 2016](#); [Petersen et al., 2005](#); [Wang et al., 2016](#)), and seismic velocities can be converted to soil strength ([Donohue et al., 2013](#); [Keller et al., 2013](#)).

Very few references are dedicated to viticultural soils. In a transect across a vineyard, [André et al. \(2012\)](#) attributed GPR reflections to soil compaction. Zones with strong reflections presented a compacted soil profile and poor vine development in comparison to a weak reflection in an uncompacted zone, where the vine presented a more favorable development. In 2020, [Iwasaki et al.](#) concluded that the combination of GPR and punctual penetrometer data is the ideal combination about soil hardness evaluation.

[Donohue et al. \(2013\)](#) studied the detection of soil compaction using seismic surface waves. A significant difference was detected in shear wave velocity between a heavily compacted headland and an uncompacted location. [Romero-Ruiz et al. \(2021\)](#) report how seismic signatures can reveal persistence of soil compaction at the management scale.

Compaction, or more generally speaking impact of tillage, can also be studied successfully with ERT ([Besson et al., 2004](#); [Rossi et al., 2013](#)). [Blanchy et al. \(2020\)](#) reported for various case studies that ERT and EMI methods are able to monitor the effects of different agricultural practices (cover crops, compaction, irrigation, tillage, and fertilization).

[Petersen et al. \(2005\)](#) explored the value of a combination of geophysical methods (GPR, EMI, and refraction seismic) to assess soil structural changes caused by soil compaction. For the compacted soil, they observed strong reflections in GPR signals under humid conditions. The contrast in dielectric constant that was causing these reflections was attributed to layers with variable water content that were considered indicators of soil compaction.

6.9. Soil mineral and organic nitrogen content, organic matter content

A few publications deal with successful determination of soil organic carbon and soil inorganic nitrogen content thanks to the measurement of ECa. Nitrogen decomposes into nitrate and ammonium, contributing to the ionic content of the soil matrix and fluid. The accumulation of these ions results in an increase in electrical conductivity. Soil organic nitrogen content cannot yet be estimated with geophysical methods. [Korsaeth \(2005\)](#) showed that the use of ECa parameters obtained by EMI appears

to be quite robust in terms of detecting relative spatial differences in soil inorganic nitrogen content, whereas a determination of absolute levels is unreliable.

[Rentschler et al. \(2020\)](#) carried out 3D mapping of soil organic carbon content and soil moisture with multiple geophysical sensors. They used machine-learning models integrating multiple EMI depth related data and gamma-ray spectrometer data to successfully explore the possibility to determine the horizontal and vertical variation of soil organic C and soil moisture. [de Benedetto et al. \(2022\)](#) estimated soil organic carbon content obtained from EMI and GPR data with multivariate adaptive regression splines. [Klotzsche et al. \(2024\)](#) showed that fertilizer additions have an effect on the ERT, EMI and GPR signals, while high conductivity (induced by high fertilizer dosage) damps GPR signals. [Lavaud et al. \(2024, submitted\)](#) showed that under specific conditions, EMI allows to detect soil and vine nitrogen availability, which was validated by measurements of nitrogen in vine leaves.

In summary, the mineral nitrogen and organic matter content in vineyards can be characterized, but this process requires calibration points due to initial soil heterogeneity. For these components to be detectable, their concentrations must exhibit significant geographical or temporal variability, allowing their signals to be distinguished from other sources of geophysical parameter variation.

6.10. Soil salinization characterization

Soil and/or water salinization can be well measured with geoelectrical methods. Moreover, in salt-affected soils, salt dominates the response of the EM ([Amakor et al., 2014](#); [Cassel et al., 2015](#)).

EMI methods have been widely used to map the spatial distribution of underground soil salinity, as well as for spatiotemporal monitoring of soil salinity ([Guo et al., 2015](#); [Ben Slimane et al., 2022](#)). Through a review dedicated to soil salinization monitoring in an arid context, [Zarai et al. \(2022\)](#) conclude that ECa measured with EMI, followed by calibration, is efficient to predict salinization in the soil surface.

Many EMI studies have explored the regional distribution of saline soils and the characteristics of salinization. Still, much less are available on vertical electrical resistivity distribution and the transfer of salt to deeper soil layers. In contrast, these are necessary to calibrate properly ECa data obtained by EMI methods ([Johnson et al. 2005](#), among others).

There is a wealth of literature about ERT methods for groundwater characterization, in general and for salinization characterization, specifically. The ERT methodology permits the study of the evolution over time of freshwater availability in coastal zones ([Greggio et al., 2018](#)). Moreover, monitoring groundwater and soil quality is possible ([Lech et al., 2016](#)), while the method is sensitive enough to characterize the increase of nitrates, sulphates and bicarbonates, in addition to phosphorus, in the soil and chlorides in the groundwater ([Sainato et al., 2010](#)).

To improve the method's characterization capacities some authors implement an integrated study, combining ERT and EMI, to show vertical and lateral salinity variations due to changes in the soil type, texture and moisture content ([Mohammed et al., 2022](#)).

7. Conclusion

In the current state of the art, soil texture, soil depth and soil compaction can be addressed with NSG technology. The combination of methods (various NSG techniques and/or the associating of NSG with punctual calibration points) increases the reliability of the results, especially when different variables are considered together (e.g., soil compaction and texture).

Many NSG methods provide results related to soil water content, particularly those based on geoelectrical principles. Nevertheless, it is not easy to assess water content variation in the root zone. Characterization of free water (i.e., water located in pores > 10 µm) is not possible in an operational vineyard, because of interference of available NSG

techniques with metal posts and wires.

Root imaging is still work in progress, especially in field conditions. Ongoing research projects focus on imaging the global rootzone from a structural point of view, but also try to address the understanding of root functioning. Measurement of soil mineral nitrogen and organic matter content with NSG technology is not yet operational in field conditions.

Many NSG methods are challenging in terms of acquisition speed and the need of specific skills for data processing (Table 1). The easiest methods to implement in field conditions are EMI and ARP, but the results cannot directly be linked to physical or chemical soil properties, as they consist of averaged data. They are in particular limited to show vertical variation in soil properties. Other NSG techniques allow to assess vertical property distribution across a soil profile. The GPR method is fast to run, but requires a high degree of expertise. Moreover, the measurements are limited to dry periods of the year and cannot characterize the medium below clay and/or water saturated soil layers. Data acquisition for ERT is quite fast and the output provides vertical images of electrical resistivity, generally linked to soil water content and/or lithological limits. Refraction seismic is as fast and easy as ERT to implement and is generally used to characterize vertical limits of layer densities or compaction. SASW and IP require a high degree of expertise and data acquisition is more time consuming. SASW provides reliable information about soil density variability near the surface. IP is very promising considering its ability to distinguish soil water content and Cation Exchange Capacity. SNMR is the most time consuming method and requires the highest degree of expertise, but it is the only one providing results directly linked to soil water content.

NSG technologies have a great potential to contribute to improved understanding and management of soil related terroir factors in vineyards. Future technologies of interest would (1) address relevant factors in terroir expression, (2) be able to be deployed in field conditions with fast data acquisition, (3) allow for three-dimensional characterization, and (4) be available at a reasonable cost.

List of abbreviations

Abbreviation	Full spelling
ARP	Apparent Resistivity Profiling
AWC	Available Water Content
CSEM	Controlled Source ElectroMagnetism
DOI	Depth Of Investigation
ECa	Apparent Electrical Conductivity
EMI	ElectroMagnetic by Induction
ERT	Electrical Resistivity Tomography
FDEM	Frequency Domain ElectroMagnetism
GPR	GeoPenetrating Radar
HMD	Horizontal Magnetic Dipole
IP	Induced Polarization
NMR	Nuclear Magnetic Resonance
SASW	Spectral Analysis of Surface Waves
SIP	Spectral Induced Polarization
SIPT	Spectral Induced Polarization Tomography
SNMR	Surface Nuclear Magnetic Resonance
SWHC	Soil Water Holding Capacity
TDEM	Time Domain ElectroMagnetism
VMD	Vertical Magnetic Dipole

List of acronym parameters

Parameter acronym	Correspondence
ρ	Electrical resistivity
ρ_a	Apparent electrical resistivity
σ	Electrical conductivity
σ_a	Apparent electrical conductivity
InPhase	2^{nd} measured parameter from EMI methods, corresponds to real part of the conductivity
ϕ	Phase lag measured in IP methods
Mn	Normalized chargeability in IP methods

(continued on next column)

List of acronym parameters (continued)

Parameter acronym	Correspondence
ϵ	Dielectric permittivity measured in GPR
Vp	Velocity of compressional (primary) waves detected in Seismic refraction
Vs	Velocity of shear (secondary) waves studied in SASW
E0	Amplitude (number of protons) in SNMR
T*2	Decay time in SNMR

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Cornelis van Leeuwen: Writing – original draft, Project administration, Conceptualization. **Myriam Schmutz:** Writing – original draft, Conceptualization. **Laure de Ressaiguier:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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