SOIL Discuss., 1, 677–707, 2014
www.soil-discuss.net/1/677/2014/
doi:10.5194/soild-1-677-2014

SOIL Discussions Open Access

The use of soil electrical resistivity to monitor plant and soil water relationships in vineyards

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Received: 13 October 2014 – Accepted: 16 October 2014 – Published: 29 October 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Soil water availability deeply affects plant physiology. In viticulture it is considered as a major contributor to the "terroir" expression. The assessment of soil water in field conditions is a difficult task especially over large surfaces. New techniques, are therefore required to better explore variations of soil water content in space and time with low disturbance and with great precision. Electrical Resistivity Tomography (ERT) meets these requirements, for applications in plant sciences, agriculture and ecology. In this paper, possible techniques to develop models that allow the use of ERT to spatialise soil water available to plants are reviewed. An application of soil water monitoring using ERT in a grapevine plot in Burgundy (north-east of France) during the vintage 2013 is presented. We observed the lateral heterogeneity of ERT derived Fraction of Transpirable Soil Water (FTSW) variations, and differences in water uptake depending on grapevine water status (leaf water potentials measured both at predawn and at solar noon and contemporary to ERT monitoring). Active zones in soils for water movements were identified. The use of ERT in ecophysiological studies, with parallel monitoring of plant water status, is still rare. These methods are promising because they have the potential to reveal a hidden part of a major function of plant development: the capacity to extract water from the soil.

1 Introduction

In viticulture and oenology it is acknowledged that the natural environment has a major impact on the sensory attributes of the final product. This link between the characteristics of a wine and its origin is called the "terroir effect" (van Leeuwen and Seguin, 2006). It has been studied on a scientific basis since the 1960s (Seguin, 1969). This relationship is not mediated through the effect of particular soil minerals or flavour compounds, although the popular wine press often erroneously describes it thus (van Leeuwen and Seguin, 2006). The terroir effect must be sought in interactions at the ecosystem level.

Major factors in the terroir effect are the supplies of water and nitrogen (van Leeuwen, 2010). Water and nitrogen are major drivers of vine physiology at the whole-plant level. This paper focuses on soil and vine water relationships.

First, the grapevine physiological response to drought will be briefly reviewed, with special regard to plant and soil relationships, and to soil properties that affect plant water status. Then, the concept of soil-water availability to plants will be discussed. Finally the contribution of geophysical methods, and in particular electrical resistivity, to the study of plant and soil water relationships in vineyards will be discussed. These tools are very promising for the quantification and visualisation of plant and soil water relationships.

2 Plant and soil water relations in terroir

The effect of water on fruit production has received great interest because it directly affects both the quantity and quality of the final product. Water deficits have a physiological impact at the whole-plant level. The need to acquire knowledge of these phenomena is further increased by the current context of global warming. A number of studies have therefore flourished on the subject in recent years and, among trees, grapevines can now be considered as model plants from both the physiological and molecular points of view. Among the reasons for such success can be mentioned here the great progress made in grapevine genomics (Jaillon et al., 2007) and the long history of ecophysiological research for this plant. A complete physiological and molecular update can be found in Lovisolo et al. (2010). In this section we will provide only a brief overview of water relationships between plants and soils and their effects on the expression of terroir.

Water is vital to plants, but in several species it has been shown that a moderate water deficit can increase fruit quality, especially if fruit is destined for transformation instead of fresh consumption. Indeed, a moderate water deficit will reduce berry size and increase technological quality (higher sugar levels and lower acidity, for example).

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The reason is that the vegetative and reproductive organs are competing sinks for carbohydrates produced by photosynthesis. Apexes are the most important sinks when fruits are not present. When fruits develop, they become progressively more important sinks for carbohydrates. If shoot growth stops before veraison, there is no competition for carbohydrates between fruits and apexes during ripening. Optimal water supply varies for table or wine grape production, but it will also be different depending on the type of wine to be produced. Red wines benefit from a moderate water deficit, while sparkling or white wines do not (Sadras and Schultz, 2012). Soils favourable to the installation of a moderate water deficit during the summer, which are generally well suited to the production of high quality red wines, have been described in France (Seguin, 1975; Chone et al., 2001; van Leeuwen et al., 2009), Italy (Storchi et al., 2005; Tomasi et al., 2013), Hungary (Zsófi et al., 2009), USA (Chapman et al., 2005) and in many other regions in the world. Research into the effect of water deficit on the quality of white wines is rare, but one such study has been made by des Gachons et al. (2005). The effect of water deficit on grape quality potential can be negative, because it causes an increase in phenolic compounds, which is not considered favourable for the quality of white wine (Sadras and Schultz, 2012). White wine also need a certain level of acidity, which is rapidly degraded during water deficit (Ollat et al., 2002).

The amount of plant available water in soils varies according to soil characteristics, such as soil texture, amount of organic matter and gravel content. Soil characteristics also affect the absorption process and have a direct physiological effect on plants. When the texture of the soil is fine, the soil matrix potential is low, because of greater forces retaining water in capillary pores and at the surface of clay minerals. Therefore, the plant water potential must be more negative to allow absorption, even if soil volumetric water content is higher in fine-textured soils compared to sandy soils. Indeed, at the wilting point, the soil volumetric water content of fine-textured soil is always higher than that of coarse-textured soils (Kramer and Boyer, 1995). Water in macro and meso-pores is generally more easily available to plants, but it is also more mobile, as it is not retained by capillary forces. Its availability is highly variable in time.

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Contact between roots and soil, which is necessary for absorption, is favoured in fine-textured soils and more difficult in coarse-textured soils, and in soils rich in gravels. These parameters influencing soil water potential and water absorption by vines have an important effect on terroir expression, which is probably indirect and mediated by the physiological adaptations of vines to the surrounding environment (van Leeuwen, 2010). In Bordeaux vineyards, wines produced on clayey soils, where the soil matrix potential is lower, are higher in anthocyanin content than those produced on sandy soils (van Leeuwen et al., 2004). Grapes also ripen faster on clayey soils. In Tuscany, moderately saline soils have been shown to produce the best wines (as evaluated by a sensory panel) even if water is not limited, probably because the lower osmotic potential induces a moderate water deficit, as measured by $\delta^{13}C$ (Costantini et al., 2009, 2010). Soil texture modifies the plant's response to drought, as shown by Tramontini and coworkers in 2012, studying the effect of texture on grapevine physiology in neighbouring soils during the same vintage. They observed that gravel soils limited stomatal conductance and predawn water potential more than clayey and sandy soils. In sandy soils, stomatal conductance was highly variable, while it was much more consistent in clayey soil. On gravel soils, stomatal conductance was constantly low, independently from the level of water stress. Some authors have attributed the reported physiological differences observed in various soils to differences in root-shoot signalling mediated by ABA (Lovisolo et al., 2010; Ferrandino and Lovisolo, 2014). The water-holding capacity of a soil varies with soil depth. In deeper soils, vine vigour is higher and phenology is delayed (Bodin and Morlat, 2006). Soil depth can also have a direct effect on plant physiology, independently from the water amount, which is known as the bonsai effect (Passioura, 2002). However, the influence of such physiological modifications in field conditions should be further investigated.

With increasingly dry soil conditions, the root/shoot biomass ratio increases (Dry et al., 2000; Hsiao and Xu, 2000). While root growth continues in the most humid soil layers (Bauerle et al., 2008), generally located at greater depths, shoot growth is quickly inhibited by water deficit (Schultz and Matthews, 1988; Lebon et al., 2006). The

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exploitation of soil water tends to be as complete as possible. Indeed, the use of lateral resources plays a very important role during drought periods (Bauerle et al., 2008). Plants can also lose water during the absorption process, at root level. This process is called hydraulic lift, i.e. water redistribution through plant roots from wet to dry soil layers. The amount of water involved can be extremely significant (2–154 %), and the movement of water has been documented in every direction, including lateral transfer (Smart et al., 2005). The phenomenon has several physiological and environmental implications. It increases the survival of roots and maintains root-soil contact in the more easily drying part of the soil; it moistens nutrients in the shallower soil layers; it maintains fine roots alive in this part of the soil (Neumann and Cardon, 2012; Prieto et al., 2012). Soil is not a homogeneous medium, and is therefore not explored by roots in a homogeneous way. Hence, during drought, soil cannot dehydrate in a homogeneous way. It is surprising that such evidence is often neglected, and that available soil water capacity is generally considered as a soil characteristic, independently from the plant. The highly variable spatio-temporal distribution of wet and dry zones in soils has profound physiological implications for plants. Indeed, while chemical and hydraulic root signals are produced in moderately dry soil regions, the part of roots in wet soil regions ensures the water supply, and therefore transpiration and photosynthetic activity. Partial Rootzone Drying (PRD) is an irrigation concept based on this knowledge (Dry et al., 1996; Loveys et al., 2000; Stoll et al., 2000). It maintains reasonably high yields, because vines pick up water from the wet soil zones, while quality is high, because roots produce ABA in the dry zones of the soil profile. In natural conditions, such spatial soil water heterogeneity can also be found. The magnitude of such variations in soil moisture has rarely been studied and their impact on vine physiology has rarely been taken into account (among few, Bauerle et al., 2008). They might play a key role in terroir expression. In a recent review, Schultz and Stoll (2010) remarked that soil water monitoring is a challenging task, because root distribution is generally unknown and therefore it is difficult to understand how much water is effectively absorbed in each soil layer. To assess the spatial variability of soil moisture, electrical resistivity can be a powerful tool to address such questions. Hence, this geophysical approach can advance research into plant and soil water relationships, and also be of interest in terroir studies.

3 Assessing the soil water availability to plants

The available water capacity of a soil (also called Soil Water Holding Capacity or SWHC) has been defined as the difference between two limits of soil water content. The upper limit is the volumetric soil water content at field capacity (the maximum amount of soil water, excluding free water, that a soil is able to store in the root zone), while the lower limit is the volumetric soil water content at the permanent wilting point (the amount below which water is so strongly retained that plants are unable to absorb it). Field capacity corresponds to a soil potential −0.33 kPa (pF = 2.45), while the permanent wilting point have been defined at −15 kPa (pF = 4.2) (Richards and Weaver, 1944). The concept of plant available soil water capacity, in the form described here, was first introduced by Veihmeyer and Hendrickson (1950). Its simplicity helped to popularise it for irrigation purposes, but is far from being unanimously accepted in the scientific community. It has been argued that the definition of the two extremes lacks a universal physical basis (Hillel, 1998), and also that water cannot be considered equally available in the expected range because availability decreases as the soil dries out and soil water potential decreases (Richards and Wadleigh, 1952). Furthermore, it is obvious that water availability to plants cannot be assessed without considering the plant. Roots are not uniformly distributed in the soil, water availability is heterogeneous in space and time, and such heterogeneity affects plant physiology at the whole-plant level. Finally it has been observed that plants, including grapevines (Costantini et al., 2009), can absorb water at lower levels than the theoretical wilting point (i.e., −15 kPa). It is worth noting that Veihmeyer and Hendrickson (1950) already reported a similar observation for plants grown in containers. These observations cannot be ruled out and have to be taken into account both for irrigation scheduling and for ecophysiological research. One possible but only partial solution is the concept of Total Transpirable Soil Water, (TTSW). The TTSW seeks to include root distribution in the assessment of soil water availability for plants (because root absorption is the first cause of water content variation in soils), and also to evaluate soil water capacity on the basis of the physiological response of plants. The TTSW is defined as the difference between soil water at field capacity and soil water measured when plants are no longer able to extract water from the soil, which depends on the plant species. Both limits are directly estimated in the field, and not in the laboratory, by moisture release curves. The idea was first advanced by Ritchie (1981) and then experimented with success both in herbaceous crops (Lacape et al., 1998; Lecoeur and Guilioni, 1998; Guilioni and Lhomme, 2006, to name but a few) and in woody species (Sinclair et al., 2005; Lu et al., 2010, to name but a few). In grapevines the concept has been used in the most recently developed water balance model (Lebon et al., 2003; Pellegrino et al., 2006; Celette et al., 2010). Water balance modeling is an interesting approach to assess vine water status in both irrigated and non irrigated vineyards, especially when coupled to plant-based measurements (van Leeuwen et al., 2010). Soil moisture can be difficult to measure in field conditions because the grapevine is a deep-rooting species, often grown on soils rich in gravels. Hence, measuring soil water potential with tensiometers, or soil water content using Time Domain Reflectometry (TDR), or neutron moisture probes, can be difficult or even impossible to implement. Furthermore, these devices measure only a very small volume of soil, and even when the measurement is replicated by increasing the number of probes, no information is generally obtained about the lateral variation of the TTSW. Only a vertical soil moisture profile can be established. In addition, multiplying the number of such devices can lead to major perturbations of the system and prohibitive costs. The estimation of TTSW with such devices depends greatly on the position of access tubes or probes and can therefore yield misleading information. Geophysical imaging measurements such as electrical resistivity provide visual quantification of soil water content in two or three dimensions, and assess its variations over time. Electrical resistivity is therefore a powerful tool to study soil water relationships at high spatial and temporal resolution.

4 Electrical imaging of the soil water

Applications of geophysical imaging techniques, and specifically electrically based techniques, have been tested and reviewed in hydrology (Robinson et al., 2008), ecology (Jayawickreme et al., 2014), in plant science (Attia Al Hagrey, 2007), soil sciences and agronomy (Samouelian et al., 2005), which also review the basic principles). They offer promising perspectives in agronomy, for both production and research. The main techniques are based on the direct or indirect measurement of electrical resistivity (or of its opposite, electrical conductivity), such as electrical resistivity tomography (ERT, or or Electrical Resistivity Imaging, ERI) and Electro Magnetic Induction (EMI). Measurements can also be recorded with mobile devices, and several commercial sensors have been developed to assist in soil mapping. The success of electrical resistivity is based on its sensitivity to soil properties, including water (Friedman, 2005; Hadzick et al., 2011; Brillante et al., 2014). It can be implemented for many purposes, like soil texture mapping (Triantafilis and Lesch, 2005), assessment of coarse element content in soils (Tetegan et al., 2012), the study of soil structure and compaction (Besson et al., 2004), soil hydraulic conductivity, (Doussan and Ruy, 2009), soil horizonation (Tabbagh et al., 2000), assessing the effect of different tillage systems (Basso et al., 2010), to map root distribution and quantify biomass (Amato et al., 2008, 2009; Rossi et al., 2011), and absorption (Srayeddin and Doussan, 2009), for agricultural management purposes, especially in precision agriculture (Jaynes et al., 2005; Lesch et al., 2005; Corwin and Lesch, 2005; Andrenelli et al., 2013; André et al., 2012), for the evaluation of soil volume wetness and of transpirable soil water both at the plot scale (Michot et al., 2003; Attia Al Hagrey, 2007; Werban et al., 2008; Garré et al., 2011, 2013; Brillante et al., 2014, to name but a few), and at the field scale (Besson et al., 2010), with interesting perspectives for applications in plant ecophysiology.

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4.1 Acquiring data

The relationship between Electrical Resistivity (ER) and Soil Water (SW) has been observed in many studies, by many authors and in many different settings. It is dependant on soil characteristics and is therefore site specific. Hence, in order to use ER to monitor soil water it is necessary to perform a calibration, which can be carried out in the field or in the laboratory. The following section will review and compare the procedures used to acquire data to explore the relationship between ER and SW. Modelling details will be described, but the technical and practical aspects of ERT measurements will not be discussed (see the tutorial provided by Loke, 2014).

4.1.1 Laboratory methods

Data for successful modeling of the ER-SW relationship can be acquired with either laboratory or field calibration. Laboratory practices ensure tight control over all the environmental parameters, and therefore make it possible to develop equations for the complete range of moisture conditions in a given soil in a fast and easy way. Different methods of sample analysis are reported in the literature, from cylindrical undisturbed soil cores (Michot et al., 2003; Michot, 2003) to repacked samples in boxes (Hadzick et al., 2011). The validity of calibration developed in the laboratory for field applications is today a matter of debate, especially when the soil structure is disturbed during sampling. Indeed, soil structure, and especially its porosity greatly affects soil bulk resistivity (Archie, 1942, and derived models), therefore Friedman (2005) remarked that field application of calibration obtained with repacked samples should be avoided, because of the possibility of large systematic errors. On the other hand, Nadler (1991), observed that ER-SW relations were stable, whether measured on "field", "packed" or "severely disturbed samples". Soil structure is not the only problem. Michot et al. (2003) used both laboratory (measuring the resistivity of cylindrical soil cores) and field methods (with the 4P method, described hereafter). They had to discard the first method because the saturation water conductivity of the cylindrical soil cores was different from the conductivity of the soil solution. In addition, they remarked great variability in the resistivity values obtained for different volumes of soil, for the same soil moisture content: the higher the volume of the soil core, the higher the Electrical Resistivity.

4.1.2 Field methods

Field methods permit calibrations specifically adapted to the local context. They are more difficult to implement and the control over the environment is lower than for laboratory methods. In field conditions, it can take a long period of time to obtain a variation in soil water content large enough to fit the model, particularly in deeper soil layers, except for irrigated vineyards located in dry regions. Different methods have been used to examine SW-ER relationships in the field, using electrical resistivity, whether inverted or not. Two methods can be used to measure the bulk ER (i.e. not inverted) of a soil in undisturbed conditions and then to explore ER-SW relationships. The first is the 4P method (principles and an example of application are provided in Michot et al., 2003). This method uses 4 electrodes inserted in the soil, in a trench, perpendicularly to the soil profile. The major part of each electrode is isolated, except the end, to ensure a punctiform contact with the soil (1–2 cm, or more in stony soils). Because the soil surrounds the electrodes in all directions, and current propagation is not limited by the air, as is the case when electrodes are at the soil surface, the function that allows the measurement of the potential difference, ΔV, uses 4π instead of 2π. The second technique, which is easier to implement, uses the electrical conductivity given by TDR probes, to fit the relationship between ER and SW (an example is in Beff et al., 2013). If the TDR device is combined with a datalogger, a large amount of data may be acquired, easily, rapidly and economically.

When inverted electrical resistivity is used, the inversion uses a grid with the spatial resolution that best fits the soil water measurements. The cells corresponding to the soil layer where soil water measurements are available are selected, and their ER is laterally averaged. The final data that will be used for the spatialisation and imaging in ERT are used to fit the relationships (an example of the procedure is provided in

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Brillante et al. (2014). The drawback of this approach is that the inversion process, whether for the ERT technique or for any other imaging technique, only yields estimated values of ER (there is no single solution). The true value approached by inversion is the bulk ER data of a specific region of soil. The bulk ER data would be the most accurate choice, but it is more complicated to obtain, because the device used for measuring has to be inserted in the specific region of interest, while with inversion the device can generally be at the soil surface. An advantage of the use of inverted ER is that a greater amount of data can be acquired, therefore providing greater spatial coverage, both vertically and laterally. In addition, Brillante et al. (unpublished data) tested both possibilities, and concluded that if the inversion process converges with a low associated error (lower than 5%), the difference between inverted ER and bulk ER is low enough to justify the use of inverted data. The iteration to select and fit the model also has to be defined. One possibility is to use the iteration with the best performances in the relationship with SW, another is to use the iteration with the lowest error (as measured by RMSE, and lower than 5 %).

4.2 Temperature correction

Electrical current in soils is mainly electrolytic, i.e. based on the displacement of ions in pore water. The electrical resistivity of soil therefore depends on the amount of water in the pores and on its concentration in electrolytes. The ER decreases with a decrease in soil water content (Samouelian et al., 2005). However, the electrical resistivity is also dependent on other soil characteristics, such as temperature, because of kinetic effects on ion mobility in pore water. It is important before fitting any relationship between ER and soil water content to adapt the ER to the reference temperature of 25 °C (Samouelian et al., 2005). A linear correction equation is generally used to increase (or reduce) ER by a factor α, if soil temperature is higher (or lower) than the reference temperature (Campbell et al., 1948). The value of the correction factor, is approximately equal to 2 % (in the literature, the factor varies from 1.9 % in Amente et al., 2000, to 2.5 % in Brunet et al., 2010). It has also been observed that the α factor can vary slightly for a given soil depending on its temperature (Illiceto, 1969). Although some studies have neglected this correction (in particular when temperature variations are low), its use should be considered good practice (Brevik et al., 2004; Nijland et al., 2010).

4.3 Modelling of relationship between ER and SW

The relationships between Electrical Resistivity and Soil Water have been investigated since the 1940s, initially for petroleum research, and then in geological contexts (Archie, 1942). Soil ER is dependant on soil properties other than water. Hence, a unique relationship for an entire soil profile is possible only for homogeneous soils. Examples can be found in Bernard-Ubertosi et al. (2009), Brunet et al. (2010) and Brillante et al. (2014). If the soil is heterogeneous, this has to be taken into account in the relationship. One possible solution is to fit specific relationships for each soil layer (see Michot et al., 2003; Beff et al., 2013; Garré et al., 2011, among others). This method is efficient when SW probes are fixed in the soil. The fitting of many individual relationships for a number of thin and regularly spaced soil layers (every 0.1 m for example in Brillante et al., 2014) can be accurate when soil water is measured by probes inserted in access tubes. The separation of data between the soil surface and the deeper soil layers, also improves the fit, (Hadzick et al., 2011). Another solution is to include soil properties in the model to used to develop pedotransfer functions (Hadzick et al., 2011; Brillante et al., 2014). Many authors have developed semi-empirical geophysical models to describe the relationships and investigate the main soil factors involved. Other authors have developed purely empirically relationships. In the following sections, different methods used to spatialise SW by ER are reviewed in two groups: petro-physical models and experimental calibrations.

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4.3.1 Petro-physical models

The first petro-physical model linking ER to SW was proposed by Archie (Archie, 1942). It assumed an hyperbolic relationship, with greater variation of ER for the lower values of SW. It was developed in pure sand without any clay and can be useful for coarse-grained soil with limited clay content (examples of applications are given in Attia Al Hagrey, 2007; Brunet et al., 2010). Indeed, clays can have a direct effect on soil resistivity because clay minerals are electrically charged and can directly conduct electric current at their surface. The model developed by Waxman and Smits (1968) was based on the Archie model, with the inclusion of a term accounting for the Cation Exchange Capacity (CEC) of the medium. Like the Archie model, the Waxman and Smith model was also developed for geological applications, but it has been successfully applied in soil contexts (Garré et al., 2011). Other modifications of the Archie law have been proposed by other authors (Revil et al., 1998; Linde et al., 2006; Revil et al., 2007; Shah and Singh, 2005), often with increasing complexity in order to better capture the details of the electrical flow in geological contexts. Many of these petro-physical models were tested, in a laboratory experiment, for application on loamy soils, by Laloy et al. (2011). The Archie law has been largely applied because of its simplicity (Frohlich and Parke, 1989), as also the Waxman and Smits model, the latter especially in its simplified form (as in Garré et al., 2011; Beff et al., 2013). The generalized form of Archie's law (proposed by Shah and Singh (2005), with an interesting application in Schwartz et al. (2008) appears to be a valid alternative when the soil contains clay and the conductivity of the soil matrix cannot be neglected.

The use of such petro-physical models is interesting from a geophysical perspective. They allow comparison with other studies, as the estimated parameters can be reused in similar contexts. They also allow further understanding of the electrical resistivity of soils. However, in some situations, there is no consensus about the meaning of some parameters in the models, which may have been included only with the aim of improving the fit (e.g., as the *a* coefficients in the modified Archie law by Winsauer et al., 1952). Moreover, and particularly for the more useful models, the factors influencing the ER-SW relationships are loosely compressed into a few global parameters (as in the simplified Waxman and Smith models), meaning that their precise interpretation remains possible, but is more difficult (Garré et al., 2011).

4.3.2 Experimental calibrations

The use of a petro-physical model is not the only way to predict soil water content by ER. It is also possible to use a direct empirical calibration, by regression analysis, and with parallel measurements of the volumetric soil water content. This can be the most direct approach, if the aim is merely to use ER as an ancillary variable to spatialise SW. This technique has an accuracy that is comparable to the application of a petro-physical model, and it has successfully been used by many authors (among others Michot et al., 2003; Calamita et al., 2012; Brillante et al., 2014). A linear regression analysis was suggested by Gupta and Hanks (1972). However, the relationship between SW and ER appears linear only when considering a limited range of variations. When looking at the data collected from different studies by Calamita et al. (2012), it appears obvious that the global relationship is not linear (as in all petro-physical models previously reviewed). Some adjustments are therefore needed in order to account for the lack of linearity (Calamita et al., 2012; Brillante et al., 2014, reviewed some possibilities of adjustment). Alternatively, non-linear regression techniques have also been used. Extrapolation (i.e. forecasting outside the observed range of data) should be avoided because, in this type of calibration, only the form of relationship relative to the observed data is modelled. Once the relationship has been established, it is applied to transform inverted ER data obtained with ERT method to spatialise the soil water content.

Pedotransfer functions, such the ones typically used in Soil Water Holding Capacity estimation, are currently under development. The aim is to estimate SVW, ASW, FTSW on the basis of ERT and a few selected soil properties (Brillante et al., 2014) in order to allow a wider use of the technique, without the necessary process of calibration and modelling, which is today the most time-consuming part of the work. Because of the

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easy application of these experimental functions, it can be worthwhile to compare them to the other methods previously reviewed.

5 Applying the electrical resistivity to monitor the Fraction of Transpirable Soil Water, in relation to plant water potentials

Following the procedure described in Brillante et al. (2014), and with a model specifically fitted to predict the Fraction of Transpirable Soil Water (FTSW), the maps in Fig. 1, show the variations of the FTSW in a vineyard soil. Measurements were carried out weekly. In parallel the evolution of grapevine leaf water potential is provided, measured both at the time of maximum rehydration (red line, pre-dawn leaf water potential), and at the time of maximum transpiration (blue line, solar noon stem water potential). Rainfall and temperatures are also indicated. The soil is a Calcaric Cambisol (Aric, Colluvic, Loamic, Protocalcic) according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2014), located in a foot-slope positions. The colluvium is mainly composed of fine earth eroded from the soils of the upper part of the slope, but also gravel (20 % in volume in the first metre of the profile). The soil profile was very homogeneous over 1.5 m, thus allowing very good observation of the spatial heterogeneity in water uptake by plants, through the use of the ERT method in field conditions. In this situation, the signal is not disturbed by spike differences in the electrical resistivity of the medium, which can be the case when large amounts of gravel or stones are present. Maps of the FTSW can at first sight be somewhat misleading, because the period of variation of all pixels is not equal. Indeed, regions of the soil that are only marginally explored by roots, where all the FTSW correspond to 0.01–0.02 $cm^3\,cm^{-3}$, (1–2 %vol.) of SVW, very soon reach their extreme low and high values. A low FTSW value is not necessarily the sign of greater root absorption, but is primarily the sign of the depletion of the water reservoir. However such confusion disappears when looking at the map time-series as a whole.

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In Fig. 1 it appears that the FTSW and grapevine leaf water potentials follow a similar temporal pattern, with alternating phases of drying out and wetting, even at a weekly scale. The pattern is also obviously related to the amount of rainfall. Soil water tended to deplete throughout the season, but heavy rains replenished the reservoir several times during the season, especially at the end of July and at the end of August. The grapevine water deficit followed the same pattern. It is very interesting to observe that the midday Ψ_{stem} appears to be more sensitive than the Ψ_{pd} to even slight variations in the FTSW, and follows well the overall pattern of soil moisture.This confirms observations by other authors (van Leeuwen et al., 2010). Between 0.10 m and 0.20 m in depth, a compacted layer shows a singular temporal behaviour, compared to the rest of the shallow soil, with low values of FTSW, even in re-wetting phases. This layer is little explored by the root system and can prevent water infiltration. The spatial variation of FTSW is not limited to a vertical gradient, but also varies laterally, even if the grapevines are planted very densely in this plot (0.9 m between plants). Traditional systems used for monitoring soil water (TDR, neutron probes, etc.) can fail to accurately assess the overall amount of the FTSW, if the choice of their location is not appropriate, and if their position relative to plants is taken into account.

Figure 2 plots the variations of ER between two dates (9/16 July 2013 and 15/21 August 2013), characterised by a steeper reduction in the FTSW, compared to other days. These measurements were carried out at the end of the two longer dry periods, with a parallel drop in leaf water potentials. Variation maps, if compared to TDR-based FTSW, may have higher errors than single date maps, because of the cumulation of errors when computing the differences between the FTSW for various dates. The colour palette chosen for presenting these maps takes into account the error (as measured by RMSE). The white colour is used for pixels that do not vary, and a gradient red or blue colour is used once the threshold of RMSE is passed. Hence, when red or blue is used, the difference in FTSW for different dates is significant. When looking at dates 16 and 23 July, and 15 and 21 August in Fig. 1 it appears that the soil globally dries out but, looking at 2, it becomes obvious that these differences are very localised. In

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July, when the water deficit is still low, the regions of greater variations of FTSW are located at the soil surface. In the maps from August, where the water deficit is higher (the predawn leaf water potential lower), greater reduction of FTSW is observed between the grapevines, and also in deeper layers of the soil. It is also interesting that FTSW variations are reduced for both maps at the location of a young vine. It appears that regions of great variations in FTSW alternate with regions of lower variation. However, the spatial organisation appears dependent on the level of water deficit experienced by the grapevines. On 16 July, the predawn leaf water potential is les negative than on 21 August and, with a lower water deficit, water absorption remains localised at the soil surface. Lateral heterogeneity of FTSW is greater than in August. Indeed, on the August map, the soil regions located immediately beneath the grapevines appear to show the greatest FTSW variations, but also seem to increase the exploitation of water in the area between plants.

Finally, Fig. 3, summarises the spatio-temporal soil water relationships, by cumulating the absolute values of all variations observed over two years (computed from the 28 dates of measurement) in order to qualitatively detect hotspots in soil for water absorption, in relation to the observed water deficit during the monitoring period.

6 Conclusions

The effect of soil water on plant physiology and thus on terroir expression is well known. New techniques, adapted to field conditions, are required to better explore variations of soil water content in space and time. These techniques should allow the imaging and quantification of these variations with low disturbance, to assess water fluxes in the root zone, under natural conditions, with great precision. Electrical Resistivity Tomography (ERT) meets these requirements, for applications in plant sciences, agriculture and ecology. In this paper, we reviewed possible techniques to develop models that allow the use of ERT to spatialise soil water available to plants. We provided an example of applications mapping the variations in the Fraction of Transpirable Soil Water and of the Available Soil Water during a vintage in a vineyard soil. Plant responses to water deficit were assessed by means of water potential weekly measurements. We observed the lateral heterogeneity of FTSW variations, and differences in water uptake depending on grapevine water status. We also identified more active zones in soils for water movements. The use of ERT in ecophysiological studies, with parallel monitoring of plant water status, is rare. These methods need further development, because they have the potential to reveal a hidden part of a major function of plant development: the capacity to extract water from the soil.

Acknowledgements. This work was funded by the Conseil Régional de Bourgogne and the Bureau Interprofessionnel des Vins de Bourgogne (BIVB). The authors wish to thank Domaine Latour for the access to the vineyard; Carmela Chateau Smith for assistance in English, Sarah De Ciantis, Céline Faivre-Primot, Thomas Marchal and Basile Pauthier for help in laboratory analysis and/or field-data acquisition.

References

Amato, M., Basso, B., Celano, G., Bitella, G., Morelli, G., and Rossi, R.: In situ detection of tree root distribution and biomass by multi-electrode resistivity imaging, Tree Physiol., 28, 1441–1448, 2008. 685

Amato, M., Bitella, G., Rossi, R., Gómez, J. A., Lovelli, S., and Gomes, J. J. F.: Multi-electrode 3D resistivity imaging of alfalfa root zone, Eur. J. Agron., 31, 213–222, doi:10.1016/j.eja.2009.08.005, 2009. 685

Amente, G., Baker, J., and Reece, C.: Estimation of soil solution electrical conductivity from bulk soil electrical conductivity in sandy soils, Soil Sci. Soc. Am. J., 64, 1931–1939, 2000. 688

André, F., van Leeuwen, C., Saussez, S., Van Durmen, R., Bogaert, P., Moghadas, D., de Rességuier, L., Delvaux, B., Vereecken, H., and Lambot, S.: High-resolution imaging of a vineyard in south of France using ground-penetrating radar, electromagnetic induction and electrical resistivity tomography, J. Appl. Geophys., 78, 113–122, doi:10.1016/j.jappgeo.2011.08.002, 2012. 685

Andrenelli, M. C., Magini, S., Pellegrini, S., Perria, R., Vignozzi, N., and Costantini, E. A. C.: The use of the ARP© system to reduce the costs of soil survey for precision viticulture, J. Appl. Geophys., 99, 24–34, doi:10.1016/j.jappgeo.2013.09.012, 2013. 685

Archie, G. E.: The electrical resistivity log as an aid in determining some reservoir characteristics, T. AIME, 146, 54–62, 1942. 686, 689, 690

Attia Al Hagrey, S.: Geophysical imaging of root-zone, trunk, and moisture heterogeneity, J. Exp. Bot., 58, 839–854, doi:10.1093/jxb/erl237, 2007. 685, 690

Basso, B., Amato, M., Bitella, G., Rossi, R., Kravchenko, A., Sartori, L., Carvahlo, L. M., and Gomes, J.: Two-dimensional spatial and temporal variation of soil physical properties in tillage systems using electrical resistivity tomography, Agronomy Journal, 102, 440–449, doi:10.2134/agronj2009.0298, 2010. 685

Bauerle, T. L., Smart, D. R., Bauerle, W. L., Stockert, C., and Eissenstat, D. M.: Root foraging in response to heterogeneous soil moisture in two grapevines that differ in potential growth rate, New Phytol., 179, 857–866, doi:10.1111/j.1469-8137.2008.02489.x, 2008. 681, 682

Beff, L., Günther, T., Vandoorne, B., Couvreur, V., and Javaux, M.: Three-dimensional monitoring of soil water content in a maize field using Electrical Resistivity Tomography, Hydrol. Earth Syst. Sci., 17, 595–609, doi:10.5194/hess-17-595-2013, 2013. 687, 689, 690

Bernard-Ubertosi, M., Dudoignon, P., and Pons, Y.: Characterization of structural profiles in clay-rich marsh soils by cone resistance and resistivity measurements, Soil Sci. Soc. Am. J., 73, 46–54, doi:10.2136/sssaj2007.0347, 2009. 689

Besson, A., Cousin, I., Samouëlian, A., Boizard, H., and Richard, G.: Structural heterogeneity of the soil tilled layer as characterized by 2D electrical resistivity surveying, Soil Till. Res., 79, 239–249, doi:10.1016/j.still.2004.07.012, 2004. 685

Besson, A., Cousin, I., Bourennane, H., Nicoullaud, B., Pasquier, C., Richard, G., Dorigny, A., and King, D.: The spatial and temporal organization of soil water at the field scale as described by electrical resistivity measurements, Eur. J. Soil Sci., 61, 120–132, doi:10.1111/j.1365-2389.2009.01211.x, 2010. 685

Bodin, F. and Morlat, R.: Characterization of viticultural terroirs using a simple field model based on soil depth I. Validation of the water supply regime, phenology and vine vigour, in the Anjou vineyard (France), Plant Soil, 281, 37–54, doi:10.1007/s11104-005-3768-0, 2006. 681

Brevik, E. C., Fenton, T. E., and Horton, R.: Effect of daily soil temperature fluctuations on soil electrical conductivity as measured with the Geonics EM-38, Precis. Agric., 5, 145–152, 2004. 689

SOILD
1, 677–707, 2014

Brillante, L., Bois, B., Mathieu, O., Bichet, V., Michot, D., and Lévêque, J.: Monitoring soil volume wetness in heterogeneous soils by electrical resistivity. A field-based pedotransfer function, J. Hydrol., 516, 55–66, doi:10.1016/j.jhydrol.2014.01.052, 2014. 685, 688, 689, 691, 692

Brunet, P., Clément, R., and Bouvier, C.: Monitoring soil water content and deficit using Electrical Resistivity Tomography (ERT) – A case study in the Cevennes area, France, J. Hydrol., 380, 146–153, doi:10.1016/j.jhydrol.2009.10.032, 2010. 688, 689, 690

Calamita, G., Brocca, L., Perrone, A., Piscitelli, S., Lapenna, V., Melone, F., and Moramarco, T.: Electrical resistivity and TDR methods for soil moisture estimation in central Italy test-sites, J. Hydrol., 454–455, 101–112, doi:10.1016/j.jhydrol.2012.06.001, 2012. 691

Campbell, R. B., Bower, C. A., and Richards, L. A.: Change of electrical conductivity with temperature and the relation of osmotic pressure to electrical conductivity and ion concentration for soil extracts, Soil Sci. Soc. Am. Pro., 13, 66–69, 1948. 688

Celette, F., Ripoche, A., and Gary, C.: WaLIS – A simple model to simulate water partitioning in a crop association: The example of an intercropped vineyard, Agr. Water Manage., 97, 1749–1759, doi:10.1016/j.agwat.2010.06.008, 2010. 684

Chapman, D. M., Roby, G., Ebeler, S. E., Guinard, J.-X., and Matthews, M. A.: Sensory attributes of Cabernet Sauvignon wines made from vines with different water status, Aust. J. Grape Wine, 11, 339–347, 2005. 680

Chone, X., Van Leeuwen, C., Chery, P., and Ribéreau-Gayon, P.: Terroir influence on water status and nitrogen status of non-irrigated cabernet sauvignon (*Vitis vinifera*). Vegetative development, must and wine composition (Example of a Medoc top estate vineyard, Saint Julien Area, Bordeaux , 1997), South African Journal of Enology and Viticulture, 22, 8–26, 2001. 680

Corwin, D. L. and Lesch, S. M.: Characterizing soil spatial variability with apparent soil electrical conductivity, Comput. Electron. Agr., 46, 135–152, doi:10.1016/j.compag.2004.11.003, 2005. 685

Costantini, E. A. C., Pellegrini, S., Bucelli, P., Storchi, P., Vignozzi, N., Barbetti, R., and Campagnolo, S.: Relevance of the Lin's and Host hydropedological models to predict grape yield and wine quality, Hydrol. Earth Syst. Sci., 13, 1635–1648, doi:10.5194/hess-13-1635-2009, 2009. 681, 683

Costantini, E. A. C., Pellegrini, S., Bucelli, P., Barbetti, R., Campagnolo, S., Storchi, P., Magini, S., and Perria, R.: Mapping suitability for Sangiovese wine by means of δ^{13}C and geophysical sensors in soils with moderate salinity, Eur. J. Agron., 33, 208–217, doi:10.1016/j.eja.2010.05.007, 2010. 681

des Gachons, C. P., van Leeuwen, C., Tominaga, T., Soyer, J. P., Gaudillère, J. P., and Dubourdieu, D.: Influence of water and nitrogen deficit on fruit ripening and aroma potential of *Vitis vinifera* L. cv Sauvignon blanc in field conditions, J. Sci. Food Agr., 85, 73–85, doi:10.1002/jsfa.1919, 2005. 680

Doussan, C. and Ruy, S.: Prediction of unsaturated soil hydraulic conductivity with electrical conductivity, Water Resour. Res., 45, 1–12, doi:10.1029/2008WR007309, 2009. 685

Dry, P., Loveys, B. R., Botting, D., and During, H.: Effects of partial root-zone drying on grapevine vigour, yeld, composition of fruit and use of water, in: Proceedings of the 9th Australian Wine Industry Technical Conference, 126–131, 1996. 682

Dry, P. R., Loveys, B. R., and During, H.: Partial drying of the rootzone of grape. II. Changes in the pattern of root development, Vitis, 39, 9–12, 2000. 681

Ferrandino, A. and Lovisolo, C.: Abiotic stress effects on grapevine (*Vitis vinifera* L.): Focus on abscisic acid-mediated consequences on secondary metabolism and berry quality, Environm. Exp. Bo., 103, 138–147, doi:10.1016/j.envexpbot.2013.10.012, 2014. 681

Friedman, S. P.: Soil properties influencing apparent electrical conductivity: a review, Comput. Electron. Agr., 46, 45–70, doi:10.1016/j.compag.2004.11.001, 2005. 685, 686

Frohlich, R. K. and Parke, C. D.: The electrical resistivity of the vadose zone – Field Survey, Groundwater, 27, 524–530, 1989. 690

Garré, S., Javaux, M., Vanderborght, J., Pagès, L., and Vereecken, H.: Three-dimensional electrical resistivity tomography to monitor root zone water dynamics, Vadose Zone J., 10, 412–424, doi:10.2136/vzj2010.0079, 2011. 685, 689, 690, 691

Garré, S., Coteur, I., Wongleecharoen, C., Kongkaew, T., Diels, J., and Vanderborght, J.: Non-invasive monitoring of soil water dynamics in mixed cropping systems: a case study in ratchaburi province, Thailand, Vadose Zone J., 12, 1–12, doi:10.2136/vzj2012.0129, 2013. 685

Guilioni, L. and Lhomme, J. P.: Modelling the daily course of capitulum temperature in a sunflower canopy, Agr. Forest Meteorol., 138, 258–272, doi:10.1016/j.agrformet.2006.05.010, 2006. 684

Gupta, S. C. and Hanks, R. J.: Influence of water content on electrical conductivity of the soil, Soil Sci. Soc. Am. Pro., 36, 855–857, 1972. 691

SOILD
1, 677–707, 2014

Use of ERT to monitor plant and soil water relations

L. Brillante et al.

Hadzick, Z. Z., Guber, A. K., Pachepsky, Y. A., and Hill, R. L.: Pedotransfer functions in soil electrical resistivity estimation, Geoderma, 164, 195–202, doi:10.1016/j.geoderma.2011.06.004, 2011. 685, 686, 689

Hillel, D.: Environmental soil physics, Academic Press, San Diego, CA, 1998. 683

Hsiao, T. C. and Xu, L. K.: Sensitivity of growth of roots versus leaves to water stress: biophysical analysis and relation to water transport, J. Exp. Bot., 51, 1595–1616, 2000. 681

Illiceto, V.: Contribution à la prospection géophysique des sites archéologiques, Ph.D. thesis, Université de Paris, 1969. 689

IUSS Working Group WRB: World reference base for soil resources 2014, International soil classification system for naming soils and creating legends for soil maps, FAO, Rome, world soil Edn., 2014. 692

Jaillon, O., Aury, J.-M., Noel, B., Policriti, A., Clepet, C., Casagrande, A., Choisne, N., Aubourg, S., Vitulo, N., Jubin, C., Vezzi, A., Legeai, F., Hugueney, P., Dasilva, C., Horner, D., Mica, E., Jublot, D., Poulain, J., Bruyère, C., Billault, A., Segurens, B., Gouyvenoux, M., Ugarte, E., Cattonaro, F., Anthouard, V., Vico, V., Del Fabbro, C., Alaux, M., Di Gaspero, G., Dumas, V., Felice, N., Paillard, S., Juman, I., Moroldo, M., Scalabrin, S., Canaguier, A., Le Clainche, I., Malacrida, G., Durand, E., Pesole, G., Laucou, V., Chatelet, P., Merdinoglu, D., Delledonne, M., Pezzotti, M., Lecharny, A., Scarpelli, C., Artiguenave, F., Pè, M. E., Valle, G., Morgante, M., Caboche, M., Adam-Blondon, A.-F., Weissenbach, J., Quétier, F., and Wincker, P.: The grapevine genome sequence suggests ancestral hexaploidization in major angiosperm phyla, Nature, 449, 463–467, doi:10.1038/nature06148, 2007. 679

Jayawickreme, D. H., Jobbágy, E. G., and Jackson, R. B.: Geophysical subsurface imaging for ecological applications, New Phytol., 201, 1170–1175, 2014. 685

Jaynes, D. B., Colvin, T. S., and Kaspar, T. C.: Identifying potential soybean management zones from multi-year yield data, Comput. Electron. Agr., 46, 309–327, doi:10.1016/j.compag.2004.11.011, 2005. 685

Kramer, P. and Boyer, J.: Water relations of plants and soils, Academic Press, San Diego, CA, 1995. 680

Lacape, M. J., Wery, J., and Annerose, D. J. M.: Relationships between plant and soil water status in five field-grown cotton (*Gossypium hirsutum* L .) cultivars, Field Crop. Res., 57, 29–43, doi:10.1016/S0378-4290(97)00111-1, 1998. 684

Laloy, E., Javaux, M., Vanclooster, M., Roisin, C., and Bielders, C. L.: Electrical resistivity in a loamy soil: identification of the appropriate pedo-electrical model, Vadose Zone J., 10, 1023–1033, doi:10.2136/vzj2010.0095, 2011. 690

Lebon, E., Dumas, V., Pieri, P., and Schultz, H. R.: Modelling the seasonal dynamics of the soil water balance of vineyards, Funct. Plant Biol., 30, 699–710, doi:10.1071/FP02222, 2003. 684

Lebon, E., Pellegrino, A., Louarn, G., and Lecoeur, J.: Branch development controls leaf area dynamics in grapevine (*Vitis vinifera*) growing in drying soil, Annals of Botany, 98, 175–185, doi:10.1093/aob/mcl085, 2006. 681

Lecoeur, J. and Guilioni, L.: Rate of leaf production in response to soil water deficits in field pea, Field Crop. Res., 57, 319–328, doi:10.1016/S0378-4290(98)00076-8, 1998. 684

Lesch, S. M., Corwin, D. L., and Robinson, D. A.: Apparent soil electrical conductivity mapping as an agricultural management tool in arid zone soils, Comput. Electron. Agr., 46, 351–378, doi:10.1016/j.compag.2004.11.007, 2005. 685

Linde, N., Binley, A., Tryggvason, A., Pedersen, L. B., and Revil, A.: Improved hydrogeophysical characterization using joint inversion of cross-hole electrical resistance and ground-penetrating radar traveltime data, Water Resour. Res., 42, 1–16, doi:10.1029/2006WR005131, 2006. 690

Loke, M. H.: Tutorial : 2-D and 3-D electrical imaging surveys, February, Geotomo Software, 2014. 686

Loveys, B. R., Dry, P. R., Stoll, M., and McCarthy, M. G.: Using plant physiology to improve the water use efficiency of horticultural crops, Acta Hortic., 537, 187–197, 2000. 682

Lovisolo, C., Perrone, I., Carra, A., Ferrandino, A., Flexas, J., Medrano, H., and Schubert, A.: Drought-induced changes in development and function of grapevine (*Vitis* spp.) organs and in their hydraulic and non-hydraulic interactions at the whole-plant level: a physiological and molecular update, Funct. Plant Biol., 37, 98–116, 2010. 679, 681

Lu, Y., Equiza, M. A., Deng, X., and Tyree, M. T.: Recovery of *Populus tremuloides* seedlings following severe drought causing total leaf mortality and extreme stem embolism, Physiol. Plantarum, 140, 246–257, doi:10.1111/j.1399-3054.2010.01397.x, 2010. 684

Michot, D.: Intérêt de la géophysique de subsurface et de la télédétection multispectrale pour la cartographie des sols et le suivi de leur fonctionnement hydrique à l'échelle intraparcellaire, Ph.D. thesis, Université Paris 6, 2003. 686

Michot, D., Benderitter, Y., Dorigny, A., Nicoullaud, B., King, D., and Tabbagh, A.: Spatial and temporal monitoring of soil water content with an irrigated corn crop cover using surface electrical resistivity tomography, Water Resour. Res., 39, 14.1–14.20, doi:10.1029/2002WR001581, 2003. 685, 686, 687, 689, 691

Nadler, A.: Effect of soil structure on bulk soil electrical conductivity (ECa) using the TDR and 4P techniques, Soil Sci., 152, 199–203, 1991. 686

Neumann, R. B. and Cardon, Z. G.: The magnitude of hydraulic redistribution by plant roots: a review and synthesis of empirical and modeling studies, New Phytol., 194, 337–352, doi:10.1111/j.1469-8137.2012.04088.x, 2012. 682

Nijland, W., van der Meijde, M., Addink, E. A., and de Jong, S. M.: Detection of soil moisture and vegetation water abstraction in a Mediterranean natural area using electrical resistivity tomography, Catena, 81, 209–216, doi:10.1016/j.catena.2010.03.005, 2010. 689

Ollat, N., Diakou-Verdin, P., Carde, J. P., Barrieu, F., and Gaudillère, J. P.: Grape berry development: a review, J. Int. Sci. Vigne Vin, 36, 109–131, 2002. 680

Passioura, J. B.: Soil conditions and plant growth, Plant Cell Environ., 25, 311–318, 2002. 681

Pellegrino, A., Gozé, E., Lebon, E., and Wery, J.: A model-based diagnosis tool to evaluate the water stress experienced by grapevine in field sites, Eur. J. Agron., 25, 49–59, doi:10.1016/j.eja.2006.03.003, 2006. 684

Prieto, I., Armas, C., and Pugnaire, F. I.: Water release through plant roots: new insights into its consequences at the plant and ecosystem level, New Phytol., 193, 830–841, doi:10.1111/j.1469-8137.2011.04039.x, 2012. 682

Revil, A., Cathles, L. M., Losh, S., and Nunn, J. A.: Electrical conductivity in shaly sands with geophysical applications, J. Geophys. Res., 103, 23925, doi:10.1029/98JB02125, 1998. 690

Revil, A., Linde, N., Cerepi, A., Jougnot, D., Matthai, S., and Finsterle, S.: Electrokinetic coupling in unsaturated porous media, J. Colloid Interf. Sci., 313, 315–327, doi:10.1016/j.jcis.2007.03.037, 2007. 690

Richards, L. A. and Wadleigh, C. H.: Soil water and plant growth, in: Soil physical conditions and plant growth, Vol. 2, edited by: Byron, T. S., 491 pp., Academic Press, 1952. 683

Richards, L. A. and Weaver, L. R.: Moisture retention by some irrigated soils as related to soil-moisture tension, J. Agr. Res., 69, 215–235, 1944. 683

Ritchie, J. T.: Water dynamics in the soil-plant-atmosphere system, Plant Soil, 58, 81–96, doi:10.1007/BF02180050, 1981. 684

SOILD
1, 677–707, 2014

Use of ERT to monitor plant and soil water relations

L. Brillante et al.

Robinson, D. A., Campbell, C. S., Hopmans, J. W., Hornbuckle, B. K., Jones, S. B., Knight, R., Ogden, F., Selker, J., and Wendroth, O.: Soil moisture measurement for ecological and hydrological watershed – scale observatories: a review, Vadose Zone J., 7, 358–389, doi:10.2136/vzj2007.0143, 2008. 685

Rossi, R., Amato, M., Bitella, G., Bochicchio, R., Ferreira Gomes, J. J., Lovelli, S., Martorella, E., and Favale, P.: Electrical resistivity tomography as a non-destructive method for mapping root biomass in an orchard, Eur. J. Soil Sci., 62, 206–215, doi:10.1111/j.1365-2389.2010.01329.x, 2011. 685

Sadras, V. O. and Schultz, H. R.: Grapevine, in: Crop yield response to water, edited by: Steduto, P., Hsiao, T., Fereres, E., and Raes, D., 501 pp., FAO, 2012. 680

Samouelian, A., Cousin, I., Tabbagh, A., Bruand, A., and Richard, G.: Electrical resistivity survey in soil science: a review, Soil Till. Res., 83, 173–193, doi:10.1016/j.still.2004.10.004, 2005. 685, 688

Schultz, H. R. and Matthews, M. A.: Resistance to Water Transport in Shoots of *Vitis vinifera* L., Plant Physiol., 88, 718–724, doi:10.1104/pp.88.3.718, 1988. 681

Schultz, H. R. and Stoll, M.: Some critical issues in environmental physiology of grapevines: future challenges and current limitations, Aust. J. Grape Wine Res., 16, 4–24, doi:10.1111/j.1755-0238.2009.00074.x, 2010. 682

Schwartz, B. F., Schreiber, M. E., and Yan, T.: Quantifying field-scale soil moisture using electrical resistivity imaging, J. Hydrol., 362, 234–246, doi:10.1016/j.jhydrol.2008.08.027, 2008. 690

Seguin, G.: Alimentation en eau de la vigne dans des sols du Haut-Médoc, Connaissance Vigne Vin, 2, 23–34, 1969. 678

Seguin, G.: Alimentation en eau de la vigne et composition chimique des mouts dans les grand crus du Médoc. Phénomènes de regulation, Connaissance Vigne Vin, 9, 23–34, 1975. 680

Shah, P. H. and Singh, D. N.: Generalized Archie's law for estimation of soil electrical conductivity, Journal of ASTM International, 2, 1–20, 2005. 690

Sinclair, T. R., Holbrook, N. M., and Zwieniecki, M. A.: Daily transpiration rates of woody species on drying soil, Tree Physiol., 25, 1469–1472, 2005. 684

Smart, D. R., Carlisle, E., Goebel, M., and Núñez, B. A.: Transverse hydraulic redistribution by a grapevine, Plant, Cell Environ., 28, 157–166, doi:10.1111/j.1365-3040.2004.01254.x, 2005. 682

SOILD

1, 677–707, 2014

Use of ERT to monitor plant and soil water relations

L. Brillante et al.

Srayeddin, I. and Doussan, C.: Estimation of the spatial variability of root water uptake of maize and sorghum at the field scale by electrical resistivity tomography, Plant Soil, 319, 185–207, doi:10.1007/s11104-008-9860-5, 2009. 685

Stoll, M., Loveys, B., and Dry, P.: Hormonal changes induced by partial rootzone drying of irrigated grapevine, J. Exp. Bot., 51, 1627–1634, 2000. 682

Storchi, P., Constantini, E. A. C., and Buceli, P.: The influence of climate and soil on viticultural and enological parameters of Sangiovese grapevines under non-irrigated conditions, Acta Hortic., 689, 333–340, 2005. 680

Tabbagh, A., Dabas, M., Hesse, A., and Panissod, C.: Soil resistivity: a non-invasive tool to map soil structure horizonation, Geoderma, 97, 393–404, 2000. 685

Tetegan, M., Pasquier, C., Besson, A., Nicoullaud, B., Bouthier, A., Bourennane, H., Desbourdes, C., King, D., and Cousin, I.: Field-scale estimation of the volume percentage of rock fragments in stony soils by electrical resistivity, Catena, 92, 67–74, doi:10.1016/j.catena.2011.09.005, 2012. 685

Tomasi, D., Gaiotti, F., and Jones, G. V.: The power of the terroir: the case study of Prosecco wine, Springer Basel, 2013. 680

Tramontini, S., Leeuwen, C., Domec, J.-C., Destrac-Irvine, A., Basteau, C., Vitali, M., Mosbach-Schulz, O., and Lovisolo, C.: Impact of soil texture and water availability on the hydraulic control of plant and grape-berry development, Plant Soil, 368, 215–230, doi:10.1007/s11104-012-1507-x, 2012. 681

Triantafilis, J. and Lesch, S. M.: Mapping clay content variation using electromagnetic induction techniques, Comput. Electron. Agr., 46, 203–237, doi:10.1016/j.compag.2004.11.006, 2005. 685

van Leeuwen, C.: Terroir: the effect of the physical environment on vine growth , grape ripening and wine sensory attributes, in: Managing Wine Quality, Vol. 1: Viticulture and wine quality, edited by: Reynolds, A., chap. 9, 624 pp., Woodhead Publishing, Cambridge, UK, 1st Edn., 2010. 679, 681

van Leeuwen, C. and Seguin, G.: The concept of terroir in viticulture, Journal of Wine Research, 17, 1–10, doi:10.1080/09571260600633135, 2006. 678

van Leeuwen, C., Friant, P., Choné, X., Tregoat, O., Koundouras, S., and Dubourdieu, D.: Influence of climate, soil, and cultivar on terroir, Am. J. Enol. Viticult., 55, 207–217, 2004. 681

SOILD
1, 677–707, 2014

Use of ERT to monitor plant and soil water relations

L. Brillante et al.

van Leeuwen, C., Tregoat, O., and Choné, X.: Vine water status is a key factor in grape ripening and vintage quality for red bordeaux wine. How can it be assessed for vineyard management purposes?, J. Int. Sci. Vigne Vin, 43, 121–134, 2009. 680
van Leeuwen, C., Pieri, P., and Vivin, P.: Comparison of three operational tools for the assessment of vine water status: stem water potential, carbon isotope discrimination measured on grape sugar and water balance, in: Methodologies and Results in Grapevine Research, edited by: Delrot, S., Medrano, H., Or, E., Bavaresco, L., and Grando, S., chap. 7, 87–106, Springer Netherlands, 1st Edn., doi:10.1007/978-90-481-9283-0, 2010. 684, 693
Veihmeyer, F. J. and Hendrickson, A. H.: Soil moisture in relation to plant growth, Annu. Rev. Plant Physiol., 1, 285–305, 1950. 683
Waxman, M. H. and Smits, L. J. M.: Electrical conductivities in oil-bearing shaly sands, Soc. Petrol. Eng. J., 8, 107–122, doi:10.2118/1863-A, 1968. 690
Werban, U., Attia al Hagrey, S., and Rabbel, W.: Monitoring of root-zone water content in the laboratory by 2D geoelectrical tomography, J. Plant Nutr. Soil Sc., 171, 927–935, doi:10.1002/jpln.200700145, 2008. 685
Winsauer, W. O., Shearin, H. M., Masson, P. H., and Williams, M.: Resistivity of brine-saturated sands in relation to pore geometry, AAPG Bulletin, 36, 253–277, 1952. 690
Zsófi, Z., Gál, L., Szilágyi, Z., Szücs, E., Marschall, M., Nagy, Z., and Bálo, B.: Use of stomatal conductance and pre-dawn water potential to classify terroir for the grape variety Kékfrankos, Aust. J. Grape Wine Res., 15, 36–47, doi:10.1111/j.1755-0238.2008.00036.x, 2009. 680

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1, 677–707, 2014

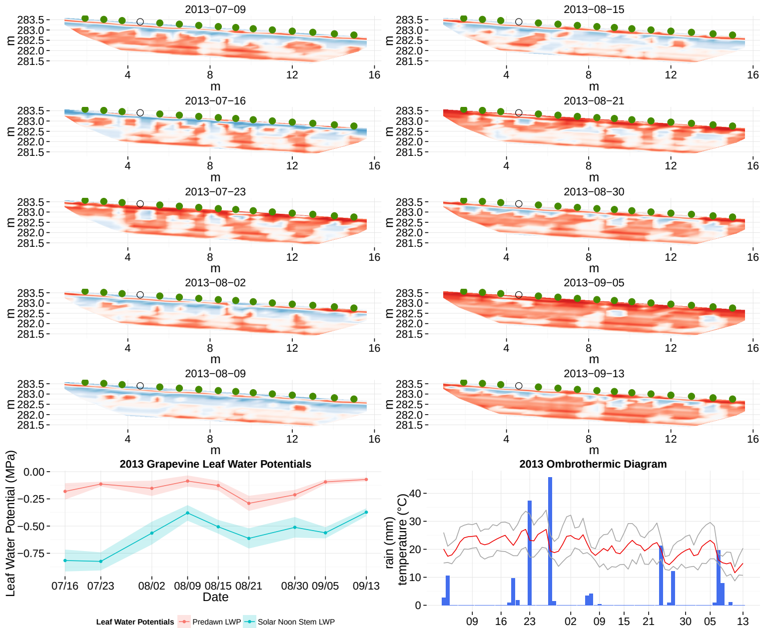

Figure 1. Weekly estimation of the Fraction of Transpirable Soil Water, FTSW, in a vineyard soil spatialised in 2-D by electrical resistivity tomography. Dots represent grapevines, they are green filled for fully developed plants, void for very young plants (1 year). In the bottom left panel the grapevine water stress variation as measured by leaf water potentials; in bottom right the ombrothermic diagram of 2013 vintages, temperatures and precipitations. For interpretation of the reference to colour in those figures, readers are kindly referred to the web version of the paper.

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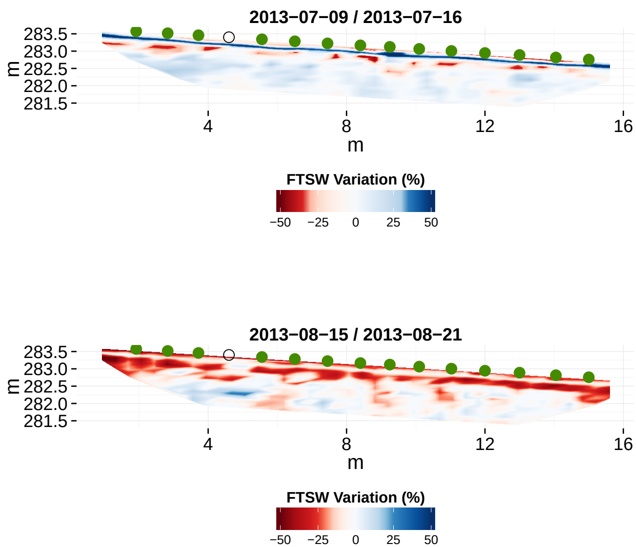

Figure 2. Variations of the Fraction of Transpirable Soil Water, FTSW, between two dates. White colour is mapped to the error associated to the computation of the difference, further explanation in the text. Dots represent grapevines, they are green filled for fully developed plants, void for very young plants (1 year). For interpretation of the reference to colour in those figures, readers are kindly referred to the web version of the paper.

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Use of ERT to monitor plant and soil water relations

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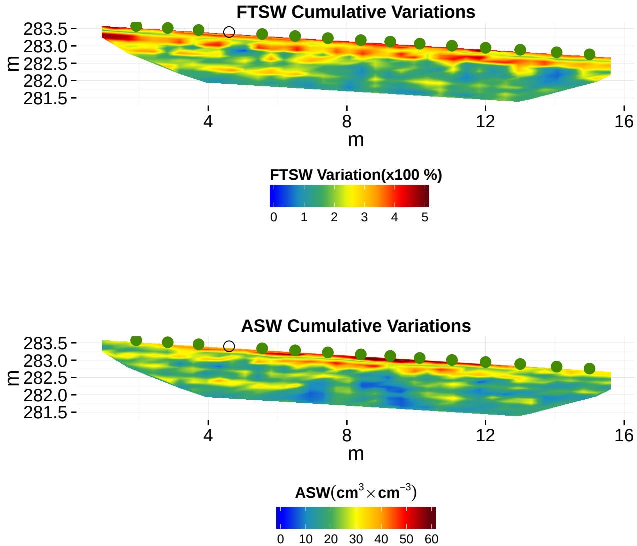

Figure 3. Cumulative variations of the Fraction of Transpirable Soil Water, FTSW, and of the Available Soil Water (ASW) in a vineyard soil. They were obtained by summing the absolute values of the variations between two successive measurements for these variables (28 measurements). For interpretation of the reference to colour in those figures, readers are kindly referred to the web version of the paper.

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