

# Potential of geoelectrical methods to monitor root zone processes and structure: A review

Mihai Octavian Cimpoiășu<sup>a,b,\*</sup>, Oliver Kuras<sup>b</sup>, Tony Pridmore<sup>c</sup>, Sacha J. Mooney<sup>a</sup>

<sup>a</sup> Division of Agriculture and Environmental Sciences, School of Bioscience, University of Nottingham, Sutton Bonington, Leicestershire LE12 5RD, UK

<sup>b</sup> Geophysical Tomography Team, British Geological Survey, Keyworth, Nottinghamshire NG12 5GG, UK

<sup>c</sup> School of Computer Science, University of Nottingham, Wollaton Road, Nottingham, Nottinghamshire NG8 1BB, UK

## ARTICLE INFO

### Keywords:

Electrical-properties  
Root zone soil moisture  
Root system monitoring  
Root zone structure  
Root detection  
modelling  
Geophysics  
Geoelectrical methods

## ABSTRACT

Understanding the processes that control mass and energy exchanges between soil, plants and the atmosphere plays a critical role for understanding the root zone system, but it is also beneficial for practical applications such as sustainable agriculture and geotechnics. Improved process understanding demands fast, minimally invasive and cost-effective methods of monitoring the shallow subsurface. Geoelectrical monitoring methods fulfil these criteria and have therefore become of increasing interest to soil scientists. Such methods are particularly sensitive to variations in soil moisture and the presence of root material, both of which are essential drivers for processes and mechanisms in soil and root zone systems. This review analyses the recent use of geoelectrical methods in the soil sciences, and highlights their main achievements in focal areas such as estimating hydraulic properties and delineating root architecture. We discuss the specific advantages and limitations of geoelectrical monitoring in this context. Standing out amongst the latter are the non-uniqueness of inverse model solution and the appropriate choice of pedotransfer functions between electrical parameters and soil properties. The relationship between geoelectrical monitoring and alternative characterization methodologies is also examined. Finally, we advocate for future interdisciplinary research combining models of root hydrology and geoelectrical measurements. This includes the development of more appropriate analogue root electrical models, careful separation between different root zone contributors to the electrical response and integrating spatial and temporal geophysical measurements into plant hydrological models to improve the prediction of root zone development and hydraulic parameters.

## 1. Introduction

Root zone is a term used to describe the region of soil that is directly influenced by plant roots and all its inherent physicochemical processes. It links directly to human activity; for example, agriculture is typically based on anthropic interactions with the root zone. In addition to its economic importance, studying the root zone provides the tools to protect and to nurture a sustainable environment. In order to understand soil–plant interactions, a detailed appreciation is essential of processes such as: root water uptake, growth of micro-organism communities, nutrient fixation, carbon sequestration and soil structure. This requires the development and routine use of well-defined investigation and quantification methods in order to translate the measurable

observations into meaningful soil and root parameters, including hydraulic conductivity, porosity, root length, root biomass or soil respiration. Assessment of root zone processes can take place in situ or ex-situ, with both experimental settings serving different purposes. Laboratory studies allow the creation of a controlled environment with defined media where experimental parameters are carefully planned and adjusted. This can help understand soil processes on a specific, localized scale (typically sub-metre). By contrast, field surveys facilitate the study of processes in an undisturbed setting. In addition, they provide the necessary benchmarks for translating laboratory results into the real environment. They allow evaluation of methods for monitoring natural and man-made inputs to the root zone system, including agricultural strategies such as inter-cropping or crop rotation, which can

*Abbreviations:* ERT, Electrical Resistivity Tomography; ECM, Electrical Capacitance Method; EIS, Electrical Impedance Spectroscopy; EIT, Electrical Impedance Tomography; EMI, Electro-Magnetic Imaging; SIP, Spectral Induced Polarization; IP, Induced Polarization; TDIP, Time-Domain Induced Polarization; FDIP, Frequency-domain Induced polarization; CT, Computed Tomography; GPR, Ground Penetrating Radar; EC, Electrical capacitance; WS, Waxman- Smits model; TDR, Time Domain Reflectometry; WC, Water Content; SWC, Soil water content; RWU, Root water uptake

\* Corresponding author at: Nicker Hill, Keyworth, Nottinghamshire, UK.

E-mail address: [mcim@bgs.ac.uk](mailto:mcim@bgs.ac.uk) (M.O. Cimpoiășu).

<https://doi.org/10.1016/j.geoderma.2020.114232>

Received 25 September 2019; Received in revised form 19 January 2020; Accepted 26 January 2020

Available online 15 February 2020

0016-7061/ © 2020 British Geological Survey (C) UKRI 2020. AND (c) The University of Nottingham. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

only be tested at the field scale (100s of metres) (Garré et al., 2012).

Over recent decades, a range of assessment methods for the root zone has been developed. These can be split into invasive/destructive and minimally/non-invasive approaches. Invasive methods disturb the integrity of the soil in order to determine soil (moisture content, calcium content, pH) and root (elongation, mass) properties. Examples include the core-break method (Moreno et al., 2005; Escamilla et al., 1991; Bland, 1989) and the use of minirhizotron tubes (Hendrick and Pregitzer, 1996; Garré et al., 2011). Whilst the results obtained in this way are accurate, useful and do not require ground-truthing, they reflect conditions at the test locality only. Achieving meaningful experimental coverage therefore requires many sampling points, which can be time-consuming and laborious. Furthermore, altering the soil properties through sampling reduces the opportunities for continuously monitoring the soil–plant system.

The literature offers many examples of minimally-invasive methods such as TDR (Michot et al., 2001) and non-invasive methods, including X-ray Computed Tomography (CT) (Peyton et al., 1992), Neutron Probe Imaging (Vrugt et al., 2001) or Magnetic Resonance Imaging (MRI) (Segal et al., 2008). These methods provide important insights concerning soil structure (Peyton et al., 1992) or soil water transport (Amin et al., 1996) and more recently they have allowed imaging of the plant root architecture in situ (Mooney et al., 2012). Even though these technologies provide high resolution 3D results, they are expensive to deploy and maintain. Also, at the current state of technology, they restrict the user to a laboratory environment. The exception is TDR, which is frequently employed in field surveys. However, the spatial coverage and resolution achievable with TDR and other non-invasive methods based on point sensors is comparatively poor.

Geoelectrical tomography represent a relatively recent, but fast growing set of tools for soil assessment and monitoring. In particular, efficient methods for investigating soil–plant interaction are increasingly in demand. Geoelectrical methods are minimally invasive and involve the use of sensors that penetrate the soil surface only (top 10 cm), thus not disturbing the integrity of the volume under investigation. Well-established methods include: Electrical Resistivity Tomography (ERT), Electrical Impedance Tomography (EIT), Electrical Capacitance Method (ECM) and Induced Polarization (IP) with some conceptual overlap between them. A significant body of research has focused on ERT, due to its robustness and ease of use, particularly in the field. Geoelectrical techniques facilitate both in situ and ex-situ assessments of soil. The methodology allows comparatively rapid data acquisition which enables near real-time measurements (Loke et al., 2013; Samouëlian et al., 2005). It also allows practically continuous measurements over time, which provides an important capability for the long-term monitoring of soil processes.

The physical principles governing this family of methods involves electrical current signals driven into the soil through electrodes and subsequent recording of differences in electrical potential associated with the subsurface current flow. Larger arrays of multiple electrodes are typically used to acquire geoelectrical data, with individual measurements made consecutively on small subsets of electrodes. Electrical parameters such as conductivity, polarization or capacitance are measured. The systematic collation of datasets with multiple point measurements allows the application of tomographic imaging techniques, which can generate 2, 3 or even 4 dimensional images of the subsurface distribution of electrical properties. This enables quantification of spatial and temporal property variations within soils.

Whilst many factors can influence soil electrical properties (e.g. porosity, density, clay content), a particularly useful application is their use as a proxy for soil water content (SWC; Michot et al. (2001)). SWC quantification is critically important for most soil studies. Firstly, it is indicative of plant water availability (Denmead, 1961) and secondly, it is a major factor controlling soil respiration (Davidson et al., 1998) or soil aggregates stability (Haynes and Beare, 1997). Geoelectrical monitoring is able to quantify temporal variations in SWC, and has been

used to monitor plant water uptake in the laboratory (Werban et al., 2008) and in the field (Michot et al., 2003), as well as to monitor soil water availability (Brillante, 2016; Srayeddin and Doussan, 2009).

A direct correlation has been found between electrical permittivity and root biomass (Dalton, 1995). Therefore, root presence and activity can be quantified directly from electrical measurements. Moreover, organic matter has the ability to polarize electrical current (Schwan, 1957). Researchers have exploited this for assessing the architecture of root systems by measuring not only conductivity (Amato et al., 2009), but also chargeability (Mary et al., 2017).

In this study we review the main opportunities for geoelectrical monitoring in root zone research and discuss the key questions that may be addressed in this way. We also seek to highlight the information each method delivers to the user and appraise the state of the art in terms of geoelectrical instrumentation and methodology for root zone research. Current gaps in knowledge and research needs are identified, covering issues such as the variability of pedotransfer functions, the use of a priori information to constrain the geoelectrical result and the advantages of complementing geoelectrical information with GPR or EMI data in a joint field surveying strategy. We conclude with an outlook to future research opportunities within the experimental observation and conceptual modelling of the root zone. Therefore, with a view to advancing our understanding of root zone processes, we suggest the root system requires a more comprehensive electrical analogue representation, the contributors to the geoelectrical response need to be appropriately separated and a coupled research framework aimed to improve root zone parametrization which jointly includes geoelectrical measurements and simulations of plant growth and hydraulic properties.

## 2. Geoelectrical monitoring – general principles

### 2.1. Electrical properties of soils and their variability

The application of geoelectrical methods in root zone research aims at determining the electrical properties of soils, namely, conduction and polarization. Electrical conduction represents the movement of electrically charged particles through liquid and solid phases of the soil medium. Their flow will depend on the amount of available charge, the distribution of conducting paths and the charge mobility. Electrical polarization represents the redistribution of positive and negative charges when exposed to an exterior electric field. In consequence, this will determine regions of charge accumulations across the soil medium.

Variability in soil electrical properties can be caused by either inorganic or organic constituents of the soil system. Soil electrical conduction is generally determined by pore fluid and mineral surface conductivity. Soil electrical polarization is determined by the pore architecture and water–mineral interface capacity of ion aggregation (Everett, 2013). Therefore, a number of properties intrinsic to the soil (i.e. its inorganic constituents) have a direct effect on the electrical response. Further essential contributors to the electrical response are components of the root zone with an organic origin, such as decomposed plant material, collectively known as humus, and plant root systems.

#### 2.1.1. Inorganic constituents

**2.1.1.1. Pore fluid.** Electrical conduction in soils is mostly electrolytic, ions in the pore fluid being the charge carriers (Everett, 2013). The amount of charges increases with fluid ionic concentration or the volumetric water content given a constant fluid conductivity.

When an electrolyte comes in contact with a charged surface of a soil particle, an electrical double layer (EDL) forms and ions are adsorbed onto the solid surface (Revil and Glover, 1997), therefore affecting ion mobility which gives rise to electrical polarization (Lyklema et al., 1983).

**2.1.1.2. Solid soil.** Generally, the solid matrix acts like a semi-

conductor with some exceptions such as the surface of clay minerals. Their inherently negative surface charge constitutes another electrical conduction pathway. Also, soils with a predominantly clay texture tend to exhibit a larger specific surface area than soils consisting primarily of sand (Pennell, 2016). Therefore, clay content implies a larger conductive particle surface which leads to an important contribution to the soil electrical conductivity (Fukue et al., 1999).

**2.1.1.3. Air filled pore space.** The volume (porosity) and connectivity of the pore network determine a soil's water holding capacity, which in turn affects the bulk soil electrical conduction. Also, the tortuous nature of the pore system generates complex patterns of fluid flow which can determine electrically conductive and non-conductive regions. As for polarization, due to the formation of EDLs, narrow pore channels may cause charge accumulation and localized disequilibria in ionic concentration (Revil, 1999).

**2.1.1.4. Temperature.** An increase in pore fluid temperature causes a decrease in pore fluid viscosity, which in turn increases the ion agitation in the solution. Alternatively, in freezing conditions, molecules of salt are rejected into unfrozen pore water, thus changing the concentration of the pore solution (Banin and Anderson, 1974). Superficial soils are exposed to diurnal and seasonal fluctuations in temperature, therefore neglecting such variability may lead to serious errors in geoelectrical data interpretations (Samouëlian et al., 2005).

## 2.1.2. Organic constituents

**2.1.2.1. Organic matter (OM).** The capacity of the soil to retain ions (or ion exchange capacity) is a measure of soil surface charge (Zelazny et al., 1996). A considerable proportion of soil cation exchange capacity (CEC) is associated with soil organic matter. Interactions between OM and soil minerals result in a decrease in ion mobility, and thus a decrease in polarization (Schwartz and Furman, 2015).

**2.1.2.2. Plant roots.** The living root system has a very complex electrical response that depends on root characteristics, such as: mass, length, structure, type (woody or herbaceous) or tortuosity. Woody root tissue does not contain charge carriers therefore their presence in the soil system will reduce the overall bulk electrical conductivity (Vanderborght et al., 2013). However, electrical current will flow through the root xylem as the fluid contains electrical charges. EDLs form both at the contact between the outer and inner root surface, therefore the magnitude of root polarization relates to their overall surface area (Weigand and Kemna, 2018).

## 2.2. Methods of measuring soil electrical properties

A range of geoelectrical methods is available to measure soil properties. In this section we aim to provide a short introduction to the physical and functionality principles governing these methods.

### 2.2.1. Complex electrical impedance

In practice an electrical measurement on soil involves a measurement of the complex impedance  $\hat{Z}$  of the material, a frequency  $f$  dependent function expressed as:

$$\hat{Z} = (Z'(\omega) + iZ''(\omega)), \quad (1)$$

where  $i$  is the imaginary unit,  $\omega = 2\pi f$ ,  $Z'$  and  $Z''$  are the real and imaginary parts of the impedance respectively. This can in turn be translated into effective material properties by taking into account the dimensions and spatial geometry of the measurement, represented through the geometric factor  $K$ . Therefore we can obtain an expression for the 'apparent' complex conductivity  $\hat{\sigma}_a$  and its inverse, complex resistivity  $\hat{\rho}_a$ , which describe how well a material conducts electrical current flow:

$$\hat{\sigma}_a = (K^* \hat{Z})^{-1} = \sigma' + i\sigma'' = |\rho_a| e^{-i\phi}, \quad (2)$$

where the real part  $\sigma'$  quantifies conduction and  $\sigma''$  quantifies polarization.  $\phi$  is the phase angle that represents the phase shift between the injected current and measured voltage.

### 2.2.2. ERT

For this review we selected 72 articles spanning across 22 years (1996–2018) which feature the application of geoelectrical methods in root zone research (Complete list in Appendix A and B). ERT is one of the most extensively used near surface geophysical methods and is also extremely popular for the study of soil–plant interaction. 65% of the studies reviewed for this paper employed ERT as the primary method of imaging soil–plant interaction. ERT applications inject DC or low-frequency current into the soil and tend to measure the magnitude  $|\hat{Z}|$  of the electrical impedance only. Provided that the geometric factor  $K$  is known, the bulk resistivity of the soil can be calculated according to Ohm's law:

$$\rho = K^* \frac{\delta V}{I}, \quad (3)$$

where  $\delta V$  is the observed potential difference and  $I$  is the injected current. The primary concern is with the strength of the received signal, rather than its phase relationship. A standard procedure is to use a pair of electrodes for current injection and separate pair of electrodes to record the potential difference. After making multiple spatially distributed measurements the recorded data is used to generate a tomographic image of the subsurface, in order to determine the spatial distribution of soil electrical properties. These are interpreted in the context of a heterogeneous subsurface structure. Inverse modelling is used to fit an earth model to the measured dataset. The inversion procedure uses adjustments to the predicted model parameters to achieve convergence between the measured and predicted datasets. A typical approach is to change the model until the misfit reaches a minimum. The model is built upon a mesh (dimensionality is case dependent) which follows a pre-defined discretisation of the target geometrical space and other constraints (e.g. limit values, smoothing factor, boundary conditions). The model cells have corresponding cartesian coordinates and a parametric value associated, in this case a geoelectrical parameter (e.g. resistivity, phase). Additional a priori information about the environment (e.g. soil structure, temperature, topography) will significantly improve the inversion result. However, inherent problems with geoelectrical inversion are:

1. Non-linearity. The relation between parameters and data is often non-linear, therefore a linear approximation is required to help solve the system of equations.
2. Solution stability. A small perturbation in the initial conditions can cause very different outcomes.
3. Non-uniqueness. Multiple models fit the data to the same degree of accuracy, hence choosing the "correct" model is a challenge both conceptually and practically. These limitations of geoelectrical inversion apply to all geoelectrical techniques that employ tomographic reconstruction of the data.

### 2.2.3. IP

In the absence of polarization, a sudden switch off of the current injected in the target medium should cause the voltage between a pair of potential electrodes to drop from an initial value  $V_0$  instantaneously to 0. However, if the soil exhibits polarization, a gradual decay of the voltage can be observed over a finite time period, which is known as the IP effect (Everett, 2013). In practice, this behaviour can be measured both in the time-domain and in the frequency domain.

**2.2.3.1. Time-domain IP.** The acquisition principle here is technically similar to the one used for ERT. From the IP recorded discharge curve

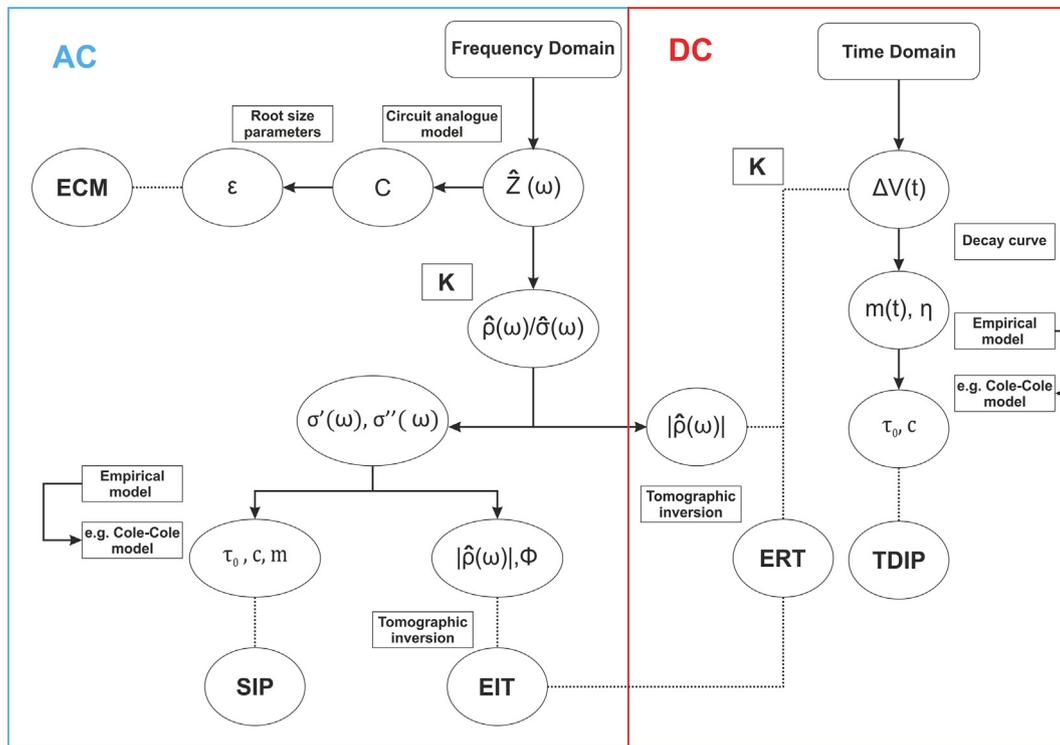


Fig. 1. Diagram of key theoretical characteristics associated to geoelectrical methods described. The dotted line connects the scheme branch with the corresponding geoelectrical method.

we can obtain measurable quantities such as apparent polarizability  $\eta$  (Eq. 4) or partial chargeability  $m$  (Eq. 5):

$$\eta = \frac{V(T)}{V_0}, \tag{4}$$

where  $V_i$  is the voltage measured at time T after current switch off.

$$m = \frac{1}{V_0} \int_{t_1}^{t_2} V(t) dt, \tag{5}$$

where  $t_1$  and  $t_2$  are the two limits of a time window during the voltage decay (Everett, 2013).

**2.2.3.2. Frequency domain IP.** FDIP is often referred to as SIP or EIS and uses a range of (typically discrete) frequencies for current injection. The complex resistivity in both magnitude and phase is a function of the frequency of the injected current signal. Polarization effects cause a phase shift between injected and recorded currents, therefore in addition to ERT, FDIP method is able to measure the IP effect through its phase angle.

Empirical models such as Debye (Debye, 1929) or Cole-Cole (Eq. 6) (Cole and Cole, 1941) have been developed to describe the complex resistivity frequency dependence.

$$\rho^*(\omega) = \rho_0 \left[ 1 - m \left( 1 - \frac{1}{1 + (i\omega\tau_0)^c} \right) \right], \tag{6}$$

Fitting the Cole-Cole model parameters to experimental data yields values for the chargeability  $m$ , relaxation time  $\tau_0$  and frequency exponent  $c$ . It is worth mentioning this model can also be applied in the time-domain on chargeability curves (Pelton et al., 1978) in order to extract corresponding parameters.

**2.2.3.3. EIT.** EIT is a method which uses the measurement principles of IP, and therefore used to determine complex resistivity, but in addition incorporates a tomographic reconstruction capability, such as ERT (Zimmermann et al., 2008). Therefore, EIT brings together

information about the signal strength, shape and timing. Ultimately, it uses the data to construct a tomographic distribution.

For soil research purposes the method is still in the incipient stages. It was successfully applied previously for detecting electrical phase differences (Kelter et al., 2015), the low-polarizability of a water submerged root system (Weigand and Kemna, 2017) and changes in polarization due to diurnal cycles and gradual nutrient deprivation (Weigand and Kemna, 2018).

**2.2.4. ECM**

Chloupek (1972) found a direct correlation between root parameters, such as dry mass and surface area, and the EC of root systems. The basic measurement procedure involves the connection of an LCR (Inductance-Capacitance-Resistance) meter between an electrode attached to the base of the plant stem and another one inserted into the soil. Previous studies established such correlations at a single measurement frequency (Dalton, 1995; Ellis et al., 2013) or using a broader range of frequencies (Ozier-lafontaine and Bajazet, 2005). Primarily, the measured quantity for ECM is still complex impedance. However, the impedance measurements are interpreted in terms of an analogue electrical circuit. Dalton (1995) envisioned root segments as capacitor-resistance pairs connected in parallel. The root segment capacitor has three components: xylem as an internal electrode, soil nutrient solution surrounding the root as a second electrode and a poorly conducting plant tissue acting as a dielectric. Therefore, the complex impedance can be expressed in terms of the equivalent root system capacitance C and resistance R as:

$$\hat{Z}^{-1} = \frac{1}{R} + i\omega C = \frac{1}{R} + i\omega \frac{\epsilon A}{4\pi r_2 \ln \left( \frac{r_2}{r_1} \right)}, \tag{7}$$

where  $\epsilon$  is the dielectric constant, A is the geometrical surface area of the root tissue,  $r_1$  and  $r_2$  are the radius of the inner root xylem channel and the root segment, respectively.

### 2.2.5. Relationship between geoelectrical methods

Considering what was previously enunciated, one may reach the conclusion that there is a certain degree of interconnectivity between all the geoelectrical methods. The main common denominator is the measurement of complex electrical impedance, but different methods have different ways of mathematically expressing the recorded data, such as the magnitude of complex impedance (ERT), polarizability and chargeability (IP) or electrical permittivity (ECM). Secondly, methods differentiate by the type of current they use (DC or AC) or the domain they operate in (time-domain or frequency-domain). In Fig. 1 we formulated a summary diagram describing the relationship between different methods and their corresponding measured quantities. This will potentially serve as an aid to better understand how the geoelectrical methods were used to resolve parameters of the root zone in the studies we review in the following Section 3.

### 2.3. Translating geoelectrical measurement into root zone properties

It is important to note that geoelectrical methods do not quantify root zone properties directly. For this purpose an additional calibration measurement is required to allow direct translation of electrical measurements into root zone properties. This can be illustrated using the example of SWC. As mentioned, electrical measurements are sensitive to changes in SWC, but the relationship is a function of multiple factors and no analytical expression is readily available to describe it. Therefore, a dedicated method for estimating water content (e.g. TDR, neutron probe, destructive sampling) is usually used in parallel to the geoelectrical method, in order to determine the dependency of the electrical response on SWC variation by empirical means. The outcome of this exercise is a calibration curve, which can subsequently be used to translate the geoelectrical measurements into SWC for the specific material and under the specific circumstances. Unfortunately, a universal transfer function is unlikely to exist, due to the large number of potential input factors, used to parametrize the root zone, such as porosity, saturation status or root mass. Different calibration strategies have been adopted over the years. Earlier studies established simple linear regression correlations between measured resistivity and SWC or root biomass, respectively (Michot et al., 2003 and Amato et al., 2008). However, the calibration process has recently become more systematic and new research is looking into its simplification using deep learning prediction algorithms (Brillante et al., 2016).

#### 2.3.1. Resolving pedological parameters

A more robust strategy involves the use of quantitative conceptual models to link electrical parameters and soil properties (known as pedotransfer functions or PTFs). One of the first relationships of this kind described the resistivity behavior of a brine-saturated sandstone in the context of borehole logging and was developed by Archie (1942). However, Archie's law did not take into account surface conductivity, which becomes essential in samples with an increased clay content. Based on Archie's relation, the Waxman-Smits (WS) model, established for shaly sands, incorporates the presence of clay particles with surface conductivity effects (Waxman and Smits, 1968). More comprehensive models have been developed based on both laws. The model proposed by Rhoades et al. (1989) relies on the assumption of two separate electrical pathways, a continuous one through waterfilled macropores and a series linked soil-liquid one. A model by Mualem and Friedman (1991) is based on the fact that the tortuosity factor affecting the bulk electrical conductivity is identical to the one predicting hydraulic conductivity. Revil et al. (1998) assumes surface conduction to be restricted to the part of the EDL where ions are adsorbed to the material surface (Stern layer). The Linde et al. (2006) model takes into consideration the different behaviour of ions in the pore space. The transport regime of anions is independent of salinity as opposed to that of cations, which have a different regime for high and low salinity.

The decision over which model to apply is subjective for any given

application, as more than one model may fit the requirements. Laloy et al. (2011) compared existing pedotransfer models and suggested that the Linde model performs better for a low resistivity regime ( $< 100 \text{ Ohm.m}$ ), whilst WS performs better in the high resistivity regime.

As one can realize from early PTSs such as Archie's law, they were not initially intended for applications in the root zone but for oil exploration. Therefore, the factors describing them are strictly pedological. In order to offer a more comprehensive view of how geoelectrical methods can resolve root zone properties, the following subsection briefly presents research efforts of describing the root electrical signature.

#### 2.3.2. Resolving root system parameters

An electrical model developed by Dalton (1995) suggested that roots can be represented by a parallel resistance-capacitance (RC) circuit. More roots will imply more RC pairs connected in parallel. Therefore, the effective capacitance of a root system will depend on its structure and size. Ellis et al. (2013) concluded that capacitance was significantly related to root mass, length and surface area, but as a measurable quantity its predictive power is poor. They also obtained the best predictions for root length, which was significantly related to the ratio between capacitance and density. However, the Dalton model was tested and inconsistencies were found by both Ellis et al. (2013) and Dietrich et al. (2012), questioning the validity of a linear correlation between capacitance and root mass. Upon the removal of roots from a hydroponic solution it was realized that the capacitance of the solution was much higher than the capacitance of the root tissue. Arguably, the studies have shown that capacitance is correlated to root mass, but is not a direct means of measuring it.

Cao et al. (2010) also measured the electrical resistance of a root system submerged in a hydroponic solution. The resistance decreased with an increasing contact surface area of the root with the solution. These measurements contributed to the formulation of analogue circuits where the root system is realized as series of electrical resistors. Building on these results, Cao et al. (2011) used a spectrum of frequencies to analyse the elements of the root system analogue circuit. The study found that capacitance is a more useful parameter than resistance when it comes to root size estimation. Regression models were used in Amato et al. (2008) and Amato et al. (2009) in order to link root mass density to resistivity measurements. The strong correlations led to the formulation of a logistic-growth model which later gave accurate predictions on field data acquired by Rossi et al. (2011).

## 3. Monitoring processes and resolving structure in the root zone

Geoelectrical methods are able to (1) monitor processes in near real time and (2) resolve structure, which is important for the study of soil-plant interactions because of the high significance of water content changes (Samouëlian et al., 2005) for these interactions and the presence of root organic matter (Amato et al., 2008) in the medium of investigation. Given that access to water plays a key role in plant survival, quantitative monitoring of water dynamics is helpful for defining the requirements and constraints, such as water availability, influx access points, transport parameters, flow pathways and for characterizing the environmental conditions, including soil texture, soil porosity, root characteristics, climate, geological setting and others. Detecting and quantifying root activity is crucial for understanding the extent of plant development and their reactions to stimuli (Mooney et al., 2012). Root architecture development is a visible indicator of the quality of the impact root system has on the plant's health and productivity, or on surrounding plants. The following subsections present an overview of the current state-of-play in geoelectrical monitoring research in three main application areas, namely (1) water dynamics (2) the detection of root organic matter and (3) the modelling of root zone processes.

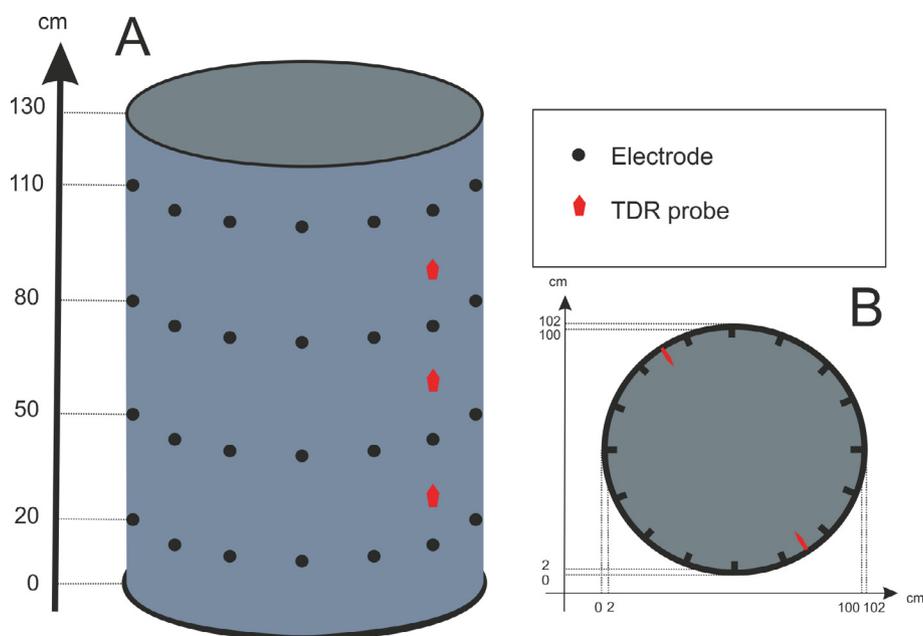


Fig. 2. Laboratory set-up of a geoelectrical soil column monitoring experiment A) Soil column lateral view B) Horizontal Cross-section view. Adapted from Garré et al. (2011), Garré et al. (2011) and Koestel et al. (2008).

### 3.1. Root zone water dynamics

Much geoelectrical research is focused on monitoring root water dynamics. a considerable body of literature focuses on monitoring root water dynamics underlining its importance for soil studies.

#### 3.1.1. Ex-situ studies

We examine studies performed ex-situ (in a laboratory environment), many of which were undertaken to try to illustrate the suitability of geoelectrical methods for monitoring solute transport in soils, or to determine soil properties in a controlled experiment, which would not be possible on a larger scale. The majority of studies have adopted a similar experimental set-up, whereby the soil volume of interest is surrounded by electrodes in order to enable electrical current flow throughout the sample (Fig. 2).

#### 3.1.2. The signature of rootless soil

It is important to acknowledge that the studies mentioned here focus on the soil as a medium which does not contain a root system, disregarding the effect such a system has on neighbouring physico-chemical properties. The existence of roots in soil adds a further layer of complexity to the geoelectrical attempt of monitoring hydrodynamic processes. Therefore, we present an initiatory body of literature that aims to decipher the contribution of rootless soil separately before expanding to applications which take roots into consideration.

Binley et al. (1996) used a dye staining experiment to show the ability of ERT to reconstruct flow pathways in soil. Olsen et al. (1999) used ERT in conjunction with X-ray CT for the purpose of solute transport characterisation. A rapid transport mode was detected through geoelectrical monitoring and was explained by the properties of the macropore system detected by X-ray tomography. However, macropores could not be directly related to the electrical tomogram because of the gap in spatial resolution, hence a causal link between the two observations could not be established. Similarly to Binley et al. (1996), Koestel et al. (2007) demonstrated the benefits of using dye as a tracer for electrical conductivity monitoring experiments. This was extended to a two-step tracer infiltration experiment through a cylindrical soil column (Koestel et al., 2008), in which bulk electrical conductivity was translated to solute concentrations. Fig. 3 shows the evolution of concentration illustrating the ability of ERT to track the

dynamics of solute injection and transport at the laboratory scale. However, this type of observation was only possible when a hydraulic steady-state existed and there was no spatial variation in the saturation states of the soil. Cassiani et al. (2009) used SIP for the purpose of monitoring organic pollutants in soils, looking at DC and chargeability responses from samples at different levels of water saturation obtained after the injection of air and a non-aqueous phase liquid (NAPL). The study observed differences between the NAPL and air samples, which were attributed to phase distributions across the samples and not to chemical interaction between solutes and surrounding liquid/solid phases.

#### 3.1.3. The signature of the root zone

By periodically irrigating a ginkgo tree, Wu et al. (2013) detected spatial and temporal variations in capacitance with increasing water content. Also, the tomographic images provided visual representation of the process of saturation and subsequent drying. Werban et al. (2008), in a pot experiment containing a *Lupinus* plant grown in fine sand, set out to monitor spatial heterogeneity of water movement. Diurnal variations were found, which were assumed to be a manifestation of RWU triggered by plant transpiration. Building on this, Garré et al. (2011) used a 3D ERT to quantify water content changes in soil due to RWU and evapotranspiration. Resistivity variations were correlated here with minirhizotron measurements of root development. Newill et al. (2014) demonstrated the feasibility of using capacitive coupling insulated electrodes whose purpose is to reduce corrosion and avoid polarization of the probes. The study presented a more efficient acquisition system for measuring impedance, which resulted in the technique being able to resolve water content fraction changes of up to 20%. However, it is important to note that their study measured the magnitude of the complex impedance only, without consideration of polarization effects.

#### 3.1.4. In-situ studies

In an industrialized world with a rising demand for food in both quantity and quality, effective soil management for agriculture is becoming increasingly critical. The majority of in situ root studies have therefore focused on water dynamics exhibited by agricultural crops. In this kind of setting it is difficult to separate the effect of rootless soil as it was previously done for ex-situ studies. This underlines the necessity

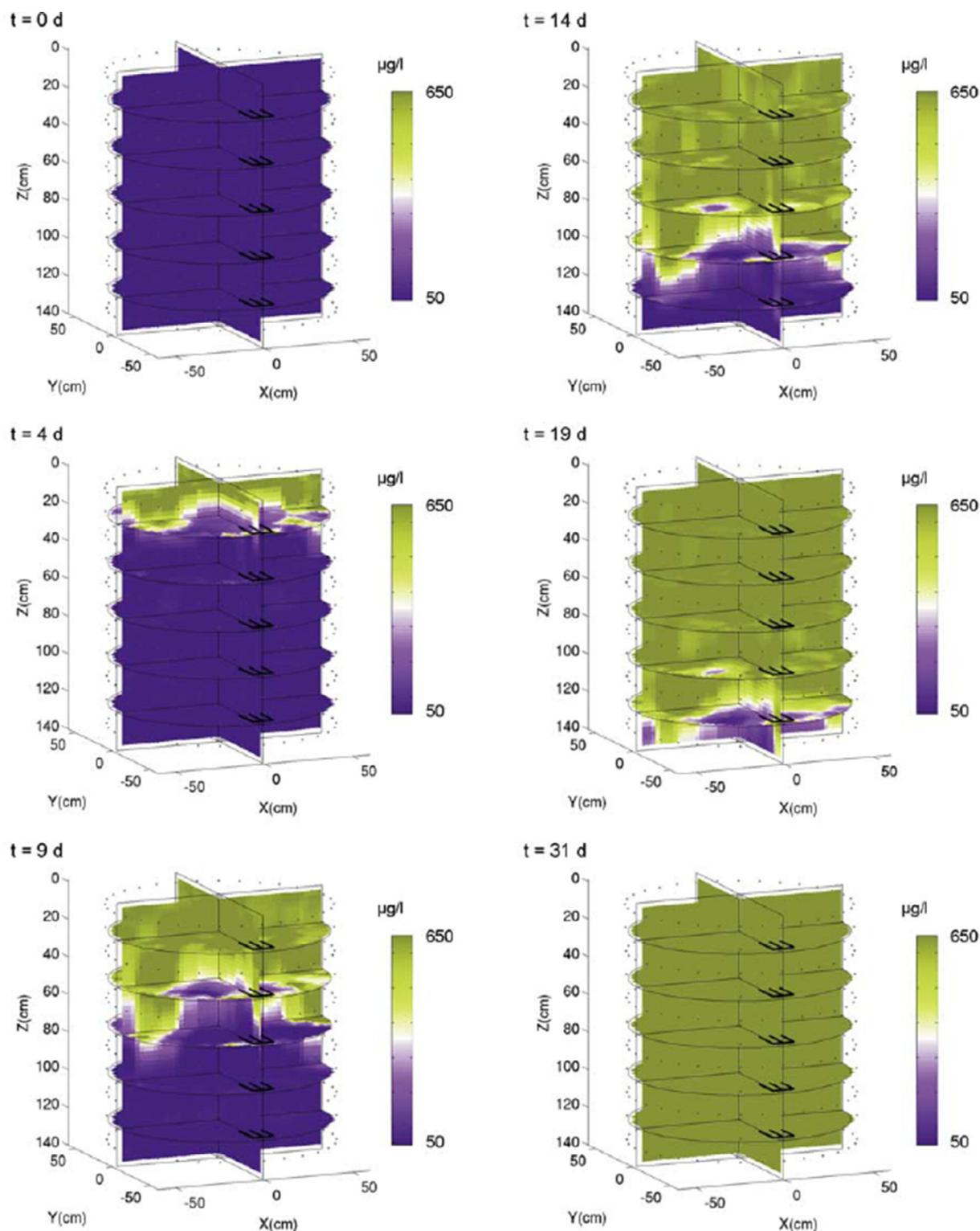


Fig. 3. Three dimensional solute concentration distribution in 6 stages of infiltration. Corresponding time-steps are listed in the top-left corner. Extracted from Koestel et al. (2008).

of laboratory trials that attempt to understand and parametrize the more localized behavior of the root zone, which will subsequently support and serve as reference for field trials.

One of the first studies that assessed the effectiveness of the ERT method in an agricultural context was by Panissod et al. (2001). It revealed the existence of high resistivity patches under cover crops, and these patches were inferred to be linked to plant water uptake. In the absence of appropriate pedotransfer functions, which create the link

between water content and electrical resistivity, the water distribution could not be estimated. Also, no ground truth was available for comparison. The study was able to map anomalies in the resistivity distribution, thus showing the potential of the ERT method, but the causal link between resistivity variation and water content depletion remained an assumption. Michot et al. (2001) presented a more robust experimental design using TDR measurements in parallel with ERT. Resistivity variations with time were observed under crops similar to the

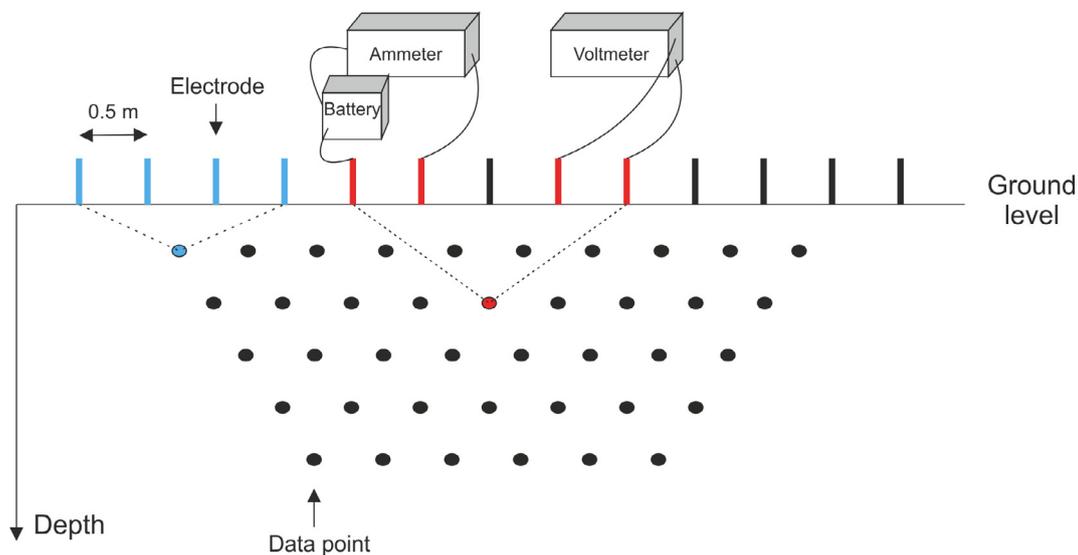


Fig. 4. Field acquisition pseudosection line used for ERT surveys. Electrodes are grouped in a Dipole-Dipole sequence.

ones identified by Panissod et al. (2001). Moreover, a wetting front was localized from the electrical tomogram and preferential flow directions were identified. Michot et al. (2003) subsequently conducted a very similar field trial. The resistivity-estimated water content was compared to that obtained from TDR. The %RMS (Root Mean Square) error was less than 5 and the correlation factor around 0.8, which suggests good agreement between both techniques. Consequently, the work proves the suitability of ERT to monitor soil available water reserves on the field scale. One of the reference works for root zone water dynamics was presented by Srayeddin and Doussan (2009), who conducted a field monitoring study of water uptake under sorghum and maize fields subjected to different watering regimes. The study showed heterogeneous patterns of water depletion in the moderated and poorly irrigated fields. Direct field water content measurements were used to calibrate the resistivity results. The water uptake was found to have a quantitative (and not just qualitative) relationship with resistivity.

The field studies follow a similar experimental set-up to the studies mentioned in Section 3.1.1. Fig. 4 shows an example of a typical survey arrangement on a linear profile. 2D resistivity images resulting from such an acquisition scenario are presented in Fig. 5. They demonstrate the extent to which ERT resolved the spatial distribution of resistivity. Here, both the lateral and the vertical variability was likely caused by the plant water uptake.

Celano et al. (2011) compared two different soil management regimes, tillage and cover cropping, and found a significant water reserve in the soil beneath the cover crops. The authors used laboratory derived calibration curves between soil moisture and resistivity. The correlation coefficients between resistivity-estimated and directly measured water content was found to be stronger than that observed by Srayeddin and Doussan (2009). However, the latter measurements were carried out in situ, whereas the former ones were undertaken ex situ, which typically requires additional experimental time and effort. All applications of geophysical monitoring represent a trade-off between time, effort and data quality.

Nijland et al. (2010) presented a case study that used geoelectrical methods to quantify water availability in a Mediterranean soil ecosystem. The study highlighted the power of the roots to penetrate the fractured bedrock to reach water. Robinson et al. (2012) underlined the ease of use and convenience of data collection that an ERT survey provides. They conducted a 3D survey to monitor moisture content in an oak-pine forest, which suggested moisture stability in tree-covered areas and moisture instability in open areas. Beff et al. (2013) monitored WC under a maize field through a joint assessment of ERT and

TDR. The latter was used to achieve spatial coverage and the former to achieve temporal coverage. The resistivity distributions reflected the maize row arrangements in the field. Garré et al. (2013) monitored resistivity changes in mixed cropping systems showing a smaller depletion depth for chili cultures compared to maize and Leucaena. Also, a higher depletion was detected close to the intercrop hedges which implied a competition for water between different crop species. Garré et al. (2012) used semivariogram interpretation of WC spatial distribution indicating moisture variability is highly influenced by soil heterogeneity. Kelly et al. (2011) monitored water migration beneath crops. The resulting resistivity tomograms were compared with WC values obtained using a capacitance probe. Moreover, the study recommended that ERT monitoring should be integrated into irrigation programs.

ERT monitoring was also used by Musgrave and Binley (2011) to characterize the stratigraphy of a wetland site. The 2D characterization with ERT was performed in combination with GPR. The study highlighted the suppression of temporal changes in resistivity, which was explained by the occurrence of groundwater recharge, providing a means of identifying such recharge areas.

### 3.2. Root structural and functional properties

#### 3.2.1. Woody roots

3.2.1.1. Correlating root properties and geoelectrical measurements. Amato et al. (2008) and Rossi et al. (2011) found a strong positive correlation between resistivity measurements and root biomass. Rossi et al. (2011) also observed a dominating effect of the root biomass over other root zone properties, such as root length density (root length per unit volume), which raised the concern that this has to be taken into account by future studies to avoid bias.

In an in situ experiment, Čermák et al. (2006) successfully estimated tree root absorption surface area with resistivity measurements. Also, the study showed a positive correlation between stem area and root absorption area. In addition, Mares et al. (2016) used ERT to capture the spatiotemporal variability in an active sapwood, which reflects the sapflow upscaling. Guyot et al. (2013) attempted to estimate sapwood area with the use of resistivity monitoring. However, the  $R^2$  correlation between resistivity derived estimates and actual area was low. Jones et al. (2009) used ERT as a means of visualizing tree-induced subsidence. Leveling data indicating subsidence and ERT profiles were in agreement, both being influenced by climatic conditions. As the study did not include quantitative models to accompany and fit the resistivity

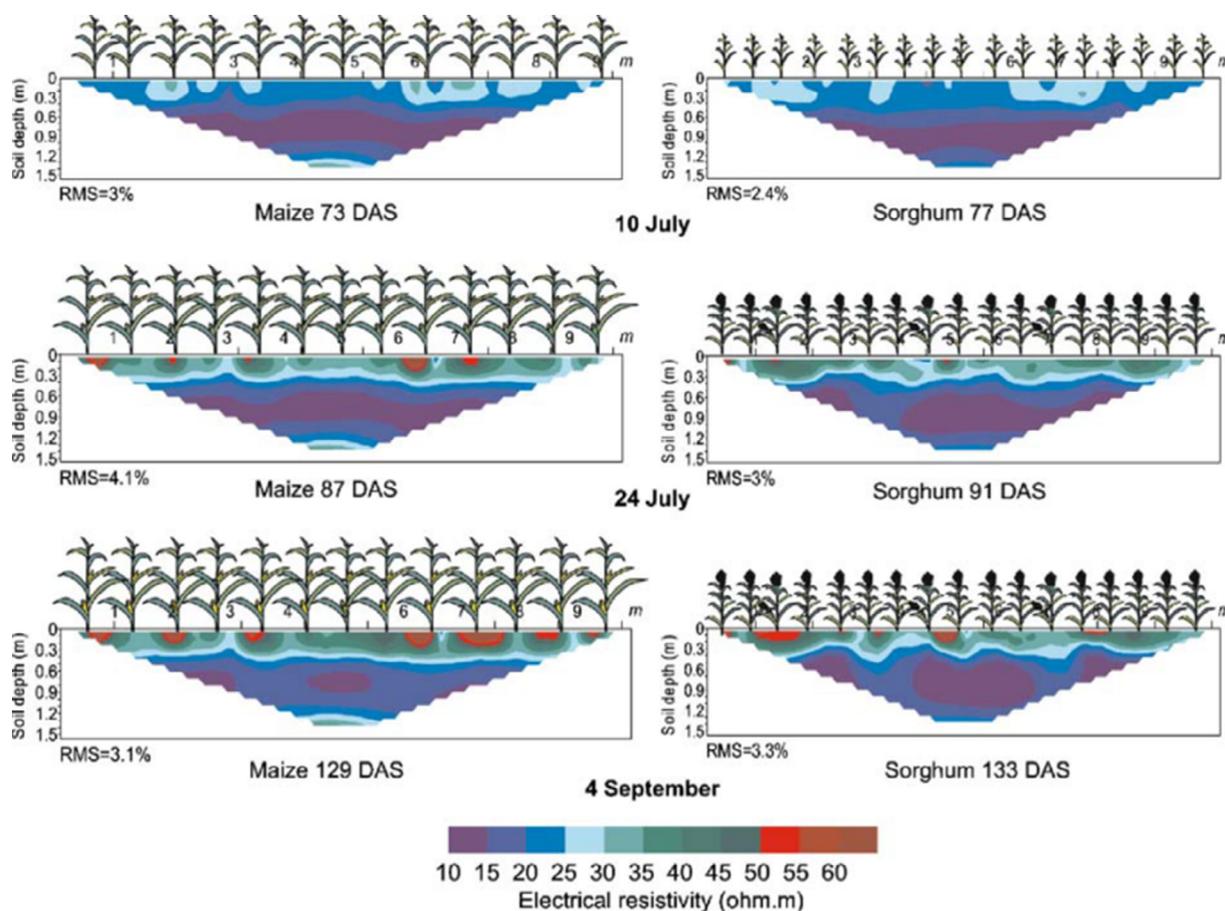


Fig. 5. 2D ERT field resistivity distribution variation with time under crops of Maize left and Sorghum right. Extracted from [Srayeddin and Doussan \(2009\)](#).

datasets, the correlations are qualitative.

**3.2.1.2. Mapping tree root systems.** [Mary et al. \(2018\)](#) showed the potential of ERT and the Mise-à-la-masse (MALM) technique for mapping woody root system distribution in soil. The concept of MALM measurements is to inject electrical current into a conductive body and make surrounding measurements of voltage. Based on these measurements the extent of the body can be calculated. The assumption is made that the roots are the conductive body and that the current injected through the plant stem will eventually be passed into the subsoil through the root terminations (root hairs). Another study by [Zenone et al. \(2008\)](#) combined ERT reconstruction and GPR sections for the purpose of root detection. [Fig. 6](#) shows the level of performance that can be expected from ERT when imaging root architecture. The root system is not resolved accurately, but the potential to localize roots is undeniable and the overall shape of the root system is captured well. The study also concluded that combining electrical resistivity with GPR data is useful in the investigation of root shape and behavior. It was shown that the contemporaneous use of multiple geophysical methods improves the quality of the results. GPR was successful for identifying the distribution of the roots in the subsoil, whereas ERT was useful for estimating the root volumes. [Leucci \(2010\)](#) used ERT, GPR and seismic refraction to produce 3D images of tree-root distribution. GPR revealed the extent of the root system, seismic refraction delineated the subsurface layers and ERT distinguished the roots from an old pipe system. The study reinforced the utility of the methods for this application emphasized the benefits of combining the techniques.

**3.2.1.3. Root polarization.** [Zanetti et al. \(2011\)](#) observed the complex conductivity signature of multiple samples of dead roots in three different soil textural environments dominated by gravel, sand and

silt, respectively. Additionally, the methodology was able to indicate the presence, type, size and orientation of buried material. However, measurements were limited to 1D, hence no information about the spatial distribution of the buried samples could be obtained. Polarization effects have also been observed by [Martin \(2012\)](#) when studying wood, suggesting that the methodology was able to identify infection damage in wood cells, which could add significant value to the technique.

[Mary et al. \(2016\)](#) and [Mary et al., 2017](#) demonstrated the feasibility of using IP for root detection, whilst performing in situ experiments. [Mary et al. \(2016\)](#) concluded that a dry soil medium is more appropriate for IP measurements as the contrast between the response from roots and surrounding soil is higher. [Mary et al. \(2017\)](#) concluded that, at low frequencies (1 Hz chosen as adequate), significant effects of polarization are dependent on root per soil volume ratio and are sensitive to root orientation. Furthermore, [Mary et al. \(2017\)](#) suggests root WC is proportional to the amplitude of polarization. These results suggest that there is an increasing prospect of using this method in the study of soil-plant interactions.

### 3.2.2. Herbaceous roots

[Aulen and Shipley \(2012\)](#) identified a significant relationship between root mass and capacitance. Unfortunately this was too weak without prior species specific calibrations ( $R^2 = 0.3$ ). [Ellis et al. \(2013\)](#) confirmed a weak predictive power of ECM ( $R^2 = 0.21 - 0.31$ ), but suggest an empirical model as a reasonable predictor of root length ( $R^2 = 0.56$ ). [Amato et al. \(2009\)](#) tested the ability of resistivity tomography to detect low-density root systems. They concluded that, although promising for more developed root systems, the resistivity contrast is not sufficient for a low-density regime.

[Sabo et al. \(2016\)](#) and [Sabo et al. \(2016b\)](#) proposed the use of

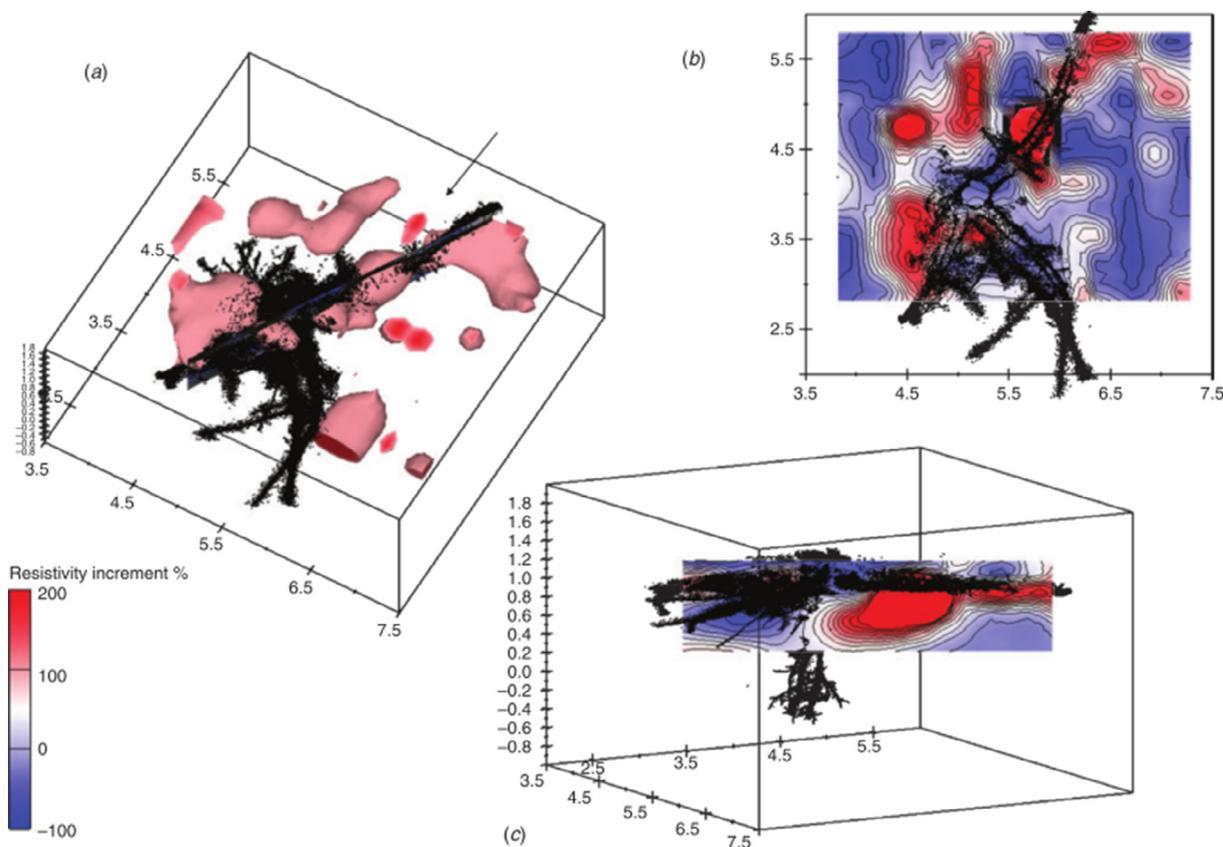


Fig. 6. Resistivity increment percent differences overlapped on 3D rendering of laser-scan point cloud of *Pinus Pinea* root system. a) 3D view b) 25 cm below surface c) vertical section. Extracted from Zenone et al. (2008).

capacitance tomography to assess the difference between healthy and dead roots by their ability to absorb water containing nano-particles of iron. Healthy roots showed capacitive readings that were up to three times lower than diseased ones. A series of pot experiments demonstrated the capability of capacitance measurements to monitor root system properties (e.g. dimensions, mass, root surface) when subjected to herbicide aceochlor (Cseresnyés et al., 2012), mycorrhizal fungal colonization (Cseresnyés et al., 2013), different RWU rates (Cseresnyés et al., 2014; Cseresnyés et al., 2016) and SWC changes together with mycorrhizal activity under field conditions (Cseresnyés et al., 2018). The latter study concluded that EC dependency on SWC is plant species dependent, which underlines the importance of root system architecture through its impact on RWU rate of change. Weigand and Kemna (2017) applied EIT to monitor the root activity of oil seed plants, which were grown in hydroponic conditions. The study discovered a low-frequency polarization response associated to root presence, and the methodology was able to delineate the extension of the root system. The study also observed changes in electrical properties due to root physiological stress imposed by nutrient deprivation.

### 3.3. Root zone conceptual models

Root zone processes and structure are vastly complex. Formulating both conceptual and quantitative models of the root zone is important to help develop our understanding of their complexity. Improved root zone models may help fulfill the long-term ambition to be able to predict future states of the soil-plant system. However, existing root zone models are not universally valid and dependent on locally derived parameters, such as soil texture, porosity, temperature fluctuations, root mass and others.

Geoelectrical monitoring can help improve root zone modelling. As discussed in Sections 3.1 and 3.2, geoelectrical methods have

demonstrated their capability to assess root water dynamics and root structure. The recorded variation in electrical properties reflects root functions (e.g. water uptake) or root-system structural indicators (e.g. mass, length, density). In this section we discuss how this information was in turn used as a basis for models of the root zone in order to 1. estimate the water balance determined by the soil-vegetation interaction 2. estimate effective water uptake in order to optimize irrigation practices and 3. improve conversion between electrical data and crop-scale root zone parametrization. A list of cited articles and corresponding models used can be found in Supplementary materials (Appendix A and B).

#### 3.3.1. Modelling root zone water dynamics

3.3.1.1. Interaction between vegetation cover and soil water balance. Cassiani et al. (2012) used ERT in conjunction with EMI method and TDR to investigate the effect of vegetation upon water dynamics. A strong correlation was found between the presence of vegetation and the variability of SWC. It was suggested that spontaneously grown vegetation on the bare soil influences the degree of soil compaction, which led to a slow infiltration of meteoric water in the upper layers. This is one of the few studies that have attempted to model vegetation-soil interaction based on electrical monitoring data. This approach holds promise for future research and opens the door for more comprehensive modelling which should take into account the dynamics of vegetation growth. Michot et al. (2003) demonstrated the effectiveness of combining ERT and TDR, in 2D some 10 years prior, but Cassiani et al. (2012) undertook 3D reconstruction of SWC distribution. Whilst geoelectrical methods alone are capable of providing time-lapse information, TDR can be useful for its superior temporal resolution. It is also worth noting ERT systems with permanently deployed sensor arrays and instrumentation are actively being developed, providing superior repeatability and high temporal

resolution from ERT measurements alone (Chambers et al., 2014).

Boaga et al. (2014) used ERT to demonstrate flooded plants are able to create aerated layers below the flooded surface when transpiration rate was high. The study found the results were in agreement with the model previously developed by Tosatto et al. (2009), which solved the 2D two-phase flow equations in porous media. Ursino et al. (2014) showed that in fallow plots infiltration is heterogeneous, water redistribution takes place below ground where roots have access to the active volume and the root-soil interplay reduces runoff and increases evapotranspiration. Their study promoted the integration of measurements of soil properties such as electrical resistivity, moisture content and vegetation density in order to develop a comprehensive soil-plant interaction model. However, the study did not employ a meaningful quantitative translation between electrical measurements and soil properties.

**3.3.1.2. Contributing towards irrigation efficiency.** Boaga et al. (2013) used ERT for temporal monitoring in order to characterize water balance exchanges in the subsoil under an apple orchard. Root growth was closely connected to the geometry of the irrigation system as roots developed in a shallow area, and were aligned with the irrigation lines. Cassiani et al. (2016) built on this approach by developing a model of the unsaturated zone flow using 3D Richard's equations. This revealed the potential of the method for monitoring and possibly predicting the time at which fresh irrigated water replaced saline water already present in the soil.

Cassiani et al. (2015) used a 3D ERT system to monitor the root zone of an orange tree. Other measurements of sap flow, eddy covariance and evapotranspiration were used in combination to develop a 1D model based on Richard's equation, which described the water dynamics of the monitored soil volume. This calibration was successful and predicted a much smaller water volume than the resistivity derived estimation. The implication was that over 50% of irrigated water was not taken up by plants, illustrating the importance of quantitative modelling to help interpret electrical monitoring data. Furthermore, Consoli et al. (2017) monitored and compared the impact of full versus partial irrigation, based on a reduction of water input by 50%. The study showed that water efficiency and fruit yield increased when a partial irrigation regime was used, which also implied that over-irrigation affected productivity.

**3.3.1.3. Enhancing the pedotransfer calibration.** In an effort to avoid site-specific calibrations and to make the irrigation process more efficient, Brillante et al. (2014) developed a pedotransfer function to estimate WC from ER data. The function is obtained through the use of a learning algorithm and estimated soil water wetness. It performed moderately well, showing a correlation of 0.67 between measured values and resistivity derived estimates of WC. Nonetheless, the methodology holds promise due to its potential to reduce laboratory effort to calibrate the resistivity results.

Moreno et al. (2015) used a model of water flow and solute transport to differentiate between the contribution of state variables (WC and salinity) to resistivity. Other studies discussed above have focused on plant inputs (Cassiani et al., 2015; Ursino et al., 2014), whereas their study was aimed at improving the quantification of non-plant related inputs to bulk resistance values. Both approaches are necessary in future modelling efforts. Plant physiological measurements were combined with ERT measurements by Brillante et al. (2016), in a study of grapevine. The work revealed that variability in the water uptake regimes was highly dependent on plant water stress as striking differences between regimes during night and day were found. Brillante (2016) fitted two models to predict soil water variation with the aid of field measurements of electrical resistivity. Instead of using absolute values of electrical resistivity for model fitting, this study used their variations as predictors. They also used several machine-learning techniques to tune the model parameters in order to avoid over-fitting. For the

current datasets, the gradient boosting machine method outperformed the others. Finally, the model results were compared to TDR measurements reaching to a satisfactory agreement (RMSE 22.6%).

### 3.4. Other applications

#### 3.4.1. Resolving pedological parameters

Morari et al. (2009) combined resistivity imaging, EMI and geostatistics and concluded that conductivity correlated positively with coarser textural soil components and negatively with finer components. Furthermore, this approach served as a basis for mapping subregions of the field within which crops are similarly affected by seasonal differences in weather and soil management. Celano et al. (2010) conducted a survey with the aim of establishing a correlation between pedological parameters, calculated through field sampling measurements, and electrical resistivity measurements. As resistivity measurements are sensitive to differences in salinity, ERT proved efficient in detecting salt accumulation in soil. Electrical monitoring was used to distinguish between different tillage systems in Basso et al. (2010). Soil properties such as bulk density or water storage are affected by tillage, therefore resistivity profiles showed significant differences between the soil practices. Future studies on this subject should consider correlating the variation in the electrical response with soil structure appraised by higher resolution imaging methods (e.g. X-ray CT). Kowalczyk et al. (2015) attempted to identify peat horizons through application of ERT, however, the heterogeneity of the soil made the inversion results inconclusive. The inversion generalized the resistivity values associated with the organic layers and treated them as parts of a sand layer, a result confirmed by a forward model based on geological units determined by drilling. It would seem that, identifying soil peat horizons in this manner is currently below the ability of the ERT method alone due to the length scales involved.

#### 3.4.2. Plant phenotyping

Plant phenotyping is an emerging research area concerned with quantitative measurement of the structural and functional properties of plants. Lu et al. (2018) compared root zeta potential for 17 types of crops using streaming potential measurements whereby an electrical potential is generated when an electrolyte passes through a porous plug with charged surfaces. The study only found distinctive differences between legumes and non-legumes, due to a higher concentration of functional groups in the former. Combined ERT and EMI measurements were used to phenotype roots in the field by Whalley et al. (2017). The result of their study suggested that by comparing the shifts in patterns of soil moisture content, genotypes may be differentiated. Genotypic differences, more obvious in dry conditions, were observed in depth of water uptake and in the extent of surface drying. This result is very important for the economics of agricultural practices as the geophysical approach potentially saves time and effort spent on root excavation for direct measurements. The effect of soil physicochemical properties on the discrimination power of this method has yet to be investigated. Therefore, the first step is to test the phenotype discrimination methodology under different agropedoclimatic conditions and subsequently verify which factors enhance or diminish it.

## 4. Discussion and future outlook

### 4.1. Geoelectrical methodology and capabilities

#### 4.1.1. Choice of geoelectrical method

The majority of geoelectrical methods are concerned with measurements of electrical impedance (Section 2.3). The main distinction between the nature and complexity of information resides in the information extracted from such measurements. Firstly, we can distinguish between single-frequency and multi-frequency acquisition strategies. Multi-frequency measurements offer additional information

about polarization processes, but extracting electrical parameters, such as chargeability or relaxation time across a frequency spectrum is not straightforward and requires more acquisition time. However, methodology (Weigand and Kemna, 2017), instrumentation (Zimmermann et al., 2008) and sampling strategies (Weigand and Kemna, 2016) associated with spectral methods are rapidly developing and are likely to replace the more extensively used single-frequency or DC methods, such as ERT, for root zone monitoring applications.

One of the overarching themes of this review is root detection. There is clear evidence for a strong correlation between the imaginary resistivity component and root parameters (Chloupek, 1972; Ellis et al., 2013; Weigand and Kemna, 2017), but several studies have also found a correlation between the real part and root parameters (Čermák et al., 2006; Amato et al., 2008; Rossi et al., 2011). However, electrical resistivity was only correlated to root biomass and failed to reflect other root physical parameters such as root length density. In addition, resistivity studies showed greatest success when investigating woody roots, and further studies indicated that the resistivity contrast generated by low-density herbaceous roots is indistinguishable from the effect of other root zone features such as WC or grain size (Rossi et al., 2011). Furthermore, methods that include measurements of polarization have the potential of resolving not only root physical parameters, but characteristics of root activity such as interactions with fungi colonies (Cseresnyés et al., 2013) and reaction to physiological stress (Weigand and Kemna, 2017) or even root health (Sabo et al., 2016). In summary, measurements of imaginary impedance have proven more conclusive for root investigation and offer a broader range of applications.

Fig. 7 shows the increase in research articles featuring geoelectrical applications in the root zone, which highlights the rising interest in the use of such methods. It also shows that the use of classical ERT is in decline compared with other methods, whereas the use of ECM and SIP is growing. In addition, our analysis shows that the number of laboratory studies in this area has grown over time. This clearly reflects the increased effort dedicated to method development, especially for advance geoelectrical methods beyond ERT. These tend to require significantly more sophisticated instrumentation and greater care to obtain good quality measurements. So far they have therefore mostly been employed ex-situ, although field applications are likely to increase once the methodology development has reached a greater level of maturity.

#### 4.1.2. Acquisition set-up and inversion algorithm

The dimensionality aspect of geoelectrical investigation is not to be treated lightly in the context of root zone monitoring. Previous research makes a clear distinction between the appraisal of a finer discretized model monitoring a singular root system, usually at lysimeter scale, and coarser models, usually at field scale. In addition, field surveys obtain a

3D properties distribution either by collating multiple 2D acquisition lines of superficial electrodes (Leucci, 2010) or by using a square array of acquisition with borehole electrodes (Cassiani et al., 2016). Using just one acquisition line, for 2D surveys, implies an easier set-up and quicker repetitive measurements. However, an agricultural field-site displays spatial heterogeneity, which this type of set-up fails to capture. A 3D survey by multiple superficial electrodes will provide the data coverage required, but will imply an expense in resolution. In contrast, using borehole electrodes allows higher resolution (especially in depth) but limits the user to a confined field sub-volume of investigation (1–2 m<sup>3</sup>).

We mentioned previously (Section 2.3) that the tomographic model mesh of the subsurface is discretized according to the specific volume of investigation. However, the inversion problem becomes increasingly delicate when one attempts to obtain a model of the root zone. Firstly, there is a question of scale which closely matches the acquisition options described above. A lower resolution survey (depending on electrode arrangement) will imply coarser mesh discretization. Secondly, there is a question of electrical property variability. The root, rootles soil and the volume surrounding their interface (i.e. the rhizosphere) can be considered as electrically distinct areas, which in consequence can be constrained differently. As we have demonstrated, knowledge about each of these areas exists individually. However, the challenge for future research is to collate this information into one electrical model and further refine inversion strategies around this parametrization. For example, providing one has information about the extent of the root system, this volume can be also meshed, disconnected and assigned a different smoothing factor from the rest of the surrounding soil.

#### 4.1.3. Electrical response from woody versus herbaceous roots

The two categories of roots display different electrical responses. Essentially, the difference in size, not the root functionality, appears to account for the distinction. The larger woody root, with a higher density and surface area, showed higher correlations with electrical resistivity and had a bigger impact on its change than finer roots found in the same system (Rossi et al., 2011). In terms of polarization, other soil properties, such as WC, are important in order to obtain a good response (Mary et al., 2016,2017\*\*\*). Furthermore, both types of roots show polarization, but not necessarily at the same frequencies. Weigand and Kemna (2017) reported a strong polarization at 70 Hz for herbaceous roots and Mary et al. (2017) reported 1 Hz to be suitable for woody roots. The distinct polarization frequencies could prove to be important for root classification if future research considers the analysis of larger scale root systems, which contain both kinds of roots.

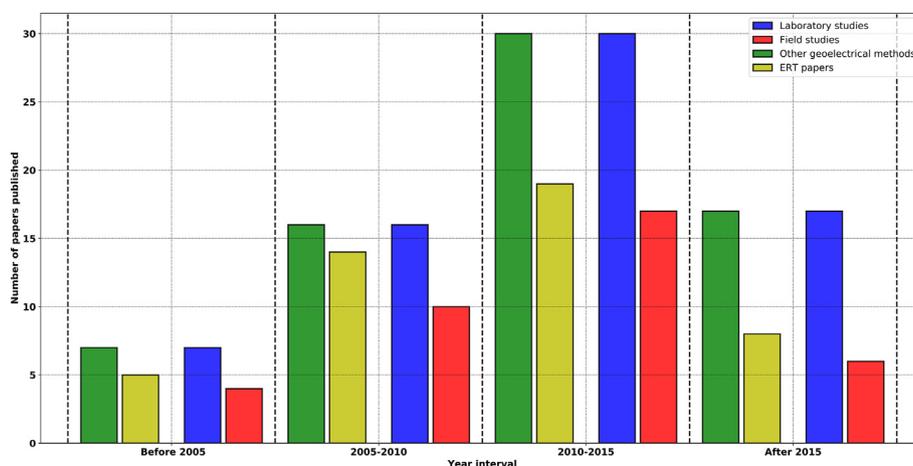


Fig. 7. Bar chart indicating number of published articles which use Geoelectrical monitoring methods for the study of root zone processes.

## 4.2. Knowledge gaps in pedophysical relationships

It is a common observation in the literature that none of the previously developed pedophysical relationships (pedotransfer functions for geoelectrical data) is perfectly adapted to the specific site conditions (e.g. soil texture, porosity, organic matter content) under investigation (Laloy et al., 2011). Therefore, calibration is usually required in order to empirically determine new functional parameters corresponding to each individual site.

### 4.2.1. Formulating pedophysical relationships in the lab

When considering a rootless soil calibration, most of the studies that have employed pedophysical calibration for field measurements have used soil samples repacked ex-situ. It is extremely difficult to recreate the chemical composition of the pore water (Furman et al., 2013) and a sample's natural pore structure under laboratory conditions. Working with disturbed samples disregards the effect of pore tortuosity, considered essential when evaluating conductivity pathways and consequently bulk resistivity measurements (Rhoades et al., 1989). Also, agricultural soils are quite frequently subjected to anthropic interactions, which generate spatial and temporal variations which can effect soil compaction. The latter is known to be a direct control on resistivity (Romero-Ruiz et al., 2018). In these circumstances a well suited approach is performing calibration measurements on undisturbed soil samples or to be attempted in situ (Srayeddin and Doussan, 2009; Michot et al., 2003).

We previously mentioned (Section 2.2 and 3.1.1) the distinction some of the studies make between analysing electrical properties of the rootless soil, the root system or the root zone as a whole. We consider each has its own merit and corresponding relationships between root zone properties and electrical parameters important for future research. Currently, many studies referenced in our review (Srayeddin and Doussan, 2009; Celano et al., 2011; Garré et al., 2013) are interested in the observation of root activity (e.g. suction), therefore being able to translate electrical measurements to WC balance of the target volume is crucial. In this case one would not be able to depict the outline of root system itself, but only delineate the impact on the surrounding soil. However, one can expand this methodology and determine root suction variability under different climatic, nutrient availability or soil textural conditions. This will contribute to our knowledge of plant health and yield potential. Also, plant phenotyping represents a promising potential application of geoelectrical research as suggested (Whalley et al., 2017). However, the methodology needs to be proven suitable in different environments before its effectiveness can be demonstrated. Furthermore, one may be interested in quantifying root development, therefore firstly would require the derivation of a clear electrical response from the rootless soil. Any variation from the base electrical spectrum would imply root mass development or root activity. The rate of development obtained as such could determine a plant's medium adaptability or its interaction with other elements of the ecosystem.

### 4.2.2. On the variability of pedophysical relationships

Garré et al. (2011) underlined the necessity for horizon-specific calibrations for an undisturbed soil column. Also, Furman et al. (2013) acknowledged seasonal variations in climate cause not only changes in WC, but also salt accumulations, thus making concentration of solutes in the water-filled pore spaces variable with time. Ultimately, for an accurate description of soil properties it is desirable to include high spatial and seasonal temporal variability.

We have mentioned above the effect of roots on bulk resistivity measurements, which is caused by the electrically conductive pathways they form (created by the nutrient solution absorbed through the xylem) and EDLs both at the exterior and interior surfaces of the root. The literature offers examples of empirical relationships between root biomass and resistivity (Amato et al., 2008), therefore we recommend future studies should include this aspect in the formulation of

pedotransfer functions. Also, root system development alters the soil structure and its chemical properties, invariably changing the electrical properties of the surrounding soil. Future research should therefore consider combining existing numerical simulations of root architecture and its impact on soil hydraulic properties (Postma et al., 2017) with geoelectrical numerical models in order to achieve a more realistic pedophysical calibration.

### 4.2.3. Computational approaches in pedophysical calibration

A different way of approaching the translation is emerging from the field of data science, including 'big data' analytics and parameter prediction methods based on machine learning. Rather than attempting to develop a universal analytical transfer function, a more adequate result might be obtained by calculating an 'educated estimate' based on prior knowledge from existing data. Provided a sufficiently large input dataset exists, deep learning algorithms can be utilized to predict an effective representation of the desired output parameter. Examples of work in this direction have already appeared in the literature (Brillante, 2016). An emerging trend in data science is convolutional neural networks (Pound et al., 2017). These computational systems, inspired by natural neuronal architectures, have the capability of developing a learned strategy that extracts the relevant characteristics from an existing series of inputs. When presented with a new input, the neural networks are able to identify in the new input the characteristics previously learned (based on the learned model) and subsequently classify or make a prediction from it. These kinds of algorithms are now widely used in image processing and pattern recognition. In soil science applications, a neural network could be used to predict moisture content, provided it was 'trained' with a large enough dataset containing other soil parameters including electrical data. Future opportunities will lie in the potential of such networks to transfer between domains. This implies that a network trained on a wide range of different experimental conditions could capture a more general model of the transformation which in turn could be tuned to new conditions by additional training with a comparatively small amount of data. Attempts to use such networks in soil and rock physics have already been reported in the literature (e.g. Pachevski and Timlin, 1996; Koekkoek and Booltink, 1999). Also, different machine learning methods are already being employed in an effort to enhance the fit between models of soil water balance and electrical resistivity data (Brillante, 2016).

## 4.3. Enhancing the geoelectrical characterization of the root zone

The tomographic imaging capability of geoelectrical methods offers unique quantitative information about the spatial variability of soil properties. Especially for field investigations it is desirable to be able to obtain large scale images of the subsurface. However, geophysical inversion is ill-posed and requires regularization, ideally combined with additional (a priori) information in order to create an accurate model of the subsurface. The constraints are often unsatisfactory when inversion is applied to geoelectrical data alone. In this section we discuss strategies to reduce the uncertainty in the geoelectrical images.

### 4.3.1. Use of complementary datasets

In Section 3.1 and 3.2 we have discussed studies that simultaneously employed ERT together with other electromagnetic methods for synergistic monitoring and characterization of soil moisture. Complementary techniques include TDR (Beff et al., 2013; Boaga et al., 2013; Michot et al., 2003) GPR (Musgrave and Binley, 2011; Leucci, 2010) or EMI (Cassiani et al., 2012; Morari et al., 2009; Whalley et al., 2017).

The most commonly used method that provides complementary data is TDR. It measures the dielectric permittivity of the soil which is subsequently converted into SWC (Topp et al., 1980). TDR probes position usually follows the electrode arrangement used for geoelectrical surveying (Fig. 2). This offers the advantage of directly comparing

results without the need for correction for spatial distribution, scale or mesh discretization. Therefore, in the context of geoelectrical research, TDR data is mainly used for ground truth and can help isolate the contribution of SWC to the bulk resistivity response. Given the prevalence of TDR measurements in the literature, it could easily be assumed that TDR is sufficient for monitoring soil moisture variability. However, whilst TDR does provide good temporal resolution, is restricted to single point measurements, and therefore offers only limited spatial coverage.

In contrast to TDR, the output of GPR and EMI is an image of the subsurface, therefore they generally provide good spatial coverage. GPR offers a high spatial resolution and is primarily used to delineate zones with different lithology. Due to the physics of low frequency electrical flow, it is difficult to obtain sharp lithological boundaries (including soil horizons) from ERT images (e.g. Fig. 5), but GPR data has the potential to enhance this (Musgrave and Binley, 2011). Due to the nature of the instrumentation, EMI provides a very fast and effective way of determining the spatial distribution of soil electrical conductivity and resolving lateral contrasts on a large (field-) scale. However, EMI is faced with intrinsic challenges such as the lack of vertical resolution. When combined with ERT, it is possible to obtain comprehensive field-scale models of conductivity variation both laterally and vertically. Joint interpretation of this kind has proved successful for aquifer characterization (Linde et al., 2006) or estimating field scale soil hydraulic conductivity (Farzaman et al., 2015). Previous authors have highlighted the capabilities of a combination of EMI and ERT for root zone imaging and soil moisture characterization (al Hagrey, 2007).

Other complementary methods involve measuring soil parameters destructively. A number of studies presented in this review (Amato et al., 2008; Rossi et al., 2011; Celano et al., 2010; Zenone et al., 2008) quantified root length density (RLD) or root biomass (RMD) by collecting all the roots in the analysed sample and measuring their length and weight, before correlating this information to electrical results. This procedure is perhaps useful for proof of concept, but a fully non-invasive strategy is clearly more desirable for practical applications, particularly for monitoring processes in the root zone over time.

#### 4.3.2. *A-priori information about the root zone*

Soil structural details are an example of the kind of highly relevant additional information required and represent a good source of a priori knowledge. Alternative methods of tomographic imaging from other fields of science are well developed, including X-ray CT, MRI or neutron imaging. These are able to provide details of soil structure at high resolution (down to 1  $\mu\text{m}$ ). There is significant future research potential in conducting joint experiments that include the synergetic application of geoelectrical methods and high-resolution structural imaging methods, both appraising the same soil volume. Early attempts were made by Olsen et al. (1999) and Cassiani et al. (2009) using X-ray information to explain patterns in the electrical response, but conclusions were qualitative and a quantitative link is currently missing. Three-dimensional reconstruction of the pore architecture to a high resolution allows the calculation of pore network parameters (e.g. pore diameter, connectivity). On this basis, subvolumes of the pore space that account for fluid percolation in the soil sample can be identified (Koestel et al., 2018). This information can in turn be used to constrain geoelectrical inversion results, e.g. by specifying regions of the soil volume with an increased or decreased propensity to fluid movement. Those regions are likely to be associated with greater changes in electrical properties.

X-ray CT is also a very effective ground-truth method for root characterization as it permits reconstruction of the root system to a high spatial resolution by segmenting radiograms of the root zone (Mairhofer et al., 2016). This kind of information can be parametrized accordingly and included into coupled frameworks containing both 3D electrical and root architectural data. As previous laboratory polarization studies have looked at roots in hydroponic solutions (Cao et al., 2010; Weigand and Kemna, 2017, 2018) this strategy can serve to

develop our understanding of root electrical properties in soils. The exact spatial position of every root segment can be used to modify the finite element mesh of the starting model for the geoelectrical inversion. We have highlighted studies that represent the root system as an electrical circuit analogue (Dalton et al.; Cao et al., 2011); in that context the root segment contribution to electrical properties can be quantified. Subsequently this contribution can be associated with the corresponding mesh element and its impact on the electrical inversion results assessed (Rao et al., 2018). Given that previous research has established that preferential infiltration can happen along main root channels (Werban et al., 2008), it is therefore possible to quantify the contribution of individual root segments to water uptake using suitable parametrization in the geoelectrical model.

#### 4.4. *Enhancing root zone conceptualisation*

Various authors have suggested conceptual models for the root zone, including models (complete list in Appendix B) that represents root materials as resistors (Cao et al. 2010; Ellis et al. 2013), models which account for water movement (Cassiani et al. 2016; Ursino et al. 2014) or a model that accounts for both, biomass and soil moisture (Cassiani et al., 2012). In this section we will discuss the current state of conceptualization of the root zone and propose future research opportunities from a geoelectrical perspective.

##### 4.4.1. *Root analogue electrical circuit models*

According to Ozier-lafontaine and Bajazet (2005), the root zone system can be electrically divided into multiple components, namely the stem-root internal medium, the soil-root interface, the soil medium and the electrode contact with the plant/soil. Every component has a different manifestation with respect to conduction and polarization. Each requires careful electrical parametrization and their contribution to the overall electrical response needs to be appropriately quantified. For example, currently there is no clear distinction between the contributions from the root mass and the root-soil interface to capacitance measurements.

The Dalton model is considered an important benchmark for the way the root system is electrically represented, as multiple groups of Resistance–Capacitance (RC) pairs connected in parallel. However, inconsistencies in the Dalton model have been reported (Dietrich et al., 2012; Ellis et al., 2013), forcing a rethink in the way the soil-root system is electrically interpreted. One can regard the Dalton model as an oversimplified analogue, and in fact a more comprehensive model includes a combination of series and parallel RC groups (Cao et al. 2010). Furthermore, for hydroponic systems, both Dietrich et al. (2012) and Cao et al. (2010) suggest that the root tissue above the solution surface is the main contributor to capacitance and resistance. The analogue circuit model architecture and relative contribution of individual components are key concepts that will guide the future quest for more effective models of the root zone.

##### 4.4.2. *Separating contributors to the electrical response*

Recent studies have attempted to develop models which simulate the soil system water balance and use them as a substitute for collecting field data, highlighting the effectiveness of an accurate model (Cassiani et al., 2012). Frequently, soil electrical conductivity changes are solely attributed to variations in WC, but in fact multiple contributors can be responsible, including levels of salinity or organic content and distribution. Therefore, quantitative models require a clear separation between such contributors when computing electrical conductivity. It is also important that model boundaries take into account the open nature of the system being studied, as energy and mass are exchangeable with the medium surrounding the modeled system. Many models lack robustness from the poor definition of boundary fluxes (Garré et al., 2011). Therefore, better mathematical expressions of such exchanges are required, reflecting evapotranspiration, rain water influx,

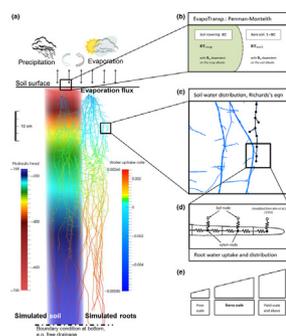
groundwater movement and others.

Future laboratory studies should firstly focus on the rootless electrical response to water content variation and only secondly introduce roots into the system once the medium is appropriately parametrized. Furthermore, the presence of roots will undoubtedly change their surrounding medium. How much the different resulting elements, such as: a modified soil structure, the suction power of root, mucilage formation or the presence of organic material itself contribute to such change remains an unknown and must be explored.

#### 4.4.3. Integrating plant hydrology models and geoelectrical measurements

The current state of computational technology allows the simulation and visualization of reasonably complex root zone processes in four dimensions. Elucidating the impact of root architecture on root zone hydraulics is of increasing interest especially for practical purposes, such as sustainable irrigation (Green et al., 2006). As different components of the root system have different hydraulic properties (Javaux et al., 2013) the ability to simulate and quantify this structural effect is essential for an accurate interpretation of monitoring root-water uptake. Access is already available to models that can simulate root-growth for different plant types (e.g. CRootBox; Schnepf et al. (2017)) and even models that couple root growth with water or nutrient uptake simulations (e.g. OpenSimRoot; Fig. 8). However, as underlined by Draye et al. (2010), it is still unknown if the soil or the plant is the main driver of water flow, or indeed where the greatest barrier to water flow resides (e.g. root-soil interface, in the soil, in the root). As geoelectrical data provide a proxy for imaging changes in WC, there is potential in developing a coupled hydrological model of the root zone. From a plant research perspective, an useful review focused on plant biological models across scales is given by Hill et al. (2013), who discusses the interplay between root biology and surrounding soil system from cellular to crop level. The authors emphasize the need for monitoring quantitative changes in root biology (e.g. hormones, water status, nutrients), a need that could potentially be fulfilled by geoelectrical monitoring, as there is evidence that geoelectrical techniques are sensitive to root functional stress (Weigand and Kemna, 2017). Hill et al. (2013) also argue for bridging the gap between genetic and environmental regulation. In that context we believe that field scale geoelectrical surveys could provide an appropriate assessment of changes in water dynamics, root activity or even root growth.

In the light of this, there is significant future research potential in developing a coupled multidisciplinary framework for characterizing



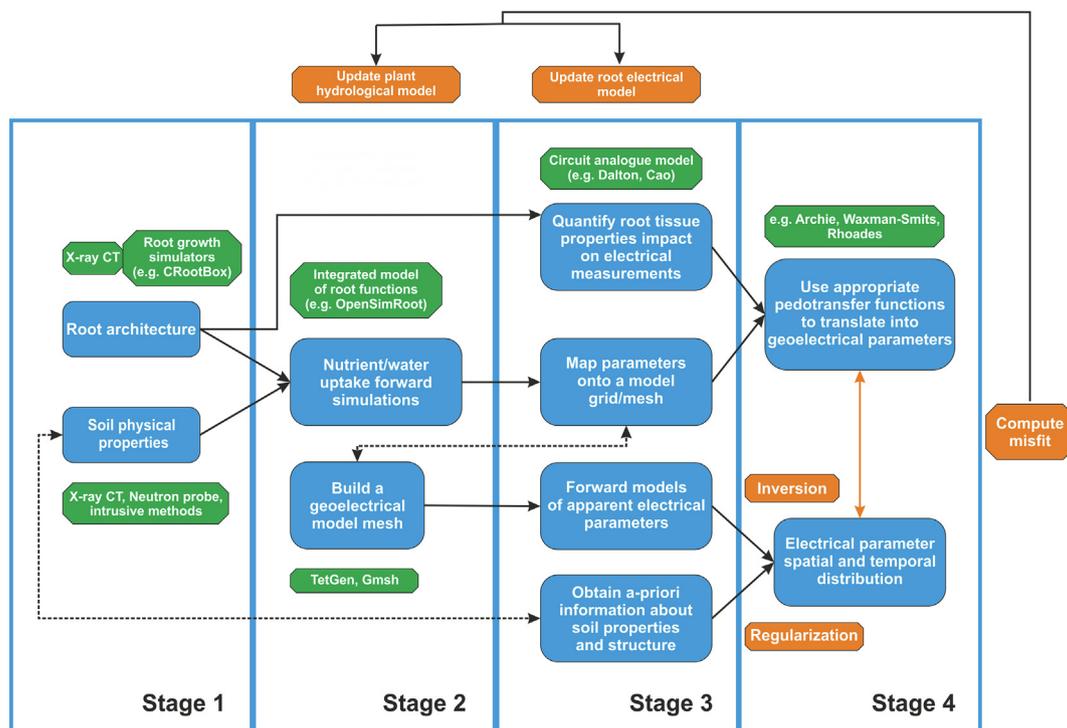
**Fig. 8.** Schematic representation extracted from Postma et al. (2017) representing the model used that couples evapotranspiration, xylem transport and soil water dynamics. a) Soil pedon with the hydraulic head indicated in pseudocolor (left) and three barley root systems (right) taking up water from that column. b) Penman- Monteith equation was used for the simulation of transpiration and evaporation. c) Section of the simulated root network showing its edges and vertices d) Network model used for the simulation of water flow through the roots (Alm et al., 1992) e) Water transport in three dimensions in the soil was simulated by solving the Richards equation, which combines Darcy's law with mass conservation, using the finite element method.

and monitoring root zone hydraulics (Fig. 9). This framework comprises both a hydraulic and an electrical model of the root zone. It will undertake forward simulations of root zone hydraulics and translate the results to electrical properties via appropriate pedotransfer functions. The results will then be compared with simulated electrical measurements acquired on the same soil volume. In Stage 1 we establish the baseline soil medium and root network properties. This is followed by flow process modelling, expressing how does the properties determined in the previous stage affect root nutrient/water uptake (Stage 2), mapping prior obtained parameters on an appropriate mesh (Stage 3) and finally translating the model results into geoelectrical parameters (Stage 4). A disagreement between both sets of results (measured and modelled geoelectrical parameters) would imply a shortfall either in the way flow processes are implemented in the model or in the conversion between hydraulic and electrical root zone properties (Fig. 9 stage 2–3). The simulations could be iteratively repeated until the discrepancy is minimized hence providing an opportunity to determine the value of unknown parameters which lead to the initial misfit. This overall approach should allow us to simulate the electrical response in space and time holistically as a function of both soil and root properties. At present, tools are available to conduct numerical simulations of this kind at the individual plant scale, for example in laboratory containers under controlled conditions. Future research could follow a similar strategy for field scale simulations, although there are other external effects such as climate or vegetation growth (Cassiani et al., 2012), which need to be parametrized and integrated into the modeling framework.

## 5. Conclusions

We sought to highlight the potential advantages and limitations that geoelectrical methodology can bring to research in the soil sciences and in particular to root zone studies. Geoelectrical methods offer minimally invasive data acquisition, are cost effective and have the ability to monitor key physical (soil water balance), chemical (soil water salinity) and biological (root growth) processes in the root zone both in space and time. A body of literature has developed, which shows these methods to be very effective for the examination of root zone water dynamics and the detection and characterization of root architecture. We have presented and discussed the main characteristics of both established and emerging geoelectrical methodologies. Currently, ERT is one of the best established and most evolved techniques, however the information it delivers is limited to a single physical parameter and not without ambiguity. ERT is by far the most frequently used technique in the literature, but other methods (e.g. SIP, TDIP, EIT) provide more holistic measurements including electrical polarization. These have also proven their ability to determine soil properties (albeit often under more controlled laboratory conditions), and can provide superior sensitivity to root properties (e.g. mass, length), type (woody or herbaceous) and functions (e.g. evapotranspiration, nutrient absorption). Future root zone research must therefore carefully consider the choice of geoelectrical methodology in experimental design. Particularly for larger scale root zone field studies the availability of techniques and instrumentation is more limited.

Our evaluation of previous research has highlighted the difficulty of determining robust pedophysical relationships (i.e. pedotransfer functions for geoelectrical data), which are required for meaningful property translation and experimental calibration. We expect future research to take into account their variability in space and time and to consider emerging trends in data science, including convolutional neural networks. Furthermore, due to the inherent limitations in the spatial resolution of geoelectrical methods, we highlight the value of synergetic studies with other soil assessment methods (e.g. TDR, EMI, GPR). Such a strategy is suitable for field scale characterizations of the root zone and offers the potential of including high resolution soil and root structural information into geoelectrical inversion models. Finally, we have demonstrated the benefits of geoelectrical information in root



**Fig. 9.** Stages of an interdisciplinary strategy to perfect root zone geoelectrical monitoring and corresponding conceptual models. In blue: Main steps of the strategy flowchart; In green: Existent auxiliary methods or models that can be used; In orange: Mathematical algorithms needed; Black arrow: Indicates the step succession; Dashed double arrow: Underlines the need of consistency between the two steps; Orange double arrow: Implies a comparison between the results.

zone conceptual modeling. We call for improvements to the analogue circuit representation of the root system components, underlining the need for separating the main contributors to the electrical property variations when constructing a model and propose a coupled multi-disciplinary characterization and monitoring framework incorporating simulations of plant growth-hydrological parameters and geoelectrical measurements.

#### Funding declaration

This work was supported by the Biotechnology and Biological Sciences Research Council; and the Natural Environment Research Council [Grant No. NE-M009106-1], through the Soils Training and Research Studentships (STARS) Centre for Doctoral Training grant to M.O.C. STARS is a consortium consisting of Bangor University, British Geological Survey, Centre for Ecology and Hydrology, Cranfield University, James Hutton Institute, Lancaster University, Rothamsted Research and the University of Nottingham.

#### Conflict of interest

None.

#### Acknowledgements

We would like to thank all the reviewers of this article for their constructive comments that made this publication possible. A special mention to Dr. Maximilian Weigand for offering us very in-depth insights on how to improve our work.

#### Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.geoderma.2020.114232>.

#### References

- al Hagrey, A.S., 2007. Geophysical imaging of root-zone, trunk, and moisture heterogeneity. *J. Exp. Bot.* 58 (4), 839–854.
- Alm, D., Cavelier, J., Nobel, P., 1992. A finite-element model of radial and axial conductivities for individual roots – development and validation for 2 desert succulents. *Ann. Bot.* 69, 87–92.
- Amato, M., Basso, B., Celano, G., Bitella, G., Morelli, G., Rossi, R., 2008. In situ detection of tree root distribution and biomass by multi-electrode resistivity imaging. *Tree Physiol.* 28 (10), 1441–1448.
- Amato, M., Bitella, G., Rossi, R., Gómez, J.A., Lovelli, S., Gomes, J.J., 2009. Multi-electrode 3D resistivity imaging of alfalfa root zone. *Eur. J. Agron.* 31 (4), 213–222.
- Amin, M.H.G., Richards, K.S., Chorley, R.J., Gibbs, S.J., Carpenter, T.A., Hall, L.D., 1996. Studies of soil-water transport by MRI. *Magn. Reson. Imaging* 14 (7–8), 879–882.
- Archie, G., 1942. The electrical resistivity log as an aid in determining some reservoir characteristics. *Trans. AIME* 146 (01), 54–62.
- Aulen, M., Shipley, B., 2012. Non-destructive estimation of root mass using electrical capacitance on ten herbaceous species. *Plant Soil* 355 (1–2), 41–49.
- Banin, A., Anderson, D., 1974. Effects of salt concentration during freezing on the unfrozen content of porous materials. *Water Resour. Res.* 10, 124–128.
- Basso, B., Amato, M., Bitella, G., Rossi, R., Kravchenko, A., Sartori, L., Carvahlo, L.M., Gomes, J., 2010. Two-dimensional spatial and temporal variation of soil physical properties in tillage systems using electrical resistivity tomography. *Agron. J.* 102, 440–449.
- Beff, L., Günther, T., Vandoorne, B., Couvreur, V., Javaux, M., 2013. Three-dimensional monitoring of soil water content in a maize field using Electrical Resistivity Tomography. *Hydrol. Earth Syst. Sci.* 17 (2), 595–609.
- Binley, A., Shaw, B., Henry-Poulter, S., 1996. Flow pathways in porous media: electrical resistance tomography and dye staining image verification. *Meas. Sci. Technol.* 7, 384–390.
- Bland, W.L., 1989. Estimating Root Length Density by the core-break method. *Soil Sci. Soc. Am. J.* 53, 1595–1597 In press.
- Boaga, J., D'Alpaos, A., Cassiani, G., Marani, M., Putti, M., 2014. Plant-Soil interactions in salt marsh environments: experimental evidence from electrical resistivity tomography in the Venice Lagoon. *Geophys. Res. Lett.* 41 (17), 6160–6166.
- Boaga, J., Rossi, M., Cassiani, G., 2013. Monitoring soil-plant interactions in an apple orchard using 3D electrical resistivity tomography. *Proc. Environ. Sci.* 19, 394–402.
- Brillante, L., 2016. Electrical imaging of soil water availability to grapevine: a benchmark experiment of several machine-learning techniques. *Precision Agric.* 17, 637–658.
- Brillante, L., Bois, B., Lévêque, J., Mathieu, O., 2016. Variations in soil-water use by grapevine according to plant water status and soil physical-chemical characteristics-A 3D spatio-temporal analysis. *Eur. J. Agron.* 77, 122–135.
- Brillante, L., Bois, B., Mathieu, O., Bichet, V., Michot, D., Lévêque, J., 2014. Monitoring soil volume wetness in heterogeneous soils by electrical resistivity. A field-based pedotransfer function. *J. Hydrol.* 516, 56–66.

- Cao, Y., Repo, T., Silvennoinen, R., Lehto, T., Pelkonen, P., 2010. An appraisal of the electrical resistance method for assessing root surface area. *J. Exp. Bot.* 61 (9), 2491–2497.
- Cao, Y., Repo, T., Silvennoinen, R., Lehto, T., Pelkonen, P., 2011. Analysis of the willow root system by electrical impedance spectroscopy. *J. Exp. Bot.* 62 (1), 351–358.
- Cassiani, G., Boaga, J., Rossi, M., Putti, M., Fadda, G., Majone, B., Bellin, A., 2016. Soil-plant interaction monitoring: small scale example of an apple orchard in Trentino, North-Eastern Italy. *Sci. Total Environ.* 543, 851–861.
- Cassiani, G., Boaga, J., Vanella, D., Perri, M.T., Consoli, S., 2015. Monitoring and modelling of soil-plant interactions: the joint use of ERT, sap flow and eddy covariance data to characterize the volume of an orange tree root zone. *Hydrol. Earth Syst. Sci.* 19 (5), 2213–2225.
- Cassiani, G., Kemna, A., Cassiani, G., Kemna, A., Villa, A., Zimmermann, E., 2009. Spectral induced polarization for the characterization of free-phase hydrocarbon contamination of sediments with low clay content. *Near Surface Geophys.* 7, 547–562.
- Cassiani, G., Ursino, N., Deiana, R., Vignoli, G., Boaga, J., Rossi, M., Perri, M.T., Blaschek, M., Duttmann, R., Meyer, S., Ludwig, R., Soddu, A., Dietrich, P., Werban, U., 2012. Noninvasive monitoring of soil static characteristics and dynamic states: a case study highlighting vegetation effects on agricultural land. *Vadose Zone J.* 11 (3).
- Celano, G., Palese, A., Tuzio, A., Zuardi, D., Lazzari, L., Xiloyannis, C., 2010. Geo-electrical survey on the soil of an apricot orchard grown under semi-arid conditions. *Acta Horticulturae* 862, 425–428.
- Celano, G., Palese, A.M., Ciucci, A., Martorella, E., Vignozzi, N., Xiloyannis, C., 2011. Evaluation of soil water content in tilled and cover-cropped olive orchards by the geoelectrical technique. *Geoderma* 163 (3–4), 163–170.
- Čermák, J., Ulrich, R., Staněk, Z., Koller, J., Aubrecht, L., 2006. Electrical measurement of tree root absorbing surfaces by the earth impedance method: 2. Verification based on allometric relationships and root severing experiments. *Tree Physiol.* 26 (9), 1113–1121.
- Chambers, J.E., Gunn, D.A., Wilkinson, P.B., Meldrum, P.I., Haslam, E., Holyoake, S., Kirkham, M., Kuras, O., Merritt, A., Wrang, J., 2014. 4D electrical resistivity tomography monitoring of soil moisture dynamics in an operational railway embankment. *Near Surface Geophys.* 12 (1), 61–72.
- Chloupek, O., 1972. The relationship between electric capacitance and some other parameters of plant roots. *Biol. Plant.* 14, 227–230.
- Cole, K.S., Cole, R.H., 1941. Dispersion and absorption in dielectrics. *J. Chem. Phys.* 9 (1913), 98–105.
- Consoli, S., Stagno, F., Vanella, D., Boaga, J., Cassiani, G., Rocuzzo, G., 2017. Partial root-zone drying irrigation in orange orchards: Effects on water use and crop production characteristics. *Eur. J. Agron.* 82, 190–202.
- Cseresnyés, I., Fekete, G., Végh, K.R., Székács, A., Mörtl, M., Rajkai, K., 2012. Monitoring of herbicide effect in maize based on electrical measurements. *Int. Agrophys.* 26, 243–247.
- Cseresnyés, I., Szitár, K., Rajkai, K., Füzy, A., Mikó, P., 2018. Application of electrical capacitance method for prediction of plant root mass and activity in field-grown crops. *Frontiers in Plant Science* 9 (February), 1–11.
- Cseresnyés, I., Takács, T., Végh, K.R., Anton, A., Rajkai, K., 2013. Electrical impedance and capacitance method: a new approach for detection of functional aspects of arbuscular mycorrhizal colonization in maize. *Eur. J. Soil Biol.* 54, 25–31.
- Dalton, F., 1995. In-situ root extent measurements by electrical capacitance methods. *Plant Soil* 173, 157–165.
- Davidson, E.A., Belk, E., Boone, R.D., 1998. Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. *Glob. Change Biol.* 4 (2), 217–227.
- Debye, P., 1929. *Polar Molecules*. Chemical Catalogue Co., New York, pp. 172.
- Denmead, O.T., 1961. Availability of Soil Water to Plants. Iowa State University.
- Dietrich, R.C., Bengough, A.G., Jones, H.G., White, P.J., 2012. A new physical interpretation of plant-root capacitance. *J. Exp. Bot.* 63, 6149–6159.
- Draye, X., Kim, Y., Lobet, G., Javaux, M., 2010. Model-assisted integration of physiological and environmental constraints affecting the dynamic and spatial patterns of root water uptake from soils. *J. Exp. Bot.* 61 (8), 2145–2155.
- Ellis, T., Murray, W., Kavalieris, L., 2013. Electrical capacitance of bean (*Vicia faba*) root systems was related to tissue density—a test for the Dalton Model. *Plant Soil* 366 (1–2), 575–584.
- Escamilla, J.A., Comerford, N.B., Neary, D.G., 1991. Soil-core break method to estimate pine root distribution. *Soil Sci. Soc. Am.* 55 (6), 1722–1726.
- Everett, M.E., 2013. *Near-surface Applied Geophysics*. Cambridge University Press.
- Farzamian, M., Monteiro, F.A., Khalil, M.A., 2015. Application of EM38 and ERT methods in estimation of saturated hydraulic conductivity in unsaturated soil. *J. Appl. Geophys.* 112, 175–189.
- Fukue, M., Minato, T., Horibe, H., Taya, N., 1999. The micro-structures of clay given by resistivity measurements. *Eng. Geol.* 54, 43–53.
- Furman, A., Arnon-Zur, A., Assouline, S., 2013. Electrical resistivity tomography of the root zone. In: *Soil-Water-Root Processes: Advances in Tomography and Imaging*. SSSA Special Publications, pp. 223–245.
- Garré, S., Coteur, I., Wonglecharoen, C., Kongkaew, T., Diels, J., Vanderborght, J., Province, R., 2013. Noninvasive monitoring of soil water dynamics in mixed cropping systems: a case study in Ratchaburi Province, Thailand. *Vadose Zone J.* 12, 1–12.
- Garré, S., Günther, T., Diels, J., Vanderborght, J., 2012. Evaluating experimental design of ERT for soil moisture monitoring in contour hedgerow intercropping systems. *Vadose Zone J.* 11, 1–14.
- Garré, S., Javaux, M., Vanderborght, J., Pagès, L., Vereecken, H., 2011. Three-dimensional electrical resistivity tomography to monitor root zone water dynamics. *Vadose Zone J.* 10 (1), 412–424.
- Green, S.R., Kirkham, M.B., Clothier, B.E., 2006. Root uptake and transpiration: from measurements and models to sustainable irrigation. *Agric. Water Manage.* 86 (1–2), 165–176.
- Guyot, A., Ostergaard, K.T., Lenkopane, M., Fan, J., Lockington, D.A., 2013. Using electrical resistivity tomography to differentiate sapwood from heartwood: application to conifers. *Tree Physiol.* 33, 187–194.
- Haynes, R., Beare, M.H., 1997. Influence stability of six crop species on aggregate and some labile organic matter fractions. *Science* 29 (1), 1647–1653.
- Hendrick, R.L., Pregitzer, K.S., 1996. Applications of minirhizotrons to understand root function in forests and other natural ecosystems. *Plant and Soil* 185, 293–304 In press.
- Hill, K., Porco, S., Lobet, G., Zappala, S., Mooney, S., Draye, X., Bennett, M.J., 2013. Root systems biology: integrative modeling across scales, from gene regulatory networks to the rhizosphere. *Plant Physiol.* 163, 1487–1503.
- Javaux, M., Couvreur, V., Vanderborght, J., Vereecken, H., 2013. Root water uptake: from three-dimensional biophysical processes to macroscopic modeling approaches. *Vadose Zone J.*
- Jones, G.M., Cassidy, N.J., Thomas, P.A., Plante, S., Pringle, J.K., 2009. Imaging and monitoring tree-induced subsidence using electrical resistivity imaging. *Near Surface Geophys.* 7 (3), 191–206.
- Kelly, B.F., Acworth, R.L., Greve, A.K., 2011. Better placement of soil moisture point measurements guided by 2D resistivity tomography for improved irrigation scheduling. *Soil Res.* 49 (6), 504–512.
- Kelter, M., Huisman, J.A., Zimmermann, E., Kemna, A., Vereecken, H., 2015. Quantitative imaging of spectral electrical properties of variably saturated soil columns. *J. Appl. Geophys.* 123, 333–344.
- Koestel, J., Dathe, A., Skaggs, T.H., Klakegg, O., Ahmad, M.A., Babko, M., Giménez, D., Farkas, C., Nemes, A., Jarvis, N., 2018. Estimating the permeability of naturally structured soil from percolation theory and pore space characteristics imaged by X-ray. *Water Resour. Res.* 54 (11), 9255–9263.
- Koestel, J., Kasteel, R., Esser, O., Kemna, A., Javaux, M., Binley, A., 2007. Imaging brilliant blue stained soil by means of electrical resistivity tomography. *Vadose Zone J.* 8, 963–975.
- Koestel, J., Kemna, A., Javaux, M., Binley, A., Vereecken, H., 2008. Quantitative imaging of solute transport in an unsaturated and undisturbed soil monolith with 3-D ERT and TDR. *Water Resour. Res.* 44, 1–17.
- Kowalczyk, S., Zawrzykraj, P., Mieszkowski, R., 2015. Application of electrical resistivity tomography in assessing complex soil conditions. *Geol. Q.* 59 (2), 367–372.
- Laloy, E., Javaux, M., Vanclooster, M., Roisin, C., Bielders, C.L., 2011. Electrical resistivity in a loamy soil: identification of the appropriate pedo-electrical model. *Vadose Zone J.* 10 (3), 1023–1033.
- Lucci, G., 2010. The use of three geophysical methods for 3d images of total root volume of soil in urban environments. *Explor. Geophys.* 41, 268–278.
- Linde, N., Binley, A., Tryggvason, A., Pedersen, L.B., Revil, A., 2006. Improved hydro-geophysical characterization using joint inversion of cross-hole electrical resistance and ground-penetrating radar traveltime data. *Water Resour. Res.* 42 (12), 1–16.
- Loke, M.H., Chambers, J.E., Rucker, D.F., Kuras, O., Wilkinson, P.B., 2013. Recent developments in the direct-current geoelectrical imaging method. *J. Appl. Geophys.* 95, 135–156 In press.
- Lu, H.-L., Liu, Z.-D., Zhou, Q., Xu, R.-K., 2018. Zeta potential of roots determined by the streaming potential method in relation to their Mn (II) sorption in 17 crops. *Plant Soil* 428, 241–251.
- Lyklema, J., Dukhin, S., Shilov, D., 1983. The relaxation of the double-layer around colloidal particles and the low-frequency dielectric-dispersion. I. theoretical considerations. *J. Electroanal. Chem.* 1–2, 1–21.
- Mairhofer, S., Johnson, J., Sturrock, C.J., Bennett, M.J., Mooney, S.J., Pridmore, T.P., 2016. Visual tracking for the recovery of multiple interacting plant root systems from X-ray  $\mu$ CT images. *Mach. Vis. Appl.* 27 (5), 721–734.
- Mares, R., Barnard, H.R., Mao, D., Revil, A., Singha, K., 2016. Examining diel patterns of soil and xylem moisture using electrical resistivity imaging. *J. Hydrol.* 536, 327–338.
- Martin, T., 2012. Complex resistivity measurements on oak. *Eur. J. Wood Wood Prod.* 70 (1–3), 45–53.
- Mary, B., Abdulsamad, F., Saracco, G., Peyras, L., Vennetier, M., Mériaux, P., Camerlynck, C., 2017. Improvement of coarse root detection using time and frequency induced polarization: from laboratory to field experiments. *Plant Soil* 417 (1–2), 243–259.
- Mary, B., Peruzzo, L., Boaga, J., Schmutz, M., Wu, Y., Hubbard, S.S., Cassiani, G., 2018. Small-scale characterization of vine plant root water uptake via 3-D electrical resistivity tomography and mise-à-la-masse method. *Hydrol. Earth Syst. Sci.* 22, 5427–5444.
- Mary, B., Saracco, G., Peyras, L., Vennetier, M., Mériaux, P., Camerlynck, C., 2016. Mapping tree root system in dikes using induced polarization: Focus on the influence of soil water content. *J. Appl. Geophys.* 135, 387–396.
- Michot, D., Benderitter, Y., Dorigny, A., Nicoullaud, B., King, D., Tabbagh, A., 2003. Spatial and temporal monitoring of soil water content with an irrigated corn crop cover using surface electrical resistivity tomography. *Water Resour. Res.* 39 (5), 1–20.
- Michot, D., Dorigny, A., Benderitter, Y., 2001. Mise en évidence par résistivité électrique des écoulements préférentiels et de l'assèchement par le maïs d'un calcosil de beauce irrigué. *Earth Planet. Sci.* 332, 29–36.
- Mooney, S.J., Pridmore, T.P., Helliwell, J., Bennett, M.J., 2012. Developing X-ray computed tomography to non-invasively image 3-D root systems architecture in soil. *Plant Soil* 352 (1–2), 1–22.
- Morari, F., Castrignanò, A., Pagliarin, C., 2009. Application of multivariate geostatistics in delineating management zones within a gravelly vineyard using geo-electrical sensors. *Comput. Electron. Agric.* 68 (1), 97–107.
- Moreno, Z., Arnon-Zur, A., Furman, A., 2015. Hydro-geophysical monitoring of orchard root zone dynamics in semi-arid region. *Irrig. Sci.* 33 (4), 303–318.

- Moreno, G., Obrador, J.J., Cubera, E., Dupraz, C., 2005. Fine root distribution in Dehesas of Central-Western Spain. *Plant and Soil* 277, 153–162. <https://doi.org/10.1007/s11104-005-6805-0>. In press.
- Mualem, Y., Friedman, S., 1991. Theoretical prediction of electrical conductivity in saturated and unsaturated soil. *Water Resour. Res.* 27 (10), 2771–2777.
- Musgrave, H., Binley, A., 2011. Revealing the temporal dynamics of subsurface temperature in a wetland using time-lapse geophysics. *J. Hydrol.* 396 (3–4), 258–266.
- Newill, P., Karadagli, C.D., Podd, F., Grieve, B.D., York, T.A., 2014. Electrical impedance imaging of water distribution in the root zone. *Meas. Sci. Technol.* (25), 5.
- Nijland, W., van der Meijde, M., Addink, E., de Jong, S., 2010. Detection of soil moisture and vegetation water abstraction in a mediterranean natural area using electrical resistivity tomography. *Catena* 81 (3), 209–216.
- Olsen, P.A., Binley, A., Tych, W., 1999. Characterizing solute transport in undisturbed soil cores using electrical and X-ray tomographic methods. *Hydrol. Process.* 13, 211–221.
- Ozier-lafontaine, H., Bajazet, T., 2005. Analysis of Root Growth by Impedance Spectroscopy (EIS) Analysis of root growth by impedance spectroscopy (EIS). *Plant Soil* 255 (December), 299–313.
- Panissod, C., Michot, D., Benderitter, Y., Tabbagh, A., 2001. On the effectiveness of 2D electrical inversion results: An agricultural case study. *Geophys. Prospect.* 49 (5), 570–576.
- Pelton, W., Ward, S., Hallof, P., Sill, W., Nelson, P.H., 1978. Mineral discrimination and removal of inductive coupling with multifrequency ip. *Geophysics* 43, 588–609.
- Pennell, K.D., 2016. Reference Module in Earth Systems and Environmental Sciences. Elsevier.
- Peyton, R.L., Haeffner, B.A., Anderson, S.H., Gantzer, C.J., 1992. Applying X-ray CT to measure macropore diameters in undisturbed soil cores. *Geoderma* 53 (3–4), 329–340.
- Postma, J.A., Kuppe, C., Owen, M.R., Mellor, N., Griffiths, M., Bennett, M.J., Lynch, J.P., Watt, M., 2017. OpenSimRoot: widening the scope and application of root architectural models. *New Phytol.* 215, 1274–1286.
- Pound, M.P., Atkinson, J.A., Townsend, A.J., Wilson, M.H., Griffiths, M., Jackson, A.S., Bulat, A., Tzimiropoulos, G., Wells, D.M., Murchie, E.H., Pridmore, T.P., French, A.P., 2017. Deep machine learning provides state-of-the-art performance in image-based plant phenotyping. *GigaScience* 6 (10), 1–10.
- Rao, S., Meunier, F., Ehosioke, S., Lesparre, N., Kemna, A., Nguyen, F., Garré, S., Javaux, M., 2018. A mechanistic model for electrical conduction in soil-root continuum: a virtual rhizotron study. *Biogeosciences Discussions*.
- Revil, A., 1999. Ionic diffusivity, electrical conductivity, membrane and thermoelectric potentials in colloids and granular porous media: a unified model. *J. Colloid Interface Sci.* 212, 503–522.
- Revil, A., Cathles, L.M., Losh, S., Nunn, J., 1998. A Electrical conductivity in shaly sands with geophysical applications. *J. Geophys. Res.* 103, 23925–23936.
- Revil, A., Glover, P., 1997. Theory of ionic-surface electrical conduction in porous media. *Phys. Rev. B – Condensed Matter Mater. Phys.* 55 (3), 1757–1773.
- Rhoades, J., Manteghi, N., Shouse, P., Alves, W., 1989. Soil electrical conductivity and soil salinity: new formulations and calibrations. *Soil Sci. Soc. Am.* 53, 433–439.
- Robinson, J.L., Slater, L.D., Schäfer, K.V., 2012. Evidence for spatial variability in hydraulic redistribution within an oak-pine forest from resistivity imaging. *J. Hydrol.* 430–431, 69–79.
- Romero-Ruiz, A., Linde, N., Keller, T., Or, D., 2018. A review of geophysical methods for soil structure characterization. *Rev. Geophys.* 56 (4), 672–697.
- Rossi, R., Amato, M., Bitella, G., Bochicchio, R., Ferreira Gomes, J.J., Lovelli, S., Martorella, E., Favale, P., 2011. Electrical resistivity tomography as a non-destructive method for mapping root biomass in an orchard. *Eur. J. Soil Sci.* 62 (2), 206–215.
- Sabo, D., McMurray, G., Rains, G., 2016. Presymptomatic disease detection and nanoparticle-enhanced electrical capacitance tomography. *IFAC-PapersOnLine* 49 (16), 116–120.
- Sabo, D., McMurray, G., Rains, G., 2016. Root monitoring system using electrical capacitance tomography (ect) for pre-symptomatic disease detection. *ASABE Annual International Meeting*.
- Samouëlian, A., Cousin, I., Tabbagh, A., Bruand, A., Richard, G., 2005. Electrical resistivity survey in soil science: a review. *Soil Tillage Res.* 83, 173–193.
- Schnepf, A., Leitner, D., Landl, M., Lobet, G., Hieu, T., Morandage, S., Sheng, C., Zörner, M., Vanderborght, J., 2017. CRootBox: a structural-functional modelling framework for root systems. *Ann. Bot.* 121 (5), 1033–1053.
- Schwan, H., 1957. Electrical properties of tissue and cell suspensions. *Adv. Biol. Med. Phys.* 5, 147–209.
- Schwartz, N., Furman, A., 2015. On the spectral induced polarization signature of soil organic matter. *Geophys. J. Int.* 200, 589–595.
- Segal, E., Kushnir, T., Mualem, Y., Shani, U., 2008. Water Uptake and Hydraulics of the Root Hair Rhizosphere. *Vadose Zone J.* 7 (3), 1027–1034.
- Srayeddin, I., Doussan, C., 2009. Estimation of the spatial variability of root water uptake of maize and sorghum at the field scale by electrical resistivity tomography. *Plant Soil* 319 (1–2), 185–207.
- Topp, G., Davis, J., Annan, A., 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. *Water Resour. Res.* 14, 574–582.
- Tosatto, O., Belluco, E., Silvestri, S., Ursino, N., Comerlati, A., Putti, M., Marani, M., 2009. Reply to comment by L. R. Gardner on "Spatial organization and ecohydrological interactions in oxygen-limited vegetation ecosystems". *Water Resour. J.* 45, 2–5.
- Ursino, N., Cassiani, G., Deiana, R., Vignoli, G., Boaga, J., 2014. Measuring and modeling water-related soil-vegetation feedbacks in a fallow plot. *Hydrol. Earth Syst. Sci.* 18 (3), 1105–1118.
- Vanderborght, J., Huisman, J., Kruk, J., Vereecken, H., 2013. Geophysical methods for field-scale imaging of root zone properties and processes. In: *Soil-Water-Root Processes: Advances in Tomography and Imaging*. SSSA Special Publications, pp. 247–282.
- Vrugt, J., Hopmans, J., Simunel, J., 2001. Calibration of a two-dimensional root water uptake model. *Soil Sci. Soc. Am.* 65 (4), 1027–1037.
- Waxman, M., Smits, L., 1968. Electrical conductivities in oil-bearing shaly sands. *Soc. Petrol. Eng. J.* 243, 107–122.
- Weigand, M., Kemna, A., 2016. Debye decomposition of time-lapse spectral induced polarisation data. *Comput. Geosci.* 86, 34–45.
- Weigand, M., Kemna, A., 2017. Multi-frequency electrical impedance tomography as a non-invasive tool to characterize and monitor crop root systems. *Biogeosciences* 14 (4), 921–939.
- Weigand, M., Kemna, A., 2018. Imaging and functional characterization of crop root systems using spectroscopic electrical impedance measurements. *Plant Soil* 435, 201–224.
- Werban, U., Al Hagrey, S.A., Rabbel, W., 2008. Monitoring of root-zone water content in the laboratory by 2D geoelectrical tomography. *J. Plant Nutr. Soil Sci.* 171 (6), 927–935.
- Whalley, W.R., Binley, A., Watts, C.W., Shanahan, P., Dodd, I.C., Ober, E.S., Ashton, R.W., Webster, C.P., White, R.P., Hawkesford, M.J., 2017. Methods to estimate changes in soil water for phenotyping root activity in the field. *Plant Soil* 415 (1–2), 407–422.
- Wu, S.Y., Zhou, Q.Y., Wang, G., Liu, T.M., 2013. Response characteristics and tomographic monitoring of the electric capacitance after irrigation in the soil-plant (ginkgo tree) continuum in a laboratory. *Environ. Earth Sci.* 68 (3), 655–666.
- Zanetti, C., Weller, A., Vennetier, M., Mériaux, P., 2011. Detection of buried tree root samples by using geoelectrical measurements: a laboratory experiment. *Plant Soil* 339 (1), 273–283.
- Zelazny, L., He, L., Vanwormhoudt, A.M., 1996. Charge analyses of soils and anion exchange. *Methods of soil analysis, Part 3-Chemical methods*, pp. 1231–1255.
- Zenone, T., Gianfranco, M., Maurizio, T., Federico, F., Marco, M., Matteo, S., Alessio, A., Chiara, F., Tommaso, C., Guenther, S., 2008. Preliminary use of ground-penetrating radar and electrical resistivity tomography to study tree roots in pine forests and poplar plantations. *Funct. Plant Biol.* 35, 1047–1058.
- Zimmermann, E., Kemna, A., Berwix, J., Glaas, W., Vereecken, H., 2008. EIT measurement system with high phase accuracy for the imaging of spectral induced polarization properties of soils and sediments. *Meas. Sci. Technol.* 19 (9), 094010.