The geophysical toolbox applied to forest ecosystems – A review

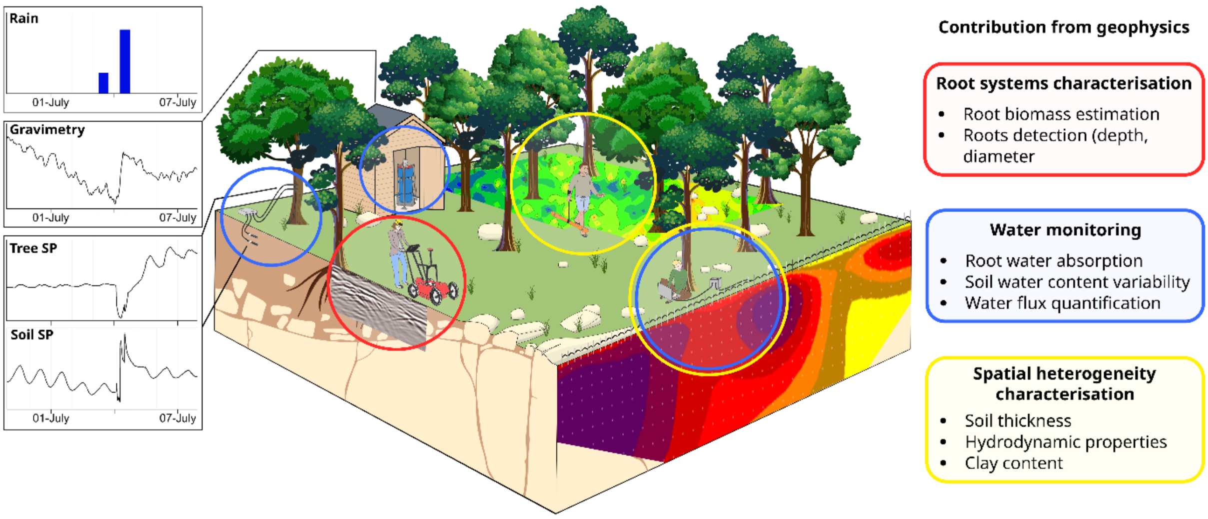
Bertille Loiseau, Simon D Carrière, Damien Jougnot, Kamini Singha, Benjamin Mary, Nicolas Delpierre, Roger Guérin, Nicolas Martin-StPaul

Accepted in Science of the Total Environment in July 2023

The geophysical toolbox applied to forest ecosystems – a review

Bertille Loiseau[1], Simon D. Carrière[1], Damien Jougnot[1], Kamini Singha[2], Benjamin Mary[3], Nicolas Delpierre[4, 5], Roger Guérin[1], Nicolas K. Martin-StPaul[6]

[1]UMR METIS, Sorbonne Université, UPMC, CNRS, EPHE, 75005 Paris, France
[2]Colorado School of Mines, Golden, CO 80401, USA
[3]Geoscience Department, University of Padova, 35100 Padova, Italy
[4]Université Paris-Saclay, CNRS, AgroParisTech, Ecologie Systématique et Evolution, 91405, Orsay, France
[5]Institut Universitaire de France (IUF), France
[6]URFM, INRAE, Domaine Saint Paul, Site Agroparc, 84000 Avignon, France



Highlights

- Near-surface geophysical methods can efficiently address forest ecology issues
- Geophysical methods provide spatial and temporal information on soils non-intrusively
- Geophysics can help to detect and describe tree root systems
- Geophysics allows to monitor the spatial distribution and dynamics of water
- Geophysics allows characterisation of spatial heterogeneity in subsurface properties

Keywords

Near-surface geophysics, forest ecology, ecohydrology, plant-soil interaction, critical zone, root zone

Abstract

Studying the forest subsurface is a challenge because of its heterogeneous nature and difficult access. Traditional approaches used by ecologists to characterize the subsurface have a low spatial representativity. This review article illustrates how geophysical techniques can and have been used to get new insights into forest ecology. Near-surface geophysics offers a wide range of methods to characterize the spatial and temporal variability of subsurface properties in a non-destructive and integrative way, each with its own advantages and disadvantages. These techniques can be used alone or combined to take advantage of their complementarity. Our review led us to define three topics how near-surface geophysics can support forest ecology studies: 1) detection of root systems, 2) monitoring of water quantity and dynamics, and 3) characterisation of spatial heterogeneity in subsurface properties at the stand level. The number of forest ecology studies using near-surface geophysics is increasing and this multidisciplinary approach opens new opportunities and perspectives for improving quantitative assessment of biophysical properties and exploring forest response to the environment and adaptation to climate change.

1. Introduction

Forests cover almost one third of the Earth's land area and are central in the carbon and water cycles. They form a major atmospheric carbon sink by storing about 25% of the annual anthropogenic CO_2 emissions (e.g., Friedlingstein et al., 2019). Forests also play an important role in the distribution of precipitation and continental water dynamics (e.g., Ellison et al., 2017). Transpiration accounts for about 60% of terrestrial evapotranspiration, the most important component of the water cycle, and the fraction is higher in forests (e.g., Schlesinger and Jasechko, 2014). Soil water availability is one of the most important factors regulating transpiration, biomass production and plant species distribution in ecosystems (e.g., Mathys et al., 2014; Rambal et al., 2003); however, recent work also suggests that woody plants are able to mobilize water stored deeper into the bedrock through pores and fractures, the so-called "rock moisture" (e.g., McCormick et al., 2021). The carbon and water cycles are closely linked and so understanding the functioning and evolution of forest environments and their relation to subsurface structure and water availability is essential to improve understanding of the water cycle under a changing climate. An increase of drought frequency and severity is observed in many regions, over most of Africa, Americas, southern Europe, the Middle East, Australia and Southeast Asia (e.g., Dai, 2013). Drought events strongly affect the biomass production and consequently carbon sequestration within forests (e.g., Fan et al., 2023; Liu et al., 2022).

We define the "forest subsurface" as the crucial compartment composed of soil and the weathered bedrock underneath, where water and roots activity are most important (from the surface to about <10 m depth). The forest subsurface is difficult to characterize due to high heterogeneity and rock fraction. Most of the methods classically used to study the subsurface of forest ecosystems are invasive, destructive, and provide a limited spatial representation (often measures at a point in space), such as soil pits, soil and root cores, excavation studies (e.g., Niiyama et al., 2010; Park et al., 2007), or soil moisture probes (e.g., Robock et al., 2000). More integrative methods that can support or extend these conventional methods non-destructively and allow spatially (e.g., at the stand level) and temporally (e.g., seasonal, annual) extensive monitoring would help to quantify subsurface heterogeneity as well as changes in soil and rock moisture over larger scales.

Near-surface geophysics (usually up to tens of metres depth) offers a wide range of methods to characterize the subsurface and associated processes that occur in the critical zone, which is defined from the top of the canopy to the bottom of groundwater (e.g., Banwart et al., 2013; National Research Council (NRC), 2001; Parsekian et al., 2015). These methods estimated different physical properties, such as density, resistivity or seismic velocities, in an active or passive manner (Table 1). Initially, geophysical exploration methods were largely developed for mining and petroleum prospecting, which include investigations up to a kilometre in depth with low resolution varying according to the depth, ranging from ten to a hundred metres (e.g., Dobrin and Van Nostrand, 1956; Hatherly, 2013). More recently, geophysics has been used to explore water-related issues at shallower investigation depths (a few metres to a hundred metres) with better resolution (meter to decimeter), leading to the field of hydrogeophysics (e.g., Auken et al., 2009; Binley et al., 2015; Chen, 2022; Guérin, 2005; Hermans et al., 2022; Hubbard and Linde, 2005; Robinson et al., 2008). Hydrogeophysics encompasses studies that use geophysical methods to characterize hydrologic systems including complex aquifer reservoirs such as karst (e.g., Chalikakis et al., 2011), hydrodynamic properties of aquifers (e.g., Vouillamoz et al., 2012), groundwater flow (e.g., Jougnot et al., 2020; Revil and Jardani, 2013), and water dynamics in soils (e.g., D. Robinson et al., 2008). Additionally, challenges associated to agronomy have been explored, including the characterization of hydrodynamic properties of agricultural soils (e.g., Besson et al., 2010; Doussan and Ruy, 2009), water use by crops (e.g., Michot et al., 2003; Srayeddin and Doussan, 2009), soil heterogeneity (e.g., Séger et al., 2014), soil depth (e.g., Doolittle et al., 1994), or for the study of other properties such as porosity, density, clay content or salinity (e.g., Romero-Ruiz et al., 2018). The operational goal of these studies is to use geophysics for agricultural planning and management (e.g., Allred et al., 2008; Samouëlian et al., 2005) and agrogeophysics is becoming recognized as an independent discipline (e.g., Garré et al., 2021).

More recently, geophysicists have become interested in the study of the forest subsurface while ecologists have shown interest in geophysical methods to better understand these complex and heterogeneous environments (e.g., Jayawickreme et al., 2014). Both want to determine the structure and composition below the Earth's surface (e.g., Bréchet et al., 2012; Fäth et al., 2022; Yan et al., 2013) and to characterise the properties and water dynamics that occur there in relation to the vegetation (e.g., Carrière et al., 2021b; Dick et al., 2018; Voytek et al., 2019). Imaging methods are not limited to the subsurface characterisation and are also used to image tree trunks (see the Supplementary Material), understand the anatomical structure of trees (e.g., Al Hagrey, 2007) and their health status (e.g., Goh et al., 2018; Martin et al., 2021), as well as exploring connections in the soil-plant-atmosphere continuum (e.g., Gibert et al., 2006; Harmon et al., 2021; Mares et al., 2016).

In this article, we propose to review the growing interest in the use of near-surface geophysics to explore issues in forest ecology as illustrated in Fig. 1. This review article will only focus on the study of the forest subsurface and make a small aside in supplementary material on the study of tree trunks. The first part of this paper summarizes the geophysical methods primarily used in forested systems, their principles, and their implementation to forest systems. The second part is devoted to state-of-the-art geophysical applications organized around three forest ecology issues: 1) detection of root systems, 2) monitoring of water quantity and dynamics, and 3) characterisation of spatial heterogeneity in subsurface properties at the stand level.

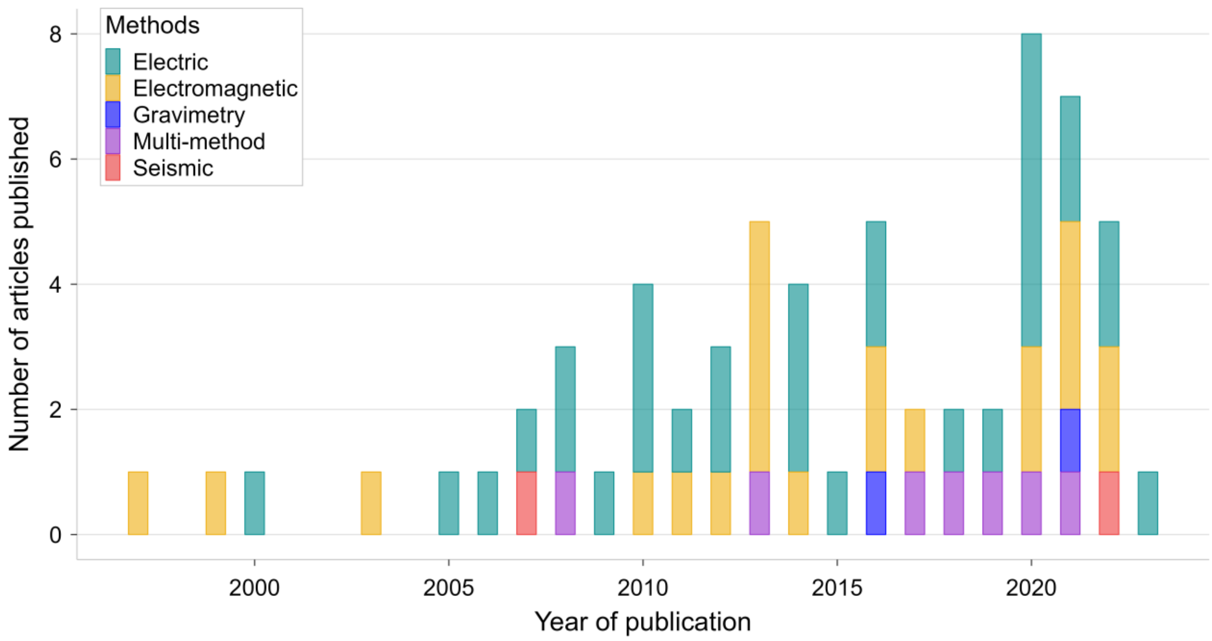


Figure 1: Evolution of the published papers number using near-surface geophysics in forests or on isolated trees to study forest ecology issues. Articles in this graph are mentioned in the second part "Geophysical applications for forest ecology" of this review. The initial keywords used in Google scholar to identify the articles were "forest ecology" and "geophysics" and then the different names of the geophysical methods. The articles were classified according to their applications, and then other articles were identified using the highlighted topics as keywords.

2. Geophysical methods

Near-surface geophysics encompasses a variety of imaging methods and sensing techniques (active or passive, i.e. using artificial or natural sources) allowing 1D (time series), 2D (map or cross section) or a 3D view of the subsurface with possible temporal monitoring (4D) (Hermans et al., 2022). These images provide information on the geometry and physical properties of the subsurface as well as the movement of fluid in the subsurface. The depth of investigation of each technique is variable and generally depends on the physics of the method, the physical properties of the subsurface, as well as the acquisition set-up. Four methods applied to forest ecology studies currently exist in the literature: electrical, electromagnetic, seismic and gravimetric. This section introduces these different techniques, where case studies using these methods are reviewed in the following section.

2.1. Electrical methods

2.1.1. Electrical resistivity tomography (ERT)

Electrical resistivity tomography (ERT), also called electrical resistivity imaging (ERI), is an active geophysical technique based on the measurement of the electrical resistivity ρ (in Ω.m) or its reciprocal, electrical conductivity $\sigma=1/\rho$ (in S/m). Electrical resistivity is affected by properties such as texture and structure of the medium (e.g., porosity, fracturing), lithology (e.g., clay content), fluid saturation (e.g., water saturation), chemical compositions of the pore water (e.g., salinity) or temperature (for a complete review, see Glover, 2015). Pedophysical (or petrophysical) relationships exist to quantitatively relate electrical resistivity to these different parameters (e.g., Firedman, 2005; Samouëlian et al., 2005; Laloy et al., 2012). The measurement consists of injecting a direct current into the soil through two electrodes (the “transmitter dipole”) hammered into the soil. An electrical voltage difference generated by this injection is measured between another couple of electrodes (the "receiver dipole"). The electrical resistivity is calculated according to Ohm's law using the measured potential difference, the injected current and the electrode position (called the geometric factor).

Measurements are repeated with different combinations of position and electrode spacing to prospect different locations and depth (Fig. 2E). Different types of electrode arrays exist (e.g., Wenner, Schlumberger, dipole-dipole), each with their own advantages and limitations in terms of resolution, maximum depth of penetration or artefact production (Dalhin and Zhou, 2004). This process provides a map, called a pseudo-section, of the "apparent" resistivity according to a pseudo-depth depending on the spacing between the electrodes. The spatial distribution of "true" resistivity as a function of true depth can only be determined by the inversion of the pseudo-section using a discretized numerical model (e.g., Günther, 2004; Loke, 1999). ERT inversion results in a 2D map (Fig. 2E) or 3D view of the electrical resistivity of the subsurface, depending on the chosen electrode setup in the field. The investigation depth and the resolution depends on the electrode array, the spacing of electrodes (where the depth increases but the resolution decreases with increasing electrode spacing) and the electrical resistivity distribution of the medium. We point the reader to Binley and Kemna (2005) or Singha et al. (2022) for more information on ERT data collection and analysis.

2.1.2. Mise-à-la-masse (MALM)

MALM (Mise-à-la-masse) is an active geophysical technique based on the measurement of the electrical potential field, similar to ERT, but instead one current electrode located in the conductive body (like a mineral or a plant) and one measuring electrode moved for a certain arrangement of potential electrodes at the surface near the conductive body. The two other electrodes are placed at a large ("infinite") distance from the conductive body. We point the reader to Parasnis (1967) for more information on MALM data collection and analysis. A similar "stem-based" approach, called capacitance method, consists of positioning the injection electrode in the stem and then measuring the electrical capacitance at several places in the soil. For a full description of electrodes configurations and operating frequencies possible in stem based acquisition we invite the reader to refer to the Fig. 2 of Ehosioke et al. (2020).

Like with ERT, MALM investigation depth and resolution depends on the electrode geometry and the physical properties of the conductor. The acquisition time depends on the number of measurement points made and the size of the study area (Table 1). MALM results are generally presented in an equipotential map, which inform about the extension of the conductive body. To interpret the results, it is possible to invert for the current density distribution (e.g., Binley et al., 1997; Peruzzo et al., 2020). One advantage of MALM over ERT is the ability to sense directly the targeted object (tree roots for example), one disadvantage is that it does not allow to obtain such a detailed vertical distribution in its classical use.

2.1.3. Induced polarization (IP)

Induced polarization (IP), sometimes called electrical impedance tomography (EIT), is an active geophysical technique based on the joint measurement of the electrical resistivity and the chargeability of the environment. Chargeability is the measure of the electrical relaxation of the medium after injection of an electric current. It describes the polarisation capacity of the medium, which is the ability to store charge. The medium stores current and releases it over a certain period of time (usually fractions of a second) depending on its mineralogy and pore water chemistry. This method brings complementary information to ERT such as the mineralogy and texture, and is also sensitive to biogeochemical activity (e.g., Kessouri et al., 2019).

The principle and field implementation of IP is similar to ERT (Fig. 2E). IP acquisition is done using electrodes with variable inter-electrode spacing according to the desired resolution and investigation depth. The investigation depth and the resolution are correlated and evolve similarly to ERT. The acquisition time is longer than for ERT (easily doubled, Table 1) since this technique generally requires longer pulse durations for the medium to release sufficient current to be reliably recorded. The apparent chargeability measured in the field needs to be inverted to obtain a true chargeability model. IP results are generally presented in 2D maps, 3D blocks or 1D curves showing physical properties as a function of frequency or distance to current electrodes (Zonge et al., 2005). We point the reader to Kemna et al. (2012) and Singha et al. (2022) for more information on IP data collection and analysis.

2.1.4. Self-potential (SP)

Self-potential (SP) is a passive geophysical technique based on the measurement of the natural electrical field that is due to natural current circulating in the subsurface. These natural currents can be generated by various physical and biochemical processes such as water flow, ionic diffusion, or redox reactions. In environmental sciences, SP is generally used to study the spatial and temporal variability of i) water flow (e.g., Hu et al., 2020; Jardani et al., 2006), ii) contaminant transport and/or iii) biogeochemical activity (e.g., Naudet et al., 2003).

This geophysical technique is probably the simplest to implement as it only requires (at least) two non-polarizable electrodes in contact with the soil or plant and a high-impedance voltmeter. Nevertheless, Nyquist and Corry (2002) stated that it is arguably one of the most difficult to interpret due to the multiplicity of possible sources. This technique was classically deployed on the field through 1D profiles and 2D mapping to study the spatial variability of the signal; however, SP electrodes can be deployed like distributed sensors in 3D (buried at different locations and depths), able to acquire time series (Table 1), to monitor time-varying processes (e.g., Voytek et al., 2019) (Fig. 2B). The SP signal is an integrated result of the processes occurring between the electrodes, therefore, the concept of investigation depth cannot be applied to it unlike with the active methods described above. Natural electrical field are typically smaller than the ones generated by ERT control units, nevertheless, SP measurements span between few millivolts to several hundreds of millivolts depending on the electrode spacing, the soil resistivity, and the source of the signals. A qualitative analysis of SP data can be done with a limited data processing, whereas quantitative analysis requires numerical modelling and inversion procedures (e.g., Voytek et al., 2019). We point the reader to Jouniaux et al. (2009) and Revil and Jardani (2013) for more details on SP data collection and analysis.

2.2. Electromagnetic methods

2.2.1. Electromagnetic induction (EMI)

Electromagnetic induction (EMI), also called frequency-domain electromagnetism (FDEM), is an active geophysical technique based on the principle of electromagnetic (EM) induction. This technique determines the electrical conductivity of an environment without contact with the ground (Fig. 2D). Consequently, it is a rapid technique for data collection that can cover large areas (e.g., several hectares per day, Table 1). This technique consists in generating an EM field (frequencies between 0.1 and 20 kHz) with a transmitter coil. When this EM field diffuses into the ground, it generates electric currents. The currents generate a secondary EM field measured by the receiver coil. The measured electrical conductivity is proportional to the secondary EM fields.

The investigation depth of the commercial devices range between 0.2 m to a few tens of meters. The depth increases with the spacing between transmitter and receiver coils and the power of EM field as generated by the instrument. The results are generally expressed as 2D maps of the electrical conductivity (Fig. 2D). We point the reader to Allred et al. (2008) or Doolittle and Brevik (2014) for more details on EMI data collection and analysis.

2.2.2. Ground penetrating radar (GPR)

Ground penetrating radar (GPR) is an active geophysical technique based on the propagation of an EM wave pulse in the subsurface and its reflection at interfaces (e.g., faults, centimetric roots, geological strata, or the water table). The propagation of EM waves is influenced by the electrical permittivity. Permittivity contrasts generate interfaces that be detected by the GPR. For example, soil water content variation can cause changes in permittivity that can be analyzed in the GPR signal.

GPR is a fairly quick technique because there is nothing to install in the ground (Fig. 2A). There are two antennas—one transmitter and one receiver—that can be dragged on the ground, or even raised above the ground in the case of air-coupled antennas. Several kilometres of profiles can be collected per day depending on the site conditions (Table 1). Many frequencies are available in commercial devices, usually from a few tens of megahertz to a few gigahertz. Investigation depth and resolution are related to the frequency used. For the highest frequencies (GHz) these antennas allow investigation of targets from a few tens of cm with a resolution of the order of a mm, whereas for the lowest frequencies (MHz) the investigation depth can be close to 10 m with a resolution of the order of 1 m under favorable conditions (Hruska et al., 1999; Raz-Yaseef et al., 2013). However, the resolution and the investigation depth can be drastically diminished depending on the subsurface properties, especially in high electrical conductivities. Typically, the presence of clay or any conductive structure/layer/object (as soil saturated with water) produces a strong attenuation of EM waves (Doolittle et al., 2007).

Data processing consists in eliminating noise, amplifying the desired signals, and converting time to depth using the electromagnetic wave velocities. The results are generally expressed as 2D sections (Fig. 2A) or 3D blocks, allowing the user to identify reflectors such as geological interfaces, the water table, or roots. We point the reader to Huisman et al. (2003) or Allred et al. (2008) for more details on GPR data collection and analysis.

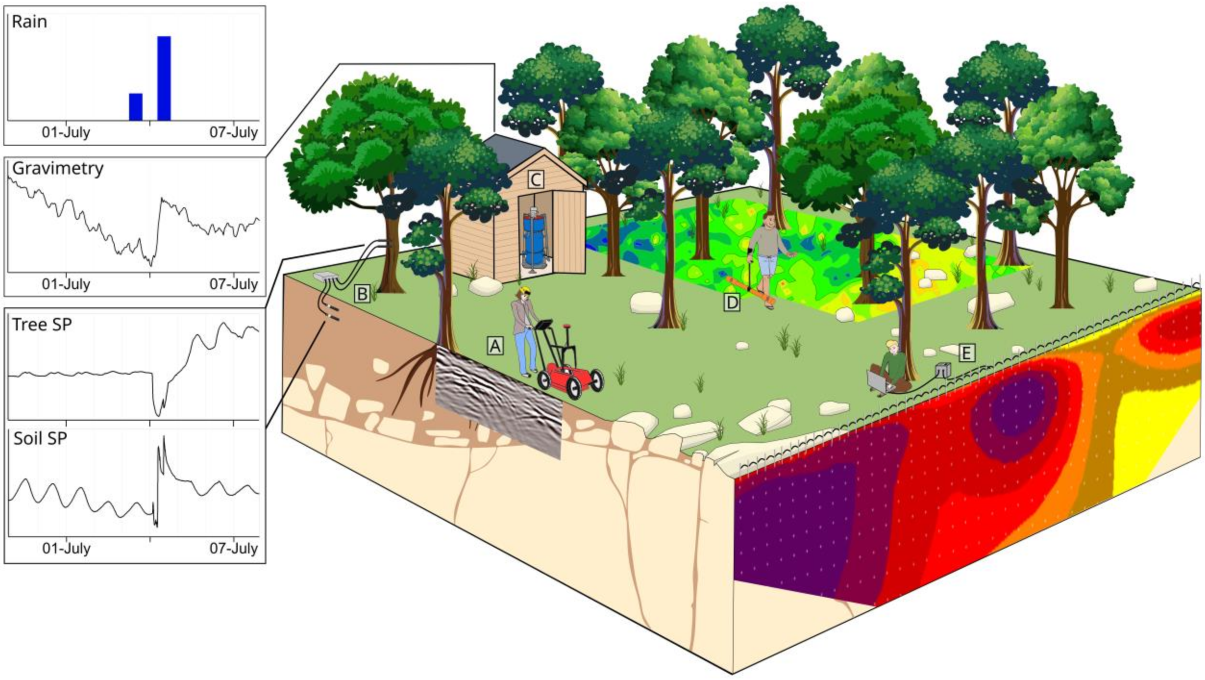


Figure 2: Field implementation of geophysical techniques mostly discussed in this review article. For each technique an example of result is given: here time-series, cross-section, and map. Methods illustrated are A) ground penetrating radar (GPR), used to detect coarse roots; B) self-potential (SP), used to monitor water flow; C) gravimetry, used to monitor water stores; D) electromagnetic induction (EMI), used to characterise the spatial heterogeneity of subsurface properties; and E) electrical resistivity tomography (ERT), used to characterise the spatial heterogeneity of subsurface properties and possibly monitor water dynamics. The implementation of ERT also works for IP (and MALM as long as two electrodes are positioned at an "infinite" distance and one electrode is placed in the stem of the tree). Seismic methods are not represented, but the implementation of seismic tomography is similar to that of ERT by replacing the electrodes with geophones and the transmitter is a shot, and it is also used to map spatial heterogeneity of subsurface properties.

2.3. Seismic methods

Seismics are usually active geophysical methods, based on the analysis of acoustic wave propagation in soils and rocks. We note that passive seismic methods exist, but are not described here, given limited use in ecologic systems to date. Several sources of energy can be used to generate acoustic waves depending to the desired investigation depth (e.g., sledgehammers, shotguns, vibroseis trucks). A line of geophones (receivers) is installed on the surface to detect wave propagation in a similar way as the ERT electrodes are installed in Fig. 2E. There are different techniques that study different types of seismic waves; for example, seismic refraction, reflection and surface waves. Articles presented in this review describe seismic refraction, which is used to characterize the nature and structure of the subsoil (e.g., wave velocities, thickness, alteration, fracturing, water table). Refraction consists of recording the propagation times of the waves between the source and the geophones multiple times to increase the signal-to-noise ratio. Other seismic techniques are less frequently used that refraction given the noisy near-surface environment as well as the time and/or effort to collect and analyze data.

Seismic methods produce cross-sections that are often complementary to ERT because they are sensitive to mechanical physical properties rather than electrical ones. They produce similar section (2D, Fig. 2A) or blocks (3D) as those obtained with GPR, representing wave arrival times as a function of distance from the signal source. Investigation depth and resolution depend on the length of the geophone array and the spacing between the geophones (the depth increases but the resolution decreases with increasing geophone spacing). Once the data have been processed, interpretation is usually done from inverted models (e.g., Mendes, 2009; Palmer, 1980). Seismic tomography, also called acoustic/sonic/ultrasonic tomography, or inversion, requires more time-consuming data post-processing than ERT, as it is necessary to study each waveform to determine the wave velocity through a first arrival picking procedure. Inversion then produces a 2D map similar to ERT (Fig 2E). We point the reader to Sheriff and Geldart (1995) for more details on seismic data collection and analysis.

2.4. Gravimetry

Gravimetry is a passive geophysical method based on the measure of the Earth's gravity field (Fig. 2C). This technique is sensitive to the spatial and temporal variations in density of the near surface. The gravity signal is influenced by several global and regional sources such as tides, the motion of the Earth's rotation pole, or atmospheric and hydrological loads; the magnitudes of these effects are summarised in Kumar et al. (2021). Due to the integrative nature of gravity measurements, the concept of investigation depth cannot therefore be applied to it, similar to SP.

There are different types of gravimeters; some are mobile and are used for single measurements that can be repeated over time, others are fixed and make continuous measurements. Articles in this review dealing with gravimetry use superconducting gravimeters (Fig. 2C), which are fixed instruments that can acquire data every second (Table 1) (Hinderer al., 2015). These instruments are extremely accurate and record gravity variations of the order of nm/s^2. In studies of the critical zone, the gravity signal is generally processed to eliminate global signals and highlight hydrological ones (e.g., Fores et al., 2017). Signal processing is done using established models; for example, MERRA2 is used to correct pressure effects (Gelaro et al., 2017) or ETERNA 3.4 is used for tidal effects (Wenzel, 1996). The gravity residuals, i.e. the gravity signal after processing and correction of the data, is then correlated to variations in water storage, gravity increases after the rains and decreases during the dry seasons (Fig. 2C). We point the reader to Crossley et al. (2013) or Van Camp et al. (2017) for more details on gravimetric method data collection and analysis.

3. Geophysical applications for forest ecology

The aim of this section is to present studies in which the geophysical methods outlined above have been used to address forest ecology issues. The section is organised around the three topics: 1) detection of root systems, 2) monitoring of water quantity and dynamics, and 3) characterisation of spatial heterogeneity in subsurface properties at the stand level. The review below explores the use of geophysical methods in forest ecosystems as well as supporting studies in laboratories or on trees outside of forests that could address forest-focused issues or be applied in forests in the future.

3.1. Detection of root systems

The rooting system plays a critical role in tree structure and stabilization and determines water and nutrient acquisition. It also represents a considerable amount of biomass and carbon storage (e.g.,

Brunner and Godbold, 2007). The rooting system in the soil could produce preferential pathways for gravitational drainage into the deeper soil.
In the last decades, several approaches have been developed to detect the root system (e.g., Cabal et al., 2021). Root extraction is the most common method, which is done by excavation or soil sampling (e.g., Butnor et al., 2003; Day et al., 2013). This approach is highly destructive and does not provide spatial information without difficulties. The rhizotron is a second method of observation; it consists of digging a hole to visualize the roots in the soil over time using a camera (e.g., Arnaud et al., 2019; Postic et al., 2019) or via direct observation (e.g., Klepper and Kaspar, 1994). This method has the advantage of monitoring root development but is intrusive and also makes the spatial coverage difficult. Moreover, the implementation of these methods can be complex depending on the nature of the subsurface, especially in environments where soils can be stony. Geophysical methods offer prospects to characterise root systems architecture spatially and non-destructively as a complement to conventional methods.

GPR is the principal geophysical method used to detect coarse roots (e.g., Alani and Lantini, 2020; Cabal et al., 2021; Lorenzo et al., 2010). This technique is sensitive to roots of at least a few millimetres in diameter. Roots appears as reflectors of EM waves. Cross-sectional images (Fig. 2A) can map root system architecture or be used to estimate root frequency (on the cm scale) categorized diameter classes (e.g., Cabal et al., 2021; Lorenzo et al., 2010). Studies using GPR focusing on root systems have attempted to estimate various properties related to root system biomass, architecture and root traits in forests using frequencies between 400 MHz and 1.5 GHz (e.g., Hruska et al., 1999; Raz-Yaseef et al., 2013). Efforts currently exist to estimate root traits using GPR in various soil conditions from homogeneous to complex and heterogeneous soils. For instance, Day et al. (2013) reported that biomass estimation of roots larger than 5 mm in diameter using GPR (1.5 GHz) in fairly homogeneous soils in a subtropical forest was comparable to estimates from soil pits and superior to those obtained with soil cores. Molon et al. (2017) demonstrated in a temperate forest that 3D GPR (1 GHz) can map root architecture in low-heterogeneity soils and obtain estimates of spatial variability in biomass distribution over large areas. Some authors studying forests in humid subtropical climate still warn that some types of roots, such as taproots, are difficult to detect because of their generally vertical orientation which does not produce reflection events (Butnor et al., 2003). For the same reason, roots below the stump are generally underestimated (Butnor et al., 2016). Raz-Yaseef et al. (2013) and Rodríguez-Robles et al. (2017) used GPR (1 GHz and 500 MHz respectively) on poorly developed rocky soils in a semi-arid climate. They validated the use of GPR to map coarse roots and estimate their biomass. Rodríguez-Robles et al. (2017) identified roots of different diameters at different depths in the soil or in rock fractures. We note that factors such as root spacing, changes in water content or surrounding conditions like the presence of stones affect the detection of roots using GPR and can lead to misinterpretation (Hirano et al., 2009).

Other studies have attempted to use GPR to answer ecological or evolutionary questions. For instance, Yan et al. (2013), Xiao et al. (2021) and Zhang et al. (2021) sought to understand the spatial distribution of root systems using GPR. Zhang et al. (2021) studied the root system of Mongolian pines in a semi-arid climate in relation to their age to understand competition for water. They observed an increase in root area with age followed by a decrease after 50 years. Yan et al. (2013) and Xiao et al. (2021) explored the abiotic and biotic factors that affect the spatial distribution of roots in subtropical forests. Yan et al. (2013) studied three habitats (ridge, slope and valley) and the dominant tree species on each.

They found that the lowest root density was on the slope and that the species *Castanopsis eyrei* had more roots distributed in deep soils than Shorea *superba*. The results of Xiao et al. (2021) indicated that root system growth and rhizome diameter are significantly correlated with soil moisture content, alkali-hydrolysed nitrogen and available phosphorus. In another example, Lombardi et al. (2021) used GPR (800 MHz) to estimate root depth, diameter and frequency of different Aleppo pine (*Pinus halepensis*) populations growing in a common garden in a Mediterranean climate. Their results suggest that rooting system traits were related to the climatic conditions of the tree population's origin and thus that GPR can be used as a high throughput phenotypic tool to target key adaptive traits.

The application of other geophysical techniques to explore root systems, such as seismics, IP and electrical stem-based approaches (including MALM), has been limited at this stage. Preliminary experiments in the laboratory and around single trees have used seismic tomography to detect soil roots (Buza and Divós, 2016; Mary et al., 2015; Proto et al., 2020). However, all of these authors reported that seismic tomography can only detect roots close to the surface (30-50 cm) and Proto et al. (2020) stated that the estimation of their diameter was not reliable. Mary et al. (2017) tested IP to detect tree roots in the laboratory and then field settings around a poplar (*Populus alba L.*). The roots polarized at lower frequencies than the soil and the effects of polarisation increased with the volume of buried roots. Since Dalton's (1995) proposal of a model for interpreting plant root capacitance results, stem-based methods have been developed over the course of several years. The model suggests that the current distributes evenly throughout the root system (Dalton, 1995). Studies from Čermák et al. (2013) and Cseresnyés et al. 2018 support this assumption, while others including Dietrich et al (2012) and Peruzzo et al. (2021), have questioned its validity. Consequently, there has been a growing interest in investigating the extent to which Dalton's theory holds true. Advanced processing techniques have been employed in studies by Peruzzo et al. (2020), Mary et al. (2019, 2018, and 2023) to gain insights into the distribution of current sources.

Studies have also used ERT to image the plant root zone and thus to indirectly detect the root biomass in forests (Zhao et al., 2019). Changes in moisture variations in the soil have been associated with root activity (Amato et al., 2008; Balwant et al., 2022). ERT is often used to complement GPR as in the studies by Zenone et al. (2008) and Rodríguez-Robles et al. (2017) in sub-humid Mediterranean and semi-arid climates respectively, where they show a correlation between soil moisture changes and the spatial distribution of roots.

3.2. Monitoring of water quantity and dynamics

Trees extract water and dissolved minerals from the soil and the parent rock (e.g., McCormick et al., 2021), as basic elements necessary to their living tissues. Water is then released into the atmosphere through the process of transpiration, which permits to regulate leaf temperature. The circulation of water in the soil-plant-atmosphere continuum is directly limited by the availability of water for the trees in the subsurface.

Several approaches have been developed over the last decades to quantify and monitor water stocks and dynamics in the critical zone at different scales (e.g., D. Robinson et al., 2008). Soil moisture quantification is historically done by the gravimetric method, which consists in drying soil samples extracted from soil pits to determine the weight of water contained (e.g., Gardner et al., 2000). This approach can be tedious, offers low spatial representativeness and does not allow for monitoring because it is destructive. The volumetric water content in the subsurface is commonly estimated using time domain reflectometry (TDR) or frequency domain reflectometry (FDR) probes based on dielectric permittivity measurements (e.g., Schaap et al., 1997; Sutinen and Middleton, 2020). These techniques have the advantage of high temporal resolution; however, they collect measurements at a single point in space. Similar to these sensors, neutron probes are also used to estimate soil or rock water content (e.g., Bréda et al., 1995; Dymond et al., 2014). The lysimeter is the most direct and reliable method to measure soil water evolution (e.g., Müller and Bolte, 2009) but it is complex to implement, especially in heterogeneous environments such as forests. Consequently, geophysical techniques such as ERT, SP and gravimetry offer integrative and non-destructive methods that can be combined with the previous approaches to monitor geophysical properties (e.g., electrical resistivity and density) that are related to water stores or even water flow through space and time.

ERT is the primary geophysical method used to assess the spatial distribution of water in the forest subsurface (e.g., Cardenas and Kanarek, 2014; Davidson et al., 2011; Dick et al., 2018; Fan et al., 2015; Jayawickreme et al., 2010, 2008; Koch et al., 2009; Ma et al., 2014; Nijland et al., 2010; Robinson et al., 2012; Zhu et al., 2007; Peskett et al., 2020; Rieder and Kneisel, 2023). The relation between electrical resistivity measured from ERT and water content measurements has been verified with sensors such as TDR or neutron probes. For instance, Zhu et al. (2007) studied a Mongolian pine plantation in a continental climate and found strong correlations between measured water content and soil electrical resistivity. For example, they obtained a coefficient of determination of 0.88 (with a P-value of 0.00024) between electrical resistivity and surface water content up to 1.5 m for an electrode spacing of 1.5 m. It has to be highlighted that their monitoring was carried out over a short period of time in a reasonably homogeneous environment, which allowed them to neglect the influence of other parameters on the geophysical signal such as temperature or salinity. As with most geophysical techniques, care must be taken when interpreting electrical resistivity results because different factors can influence the signal (Koch et al., 2009; Paillet et al., 2010). Temperature is one of the main parameters to pay attention to: electrical resistivity can decrease by up to 2% when the temperature increases by 1°C (Campbell et al., 1949). Jayawickreme et al. (2010) noted that temperature variability accounted for about 20 to 45% of the change in resistivity between cold winter months and warm summer months in long-term monitoring in a temperate forest.

The spatial assessment of water resources in forests with ERT has allowed scientists to identify the forest hydrogeological networks for example connections between runoff and groundwater (e.g., Koch et al., 2009) or the primary water flow pathways of a forested hillslope by combining ERT and seismic refraction (e.g., Thayer et al., 2018). It has also allowed to assess the extent and depth of a coastal saltwater intrusion process in forests (e.g., Satriani et al., 2012) or to compare the water spatial distribution between wet and dry periods (e.g., Cardenas and Kanarek, 2014; Ma et al., 2014; Robinson et al., 2012). ERT provides a spatial dimension to assess water content variations. Water distribution in forest soils can be highly heterogeneous as observed with ERT by Ma et al. (2014) and Dick et al. (2018) in temperate forests. ERT has been used to explore the role of vegetation on water redistribution related to rainfall interception (Cardenas and Kanarek, 2014; Fan et al., 2015; Peskett et al., 2020) or to preferential flow along trunks and roots (Guo et al., 2020). Cardenas and Kanarek (2014) and Fan et al. (2015) used ERT on areas in subtropical climate and observed that the redistribution of water at the soil surface is related to vegetation density. They compared plots after rain events and observed that rainfall infiltration is higher and deeper in bare or plots with a low tree density when compared to plots with a higher tree density. The interception of rainwater by vegetation is a hypothesis that would explain the lower amount of water where vegetation is denser. Guo et al. (2020) confirmed the funnelling effect of trunks and roots on the redistribution of precipitation in the soil by combining ERT and GPR measurements. They showed that the identified wetted areas of an American beech in continental humid forest after pouring an equivalent of 12 mm of precipitation on the trunk corresponded to the root system areas detected with GPR.

ERT has been used to detect water movement in the soil related to the tree root activity in forests (e.g., Ain-Lhout et al., 2016; Davidson et al., 2011; Dick et al., 2018; Fäth et al., 2022; Guerra, 2020; Jayawickreme et al., 2008; Mares et al., 2016; Robinson et al., 2012; Thayer et al., 2018). For example, Robinson et al. (2012) and Ain-Lhout et al. (2016) observed differences in the dynamics of electrical resistivity related to soil moisture between forested and bare plots in humid subtropical and semi-arid Mediterranean climate respectively. Comparing ERT signals between wet and dry periods, these authors found that water content fluctuations are more stable under trees than under the bare soil control, which they explain by root regulation and hydraulic redistribution. Root uptake zones can also be identified through spatio-temporal monitoring (e.g., Amato et al., 2008; Balwant et al., 2022; Davidson et al., 2011; Jayawickreme et al., 2008; Mares et al., 2016; Thayer et al., 2018; Zenone et al., 2008). Thayer et al. (2018) studied a forested subalpine hillslope and observed a relationship between tree transpiration estimated from sap flow sensors and soil water content estimated from ERT measurements. Their observations allowed them to suggest that trees can use water from the surface to at least 2.5 m depth. Differences in the depth of root water uptake have been observed between different vegetation types by Jayawickreme et al. (2008) or between different climatic conditions by Davidson et al. (2011). Jayawickreme et al. (2008) studied a forest-grassland ecotone in a temperate climate and observed deeper soil moisture changes under a forest (up to 5 m) than under a grassland (about 3 m) between the periods of early and maximum growth, suggesting deeper rooting under the forest. Similarly, Davidson et al. (2011) showed the important role of deep roots (over 11 m depth) in a rain-exclusion zone on an experimental plot in the Amazon rainforest when compared to a control plot. They found more intense soil drying at 11-18 m depth in the rain exclusion plot than in the control plot, noting a decrease of approximately 100 mm in water storage in this soil increment depth after three years of experimentation.

Moving towards a quantitative assessment of the spatial distribution of water extraction by vegetation in the subsurface may be best accomplished by coupling ERT and ecophysiological methods like sapflow. Mares et al. (2016) and Harmon et al. (2021) observed how a ponderosa pine (*Pinus Ponderosa)* in montane climate used different water sources to maintain transpiration flow using ERT, sapflow by heat dissipation, and ERT in the tree trunk (see more details on trunk geophysics in the Supplementary Material). Mares et al. (2016) showed how a tree's water source shifts from a shallow soil horizon at the beginning of the growing season to a deeper horizon later in the season. They observed that sapflow did not significantly decrease during the summer while the soil dries out, indicating access to a deeper source. Harmon et al. (2021) focused on the contribution of the internal water storage of the tree as a reservoir to support transpiration. Diel variations in sapwood electrical resistivity were observed from trunk ERT measurements. The results of electrical resistivity variations linked to water content variations follow the known water storage patterns in trees: water storage decreases from sunrise to early afternoon and increases in the late afternoon and evening. ERT monitoring showed that the use of the tree's internal water storage is highest a few days after storms and then decreases as drought conditions progress. Wavelet analyses showed that the time lag between sapwood flux and sapwood electrical resistivity are short under dry conditions and longer under wet conditions, implying that under drought conditions, tree water storage becomes increasingly important.

In order to obtain quantitative information on water stores, it is necessary to use models to interpret ERT measurements (e.g., Singha et al., 2015; Hermans et al., 2023). Combining geophysics with other methods or models can lead to reasonable estimates of localised fluxes. These combinations could help to parameterize and calibrate models simulating the soil-plant-atmosphere continuum, the functioning of plants in water-limited conditions and ultimately the survival of plants in an increasingly drier environment (e.g., Ruffault et al., 2022). Hydrodynamic properties of forest soils can be approximately estimated from ERT measurements. Conversions of electrical resistivity to water content can be done straightforward methods such as Archie (1942), which was used, for example, in the study of Dick et al. (2018) or Rieder and Kneisel (2023) in forests. However, this relationship is limited and cannot be used in all environments (e.g., Friedman, 2005; Samouëlian et al. 2005; Laloy et al., 2012) and rocks physics relationships are not rigorously correct in terms of their application to tomograms (Day-Lewis et al., 2005). There are other more elaborate methods, such as Waxman and Smits (1968), used for example in the laboratory study by Doussan and Ruy (2009) to estimate the water content and the hydraulic conductance of the soil. However, obtaining quantitative values of these properties from ERT remains challenging, especially in heterogeneous environments such as forests.

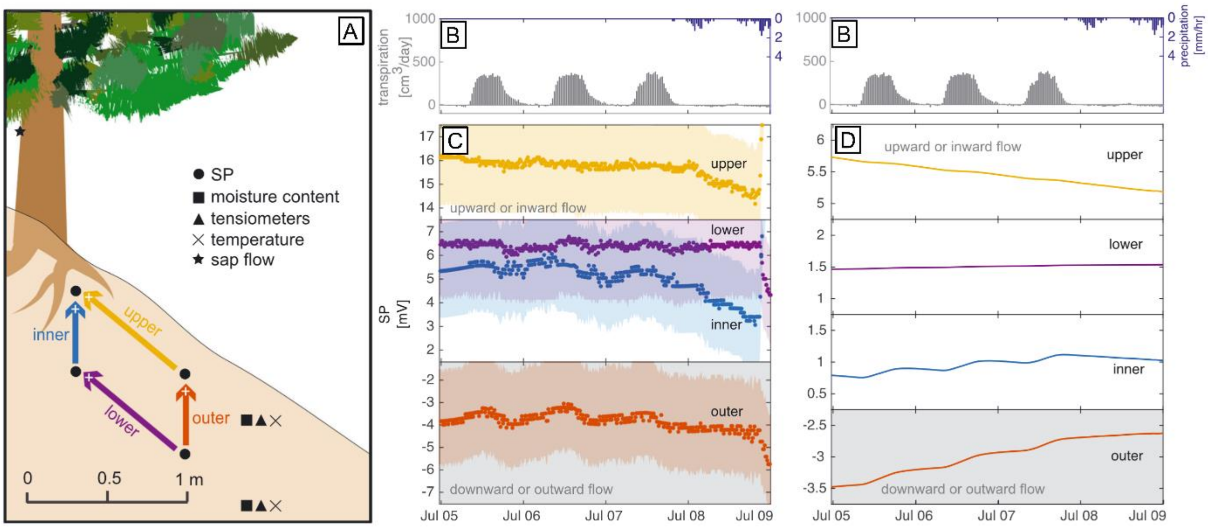


Figure 3: (A) Cross-sectional view of the SP sensor array relative to the selected tree. (B) Tree transpiration calculated from sapflow measurements and recorded precipitation. (C) Measured self-potential (SP) voltage differences between each pair of subsurface electrodes (labelled upper, lower, inner, outer in a). The shaded areas are the manufacturer-reported accuracy of measurements. (D) Simulated measured self-potential (SP) voltage differences between each pair of subsurface electrodes. (Modified from Voytek et al. (2019))

SP is another geophysical technique and has been used to directly study water flows in the soil-plant-atmosphere continuum. The SP signal is influenced by evapotranspiration (ET) because water flux in the soil or in trees generate small yet measurable electrical currents. Voytek et al. (2019) observe SP signals (Fig. 3C) in the subsurface of a temperate forest (Fig. 3A) influenced by tree transpiration dynamics as measured by a sapflow sensor (Fig. 3B). The development of a coupled fluid and electrical flow numerical model simulated transpiration generated a calculated SP signal similar to the observations (Fig. 3D). SP has also been used within the trunk to study tree transpiration; daily and seasonal variations in the SP electrical signal of tree trunks has been observed by Gibert et al. (2006) and Koppan et al. (2000) on individual trees in urban areas and Zapata et al. (2021) on several trees in a Mediterranean forest. A relationship between the SP signal and the measured sapflow has been observed by Gibert et al. (2006), but the two signals were not proportional. SP signals do not seem to be influenced by the position (height and orientation) of the electrodes in the tree (Gibert et al., 2006; Koppán et al., 2005; Zapata et al., 2020), but tree maturity seems to influence SP signals according to Zapata et al. (2020). They note that SP signals are stronger on younger trees. External parameters can also influence the SP signal such as meteorological phenomena. For instance, Zapata et al. (2021) found a strong correlation between rainfall and the SP signal in trees.

Promising results on the potential of superconducting gravimetry to estimate and quantify evapotranspiration fluxes at the stand scale have recently been shown. Gravimeters measure weight variations that occur below and above the instrument and these variations can be related to hydrological variations. Van Camp et al. (2016) compared variations in the stacked gravity signal over several days with those in the measured soil water content of a beech forest in a temperate climate. They interpreted the daily change in the gravity signal as water loss through evapotranspiration. Carrière et al. (2021a) showed a day-to-day correlation between the daily variation of gravity and the modelled ET of a Mediterranean holm oak (*Quercus ilex L.*) forest. In their study, the authors subtract the signal of two superconducting gravimeters superimposed onto each other with a 500 m altitude difference to achieve the accuracy needed to interpret the evapotranspiration signal. They observed variations in the gravity signal equivalent to water store variations in the order of a millimetre.

3.3. Characterisation of spatial heterogeneity in subsurface properties at the stand level

Local variations in soil properties (physical, chemical and biological) affect soil hydrological processes and thus have an impact on ecosystems structure and functioning (e.g., Vereecken et al., 2022). Fine-scale subsurface variations have often been neglected in forest ecology studies because limited tools exist to characterize the spatial variability of subsurface properties (e.g., Loke and Chisholm, 2022). Soil properties such as texture, water content or the chemical composition, are usually studied using soil samples. Characterising the spatial variability of these properties requires numerous samples to be taken on a regular grid, as in the study by John et al. (2007) with 253 samples over 25 ha in a tropical forest. However, spatial characterisation of soil heterogeneity using traditional methods is time-consuming and highly destructive. Geophysical methods can provide spatial information on geophysical properties that correlate with a number of subsurface physical properties (e.g., water content, soil thickness, soil type, salinity) to which plants may be sensitive. There are different forest ecology topics where the combination of geophysical methods with traditional soil and vegetation methods could provide important spatial insights, such as ecohydrology, or vegetation community dynamics or assembly.

The ecohydrological equilibrium theory (Eagleson, 1982) is a well-established hypothesis explaining that vegetation grows in equilibrium with the climate and the soil water availability. Correlation between leaf area index and climate have been reported, although soil water capacity is known to have an important role (Hoff and Rambal, 2003). Studies such as Ma et al. (2014) in temperate forest report strong correlations between vegetation characteristics (such as tree crown area and leaf area index) and the spatio-temporal pattern of soil moisture derived from ERT during the growing season.

Soil thickness is a factor in vegetation development as it affects the potential root volume and water available to plants. Holbrook et al. (2014) estimated the minimum water storage potential in the subsurface via weathering thickness obtained from the combination of seismic and ERT measurements. The influence of soil thickness on forest stand density has been studied with geophysics by Meyer et al. (2007) and Carrière et al. (2021b). Meyer et al. (2007) used seismic refraction to estimate the thickness of different soil horizons in a mixed montane coniferous forest and found that organo-mineral horizons are correlated with basal area and canopy cover. Carrière et al. (2021b) interpret the EMI signal (Fig. 4A) as variability in soil/weathered rock thickness in a Mediterranean karst forest, where the most electrically resistive zones (i.e. electrical conductivities below 4 mS/m) are those where the soil is least developed (i.e. mostly below 40 cm). They observe a positive correlation between the thickness of the soil and the production of biomass estimated using the plant area index (Fig. 4B). Indeed, in areas where the soil is more developed, the biomass is greater (Fig. 4C). These results are consistent with Eagleson's (1982) ecohydrological equilibrium theory. GPR has also been used in different climates (e.g., boreal, temperate) in forests to estimate the depth of soils (Sucre et al., 2011) or the thickness of the organic layer (Laamrani et al., 2013; Ryazantsev et al., 2022; Zajícová and Chuman, 2022).

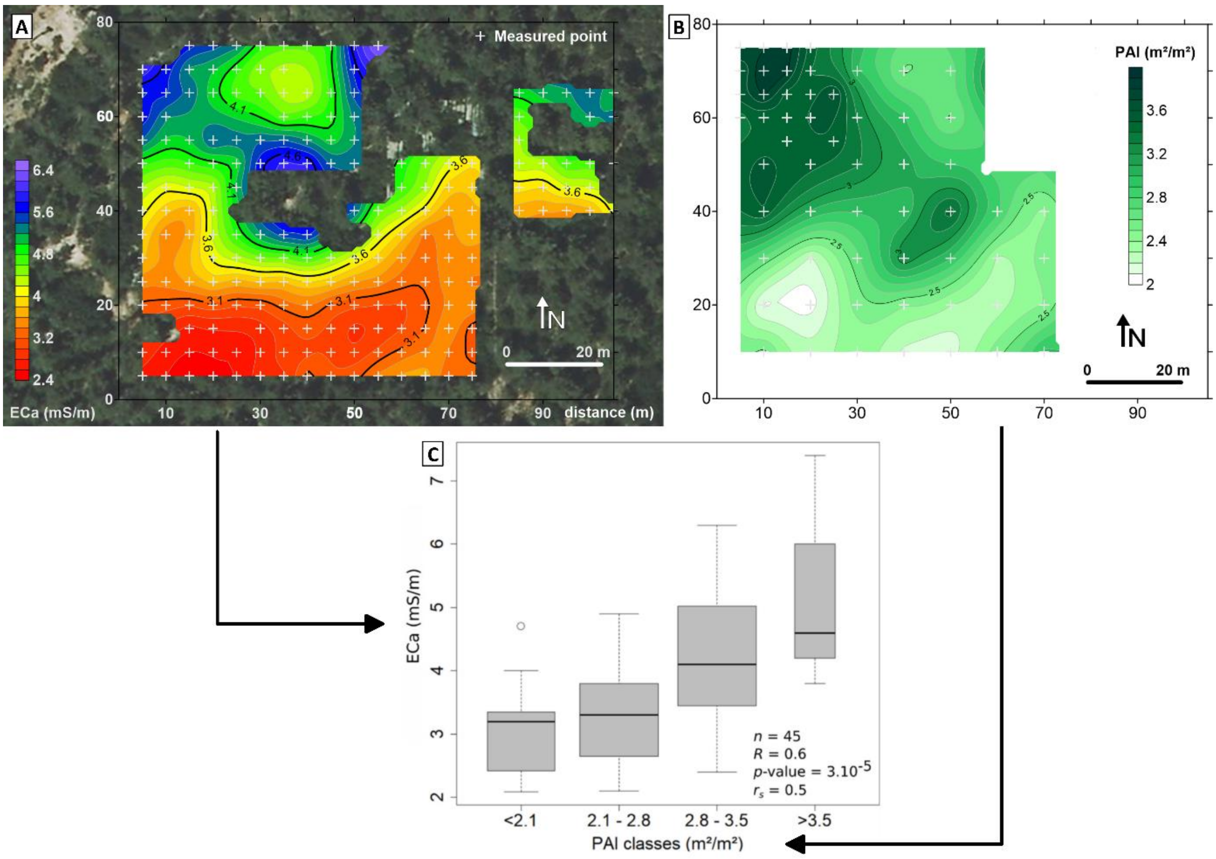


Figure 4: Geophysical results and spatial variability in plant area index (PAI) at Font-Blanche. (A) Apparent electrical conductivity (ECa) map from EM31 survey in vertical dipole. (B) Spatial interpolation of plant area index (PAI) obtained from hemispherical photographs. (C) Boxplots of apparent electrical conductivity (ECa) from EM31

survey per classes of plant area index (PAI) : n is the number of value, R is Pearson correlation, p-value is calculated on Pearson correlation, rs is the Spearman correlation. (Modified from Carrière et al. (2020a))

Soil type is another factor that can affect vegetation development as it affects water circulation and retention, as well as chemistry. Grellier et al. (2014) used EMI to determine the spatial heterogeneity of electrical conductivity as an indicator of clay content in a sub-humid sub-tropical climate. According to the formula used in their study, a clay content of 5% and 20% leads to a conductivity of 10 and 40 mS/m, respectively (Grellier et al., 2014). They observed a decrease in tree size with increasing clay content, similar to the results of Robinson et al. (2010) in Mediterranean climate, who also showed a greater likelihood of tree occurrence on soils with low clay content. Water availability in fine-textured clay soils was hypothesized to limit the root development of trees. A type of GPR known as radar surface-arrival detection has also been used to characterize the variability of boreal forests soil materials in Lapland in relation to water content (Hänninen, 1997; Sutinen and Middleton, 2020).

Characterizing the factors shaping community assembly and dynamics (including recruitment and mortality) is a key issue in community and global change ecology (Lavorel and Garnier, 2002). Many studies still neglect the potential role of heterogeneity in soil properties as an environmental filter for species installation (Sungpalee et al., 2009). Robinson et al. (2010) looked at inter-species distribution of trees in relation to soil texture in a Mediterranean climate. EMI was used to determine the variability of spatial soil heterogeneity in terms of clay content. They found difference in soil electrical conductivity between buckeye (*Aesculus californica (Spach) Nutt.*) and oak (*Quercus spp.*) communities. The soils where buckeye are located are more electrically conductive, associated with their location near streams on silty soils, than oak soils, which are located on thin and stony soils. Buckeye soils have electrical conductivity values almost twice as high as that under deciduous oaks (13 mS/m compared to 7 mS/m). Buckeyes may require a constant source of water and are less tolerant of drought, whereas oaks may be better adapted to a dry environment and able to access deeper water sources.

Intraspecific variability is an often-overlooked factor, but it could be a key feature for ecosystem resilience to climate change (Albert et al., 2012). It will be increasingly required to understand current patterns of forest mortality and distinguish the role of environment, genetics, and plasticity in population adaptation to global change. Spatial heterogeneity of soil properties could explain the survival or mortality of trees under different stresses. The role of soil on tree resilience to drought in forests was studied by Nourtier et al. (2014), Carrière et al. (2020a) and Carrière et al. (2020b) using ERT monitoring as a proxy for soil water reserves and Callahan et al. (2022) using seismic surveys as a proxy of subsurface weathering. Nourtier et al. (2014) and Carrière et al. (2020a) showed that vegetation is more vulnerable to severe water stress in areas where soil conditions appear to be favourable for growth. Indeed, Carrière et al. (2020a) observed in a Mediterranean climate that trees located in areas of high total available water in the near surface tended to delay the decline in water potential over the season but suffered greater water stress during the drought peak. This is in agreement with the results of Nourtier et al. (2014) in a Mediterranean mountain climate, who observed a higher mortality rate for trees with thicker surface soil associated with soil with higher water storage capacity. The link between variability in tree vulnerability and variability in soil water storage capacity may be explained by the adaptability of trees to extract water from greater or lesser depths. Carrière et al. (2020b) show that trees with low total available water near the surface have adapted their root system to exploit deeper water reserves more intensively. Recently, Callahan et al.

(2022) quantified subsurface weathering in forests in a mountainous Mediterranean climate from the porosity obtained with seismic refraction measurements. Their results showed that the soil water storage capacity is a function of the mineral weathering in the subsurface. They deduced that the spatial variability of forest response to drought can be explained by differences in the composition of the underlying bedrock.

Salinity is another type of stress that makes it difficult for roots to absorb water and nutrients, causing tree mortality. Satriani et al. (2012) conducted ERT measurements to assess the extent and depth of saltwater intrusion causing the decline of an overlying coastal forest in a Mediterranean climate. The ERT measurements showed the presence of two main zones characterised by different resistivity values: lower ones associated with salt-water intrusion (< 1.5 Ω.m), and higher ones corresponding to areas where trees grow better (10-220 Ω.m).

Spatial heterogeneity of soil properties could explain the survival of species during regeneration. The relationship between the survival of artificially regenerated Scots pine (*Pinus sylvestris L.)* and soil water content measured locally with TDR probes was highlighted in the study by Sutinen et al (2002). They observed significant correlations suggesting that pine regeneration on moist and wet tills (volumetric water content > 0.27 cm^3/cm^3) is risky in Lapland's climatic conditions. In the context of climate change, geophysics could be relevant for selecting species during regeneration.

4. Discussion and synthesis

In the previous sections, we highlighted the utility of the near-surface geophysical toolbox in forest ecosystems for detection of root systems, monitoring of water quantity and dynamics, and characterisation of spatial heterogeneity in subsurface properties at the stand level. The common strengths of all geophysical methods are: i) the non- or minimally destructive character that allows monitoring to study the temporal evolution of the physical properties of the subsurface, ii) the spatial coverage of the information that allows one to describe the heterogeneity of the studied area, and iii) the integrative nature of measurements that allows one to reach a satisfactory spatial representativeness. However, this last point can also be a limitation of geophysical tools. Interpretation of geophysical signals requires a comprehensive knowledge of both the forest ecosystem and geophysics in order to minimize the uncertainty from indirect methods and avoid artefacts in the inversions. Table 1 summarises the characteristics and potential of the near-surface geophysical techniques to support forest ecology studies. A synthetic overview of geophysics contribution for the three studied topics is proposed below.

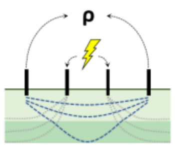
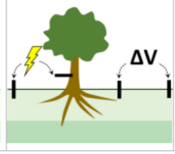
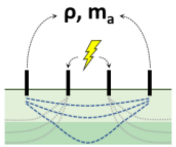
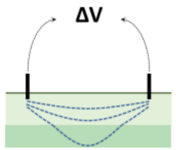
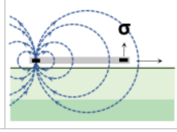
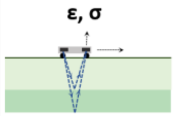
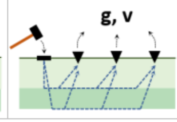
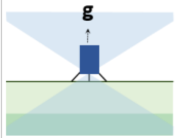
Regarding root detection, GPR has been widely used. This technique has been able to image roots on the cm scale to 2 m deep due to its high resolution. However, as the resolution and the investigation depth are inversely related, it is impossible to obtain an accurate image of the entire root system because the resolution is too low for the necessary depth and conversely to achieve satisfactory resolution to image finer roots (e.g., absorbent roots). In contrast, ERT has lower resolution, which cannot image objects as small as roots, but a greater investigation depth, going easily to several meters in depth (Table 1). ERT can therefore provide a complementary dataset to GPR. It possible to indirectly image the entire root system in forests with ERT by looking at changes in moisture as a proxy for "effective" root depth. Seismic, IP and MALM are still rarely used to study root systems. These techniques have not yet been used in forests but current research shows their potential.

For quantifying and monitoring water distribution, ERT is the most widely used technique. This automatable technique makes it possible to monitor water dynamic in forest settings. However, the considerable acquisition time of ERT (Table 1) prohibit monitoring of processes that take place on a time scale of less than 10 minutes. Gravimetry and SP can allow acquisition of data with high temporal resolution (e.g., every second). However, both are passive methods and integrate over large and difficult to quantify spatial volumes, which can be an advantage (i.e. good spatial representativity of measurements for modelling purposes) as well as a disadvantage (i.e. difficulty to determine sources in field conditions). The potential of SP to study water circulation in the soil-plant-atmosphere continuum is important because it is the only geophysical technique directly related to water flow (Table 1).

To characterize spatial variability in subsurface properties, geophysics provides powerful approaches. EMI, ERT and seismic refraction have already been used in forests to estimate heterogeneity in water content, soil thickness and type, or subsurface porosity and weathering. EMI has the great advantage of quickly characterizing large areas (Table 1) without ground contact. In contrast, ERT and seismic have longer acquisition times than EMI but easily reach deeper investigation depths for the same resolution. These techniques provide a relevant and complementary information to describe the 2- or 3-D distribution of subsurface properties.

Accepted in Science of the Total Environment in July 2023

Table 1 : Summary of geophysical techniques and their characteristics presented in this review (part 1) and their application to forest ecology issues (part 2).

Geophysical techniques	**ERT**	**MALM**	**IP**	**SP**	**EMI**	**GPR**	**Seismic**	**Gravimetry**
Estimated physical properties	Electrical resistivity (ρ)	Electrical potential (ΔV)	Electrical resistivity (ρ) + Chargeability (m_a)	Electrical potential (ΔV)	Electrical conductivity (σ)	Permittivity (ε) + Electrical conductivity (σ)	Mechanical properties (e.g., wave velocities (v), density (g))	Density (g)
Depth of investigation	A few meters to tens of meters	Centimetres to a few meters	A few meters to tens of meters	No limit	A few meters to tens of meters	Centimetres to a few meters	A few meters to tens of meters	No limit
Resolution	+	+	+	+/-	+	+++	++	-
Acquisition time	30 min - 1h per profile of about 100 m	Variable from minute to hour	1-2h per profile of about 100 m	Instantaneous (time series possible)	1-2 ha/day	A few hundred meters to km/day	2-3h per profile of about 100 m	Instantaneous (time series possible)
Implementation								

Forest ecology issues								
Detection of root systems								
Root biomass estimation	++	+				++		
Coarse/medium roots detection			+			+++	+	
Monitoring of water quantity and dynamics								
Locating root water absorption	++							
Water content variability	+++				++			++
Water flow detection				+++				
Characterisation of spatial heterogeneity in subsurface properties								
Soil thickness	++				++	++	+++	
Soil porosity/ weathering							+++	
Soil type variability (clay content)	++		++		+++	+		

(Part 1) ERT = electrical resistivity tomography; IP = induced polarization; SP = self-potential; EMI = electromagnetic induction; GPR = ground penetrating radar. The resolution defines the quality of the result obtained: +++ highly resolution measurement; ++ accurate measurement; + good resolution but not very accurate; +/- integrative measure; - very integrative measure. The acquisition time gives an idea of the time taken by the device to perform a measurement, the time taken to set up the equipment is not considered. (Part 2) +++ Technique used successfully; ++ technique used; + technique previously used.

5. Conclusions

Initially developed for extractive-industry applications, geophysical tools have been increasingly deployed in other domains of environmental earth sciences. Here, we have reviewed descriptive and functional studies that show how the geophysical toolbox can help to improve our understanding of forest ecosystems.

To illustrate how the geophysics can help ecologists to study forest ecosystems, we identified three main topics in forest ecology (Table 1). First, we outline the detection of root systems non-destructively using electromagnetic and electrical methods. Depending on the resolution of these techniques, tree roots in forests could be located and their diameters determined, or more generally, the root biomass estimated. We then describe the quantification and monitoring of water volumes and dynamics using electrical and gravimetric methods. The distribution and movement of water in forests and the evapotranspiration process could be observed and studied using these geophysical tools over the plot to hillslope scale. Finally, we highlight the ability of geophysical tool to characterise subsurface spatial heterogeneity, specifically using electrical, electromagnetic and seismic methods. The impact of edaphic conditions on the development and functioning of the forest can be explored with these methods, improving our understanding of processes related to ecohydrology or to the vegetation community dynamics or assembly. The use of geophysics coupled with soil-plant-atmosphere models could help to better quantify biophysical parameters to improve water management issues for forest adaptation to climate change. Geophysics offers new ways of studying the critical zone that may break down the boundaries between scientific communities and provide a more spatially and temporally exhaustive view than can be found from traditional methods.

Glossary

Chargeability (m_a): A physical property that describes the ability of a material to store reversible electrical charge when subjected to an electrical field.

Community: An interacting group of diverse species in a common place.

Critical zone: The heterogeneous near-surface environment that extends from the top of the canopy to the bottom of groundwater, where complex interactions between rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources (adapted from NRC (2001)).

Ecohydrology: Field that studies the interactions between water and ecosystems, e.g. the relationship between hydrological processes and the distribution, structure or function of ecosystems.

Electrical capacitance (C): A quantity that defines the capacity of a material to receive and store energy in the form of an electric charge.

Electrical conductivity (σ): A physical property (the inverse of electrical resistivity) that quantifies the ability of a material to conduct electric current, i.e. a flow of electrical charges.

Electrical field: A physical field created by electrically charged particles that exerts force on all other charged particles in the field, either attracting or repelling them

Electrical potential or electric field potential: A quantity that defines the electrical state of a point in space, i.e. the amount of work needed to move a unit charge from a reference point to a specific point against an electric field.

Electrical relaxation: The time required for a system to return into equilibrium after being disturbed, for example after being subjected to an electric field.

Electrical resistivity (ρ): A physical property (the inverse of electrical conductivity) that quantifies the strength of a material to oppose to electrical current transfer.

Electrical resistivity tomography (ERT): A geophysical technique that measures and infers electrical resistivity distributions in the subsurface or in trees.

Electromagnetic induction (EMI): A geophysical technique that measures and infers electrical conductivity distributions in the subsurface without contact with the soil.

Electromagnetic field: A physical field caused by the movement of electric charges.

Evapotranspiration: Water flow resulting from evaporation from soils and open water surfaces and from plant transpiration.

Frequency-domain reflectometry (FDR): A technique that estimates dielectric permittivity, related to the volumetric water content of the soil, by measuring the frequencies of high-frequency electromagnetic waves emitted along a metal probe buried in the soil.

Induced polarization (IP): A geophysical technique that measures the electrical resistivity and the chargeability to infer subsurface distributions and characterise grain-fluid interface properties.

Inversion: The mathematical process that allow to retrieve physical properties from measured data under the assumption of a given forward physical model.

Gravimetry: A geophysical method that measures variations in the Earth's gravity field.

Ground penetrating radar (GPR): A geophysical technique that records transmitted and reflected high-frequency electromagnetic waves sensitive to the dielectric permittivity of Earth materials.

Leaf area index (LAI): A quantity that characterizes plant canopies and defined as the leaf area of a tree or stand per unit area of soil.

Mise-à-la-masse (MALM): A geophysical technique similar to ERT but directly sensitive to the conductive body under study.

Near-surface geophysics: The use of non- or minimally invasive imaging methods to study the characteristics of the shallow soil and the processes that occur (usually up to tens of metres depth).

Permittivity or dielectric permittivity (ε): A physical property that describes the ability of a medium to charge under an electric field.

Plant area index: A quantity that characterizes plant canopies and defined as the plant area (trunk and leaf) per unit area of soil.

Plot: A term used in forest ecology to refer to study area which extent generally rang from a few hundred to a few thousands of square metres (typically a forest inventory plot).

Self-potential (SP): A geophysical technique that measures the natural electrical field due to the natural current circulating in the subsurface, for example generated by water flows.

Seismic method: A geophysical method that measures the propagation of acoustic waves in soils and rocks to obtain information on the physical and mechanical properties.

Stand level: The stand refers to a group of trees in a forest plot that may contain one or more species. A distinction is made between a stand scale and an individual scale to study the forest.

Time-domain reflectometry (TDR): A technique that estimates dielectric permittivity, related to the volumetric water content of the soil, by measuring the travel time of high-frequency electromagnetic waves emitted along a metal probe buried in the soil.

Tomography: A mathematical imaging process that estimates the spatial distribution of subsurface physical properties from surface measurements.

Water potential: A physical quantity that quantifies the binding energy of water within an element (e.g. a plant, a soil sample), i.e. the pressure required by the system to extract it.

Water stress: Situation in which the demand for water is greater than the amount of water available. A plant is under water stress when the amount of transpired water is greater than the amount of absorbed water.

Acknowledgments

The authors would like to express their gratitude to OZCAR Research Infrastructure, which is supported by the French Ministry of Research, French Research Institutions and Universities. This study is founded by the French Ministry of Education and Research for a PhD grant. Benjamin Mary acknowledges the financial support from European Union's Horizon 2020 research and innovation programme under a Marie Sklodowska-Curie grant agreement (grant no. 842922).

Author contributions

B.L., S.D.C., D.J., and N.K.M. led the conceptualization, writing and figure drafting. K.S., B.M., N.D. and R.G. supported in equal parts the conceptualization, writing and figure drafting.

Competing interests

The authors declare no competing interests.

References

Ain-Lhout, F., Boutaleb, S., Diaz-Barradas, M.C., Jauregui, J., Zunzunegui, M., 2016. Monitoring the evolution of soil moisture in root zone system of Argania spinosa using electrical resistivity imaging. Agricultural Water Management 164, 158–166. https://doi.org/10.1016/j.agwat.2015.08.007

Al Hagrey, S.A., 2007. Geophysical imaging of root-zone, trunk, and moisture heterogeneity. Journal of Experimental Botany 58, 839–854. https://doi.org/10.1093/jxb/erl237

Alani, A.M., Lantini, L., 2020. Recent Advances in Tree Root Mapping and Assessment Using Non-destructive Testing Methods: A Focus on Ground Penetrating Radar. Surv Geophys 41, 605–646. https://doi.org/10.1007/s10712-019-09548-6

Albert, C.H., de Bello, F., Boulangeat, I., Pellet, G., Lavorel, S., Thuiller, W., 2012. On the importance of intraspecific variability for the quantification of functional diversity. Oikos 121, 116–126. https://doi.org/10.1111/j.1600-0706.2011.19672.x

Allred, B., Daniels, J.J., Ehsani, M.R., 2008. Handbook of agricultural geophysics, Books in soils, plants, and the environment. CRC Press.

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 Physiology 28, 1441–1448. https://doi.org/10.1093/treephys/28.10.1441

Archie, G.E., 1942. The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics. Transactions of the AIME 146, 54–62. https://doi.org/10.2118/942054-G

Arnaud, M., Baird, A.J., Morris, P.J., Harris, A., Huck, J.J., 2019. EnRoot: a narrow-diameter, inexpensive and partially 3D-printable minirhizotron for imaging fine root production. Plant Methods 15, 101. https://doi.org/10.1186/s13007-019-0489-6

Auken, E., Guérin, R., de Marsily, G., Sailhac, P., 2009. Hydrogeophysics. Comptes Rendus Geoscience 341, 795–799. https://doi.org/10.1016/j.crte.2009.09.003

Balwant, P., Jyothi, V., Pujari, P.R., Dhyani, S., Verma, P., Padmakar, C., Quamar, R., Ramesh, J., Khare, S., Mitkari, M., 2022. Tree root imaging by electrical resistivity tomography: geophysical tools to improve understanding of deep root structure and rhizospheric processes. Trop Ecol 63, 319–324. https://doi.org/10.1007/s42965-021-00213-x

Banwart, S.A., Chorover, J., Gaillardet, J., Sparks, D., White, T., Anderson, S., Aufdenkampe, A., Bernasconi, S., Brantley, S.L., Chadwick, Oju., 2013. Sustaining Earth's critical zone basic science and interdisciplinary solutions for global challenges. The University of Sheffield, United Kingdom.

Binley, A., Daily, W., Ramirez, A., 1997. Detecting Leaks from Environmental Barriers Using Electrical Current Imaging. JEEG 2, 11–19. https://doi.org/10.4133/JEEG2.1.11

Binley, A., Hubbard, S.S., Huisman, J.A., Revil, A., Robinson, D.A., Singha, K., Slater, L.D., 2015. The emergence of hydrogeophysics for improved understanding of subsurface processes over multiple scales. Water Resour. Res. 51, 3837–3866. https://doi.org/10.1002/2015WR017016

Binley, A., Kemna, A., 2005. DC Resistivity and Induced Polarization Methods, in: Rubin, Y., Hubbard, S.S. (Eds.), Hydrogeophysics, Water Science and Technology Library. Springer Netherlands, Dordrecht, pp. 129–156. https://doi.org/10.1007/1-4020-3102-5_5

Bréchet, L., Oatham, M., Wuddivira, M., Robinson, D., 2012. Determining spatial variation in soil properties in teak and native tropical forest plots using electromagnetic induction. Vadose Zone Journal 11. https://doi.org/10.2136/vzj2011.0102

Bréda, N., Granier, A., Barataud, F., Moyne, C., 1995. Soil water dynamics in an oak stand. Plant and Soil 172, 17–27. https://doi.org/10.1007/BF00020856

Brunner, I., Godbold, D.L., 2007. Tree roots in a changing world. Journal of Forest Research 12, 78–82. https://doi.org/10.1007/s10310-006-0261-4

Butnor, J.R., Doolittle, J.A., Johnsen, K.H., Samuelson, L., Stokes, T., Kress, L., 2003. Utility of Ground-Penetrating Radar as a Root Biomass Survey Tool in Forest Systems. Soil Sci. Soc. Am. J. 67, 1607–1615. https://doi.org/10.2136/sssaj2003.1607

Butnor, J.R., Samuelson, L.J., Stokes, T.A., Johnsen, K.H., Anderson, P.H., González-Benecke, C.A., 2016. Surface-based GPR underestimates below-stump root biomass. Plant Soil 402, 47–62. https://doi.org/10.1007/s11104-015-2768-y

Buza, Á.K., Divós, F., 2016. Root Stability Evaluation with Non-Destructive Techniques. Acta Silvatica et Lignaria Hungarica 12, 125–134. https://doi.org/10.1515/aslh-2016-0011

Cabal, C., De Deurwaerder, H.P.T., Matesanz, S., 2021. Field methods to study the spatial root density distribution of individual plants. Plant Soil 462, 25–43. https://doi.org/10.1007/s11104-021-04841-z

Callahan, R.P., Riebe, C.S., Sklar, L.S., Pasquet, S., Ferrier, K.L., Hahm, W.J., Taylor, N.J., Grana, D., Flinchum, B.A., Hayes, J.L., Holbrook, W.S., 2022. Forest vulnerability to drought controlled by bedrock composition. Nat. Geosci. 15, 714–719. https://doi.org/10.1038/s41561-022-01012-2

Campbell, R.B., Bower, C.A., Richards, L.A., 1949. Change of Electrical Conductivity With Temperature and the Relation of Osmotic Pressure to Electrical Conductivity and Ion Concentration for Soil Extracts. Soil Science Society of America Journal 13, 66–69. https://doi.org/10.2136/sssaj1949.036159950013000C0010x

Cardenas, M.B., Kanarek, M.R., 2014. Soil moisture variation and dynamics across a wildfire burn boundary in a loblolly pine (Pinus taeda) forest. Journal of Hydrology 519, 490–502. https://doi.org/10.1016/j.jhydrol.2014.07.016

Carrière, S.D., Loiseau, B., Champollion, C., Ollivier, C., Martin-StPaul, N.K., Lesparre, N., Olioso, A., Hinderer, J., Jougnot, D., 2021a. First Evidence of Correlation Between Evapotranspiration and Gravity at a Daily Time Scale From Two Vertically Spaced Superconducting Gravimeters. Geophysical Research Letters 48. https://doi.org/10.1029/2021GL096579

Carrière, S.D., Martin-StPaul, N.K., Doussan, C., Courbet, F., Davi, H., Simioni, G., 2021b. Electromagnetic Induction Is a Fast and Non-Destructive Approach to Estimate the Influence of Subsurface Heterogeneity on Forest Canopy Structure. Water 13, 3218. https://doi.org/10.3390/w13223218

Carrière, S.D., Ruffault, J., Cakpo, C.B., Olioso, A., Doussan, C., Simioni, G., Chalikakis, K., Patris, N., Davi, H., Martin-StPaul, N.K., 2020a. Intra-specific variability in deep water extraction between trees growing on a Mediterranean karst. Journal of Hydrology 590, 125428. https://doi.org/10.1016/j.jhydrol.2020.125428

Carrière, S.D., Ruffault, J., Pimont, F., Doussan, C., Simioni, G., Chalikakis, K., Limousin, J.-M., Scotti, I., Courdier, F., Cakpo, C.-B., Davi, H., Martin-StPaul, N.K., 2020b. Impact of local soil and subsoil conditions on inter-individual variations in tree responses to drought: insights from Electrical Resistivity Tomography. Science of The Total Environment 698, 134247. https://doi.org/10.1016/j.scitotenv.2019.134247

Čermák, J., Cudlín, P., Gebauer, R., Børja, I., Martinková, M., Staněk, Z., Koller, J., Neruda, J., Nadezhdina, N., 2013. Estimating the absorptive root area in Norway spruce by using the common direct and indirect earth impedance methods. Plant Soil 372, 401–415. https://doi.org/10.1007/s11104-013-1740-y

Chalikakis, K., Plagnes, V., Guerin, R., Valois, R., Bosch, F.P., 2011. Contribution of geophysical methods to karst-system exploration: an overview. Hydrogeol J 19, 1169–1180. https://doi.org/10.1007/s10040-011-0746-x

Chen, H., 2022. Exploring subsurface hydrology with electrical resistivity tomography. Nature Reviews Earth & Environment 3, 1–1. https://doi.org/10.1038/s43017-022-00350-4

Crossley, D., Hinderer, J., Riccardi, U., 2013. The measurement of surface gravity. Rep. Prog. Phys. 76, 046101. https://doi.org/10.1088/0034-4885/76/4/046101

Cseresnyés, I., Szitár, K., Rajkai, K., Füzy, A., Mikó, P., Kovács, R., Takács, T., 2018. Application of Electrical Capacitance Method for Prediction of Plant Root Mass and Activity in Field-Grown Crops. Frontiers in Plant Science 9, 93. https://doi.org/10.3389/fpls.2018.00093

Dahlin, T., Zhou, B., 2004. A numerical comparison of 2D resistivity imaging with 10 electrode arrays. Geophys Prospect 52, 379–398. https://doi.org/10.1111/j.1365-2478.2004.00423.x

Dai, A., 2013. Increasing drought under global warming in observations and models. Nature climate change 3, 52–58. https://doi.org/10.1038/nclimate1633

Dalton, F.N., 1995. In-situ root extent measurements by electrical capacitance methods. Plant Soil 173, 157–165. https://doi.org/10.1007/BF00155527

Davidson, E., Lefebvre, P.A., Brando, P.M., Ray, D.M., Trumbore, S.E., Solorzano, L.A., Ferreira, J.N., 2011. Carbon Inputs and Water Uptake in Deep Soils of an Eastern Amazon Forest. Forest Science 57, 51–58. https://doi.org/10.1093/forestscience/57.1.51

Day, F.P., Schroeder, R.E., Stover, D.B., Brown, A.L., Butnor, J.R., Dilustro, J., Hungate, B.A., Dijkstra, P., Duval, B.D., Seiler, T.J., 2013. The effects of 11 yr of CO 2 enrichment on roots in a Florida scrub-oak ecosystem. New Phytologist 200, 778–787. https://doi.org/10.1111/nph.12246

Day-Lewis, F.D., Singha, K., Binley, A.M., 2005. Applying petrophysical models to radar travel time and electrical resistivity tomograms: Resolution-dependent limitations. Journal of Geophysical Research: Solid Earth 110. https://doi.org/10.1029/2004JB003569

Dietrich, R.C., Bengough, A.G., Jones, H.G., White, P.J., 2012. A new physical interpretation of plant root capacitance. Journal of Experimental Botany 63, 6149–6159. https://doi.org/10.1093/jxb/ers264

Dick, J., Tetzlaff, D., Bradford, J., Soulsby, C., 2018. Using repeat electrical resistivity surveys to assess heterogeneity in soil moisture dynamics under contrasting vegetation types. Journal of Hydrology 559, 684–697. https://doi.org/10.1016/j.jhydrol.2018.02.062

Dobrin, M.B., Van Nostrand, R.G., 1956. Review of current developments in exploration geophysics. Geophysics 21, 142–155. https://doi.org/10.1190/1.1438205

Doolittle, J.A., Brevik, E.C., 2014. The use of electromagnetic induction techniques in soils studies. Geoderma 223–225, 33–45. https://doi.org/10.1016/j.geoderma.2014.01.027

Doolittle, J.A., Minzenmayer, F.E., Waltman, S.W., Benham, E.C., Tuttle, J.W., Peaslee, S.D., 2007. Ground-penetrating radar soil suitability map of the conterminous United States. Geoderma 141, 416–421. https://doi.org/10.1016/j.geoderma.2007.05.015

Doolittle, J.A., Sudduth, K.A., Kitchen, N.R., Indorante, S.J., 1994. Estimating depths to claypans using electromagnetic induction methods. Journal of Soil and Water Conservation 49, 572–575.

Doussan, C., Ruy, S., 2009. Prediction of unsaturated soil hydraulic conductivity with electrical conductivity: Soil hydraulic-electrical conductivity. Water Resour. Res. 45. https://doi.org/10.1029/2008WR007309

Dymond, S.F., Kolka, R.K., Bolstad, P.V., Sebestyen, S.D., 2014. Long-Term Soil Moisture Patterns in a Northern Minnesota Forest. Soil Science Society of America Journal 78, S208–S216. https://doi.org/10.2136/sssaj2013.08.0322nafsc

Eagleson, P.S., 1982. Ecological optimality in water-limited natural soil-vegetation systems: 1. Theory and hypothesis. Water Resources Research 18, 325–340. https://doi.org/10.1029/WR018i002p00325

Ehosioke, S., Nguyen, F., Rao, S., Kremer, T., Placencia-Gomez, E., Huisman, J.A., Kemna, A., Javaux, M., Garré, S., 2020. Sensing the electrical properties of roots: A review. Vadose zone j. 19. https://doi.org/10.1002/vzj2.20082

Ellison, D., Morris, C.E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., Noordwijk, M. van, Creed, I.F., Pokorny, J., Gaveau, D., Spracklen, D.V., Tobella, A.B., Ilstedt, U., Teuling, A.J., Gebrehiwot, S.G., Sands, D.C., Muys, B., Verbist, B., Springgay, E., Sugandi, Y., Sullivan, C.A., 2017. Trees, forests and water: Cool insights for a hot world. Global Environmental Change 43, 51–61. https://doi.org/10.1016/j.gloenvcha.2017.01.002

Fan, J., Scheuermann, A., Guyot, A., Baumgartl, T., Lockington, D.A., 2015. Quantifying spatiotemporal dynamics of root-zone soil water in a mixed forest on subtropical coastal sand dune using surface ERT and spatial TDR. Journal of Hydrology 523, 475–488. https://doi.org/10.1016/j.jhydrol.2015.01.064

Fan, L., Wigneron, J.-P., Ciais, P., Chave, J., Brandt, M., Sitch, S., Yue, C., Bastos, A., Li, Xin, Qin, Y., Yuan, W., Schepaschenko, D., Mukhortova, L., Li, Xiaojun, Liu, X., Wang, M., Frappart, F., Xiao, X., Chen, J., Ma, M., Wen, J., Chen, X., Yang, H., Van Wees, D., Fensholt, R., 2023. Siberian carbon sink reduced by forest disturbances. Nat. Geosci. 16, 56–62. https://doi.org/10.1038/s41561-022-01087-x

Fäth, J., Kunz, J., Kneisel, C., 2022. Monitoring spatiotemporal soil moisture changes in the subsurface of forest sites using electrical resistivity tomography (ERT). J. For. Res. 33, 1649–1662. https://doi.org/10.1007/s11676-022-01498-x

Fores, B., Champollion, C., Le Moigne, N., Bayer, R., Chéry, J., 2017. Assessing the precision of the iGrav superconducting gravimeter for hydrological models and karstic hydrological process identification. Geophys. J. Int. 208, 269–280. https://doi.org/10.1093/gji/ggw396

Friedlingstein, P., Jones, M.W., O'Sullivan, M., Andrew, R.M., Hauck, J., Peters, G.P., Peters, W., Pongratz, J., Sitch, S., Le Quéré, C., Bakker, D.C.E., Canadell, J.G., Ciais, P., Jackson, R.B., Anthoni, P., Barbero, L., Bastos, A., Bastrikov, V., Becker, M., Bopp, L., Buitenhuis, E., Chandra, N., Chevallier, F., Chini, L.P., Currie, K.I., Feely, R.A., Gehlen, M., Gilfillan, D., Gkritzalis, T., Goll, D.S., Gruber, N., Gutekunst, S., Harris, I., Haverd, V., Houghton, R.A., Hurtt, G., Ilyina, T., Jain, A.K., Joetzjer, E., Kaplan, J.O., Kato, E., Klein Goldewijk, K., Korsbakken, J.I., Landschützer, P., Lauvset, S.K., Lefèvre, N., Lenton, A., Lienert, S., Lombardozzi, D., Marland, G., McGuire, P.C., Melton, J.R., Metzl, N., Munro, D.R., Nabel, J.E.M.S., Nakaoka, S.-I., Neill, C., Omar, A.M., Ono, T., Peregon, A., Pierrot, D., Poulter, B., Rehder, G., Resplandy, L., Robertson, E., Rödenbeck, C., Séférian, R., Schwinger, J., Smith, N., Tans, P.P., Tian, H., Tilbrook, B., Tubiello, F.N., van der Werf, G.R., Wiltshire, A.J., Zaehle, S., 2019. Global Carbon Budget 2019. Earth Syst. Sci. Data 11, 1783–1838. https://doi.org/10.5194/essd-11-1783-2019

Friedman, S.P., 2005. Soil properties influencing apparent electrical conductivity: a review. Computers and Electronics in Agriculture, Applications of Apparent Soil Electrical Conductivity in Precision Agriculture 46, 45–70. https://doi.org/10.1016/j.compag.2004.11.001

Gardner, C.M., Robinson, D., Blyth, K., Cooper, J.D., 2000. Soil water content, in: Smith, K.A., Mullins, E. (Eds.), Soil and Environmental Analysis. Soil Science Society of America Madison, WI, USA, pp. 1–74.

Garré, S., Hyndman, D., Mary, B., Werban, U., 2021. Geophysics conquering new territories: The rise of "agrogeophysics." Vadose zone j. 20. https://doi.org/10.1002/vzj2.20115

Gelaro, R., McCarty, W., Suárez, M.J., Todling, R., Molod, A., Takacs, L., Randles, C.A., Darmenov, A., Bosilovich, M.G., Reichle, R., 2017. The modern-era retrospective analysis for research and applications, version 2 (MERRA-2). Journal of climate 30, 5419–5454. https://doi.org/10.1175/JCLI-D-16-0758.1

Gibert, D., Le Mouël, J.-L., Lambs, L., Nicollin, F., Perrier, F., 2006. Sap flow and daily electric potential variations in a tree trunk. Plant Science 171, 572–584. https://doi.org/10.1016/j.plantsci.2006.06.012

Glover, P., 2015. 11.04–Geophysical Properties of the Near Surface Earth: Electrical Properties. Treatise geophys 89–137.

Goh, C.L., Abdul Rahim, R., Fazalul Rahiman, M.H., Mohamad Talib, M.T., Tee, Z.C., 2018. Sensing wood decay in standing trees: A review. Sensors and Actuators A: Physical 269, 276–282. https://doi.org/10.1016/j.sna.2017.11.038

Grellier, S., Florsch, N., Janeau, J.-L., Podwojewski, P., Camerlynck, C., Barot, S., Ward, D., Lorentz, S., 2014. Soil clay influences Acacia encroachment in a South African grassland: Soil clay drives spatial distribution of Acacia. Ecohydrol. 7, 1474–1484. https://doi.org/10.1002/eco.1472

Guérin, R., 2005. Borehole and surface-based hydrogeophysics. Hydrogeol J 13, 251–254. https://doi.org/10.1007/s10040-004-0415-4

Guerra, K.A., 2020. Ecohydrological analysis in a forest ecosystem of seasonal variations in the moisture content of clay-rich soil.

Günther, T., 2004. Inversion methods and resolution analysis for the 2D/3D reconstruction of resistivity structures from DC measurements.

Guo, L., Mount, G.J., Hudson, S., Lin, H., Levia, D., 2020. Pairing geophysical techniques improves understanding of the near-surface Critical Zone: Visualization of preferential routing of stemflow along coarse roots. Geoderma 357, 113953. https://doi.org/10.1016/j.geoderma.2019.113953

Hänninen, P., 1997. Dielectric coefficient surveying for oberburden classification: with 7 tables, Bulletin / Geological Survey of Finland. Geological Survey of Finland, Espoo.

Harmon, R.E., Barnard, H.R., Day-Lewis, F.D., Mao, D., Singha, K., 2021. Exploring Environmental Factors That Drive Diel Variations in Tree Water Storage Using Wavelet Analysis. Front. Water 3, 682285. https://doi.org/10.3389/frwa.2021.682285

Hatherly, P., 2013. Overview on the application of geophysics in coal mining. International Journal of Coal Geology 114, 74–84. https://doi.org/10.1016/j.coal.2013.02.006

Hermans, T., Goderniaux, P., Jougnot, D., Fleckenstein, J., Brunner, P., Nguyen, F., Linde, N., Huisman, J.A., Bour, O., Lopez Alvis, J., Hoffmann, R., Palacios, A., Cooke, A.-K., Pardo-Álvarez, Á., Blazevic, L., Pouladi, B., Haruzi, P., Kenshilikova, M., Davy, P., Le Borgne, T., 2022. Advancing measurements and representations of subsurface heterogeneity and dynamic processes: towards 4D hydrogeology. HESS. https://doi.org/10.5194/hess-2022-95

Hirano, Y., Dannoura, M., Aono, K., Igarashi, T., Ishii, M., Yamase, K., Makita, N., Kanazawa, Y., 2009. Limiting factors in the detection of tree roots using ground-penetrating radar. Plant Soil 319, 15–24. https://doi.org/10.1007/s11104-008-9845-4

Hinderer, J., Crossley, D., Warburton, R.J., 2015. Superconducting Gravimetry, in: Treatise on Geophysics. Elsevier, pp. 59–115. https://doi.org/10.1016/B978-0-444-53802-4.00062-2

Hoff, C., Rambal, S., 2003. An examination of the interaction between climate, soil and leaf area index in a Quercus ilex ecosystem. Ann. For. Sci. 60, 153–161. https://doi.org/10.1051/forest:2003008

Holbrook, W.S., Riebe, C.S., Elwaseif, M., L. Hayes, J., Basler-Reeder, K., L. Harry, D., Malazian, A., Dosseto, A., C. Hartsough, P., W. Hopmans, J., 2014. Geophysical constraints on deep weathering and water storage potential in the Southern Sierra Critical Zone Observatory. Earth Surface Processes and Landforms 39, 366–380. https://doi.org/10.1002/esp.3502

Hruska, J., Cermak, J., Sustek, S., 1999. Mapping tree root systems with ground-penetrating radar. Tree Physiology 19, 125–130. https://doi.org/10.1093/treephys/19.2.125

Hu, K., Jougnot, D., Huang, Q., Looms, M.C., Linde, N., 2020. Advancing quantitative understanding of self-potential signatures in the critical zone through long-term monitoring. Journal of Hydrology 585, 124771. https://doi.org/10.1016/j.jhydrol.2020.124771

Hubbard, S.S., Linde, N., 2005. Hydrogeophysics, Water science and technology library. Springer, Dordrecht.

Huisman, J.A., Hubbard, S.S., Redman, J.D., Annan, A.P., 2003. Measuring Soil Water Content with Ground Penetrating Radar: A Review. Vadose Zone Journal 2, 16. https://doi.org/10.2136/vzj2003.4760

Jardani, A., Dupont, J.-P., Revil, A., 2006. Self-potential signals associated with preferential groundwater flow pathways in sinkholes. Journal of Geophysical Research: Solid Earth 111. https://doi.org/10.1029/2005JB004231

Jayawickreme, D.H., Jobbágy, E.G., Jackson, R.B., 2014. Geophysical subsurface imaging for ecological applications. New Phytol 201, 1170–1175. https://doi.org/10.1111/nph.12619

Jayawickreme, D.H., Van Dam, R.L., Hyndman, D.W., 2010. Hydrological consequences of land-cover change: Quantifying the influence of plants on soil moisture with time-lapse electrical resistivity. Geophysics 75, WA43–WA50. https://doi.org/10.1190/1.3464760

Jayawickreme, D.H., Van Dam, R.L., Hyndman, D.W., 2008. Subsurface imaging of vegetation, climate, and root-zone moisture interactions. Geophys. Res. Lett. 35, L18404. https://doi.org/10.1029/2008GL034690

John, R., Dalling, J.W., Harms, K.E., Yavitt, J.B., Stallard, R.F., Mirabello, M., Hubbell, S.P., Valencia, R., Navarrete, H., Vallejo, M., Foster, R.B., 2007. Soil nutrients influence spatial distributions of tropical tree species. Proc. Natl. Acad. Sci. U.S.A. 104, 864–869. https://doi.org/10.1073/pnas.0604666104

Jougnot, D., Roubinet, D., Guarracino, L., Maineult, A., 2020. Modeling streaming potential in porous and fractured media, description and benefits of the effective excess charge density approach, in: Advances in Modeling and Interpretation in near Surface Geophysics. Springer, pp. 61–96.

Jouniaux, L., Maineult, A., Naudet, V., Pessel, M., Sailhac, P., 2009. Review of self-potential methods in hydrogeophysics. Comptes Rendus Geoscience 341, 928–936. https://doi.org/10.1016/j.crte.2009.08.008

Kemna, A., Binley, A., Cassiani, G., Niederleithinger, E., Revil, A., Slater, L., Williams, K.H., Orozco, A.F., Haegel, F.-H., Hördt, A., Kruschwitz, S., Leroux, V., Titov, K., Zimmermann, E., 2012. An overview of the spectral induced polarization method for near-surface applications. Near Surface Geophysics 10, 453–468. https://doi.org/10.3997/1873-0604.2012027

Kessouri, P., Furman, A., Huisman, J.A., Martin, T., Mellage, A., Ntarlagiannis, D., Bücker, M., Ehosioke, S., Fernandez, P., Flores-Orozco, A., Kemna, A., Nguyen, F., Pilawski, T., Saneiyan, S., Schmutz, M., Schwartz, N., Weigand, M., Wu, Y., Zhang, C., Placencia-Gomez, E., 2019. Induced polarization applied to biogeophysics: recent advances and future prospects. Near Surface Geophysics 17, 595–621. https://doi.org/10.1002/nsg.12072

Klepper, B., Kaspar, T.C., 1994. Rhizotrons: Their Development and Use in Agricultural Research. Agronomy Journal 86, 745–753. https://doi.org/10.2134/agronj1994.00021962008600050002x

Koch, K., Wenninger, J., Uhlenbrook, S., Bonell, M., 2009. Joint interpretation of hydrological and geophysical data: electrical resistivity tomography results from a process hydrological research site in the Black Forest Mountains, Germany. Hydrological Processes 23, 1501–1513. https://doi.org/10.1002/hyp.7275

Koppán, A., Szarka, L., Wesztergom, V., 2005. Local Variability of Electric Potential Differences on the Trunk of Quercus cerris L. Acta Silvatica et Lignaria Hungarica 1, 73–81.

Koppán, A., Szarka, L., Wesztergom, V., 2000. Annual fluctuation in amplitudes of daily variations of electrical signals measured in the trunk of a standing tree. Comptes Rendus de l'Académie des Sciences - Series III - Sciences de la Vie 323, 559–563. https://doi.org/10.1016/S0764-4469(00)00179-7

Kumar, S., Rosat, S., Hinderer, J., Mouyen, M., 2021. Groundwater monitoring and characterization by a vertical dipole of superconducting gravimeters in a karst aquifer, France, in: First International Meeting for Applied Geoscience & Energy Expanded Abstracts. Presented at the First International Meeting for Applied Geoscience & Energy, Society of Exploration Geophysicists, Denver, CO and virtual, pp. 889–893. https://doi.org/10.1190/segam2021-3582839.1

Laamrani, A., Valeria, O., Cheng, L.Z., Bergeron, Y., Camerlynck, C., 2013. The use of ground penetrating radar for remote sensing the organic layer - mineral soil interface in paludified boreal forests. Canadian Journal of Remote Sensing 16. https://doi.org/10.5589/m13-009

Laloy, E., Javaux, M., Vanclooster, M., Roisin, C., Bielders, C.L., 2011. Electrical Resistivity in a Loamy Soil: Identification of the Appropriate Pedo-Electrical ModelAll rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Vadose Zone Journal 10, 1023–1033. https://doi.org/10.2136/vzj2010.0095

Lavorel, S., Garnier, E., 2002. Predicting changes in community composition and ecosystem functioning from plant traits: revisiting the Holy Grail: Plant response and effect groups. Functional Ecology 16, 545–556. https://doi.org/10.1046/j.1365-2435.2002.00664.x

Liu, Q., Peng, C., Schneider, R., Cyr, D., McDowell, N.G., Kneeshaw, D., 2023. Drought-induced increase in tree mortality and corresponding decrease in the carbon sink capacity of Canada's boreal forests from 1970 to 2020. Global Change Biology 29, 2274–2285. https://doi.org/10.1111/gcb.16599

Loke, L.H.L., Chisholm, R.A., 2022. Measuring habitat complexity and spatial heterogeneity in ecology. Ecology Letters 25, 2269–2288. https://doi.org/10.1111/ele.14084

Loke, M., 1999. Electrical imaging surveys for environmental and engineering studies. A practical guide to 2-D and 3-D surveys 2, 70. https://doi.org/10.1111/j.1365-2478.1996.tb00142.x

Lombardi, E., Ferrio, J.P., Rodríguez-Robles, U., Resco de Dios, V., Voltas, J., 2021. Ground-Penetrating Radar as phenotyping tool for characterizing intraspecific variability in root traits of a widespread conifer. Plant Soil 468, 319–336. https://doi.org/10.1007/s11104-021-05135-0

Lorenzo, H., Pérez-Gracia, V., Novo, A., Armesto, J., 2010. Forestry applications of ground-penetrating radar. Forest Syst 19, 5. https://doi.org/10.5424/fs/2010191-01163

Ma, Y., Van Dam, R.L., Jayawickreme, D.H., 2014. Soil moisture variability in a temperate deciduous forest: insights from electrical resistivity and throughfall data. Environ Earth Sci 72, 1367–1381. https://doi.org/10.1007/s12665-014-3362-y

Mares, R., Barnard, H.R., Mao, D., Revil, A., Singha, K., 2016. Examining diel patterns of soil and xylem moisture using electrical resistivity imaging. Journal of Hydrology 536, 327–338. https://doi.org/10.1016/j.jhydrol.2016.03.003

Martin, L., Cochard, H., Mayr, S., Badel, E., 2021. Using electrical resistivity tomography to detect wetwood and estimate moisture content in silver fir (Abies alba Mill.). Annals of Forest Science 78, 65. https://doi.org/10.1007/s13595-021-01078-9

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, 243–259. https://doi.org/10.1007/s11104-017-3255-4

Mary, B., Iván, V., Meggio, F., Peruzzo, L., Blanchy, G., Chou, C., Ruperti, B., Wu, Y., Cassiani, G., 2023. Imaging of the active root current pathway under partial root-zone drying stress: A laboratory study for *Vitis vinifera*. Biogeosciences Discussions 1–51. https://doi.org/10.5194/bg-2023-58

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. https://doi.org/10.5194/hess-22-5427-2018

Mary, B., Saracco, G., Peyras, L., Vennetier, M., Mériaux, P., Baden, D., 2015. Preliminary Use of Ultrasonic Tomography Measurement to Map Tree Roots Growing in Earth Dikes. Physics Procedia 70, 965–969. https://doi.org/10.1016/j.phpro.2015.08.201

Mary, B., Vanella, D., Consoli, S., Cassiani, G., 2019. Assessing the extent of citrus trees root apparatus under deficit irrigation via multi-method geo-electrical imaging. Sci Rep 9, 9913. https://doi.org/10.1038/s41598-019-46107-w

Mathys, A., Coops, N.C., Waring, R.H., 2014. Soil water availability effects on the distribution of 20 tree species in western North America. Forest Ecology and Management 313, 144–152. https://doi.org/10.1016/j.foreco.2013.11.005

McCormick, E.L., Dralle, D.N., Hahm, W.J., Tune, A.K., Schmidt, L.M., Chadwick, K.D., Rempe, D.M., 2021. Widespread woody plant use of water stored in bedrock. Nature 597, 225–229. https://doi.org/10.1038/s41586-021-03761-3

Mendes, M., 2009. A hybrid fast algorithm for first arrivals tomography. Geophysical Prospecting 57, 803–809. https://doi.org/10.1111/j.1365-2478.2008.00755.x

Meyer, M.D., North, M.P., Gray, A.N., Zald, H.S.J., 2007. Influence of soil thickness on stand characteristics in a Sierra Nevada mixed-conifer forest. Plant Soil 294, 113–123. https://doi.org/10.1007/s11104-007-9235-3

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. https://doi.org/10.1029/2002WR001581

Molon, M., Boyce, J.I., Arain, M.A., 2017. Quantitative, nondestructive estimates of coarse root biomass in a temperate pine forest using 3-D ground-penetrating radar (GPR). J. Geophys. Res. Biogeosci. 122, 80–102. https://doi.org/10.1002/2016JG003518

Müller, J., Bolte, A., 2009. The use of lysimeters in forest hydrology research in north-east Germany. Landbauforschung (vTI Agric. For. Res.) 59, 1–10.

National Research Council (NRC), 2001. Basic research opportunities in earth science. National Academy Press, Washington DC, USA.

Naudet, V., Revil, A., Bottero, J., Bégassat, P., 2003. Relationship between self-potential (SP) signals and redox conditions in contaminated groundwater. Geophysical research letters 30. https://doi.org/10.1029/2003GL018096

Niiyama, K., Kajimoto, T., Matsuura, Y., Yamashita, T., Matsuo, N., Yashiro, Y., Ripin, A., Kassim, Abd.R., Noor, N.S., 2010. Estimation of root biomass based on excavation of individual root systems in a primary dipterocarp forest in Pasoh Forest Reserve, Peninsular Malaysia. J. Trop. Ecol. 26, 271–284. https://doi.org/10.1017/S0266467410000040

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

Nourtier, M., Chanzy, A., Cailleret, M., Yingge, X., Huc, R., Davi, H., 2014. Transpiration of silver Fir (Abies alba mill.) during and after drought in relation to soil properties in a Mediterranean mountain area. Annals of Forest Science 71, 683–695. https://doi.org/10.1007/s13595-012-0229-9

Nyquist, J.E., Corry, C.E., 2002. Self-potential: The ugly duckling of environmental geophysics. The Leading Edge 21, 446–451. https://doi.org/10.1190/1.1481251

Paillet, Y., Cassagne, N., Brun, J.-J., 2010. Monitoring forest soil properties with electrical resistivity. Biol Fertil Soils 46, 451–460. https://doi.org/10.1007/s00374-010-0453-0

Palmer, D., 1980. The Generalized Reciprocal Method of Seismic Refraction Interpretation. Society of Exploration Geophysicists. https://doi.org/10.1190/1.9781560802426

Parasnis, D.S., 1967. Three-dimensional electric Mise-à_la-masse survey of an irregular lead-zinc-copper deposit in central Sweden. Geophysical prospecting.

Park, B.B., Yanai, R.D., Vadeboncoeur, M.A., Hamburg, S.P., 2007. Estimating Root Biomass in Rocky Soils using Pits, Cores, and Allometric Equations. Soil Sci. Soc. Am. j. 71, 206–213. https://doi.org/10.2136/sssaj2005.0329

Parsekian, A.D., Singha, K., Minsley, B.J., Holbrook, W.S., Slater, L., 2015. Multiscale geophysical imaging of the critical zone: Geophysical Imaging of the Critical Zone. Rev. Geophys. 53, 1–26. https://doi.org/10.1002/2014RG000465

Peruzzo, L., Chou, C., Wu, Y., Schmutz, M., Mary, B., Wagner, F.M., Petrov, P., Newman, G., Blancaflor, E.B., Liu, X., Ma, X., Hubbard, S., 2020. Imaging of plant current pathways for non-invasive root Phenotyping using a newly developed electrical current source density approach. Plant Soil 450, 567–584. https://doi.org/10.1007/s11104-020-04529-w

Peruzzo, L., Liu, X., Chou, C., Blancaflor, E.B., Zhao, H., Ma, X.-F., Mary, B., Iván, V., Weigand, M., Wu, Y., 2021. Three-channel electrical impedance spectroscopy for field-scale root phenotyping. The Plant Phenome Journal 4, e20021. https://doi.org/10.1002/ppj2.20021

Peskett, L., MacDonald, A., Heal, K., McDonnell, J., Chambers, J., Uhlemann, S., Upton, K., Black, A., 2020. The impact of across-slope forest strips on hillslope subsurface hydrological dynamics. Journal of Hydrology 581, 124427. https://doi.org/10.1016/j.jhydrol.2019.124427

Postic, F., Beauchêne, K., Gouache, D., Doussan, C., 2019. Scanner-Based Minirhizotrons Help to Highlight Relations between Deep Roots and Yield in Various Wheat Cultivars under Combined Water and Nitrogen Deficit Conditions. Agronomy 9, 297. https://doi.org/10.3390/agronomy9060297

Proto, A.R., Di Iorio, A., Abenavoli, L.M., Sorgonà, A., 2020. A sonic root detector for revealing tree coarse root distribution. Sci Rep 10, 8075. https://doi.org/10.1038/s41598-020-65047-4

Rambal, S., Ourcival, J.-M., Joffre, R., Mouillot, F., Nouvellon, Y., Reichstein, M., Rocheteau, A., 2003. Drought controls over conductance and assimilation of a Mediterranean evergreen ecosystem: scaling from leaf to canopy: Scaling drought from leaf to canopy. Global Change Biology 9, 1813–1824. https://doi.org/10.1111/j.1365-2486.2003.00687.x

Raz-Yaseef, N., Koteen, L., Baldocchi, D.D., 2013. Coarse root distribution of a semi-arid oak savanna estimated with ground penetrating radar: Ground penetrating radar survey of Oak-Savanna coarse roots. J. Geophys. Res. Biogeosci. 118, 135–147. https://doi.org/10.1029/2012JG002160

Revil, A., Jardani, A., 2013. The Self-Potential Method: Theory and Applications in Environmental Geosciences. Cambridge University Press.

Rieder, J.S., Kneisel, C., 2023. Monitoring spatiotemporal soil moisture variability in the unsaturated zone of a mixed forest using electrical resistivity tomography. Vadose Zone Journal. https://doi.org/10.1002/vzj2.20251

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

Robinson, D.A., Binley, A., Crook, N., Day-Lewis, F.D., Ferré, T.P.A., Grauch, V.J.S., Knight, R., Knoll, M., Lakshmi, V., Miller, R., Nyquist, J., Pellerin, L., Singha, K., Slater, L., 2008. Advancing process-based watershed hydrological research using near-surface geophysics: a vision for, and review of, electrical and magnetic geophysical methods. Hydrol. Process. 22, 3604–3635. https://doi.org/10.1002/hyp.6963

Robinson, D.A., Lebron, I., Querejeta, J.I., 2010. Determining Soil-Tree-Grass Relationships in a California Oak Savanna Using Eco-Geophysics. Vadose Zone Journal 9, 528–536. https://doi.org/10.2136/vzj2009.0041

Robinson, J.L., Slater, L.D., Schäfer, K.V.R., 2012. Evidence for spatial variability in hydraulic redistribution within an oak–pine forest from resistivity imaging. Journal of Hydrology 430–431, 69–79. https://doi.org/10.1016/j.jhydrol.2012.02.002

Robock, A., Vinnikov, K.Y., Srinivasan, G., Entin, J.K., Hollinger, S.E., Speranskaya, N.A., Liu, S., Namkhai, A., 2000. The global soil moisture data bank. Bulletin of the American Meteorological Society 81, 1281–1300. https://doi.org/10.1175/1520-0477(2000)081<1281:TGSMDB>2.3.CO;2

Rodríguez-Robles, U., Arredondo, T., Huber-Sannwald, E., Ramos-Leal, J.A., Yépez, E.A., 2017. Technical note: Application of geophysical tools for tree root studies in forest ecosystems in complex soils. Biogeosciences 14, 5343–5357. https://doi.org/10.5194/bg-14-5343-2017

Romero-Ruiz, A., Linde, N., Keller, T., Or, D., 2018. A review of geophysical methods for soil structure characterization. Reviews of Geophysics 56, 672–697. https://doi.org/10.1029/2018RG000611

Ruffault, J., Pimont, F., Cochard, H., Dupuy, J.-L., Martin-StPaul, N., 2022. SurEau-Ecos v2.0: a trait-based plant hydraulics model for simulations of plant water status and drought-induced mortality at the ecosystem level. Geoscientific Model Development 15, 5593–5626. https://doi.org/10.5194/gmd-15-5593-2022

Ryazantsev, P.A., Hartemink, A.E., Bakhmet, O.N., 2022. Delineation and description of soil horizons using ground-penetrating radar for soils under boreal forest in Central Karelia (Russia). CATENA 214, 106285. https://doi.org/10.1016/j.catena.2022.106285

Samouëlian, A., Cousin, I., Tabbagh, A., Bruand, A., Richard, G., 2005. Electrical resistivity survey in soil science: a review. Soil and Tillage Research 83, 173–193. https://doi.org/10.1016/j.still.2004.10.004

Satriani, A., Loperte, A., Imbrenda, V., Lapenna, V., 2012. Geoelectrical Surveys for Characterization of the Coastal Saltwater Intrusion in Metapontum Forest Reserve (Southern Italy). International Journal of Geophysics 2012. https://doi.org/10.1155/2012/238478

Schaap, M.G., Bouten, W., Verstraten, J.M., 1997. Forest floor water content dynamics in a Douglas fir stand. Journal of Hydrology 201, 367–383. https://doi.org/10.1016/S0022-1694(97)00047-4

Schlesinger, W.H., Jasechko, S., 2014. Transpiration in the global water cycle. Agricultural and Forest Meteorology 189–190, 115–117. https://doi.org/10.1016/j.agrformet.2014.01.011

Séger, M., Guérin, R., Frison, A., Bourennane, H., Richard, G., Cousin, I., 2014. A 3D electrical resistivity tomography survey to characterise the structure of a albeluvic tonguing horizon composed of distinct elementary pedological volumes. Geoderma 219–220, 168–176. https://doi.org/10.1016/j.geoderma.2013.12.018

Sheriff, R.E., Geldart, L.P., 1995. Exploration Seismology. Cambridge University Press.

Singha, K., Johnson, T.C., Lewis, F.D.D., Slater, L.D., 2022. Electrical Imaging for Hydrogeology, The Groundwater Project. Eileen Poeter and John Cherry, Guelph, Ontario, Canada.

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, 185–207. https://doi.org/10.1007/s11104-008-9860-5

Sucre, E.B., Tuttle, J.W., Fox, T.R., 2011. The Use of Ground-Penetrating Radar to Accurately Estimate Soil Depth in Rocky Forest Soils. Forest Science 57, 59–66. https://doi.org/10.1093/forestscience/57.1.59

Sungpalee, W., Itoh, A., Kanzaki, M., Sri-ngernyuang, K., Noguchi, H., Mizuno, T., Teejuntuk, S., Hara, M., Chai-udom, K., Ohkubo, T., Sahunalu, P., Dhanmmanonda, P., Nanami, S., Yamakura, T., Sorn-ngai, A., 2009. Intra- and interspecific variation in wood density and fine-scale spatial distribution of stand-level wood density in a northern Thai tropical montane forest. J. Trop. Ecol. 25, 359–370. https://doi.org/10.1017/S0266467409006191

Sutinen, R., Middleton, M., 2020. Soil water drives distribution of northern boreal conifers Picea abies and Pinus sylvestris. Journal of Hydrology 588, 125048. https://doi.org/10.1016/j.jhydrol.2020.125048

Sutinen, R., Teirilä, A., Pänttäjä, M., Sutinen, M.-L., 2002. Survival of artificially regenerated Scots pine on till soils with respect to varying dielectric properties. Can. J. For. Res. 32, 1151–1157. https://doi.org/10.1139/x02-012

Thayer, D., Parsekian, A.D., Hyde, K., Speckman, H., Beverly, D., Ewers, B., Covalt, M., Fantello, N., Kelleners, T., Ohara, N., Rogers, T., Holbrook, W.S., 2018. Geophysical Measurements to Determine the Hydrologic Partitioning of Snowmelt on a Snow-Dominated Subalpine Hillslope. Water Resources Research 54, 3788–3808. https://doi.org/10.1029/2017WR021324

Van Camp, M., de Viron, O., Pajot-Métivier, G., Casenave, F., Watlet, A., Dassargues, A., Vanclooster, M., 2016. Direct measurement of evapotranspiration from a forest using a superconducting gravimeter. Geophysical Research Letters 43, 10,225-10,231. https://doi.org/10.1002/2016GL070534

Van Camp, M., de Viron, O., Watlet, A., Meurers, B., Francis, O., Caudron, C., 2017. Geophysics From Terrestrial Time-Variable Gravity Measurements: Time-Variable Gravity Measurements. Rev. Geophys. 55, 938–992. https://doi.org/10.1002/2017RG000566

Vereecken, H., Amelung, W., Bauke, S.L., Bogena, H., 2022. Soil hydrology in the Earth system. Nature Reviews Earth & Environment 3, 587. https://doi.org/10.1038/s43017-022-00324-6

Vouillamoz, J.M., Sokheng, S., Bruyere, O., Caron, D., Arnout, L., 2012. Towards a better estimate of storage properties of aquifer with magnetic resonance sounding. Journal of Hydrology 458–459, 51–58. https://doi.org/10.1016/j.jhydrol.2012.06.044

Voytek, E.B., Barnard, H.R., Jougnot, D., Singha, K., 2019. Transpiration- and precipitation-induced subsurface water flow observed using the self-potential method. Hydrological Processes 1784–1801. https://doi.org/10.1002/hyp.13453

Waxman, M.H., Smits, L.J.M., 1968. Electrical Conductivities in Oil-Bearing Shaly Sands. Society of Petroleum Engineers Journal 8, 107–122. https://doi.org/10.2118/1863-A

Wenzel, H.-G., 1996. The nanogal software: Earth tide data processing package ETERNA 3.30. Bull. Inf. Marées Terrestres 124, 9425–9439.

Xiao, L., Li, C., Cai, Y., Zhou, T., Zhou, M., Gao, X., Shi, Y., Du, H., Zhou, G., Zhou, Y., 2021. Interactions between soil properties and the rhizome-root distribution in a 12-year Moso bamboo reforested region: Combining ground-penetrating radar and soil coring in the field. Science of The Total Environment 800, 149467. https://doi.org/10.1016/j.scitotenv.2021.149467

Yan, H., Dong, X., Feng, G., Zhang, S., Mucciardi, A., 2013. Coarse root spatial distribution determined using a ground-penetrating radar technique in a subtropical evergreen broad-leaved forest, China. Sci. China Life Sci. 56, 1038–1046. https://doi.org/10.1007/s11427-013-4560-7

Zajícová, K., Chuman, T., 2022. O and A soil horizons' boundaries detection using GPR under variable soil moisture conditions. Geoderma 422, 115934. https://doi.org/10.1016/j.geoderma.2022.115934

Zapata, R., Oliver-Villanueva, J.-V., Lemus-Zúñiga, L.-G., Fuente, D., Mateo Pla, M.A., Luzuriaga, J.E., Moreno Esteve, J.C., 2021. Seasonal variations of electrical signals of Pinus halepensis Mill. in Mediterranean forests in dependence on climatic conditions. Plant Signaling & Behavior 16, 1948744. https://doi.org/10.1080/15592324.2021.1948744

Zapata, R., Oliver-Villanueva, J.-V., Lemus-Zúñiga, L.-G., Luzuriaga, J.E., Mateo Pla, M.A., Urchueguía, J.F., 2020. Evaluation of electrical signals in pine trees in a mediterranean forest ecosystem. Plant Signaling & Behavior 15, 1795580. https://doi.org/10.1080/15592324.2020.1795580

Zenone, T., Morelli, G., Teobaldelli, M., Fischanger, F., Matteucci, M., Sordini, M., Armani, A., Ferrè, C., Chiti, T., Seufert, G., 2008. Preliminary use of ground-penetrating radar and electrical resistivity tomography to study tree roots in pine forests and poplar plantations. Functional Plant Biol. 35, 1047. https://doi.org/10.1071/FP08062

Zhang, T., Song, L., Zhu, J., Wang, G., Li, M., Zheng, X., Zhang, J., 2021. Spatial distribution of root systems of Pinus sylvestris var. mongolica trees with different ages in a semi-arid sandy region of Northeast China. Forest Ecology and Management 483, 118776. https://doi.org/10.1016/j.foreco.2020.118776

Zhao, P.-F., Wang, Y.-Q., Yan, S.-X., Fan, L.-F., Wang, Zi-Yang, Zhou, Q., Yao, J.-P., Cheng, Q., Wang, Zhong-Yi, Huang, L., 2019. Electrical imaging of plant root zone: A review. Computers and Electronics in Agriculture 167, 105058. https://doi.org/10.1016/j.compag.2019.105058

Zhu, J.-J., Kang, H.-Z., Gonda, Y., 2007. Application of Wenner Configuration to Estimate Soil Water Content in Pine Plantations on Sandy Land. Pedosphere 17, 801–812. https://doi.org/10.1016/S1002-0160(07)60096-4

Zonge, K., Wynn, J., Urquhart, 2005. Resistivity, Induced Polarization, and Complex Resistivity, in: Butler, D.K. (Ed.), Near-Surface Geophysics. Society of Exploration Geophysicists. https://doi.org/10.1190/1.9781560801719