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Review

Non-invasive methods for the investigation of trees' root system in the urban environment

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Abstract: Construction activities, maintenance and expansion of below-ground grey infrastructures are known to often have precedence over tree preservation, and they have a high chance of damaging nearby trees' roots. Damages to tree root systems are often due to the fact that is difficult to locate roots. Non-invasive techniques capable to assess the presence and the position of tree roots, may help guide the excavation activities in order to avoid damaging the primary roots of the affected tree and preserve fine roots. The objective of this paper is to review and discuss the existing knowledge about the main non-invasive methods to investigate tree roots in the urban environments. The ground penetration radar (GPR) is a geophysics technique based on the emission short pulses of electromagnetic waves by an antenna and the detection of the reflected waves by a receiver. GPR show its capacity to adequately locate the position and the diameter of coarse roots, with sufficient resolution, in the first 90-100 cm, even on paved sites, with no need of pavement displacement. The electric resistivity tomography (ERT) is a geoelectric technique that consists in applying electric current into the soil through electrodes and measuring the difference in electric potential (voltage) at a selected position. Positive correlation has been found between soil resistivity and coarse root biomass. Earth impedance method (EIM) also involve electricity enforcement into the soil-tree system but allow to quantify only absorbing root surfaces and ignores non-absorbing root surfaces. Sonic tomography applied to root system have shown good results in correctly locate coarse roots in the first 30 cm of depth.

Keywords: Ground penetrating radar; electric resistivity tomography; earth impedance method; sonic tomography

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Introduction

There is growing understanding that the physical, psychologic, and social well-being of more than 50% of World's population, which actually resides in urban settings, is strictly related to the presence, the size, the quality, and the distribution of green areas (McPherson 2007; Nowak and Crane 2002; Nowak and Dwyer, 2007; Yin et al., 2017). Such appreciation of ecosystem services provided by urban vegetation led to the development of extensive tree planting programs worldwide with the aim of increasing the city's canopy cover, but positive impacts on human well-being were not observed in all cases. The urban environment is characterized by a plethora of co-occurring abiotic and biotic stresses, thus ignoring the "right tree in the right place with the right management" criteria often leads to premature tree death and increased CO_2 and particulate matter (PM) emission for tree removal and replanting (Nowak and Crane, 2002). In particular, urban redevelopment led to fluctuating canopy cover during some extensive tree planting programs carried out in North America.

Construction activities, maintenance and expansion of below-ground grey infrastructures are known to often have precedence over tree preservation, and they have a high chance of damaging nearby trees' roots which, due to soil compaction, are often concentrated in the uppermost 70 cm of soil (Jim, 2003;

Fini et al., 2020). Research recently highlighted that trenching and construction activities act as a predisposing, rather than inciting, factor in Manion's mortality spiral (Fini et al., 2020). Net photosynthesis, leaf hydration, and resistance to uprooting of two tree species declined mildly after the excavation of up to 70% of tree roots, but full recovery of pre-damage conditions did not occur within 51 months since excavation (Fini et al., 2020).

Best arboricultural practices suggest to define and fence a tree protection zone which can be sized based on either stem diameter alone (Benson et al., 2019) or a combination of attributes such as size, physiological age, and species tolerance to root manipulation (Matheny and Clark, 1998). In several instances, however, best practices are just ignored because of lack of knowledge or cost reasons and, even when they are considered, setting a properly sized tree protection zone may not be feasible due to the position of the underservice or other built structures (Jim, 2003). Damages to tree root systems are often due to the fact that it is difficult to know exactly their location and extension. Non-invasive techniques capable to assess the presence and the position of tree roots, may help guide the excavation activities in order to avoid damaging the primary roots of the affected tree and preserve fine roots (*i.e.* those with diameter <2 mm, a rapid turn-over and a large seasonal variation; Danjon and Reubens (2008).

Roots are dynamic structures connected in a three-dimensional organized network whose functioning is greatly depended on topological and geometric characteristics. Topology deals with the physical connection between plant component, while geometry includes shape, size, orientation and spatial location of the component (Danjon and Reubens, 2008). Geometry is mainly involved in plant-environment resource exchange and in plant anchorage.

The study of the topology, *i.e.* the way in which root segments are connected to each other, provides the opportunity to understand the development of the root system architecture. Previous research used topology information to compute the distribution of volume, length and number of roots, and branching pattern (Danjon and Reubens, 2008).

Root geometry is strongly related to soil environment. Different environmental condition often results in a highly heterogeneous distribution of coarse roots (Nicoll et al., 1997) that can show highly asymmetrical development relative to *e.g.* dominant wind or slope direction. The determination and the study of the geometrical properties of the 3D root system architecture is needed to fully understand coarse root system structure and functioning.

Studies of tree root systems are relatively scarce compared to those dealing with above-ground part of plant. This appear clear in the recent proliferation of models that estimate above-ground carbon storage as a function of other dendrometric attributes, such as stem diameter and tree height (Henry et al., 2013). Conversely, above-ground estimates are seldom paralleled by an adequate measurement of carbon stored in roots, which is often assumed as a percentage of above ground carbon (Hutyra et al., 2011; Strohbach and Haase, 2012). Accurate spatial and temporal estimates of the biomass and carbon allocation towards root system are critical to define the magnitude of soil carbon storage and how this will respond to different external perturbation such as environmental condition or anthropogenic activities (Sorgonà et al., 2018). It is technically challenging and time-consuming to study *in situ* tree roots, particularly in highly heterogeneous and densely built environment sites such as the urban environment. Consequently, direct methods for root assessment, such as excavation, augering, and the profile wall method (Van Noordwijk et al., 2000) are rarely applied in urban studies. Semi-invasive methods, such as AirspadeTM, have been gaining popularity in root studies, due to the absence or root damage during excavation and to the high replicability of the measurement, but still they cannot be applied in paved sites without destroying the pavements (Fini et al., 2017). To overcome this limitation, non-invasive methods for root detection, based on either geophysics or tomography, have been proposed for the measurement of key root-system traits, such as root density per unit area or volume, root number and root length (Amato et al., 2009; Rossi et al., 2011; Paglis, 2013; Sorgonà et al., 2018). In the last 20 years, these methodologies have improved, but their use is not supported by a consistent body of literature yet.

The objective of this paper is to review and discuss the existing knowledge about the main non-invasive methods to investigate tree roots in the urban environments. For the sake of completeness, we also made a brief overview of direct methods for root studies.

2. Materials and Methods

After setting the review questions ("which are the main non-invasive methods for root inspection? Which are their main advantages and drawbacks and how accurate and reliable are they in root identification?"), a literature analysis was conducted with the scientific database Scopus and Google Scholar by using different relevant keywords. Two different levels of detail were used in the literature search. Firstly, general keywords about invasive and non-invasive root inspections were searched, alone and in combination using the AND operator: "root system investigation", "non-invasive methods", "non-destructive methods", "tree root system analysis". We also added the keyword "direct methods", alone and in combination with other keywords. The initial research, after the removing of duplicates, returned a total of 9034 papers. The title and the abstract of these papers was read in order to check if they include a relevant subject and to identify the methods used for root studies. Papers that did not satisfy the inclusion criteria (see below) were removed. Article remaining were filtered looking full text to reach the final list of 34 relevant articles. Secondly, the literature survey was refined using keywords more specifically related to non-invasive methods: "geophysic techniques", "ground penetration radar", "root 3D architecture", "urban tree root system", "electrical measurements", "electrical resistivity tomography", "root distribution", and "root biomass analysis". After a selection based on the inclusion criteria, 25 papers returned by this second literature survey were added to the final list. Seventeen relevant articles found in the reference sections of selected papers but not identified by the literature search were also included in this review.

Relevancy of each article in our literature search was checked according to the following criteria (Ferrini et al., 2020):

- To be a full text paper (including original research and reviews), peer-reviewed, available in English.
- To include a relevant subject, *i.e.* anyone reporting how non-invasive technique can be used to investigate tree root systems.
- In addition, we selected papers principally published between 1990 and 2020 from any geographic location.

3. Results

3.1. Direct methods for root investigation

Direct methods, including excavation of the whole root system, tree uprooting, trenching, soil coring and minirhizotrons, have been most frequently used for root studies. Excavation of the whole root system is a labor-intensive technique which consists in extracting or uprooting the whole root system. Excavation can be carried out using manual or heavy spading, whereas uprooting can be triggered by static pulling or by the simple observation of naturally uprooted trees (Danjon et al., 2006a). Uprooting can be subjected to some criticism for trees having fibrous shallow roots, because a substantial amount of horizontal surface root volume is lost during uprooting (Danjon et al., 2006a). After loosening the substrate or the soil using water or air under pressure, roots can be mapped and directly measured. This method is more frequently used for small trees and shrubs growing in containers (Amoroso et al., 2010; Fini et al., 2011) than in the field (Frangi et al., 2016). On larger trees, root system excavation requires heavy machinery and, if sampling is conducted in public areas, may not be well perceived by residents unless proper communication. A further limitation of these methods is that they are not replicable and do not allow monitoring of root growth over time. To overcome these limitations, some minimally invasive techniques allowing the displacement of soil without damaging the roots system have been developed: (i) wet excavation (hydraulic soil excavation) with medium/low pressure, that does not damage roots, but needs a great amount of water and requires additional equipment for slurry removal; (ii) high pressure air spades (*e.g.* air-spadeTM system, that use a proprietary, synergic combination of supersonic jets of air and high flow pneumatic vacuum transport). Excavation should be done progressively in layers or sectors and, with the aim of minimising displacement, roots can be secured in position using poles and lances (Danjon and Reubens, 2008); (iii) vacuum excavation by vacuum excavator track, also known as suction excavator, that can hydraulically load dry and wet materials via vacuum hoses (Nichols et al., 2017).

These techniques, also known as "soft dig", were originally conceived to avoid damage to utility and pipeline networks, indeed now they are sometimes used to map the soil surrounding the root system in order to preserve them during construction works, as well as to reduce soil compaction. Soft dig methods cause a minimal injury to roots, thus they are replicable and useful for monitoring root growth over time in unpaved areas (Fini et al., 2020). They have also found application in research, both to collect information about the root system and to validate information obtained with non-invasive roots inspection methods (Hruska et al., 1999; Nichols et al., 2017; Sorgonà et al. 2018; Stokes et al., 2002; Tardiò et al., 2016).

The direct investigation of biometric parameters of root systems can also be carried out by trenching. Most trenching approaches are limited to the first meter and reach only occasionally soil depths of two meters below ground (Dauer et al., 2009; Maeght et al., 2013). They are invasive and destructive but allow an accurate detection and measurement of roots in the vertical plane. Conversely, they do not provide information about the horizontal distribution of roots, unless multiple trenches are dug. Common analyses at all profile-walls are root counts and estimations of the root length density (RLD), achieved using a sampling grid or marking position on plastic overlays (Van Noordwijk et al., 2000). These methods are extremely time consuming for both data collection and elaboration. Measurement in profile-walls can be also made by digital imaging method (Dauer et al., 2009). In this method a desktop scanner capture images of roots on a vertical soil surfaces, roots are manually identified in the images and analyzed by a software to determine number of roots visible in a vertical horizon (root count cm^{-2}).

Soil coring has been frequently employed to measure root mass, root density, and specific root length (Amoroso et al., 2011). Coring can be conducted manually or by pushing or hammering the sampling equipment into the soil using various devices. After weighing cores and dividing root and non-root material, specific root length (SRL), root mass density (DWroots/DWsoil+roots), and root length density (SRL/DWsoil+root) are detected (Amato and Pardo, 1994). Upscaling from core data to stand level root biomasses is in general only possible if sample numbers are sufficiently high to account for heterogeneous root distribution in the soil (Maeght et al., 2013). Coring was found to be more accurate for measuring shallow roots attributes than trenching. Conversely, the opposite was observed for deep roots (Danjon and Reubens, 2008; Dauer et al., 2009; Maeght et al., 2013).

Growth dynamics of fine roots have also been studied with bulk-root studies like ingrowth bags, minirhizotrons and rhizotrons. These two latter techniques, also called "root windows" are basically transparent walls or tubes that allow the researcher to observe roots while they are growing in soil. Minirhizotrons (MR) have the advantage of allowing the monitoring of a particular location in the soil profile and to reveal the growth of very small roots, and occasionally fungal hyphae, over time (Maeght et al., 2013). There are some major limitations with this technique. In the assessment of root turnover, MR tends to over-sample the smaller and more dynamic lower-order roots (Guo et al., 2008). Another common limitation of the MR is the difficulty in obtaining good contact between the tube and the soil: gasps frequently form along the tube, creating artificial condition for root growth (Maeght et al., 2013).

3.2. Indirect methods for root studies

Indirect methods can allow the collection of information about tree root systems without the needing to physically access the roots. Scientists have long sought reliable non-invasive methods for roots detection and analysis, both in pot and field condition. With this purpose, the application of several different technologies has been tried. Because the focus of this review is on woody roots, methods such as the magnetic resonance imaging (MIR), magnetic resonance imaging-positron emission tomography (MIR-PET), X-ray computed tomography (X-ray CT), and electrical impedance tomography (EIT), which have only been implemented on herbaceous species, will not be described here. Conversely, the theoretical background, the applicability, and the limitations will be described for those non-invasive techniques which are suitable for densely built environments thanks to their ability to locate roots with minimal disturbance to soil and infrastructure (Fan et al., 2015). In this work, four methods will be described: ground penetrating radar (GPR), electrical resistivity tomography (ERT), earth impedance method (EIM) and sonic tomography (ST).

3.3. Ground penetrating radar

3.3.1. Theory and applications

Ground penetrating radar (GPR) has been used worldwide for more than thirty years to locate subsurface object for a variety of application in civil engineering and environmental targets (Neal 2004). It has been used to locate underground services that might interfere with excavation and construction projects (Chen and Wimsatt, 2009), for geotechnical investigations, and for concrete inspections, in order to examine the structural integrity of structural supporting rebars embedded in the concrete matrix (Conyers and Goodman, 1997). GPR has been also proposed as a non-invasive and non-destructive method that can be used to locate individual roots, as well as to describe the architecture of tree root systems *in situ*, even in paved urban environments (Hruska et al., 1999).

GPR is made of an antenna, which releases short pulses of electromagnetic waves (EM) with frequencies in between 10 and 1000 MHz downward into the soil, and of a receiver (Holden et al., 2002). The EM emitted by the antenna travels in the soil at a speed v as expressed in equation 1:

$$v = c/\sqrt{(\varepsilon_r)} \qquad \text{(Eq. 1)}$$

where v is the speed of the EM wave within the media (mm/ns), c is the speed of light (300 mm/ns) and ε_r is the relative dielectric constant, a dimensionless quantity related to the behavior of a material subjected to an electric field (Table 1).

While going downward in the soil, EM is partly reflected as it moves across bodies with heterogeneous ε_r (Neal, 2004; Robinson et al., 2013). The amount of energy reflected is given by the reflection coefficient R expressed as (equation 2):

$$R = \frac{[\sqrt{(v_2)} - \sqrt{(v_1)}]}{[\sqrt{(v_2)} + \sqrt{(v_1)}]} \qquad \text{(Eq. 2)}$$

where v_1 and v_2 are the speeds of EM in the different materials (Robinson et al., 2013). It should be noted that ε_r is a key determinant of the amount of EM reflected when the EM crosses an heterogeneous media: the larger is the difference between the ε of the two materials, the larger is the portion of energy that is reflected (Robinson et al., 2013).

The reflected EM is perceived by the receiver, which calculates the two-way travel time (t) of the EM from the antenna to the body which causes the reflection, and back to the receiver. This allows to draw a two-dimensional section of the sub-soil (Davis and Annan, 1989). The depth of the object which causes the reflection (d) is then calculated, according to Neal (2004) as:

$$d = v \cdot t/2 \qquad \text{(Eq. 3)}$$

Equations 1 and 2 indicate that the accuracy of the measurement of rooting depth is very sensitive to ε, which should thus carefully assess before starting the measurement. Most georadars have pre-set dielectric constants (ε_r) for the different soil textures, which should be checked by scanning an object buried at known depth into the soil (Tardìo et al., 2016) or a root of known depth (Bassuk et al., 2011).

GPR can accurately locate objects buried in the soil if they exhibit contrasting electric properties (dielectric constant and electrical conductivity) compared to those of the soil itself. The ε_r does not differ significantly between soil (4-30) and dry wood (4.5-22), but it is significantly higher for pure water (81) (Table 1).

Healthy woody roots usually display a volumetric water content around 40-50%, which is higher than volumetric water content of most soil, unless saturated or partly saturated, thus they can be detected (Bassuk et al., 2011; Hirano et al. 2009). Even healthy roots located in soils with high water table could be identified (Gormally et al., 2011). On the contrary, roots with a volumetric water content lower than 20%, such as dead roots or roots under fungal attack could not be detected (Hirano et al., 2009; Shigo, 2003). For similar reasons, root detection is easier in dry, compared to wet soils. Thus, coarser soil textures, characterized by lower water holding capacity and lower water content at field capacity, are more suitable for root identification by GPR compared to finer textures (Butnor et al., 2001). In highly heterogeneous urban soils, local changes in soil texture and water holding capacity may cause biases in root detection. Pavements may further hasten the measurement because they act as a source of discontinuity both radially (at the interface between the unpaved planting pit and the pavement) and vertically (at the interface between the pavement and the underlying soil).

Table 1. Typical dielectric constant, electrical conductivity, velocity and attenuation values of common surfaces materials (modified from Robinson, 2013). GPR can accurately locate objects buried in the soil if they exhibit contrasting electric properties (dielectric constant and electrical conductivity) compared to those of the soil itself.

Material	Dielectric constant	Electrical conductivity (mS m^{-1})	Velocity (m ns^{-1})	Attenuation (dB m^{-1})
Air	1	0	0.3	0
Salt water	80	3000	0.033	600
Fresh water	80	0.5	0.033	0.1
Ice	3-4	0.01	0.16	0.01
Granite, dry	5	0.01	0.13	0.01
Limestone	4-8	0.5-2	0.12	0.4-1
Shales	5-15	1-100	0.09	1-100
Sand, dry	5	0.01	0.13	0.01
Sand, wet	20-30	0.1-1.0	0.06	0.03-0.3
Clay, wet	10	500	0.095	300
Soils:				
Sandy, dry	2.6	1.4	0.19	1
Sandy, wet	25	69	0.06	23
Clayey, dry	2.5	2.7	0.19	3
Clayey, wet	19	500	0.07	200
Frozen	6	0.1	0.12	0.1

While GPR analysis can be performed using a wide range of frequencies, those between 450 MHz and 1.5 GHz are the most suitable for root detection (Bassuk et al., 2011; Butnor et al., 2001; Hruska et al., 1999; Nichols et al., 2017; Stokes et al., 2002). The choice of antenna frequency is critical and should be carefully done based on the material being investigated and on the aim of the measurements, because frequency affects both the resolution of root detection and the maximum depth of penetration of the signal in the soil (Hruska et al., 1999; Robinson et al., 2013) (Table 2). Low frequencies can penetrate deeper into the soil (up to 30 m depth for frequencies of 25 MHz; about 6 m for frequencies of

450 MHz), but cannot detect root with diameter smaller than 30 mm (Barton and Montagu, 2004; Hruska et al., 1999; Stokes et al., 2002). Conversely, higher frequencies can identify roots with smaller diameter (*e.g.* 5 mm using a 1.5 GHz antenna), but can hardly penetrate the soil deeper than 50 cm below grade (Barton and Montagu, 2004; Butnor et al., 2001). The maximum depth of investigation of high frequency antennas is constrained, particularly in clay-rich soils, by ionic charge transport in water and electrochemical processes associated with cation exchange (Robinson et al., 2013).

Table 2. Some theoretical investigation depth according to Annan (2001). The choice of the antenna central frequency is crucial both for investigation depth and for resolution. Lower central frequency allows deeper analysis but with less resolution.

Depth (m)	Central Frequency (MHz)
0.5	1000
1.0	500
2.0	200
5.0	100
10.0	50
30.0	25
50.0	10

3.3.2. Data acquisition and processing

GRP scanning can be made with different spatial arrangements. The antenna is usually moved on the soil surface along concentric circular transects conducted at different distances from the trunk or along parallel and perpendicular linear transects arranged to as a square grid. The use of a circular transect can be difficult to set up because of soil roughness but it is advisable for root studies because it ensures a quasi-perpendicular scanning of root system. Usually, transects are spaced 10 to 50 cm from each other.

Calibration of a GPR technique is a critical pre-inspection step for roots detection. The dielectrics of a soil can be empirically found by: 1) locating a root with the GPR system, 2) driving a measuring rod into the soil to find the exact depth, and 3) adjusting the dielectric parameter on instrument until the depth scale on the display agrees with the actual depth. This can be done at multiple locations within the inspection area and the dielectrics must be averaged (Bassuk et al., 2011).

Besides calibrating the relative dielectric constant, according to soil texture and actual moisture, the instrumental gain should also be optimized. The gain indicates the amplitude of the signal propagating through a medium, and it decreases with increasing depth, thus making deeper object less detectable (Tardìo et al., 2016). Some instruments can automatically compensate this depth-dependent amplitude loss.

It is relatively easy and fast for an experienced user to perform the GPR scanning in the field. Conversely, data analysis is extremely labor-intensive and, until recently, very subjective and much affected by the training of the operator. The outputs of the GPR, called radargrams, are basically 2D images that represent transects of soil (Figure 1).

Any buried object with different ε compared to the media, which thus causes a significant reflection of the EM, is displayed in the radargram as a hyperbola, with the peak of the hyperbola indicating the center of the object (Zenone et al., 2008). The most identifiable hyperboles are produced by linear objects whose major axes are perpendicular to the direction of travel of the antenna, while can be obscured when the angle is less than 45° (Barton and Montagu, 2004; Butnor et al., 2001). Differently from pipes and other artificial buried objects, roots grow with irregular shapes and varying orientation into the soil, which makes them hard to detect. Further, any metal objects (e.g. metal grids) near the root-zone may reflect a large portino of EM and create, in the radargram, an echo that cover other signal in the area, following a conic shape (Figure 2).

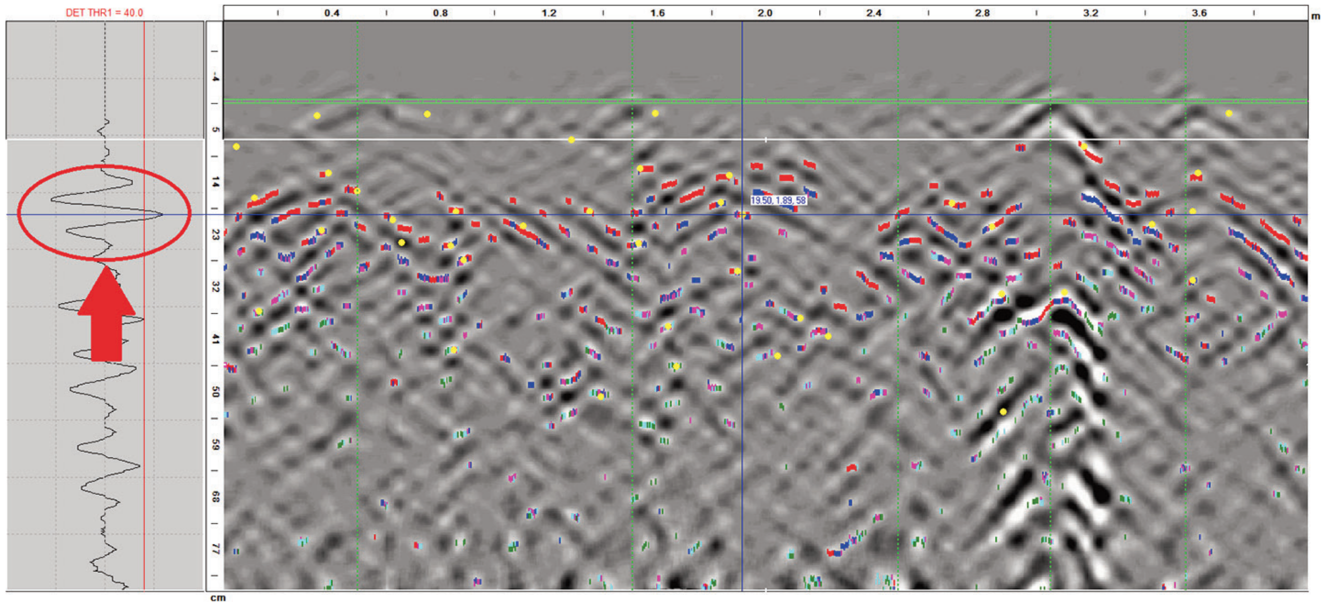

Figure 1. Output of the GPR, called radargram. It is basically a 2D section of the soil in the direction of the GPR progression. The GPR emits several electromagnetic waves, the radargram is obtained from the interpolation of the detection of the emitted waves. The red circle highlights the typical signal of a root.

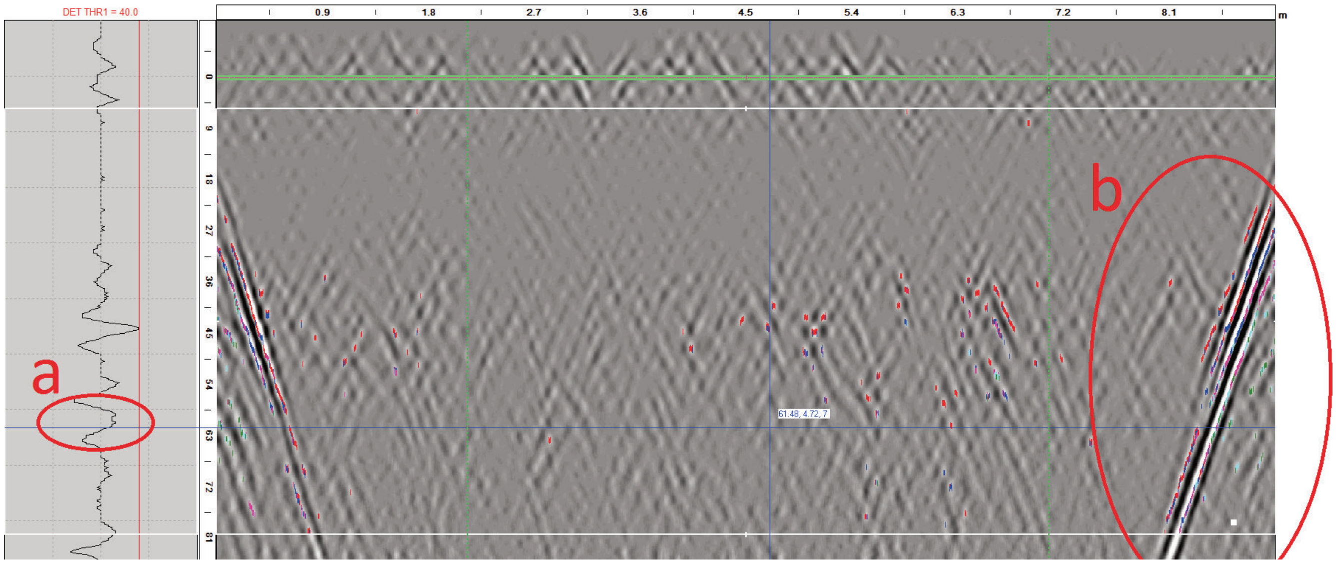

Figure 2. Radargram obtained scanning a rooted area near a metallic barrier stuck into the soil. A specific signal is produced by metal object into the soil (a) and the presence of a metal object, buried into the soil, produce a conic echo downwards that cover others signals and makes root signals unreadable (b).

Until recently, roots had to be manually identified on radargrams (Fini et al., 2017). Roots were commonly identified in the radargram as a hyperbole which re-occurs at the same position over different contiguous transects. This approach is commonly used for pipe detection, but poorly conforms to roots which can change in size, orientation, and growth direction (Fini et al., 2017). The advent of automatic root identification software (Booty, 2018) allows today the automatic location of the root signal and a more accurate discrimination of roots and non-root objects, thus allowing the 3-D mapping of the root system as well as the calculation of root density within a given soil area (Booty, 2018).

3.3.3. Accuracy in root detection and limitations

Direct methods have been frequently used in combination with GPR to validate GRP results (Bassuk et al., 2011; Hruska et al., 1999; Nichols et al., 2017; Stokes et al., 2002; Tardìo et al., 2016). Successful root assessments using the GPR technique have been reported in homogenous sandy forest soil, where root cross-sectional area measured by GPR and by trenching were tightly correlated (Tardìo et al., 2016). Nichols et al. (2017) found that GPR accurately determines the number of roots in 60% of cases, as well as their depth in the soil. Stokes et al. (2002) could locate roots in the soil with a precision of 5 cm.

Working with different types of soil, Bassuk et al. (2011) found significant linear correlation between the number of roots identified by GPR and the root counts measured after excavation, although GPR overestimated root count in compacted soils. A large number of “false positive” roots were detected because multiple small roots clustered into soil porosity were detected as a single large root by GPR (Bassuk et al. 2011; Butnor et al., 2001; Nichols et al., 2017; Stokes et al., 2002).

Size, depth and direction of roots are the main characteristics that affect their detectability (Zenone et al., 2008). Roots with diameter smaller than 2 cm can be hardly found with 450 MHz frequency GPR (Butnor et al., 2001; Stokes et al., 2002). Fini et al. (2017) could not locate roots of newly planted *Celtis australis* and *Fraxinus ornus* using a 900 MHz antenna, because root diameter was still below detection limit in such young establishing trees. Using a 1.5 GHz, Butnor et al. (2001) were able to find 0.6-cm-diameter roots at 14 cm depth in a sandy soil, but the signal was severely attenuated at 35 cm depth. The low depth of penetration of high frequency antennas is indeed a major limit to their application for studying roots of woody vegetation.

Major difficulties in root identification occur when multiple roots are crossing, overlapping, or clustering (Stokes et al., 2002). The issue is relevant when GPR is applied to trees in groups, and overlapping roots from neighbouring trees can hardly be distinguished. Overlapping roots can be identified in the radargram as a double-peaked waves (Figure 3), but the process is time consuming and sensitive

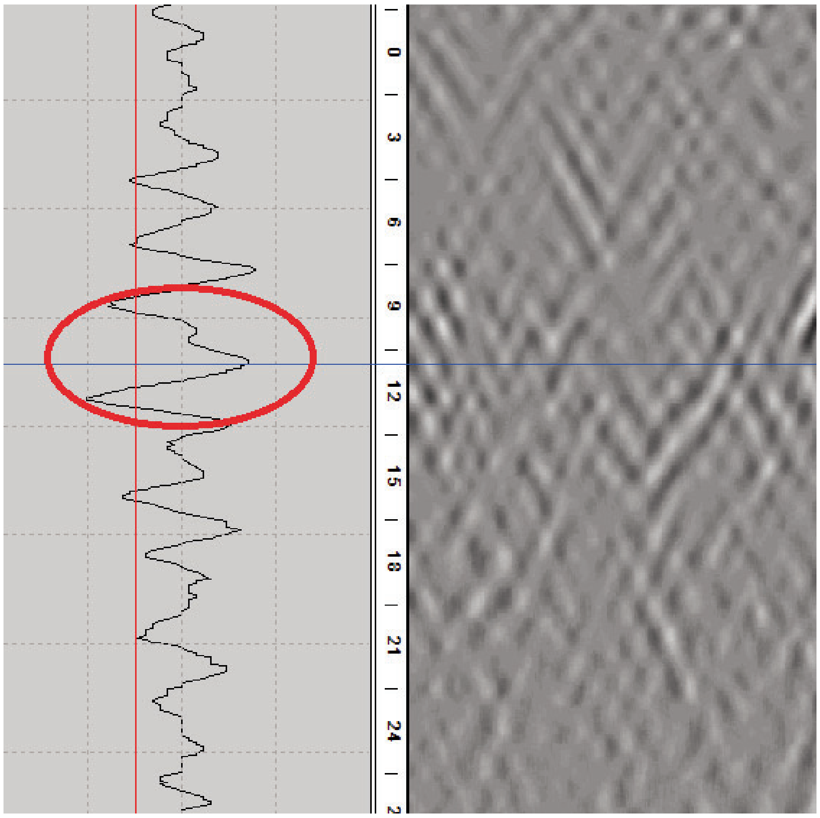

Figure 3. Portion of a Ground Penetration Radar output, called radargram. On the right the typical signal from two crossing roots is highlighted.

to personal interpretation. Besides root count and depth assessment, pioneer evidence suggests the opportunity to estimate root diameter and length from GPR scanning, but no later research supported this idea (Hruska et al., 1999).

Available studies conclude that GPR is a reliable technique for mapping roots system with some limitations:

- only woody roots with larger diameter than 10-20 mm can be detected, unless using high-frequencies antenna (*i.e.* 1.5 GHz, see Butnor et al., 2001). Antennas with low frequency (*i.e.* 450-900 MHz) can detect roots at a depth of a few meters (Bassuk et al., 2011; Butnor et al., 2001; Hruska et al., 1999; Stokes et al., 2002), whereas higher frequency antennas can penetrate the soil only for 20-50 cm;
- roots are accurately detected along the horizontal plane, but less effectively in the vertical plane, because radar cannot identify objects running parallel to the direction of the electronic wave (Nichols et al., 2017; Stokes et al., 2002);
- overlapping roots may yield a similar signal as single roots or forked roots, resulting in a significant underestimation by GPR of root number, compared to excavation (Hruska et al., 1999; Stokes et al., 2002). If multiple root overlapping occurs with neighboring trees, GRP is not accurate in detecting individual tree roots (Nichols et al., 2017).

3.4. Geoelectric measurements

A couple of geoelectric techniques have been proposed as suitable for root investigations, particularly for detecting structural roots: the electrical resistivity tomography (ERT) and the earth impedance method (EIM). Electrical soil surveys investigate ground properties, based on response of soil materials to the flux of electrical charges (Tabbagh et al., 2000) and have been used for their potential in measuring near-surface soil features.

3.4.1. Electrical resistivity tomography (ERT)

3.4.1.1. Theory and applications

In plant and soil science electrical resistivity tomography (ERT) has been used at the field and lab scale for detecting soil compaction (Besson et al., 2004), water content and flow in soil and plants (Hagrey, 2007; Hagrey and Michaelsen, 2002; Loperte et al., 2006;), soil cracks (Samouelian et al., 2003) and tillage effects (Basso et al., 2009).

The ERT technique consists in applying electric current into the soil through electrodes and measuring the difference in electric potential (voltage) at a selected position. The space distribution of voltage difference is a function of the subsurface distribution of the soil electrical resistivity of the soil volume analysed (Paglis, 2013; Zenone et al., 2008). Electrical resistivity (ρ; units: Ω m), a measure of the ability of materials to oppose to the transfer of electrical current, is defined in cylindrical geometry as

$$\rho = R\frac{S}{L} \qquad \text{(Eq. 4)}$$

where S and L are the cross-sectional area (m^2) and the length (m) of the cylinder, respectively, and R is the electrical resistance (Ω). Soil resistivity measurements require at least four electrodes (a quadrupole): two are needed for the injection of electric current (conventionally named A and B) and two for the measurement of the difference in electrical potential (potential electrodes, named M and N). The electrodes can be placed according to different geometrical configurations, with potential electrode in between current electrodes (Wenner configuration) or next to each of them (dipole-dipole configuration). In classical configurations, the Wenner array (A, M, N, B) uses equally spaced electrodes, and the dipole-dipole array (A, B, M, N) uses the dipole offset (a=A-B=M-N) and its n-multiple of the dipole-dipole offset (na = B-M), (Figure 4). The electrical imaging survey is carried out using a distribution of electrodes along individual profiles and grids placed at the outer surface of the study media.

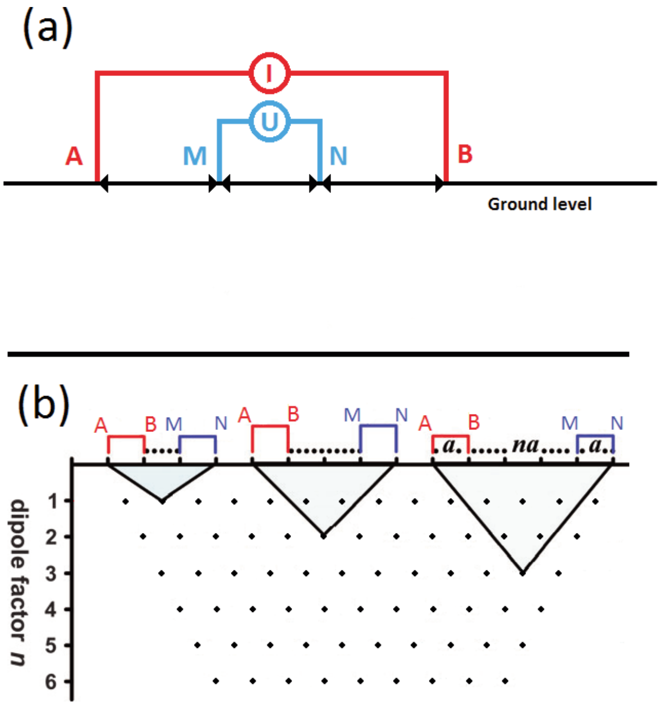

Figure 4. Different geometrical configuration between electrodes: (a) Wenner configuration, with potential electrode in between current electrodes. A and B indicate the current electrodes, M and N indicate the potential electrodes. I indicates current intensity, in amperes, and U indicates the potential difference, in volts.; (b) Dipole–dipole configuration, with potential electrode next to each of them; a indicates the distance between current electrodes, na indicates the distance between the current electrode B and potential electrode M. Modified from Hagrey (2007).

The effects of the electrode's configuration on resolution, sensibility and depth of the investigation have been reviewed by Samouëlian et al. (2005). For 2D and 3D measurements, multiple electrodes need to be placed in linear array, in grids or in boreholes. By increasing the distance between the electrodes (Figure 4), it is possible to increase the depth of soil profile investigated (Besson el al., 2004).

In isotopic media, the current flows radially from the current electrodes into the soil and equipotential lines are hemispherical, so the measured electrical resistivity of the prospected medium is called apparent resistivity (ρ_a) and calculated as:

$$\rho_a = \frac{K \Delta V}{I} \qquad \text{(Eq. 5)}$$

where ΔV is difference in electrical potential (V), I is current (A) and K is a geometrical coefficient. K can be calculated as:

$$K = \frac{2\pi}{(1/MA - 1/MB) + (1/NB - 1/NA)} \qquad \text{(Eq. 6)}$$

where MA, MB, NB, and NA are the distance between electrodes M and A, M and B, N and B, and N and A, respectively (Amato et al., 2009; Paglis, 2013; Zenone et al., 2008).

Several parameters related to soil characteristics (e.g. porosity, moisture, salinity) or climatic condition (*e.g.* temperature) can influence electrical resistivity values. Therefore, calibration is often required in ERT near-surface studies in order to identify the dominating soil variables and take them into account in the interpretation of ERT output (Amato et al., 2009; Sudduth et al., 2005). In particular, changes in soil moisture can cause large variations in ρ (Samouelian et al., 2005). Consistently, a steep inverse correlation has been identified between soil moisture and ρ, with differences of ρ between dry and wet soil in the order of 10-10^2 [ohm m] (Zhou et al., 2001).

3.4.1.2. Data processing

Classical electrical measurements are based on the contrast between *ρ* of different soil layers or heterogeneous materials within each layer. In heterogeneous media the current flow lines are deformed and tend to be concentrated in conductive volumes. Resistivities are first calculated according to the theoretical flow-line distribution in isotopic media and called "apparent resistivity values", arranged in a "pseudosection". Those values are initially assigned to soil coordinates corresponding to the hypothesis of homogeneous current distribution then, with further processing, converted to "real resistivity values" and correctly placed in space in "true section". This processing is called inversion and requires numerical modelling with soil discretization in elementary cells (Amato et al., 2009; Morelli and Labrecque, 1996).

3.4.1.3. Accuracy in root detection and limitation

ERT detects the changes in soil electrical resistivity (*ρ)* in the soil profile (Panissod et al., 2001) and allows the detection of resistivity areas generated by the plant root zone. To be effective, soil and root *ρ* must differ, which may not occur in all cases. For example, low soil moisture can reduce the difference in *ρ* between the roots and the soil enough to make the root-zone undistinguishable. Similarly, ERT may not work properly in all soil textures: Zenone et al. (2008) were able to discriminate poplar roots in a loam soil, but not pine roots in resistive sand.

The biomass of coarse roots has been most frequently and consistently assessed by ERT techniques. Indeed, only roots with diameter larger than 2 mm can cause a resistive response, making finer roots undetectable (Rossi et al., 2011). Amato et al. (2008) and Rossi et al. (2011) found a significant positive correlation between soil resistivity and coarse root biomass assessed by destructive measurements (Amato et al., 2008; Zenone et al., 2008). These studies conclude that, in natural soils (except for sandy or chronically arid ones), the effect of roots on *ρ* can be strong enough to mask potential disturbing effects from other soil components, thus yielding a highly significant univariate relationships between *ρ* and roots biomass. A drawback of this technology is the impossibility to discern roots of different trees in case of overlap of tree root systems.

Multi-temporal analyses of soil resistivity can be used for root detection in sandy or arid soils. Multi-temporal analyses allow to understand, for a given soil, how *ρ* changes with moisture. Resistivity increment (%) between wet and dry conditions in the subsoil around trees appears to be a parameter that can be directly related to the biomass of roots (Zenone et al., 2008). If multiple ERT measurements are conducted before and after a significant change in soil moisture due to natural (prolonged rainfall) or artificial (irrigation) water supply, roots should be identified as the area with minimal change in resistivity (Zenone et al., 2008).

The capacity of *ρ* to proxy for root length is more controversial: Amato et al. (2009) found a significant correlation between *ρ* and root length density (RLD) in young alfalfa plants. Conversely, Rossi et al. (2011), working on woody species, found that RLD did not affect soil resistivity, and no correlation between root biomass and RLD was found. Amato et al. (2009) suggested that the relationship between *ρ* and RLD may be found only in systems with a good correlation between root biomass and root length.

Root characteristics can also affect the ERT signal, because of different root anatomy and activity. Different authors suggested that the increase in resistivity of rooted soil cannot be ascribed to the amount of roots only, but it may occur because of the ability of root systems to interact with the electrical charge fluxes (Aubrecht et al., 2006; Rossi et al., 2011). A large variation in resistivity values has been found among woody materials from different species (Hagrey, 2007), supporting the hypothesis that species may also affect the accuracy of root detection.

3.4.2. Earth impedance method

3.4.2.1. Theory and applications

The absorbing surface area of fine roots is the main exchange interface between the plant and the soil. Reliable data on absorbing root surface are needed for modelling water transport and nutrient uptake (Eckhard and Horst, 1996). The "earth impedance method" (EIM) was developed by Aubrecht et

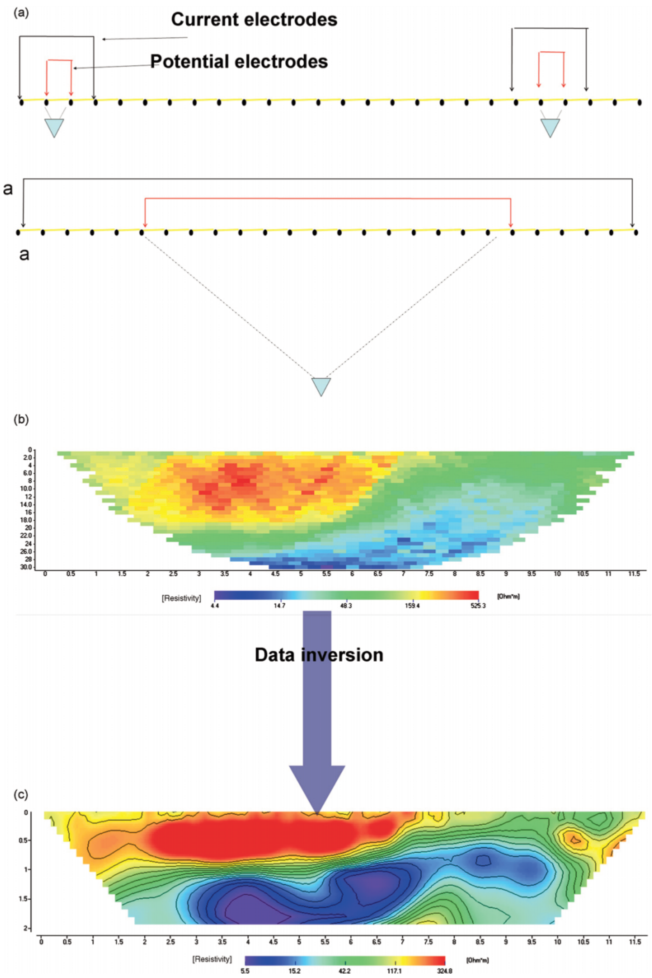

Figure 5. Data acquisition and processing in ERT; (a) linear array of electrodes with two quadrupoles at minimum spacing (top) and one quadrupole at maximum spacing (bottom). Dots represent electrodes and full triangles represent the centre of soil volumes measured by the corresponding quadrupole; (b) soil apparent resistivity 2D pseudosection obtained after data acquisition; (c) soil resistivity 2D section obtained after data inversion with numerical modelling. Modified from Amato et al. (2009). For interpretation of the references to colour in this paragraph, the reader is referred to the web version of the article.

al. (2006) to quantify the amount of absorbing root surfaces. This technique and the ERT have some similarities, as they both involve electricity enforcement into the soil-tree system. The theory behind those techniques and the final aim of the assessment, however, largely differ. The EIM allows to quantify only absorbing root surfaces and ignores non-absorbing suberised root surfaces, while ERT can only detect root with a diameter larger than 2 mm.

The method relies on a non-traditional physical approach based on the evidence that an applied electrical current flows from the root to the soil (or vice versa) through the same interfacial areas where water flow occurs (Aubrecht et al., 2006; Stanìk, 1997). The key idea of the EIM is that if a plant root system is submerged in an aqueous solution (such as soil water) and connected to a simple serial electric circuit, the electric current will flow from the external source to the plant through the electrically conducting (ion absorbing) root surfaces. Only fine roots, except for lenticels and severed roots, conduct electricity. Thus, fine root exposed area can be estimated from differences in soil conductivity observed in the soil profile (Aubrecht et al., 2006).

Aubrecht et al. (2006) calculated the actual root absorbing surface as:

$$A_{root} = \rho \, l \, \frac{I}{U} \qquad \text{(Eq. 7)}$$

where A_{root} (m^2) is total actual root absorbing surfaces, ρ (Ω m) is the resistivity of the water conducting material, l (m) is the distance of the electrode from the stem, I (A) is the current flowing from an external supply through the woody stem, root system and soil to an auxiliary metal electrode (or system of electrodes) and U (V) is the potential difference between the stem boundary and potential electrode. The set for the measurement is made by a few electrodes gentle hammered into the stem, and connected to the circuit with a generator, an ammeter and a series of auxiliary current electrodes in the soil. Electrodes can be arranged over the entire root-zone or in specific radial sectors of it, then upscaled to the whole tree. In the latter case, as few electrodes like (*e.g.* seven) can be used (Čermák et al., 2006).

Čermák et al. (2006) evaluated roots using the EIM on more than 350 trees of six species in nine experimental sites. Because no alternative method for direct measurement of absorbing root at the whole tree level (especially for large trees) was available, authors validated the EIM after comparison with indirect approaches based on allometric relationship and root severance experiments. They found a logarithmic relationship between basal area (stem cross-sectional area at 1.3 m height) and root absorbing surface (r^2 =0.9). Tree size was very important: authors found that absorbing root surface represent about 90% of the accessed root zone in small trees (DBH < 20cm) but it dropped to 20-25% in trees with DBH around 30 cm.

3.5. Sonic tomography

3.5.1. Theory and Application

Sonic tomography has been used since the 1960's for tree inspection and for the diagnostic of the trunk structural integrity. Tapping on one side of the trunk induces a sound wave that can be detected by receiving sensors attached around the trunk's circumference. Knowing the distance between the source of sound and the receiving sensors and the time of flight allows the calculation of sound speed in the trunk. The rationale for this technology is the positive correlation between the speed of the stress wave and the modulus of elasticity of wood (Rinn, 2014). Healthy wood usually displays higher sound speeds than decayed wood.

More recently, sonic tomography has been applied for the root studies (Rinn, 2016). This application was based on the notion that the speed of sound is different in roots than in the surrounding soil. The travel time of the sound wave decreases significantly when the source of sound and the receiver are physically connected by a root compared to when the wave travels through unrooted soil (Bulza and Goncz, 2015). Large diameter, shallow roots have been reported to induce higher increases in sound speed (Rinn, 2016). The acoustic signal's speed in soil is about 250-400 m/s depending on soil type and moisture content. Conversely, the speed in the roots is reported to be between 500 and 4000 m/s (Divós et al., 2009). Conversely, Rinn (2016) found that sound speed was as low as 0 to 500 m/s across a tree root plate, which may not make root distinguishable in all instances. Proto et al. (2020) tested two different olive trees and they measured sound velocity of 581 and 1266 m/s, respectively for each tree, across their root plate. Differences in plant species, environmental conditions, soil moisture content and compaction and, above all, the different instruments are probably involved in such observed differences (Proto et al., 2020; Rinn, 2014, 2016).

Two main methods adopting sonic tomography for root studies have been developed so far. Arboradix® (Rinn, 2016) uses 12-24 receiving sensors attached at known distance around the trunk flare and a source of sound made by a transmitting sensor attached to a steel rod. The rod should be repeatedly tapped or hammered manually at a known distances from the tree. If the soil is mechanically connected to the tree (most likely by roots) a signal should be detected by at least one of the vibration sensors at the tree.

Different spatial distributions of the tapping points are possible. The three most utilized are: 1) grid distribution, where the tapping points are at the crossing points of the lines of the grid. The distances between the lines can be chosen according to the size of the area to analyse; 2) circular distribution where the tapping point are arranged, at a fixed distance from each other, on a series concentric circumferences; 3) star distribution, the tapping points are displaced, at a fixed distance from each other, along 12 radial directions in correspondence of every sensor on the stem base.

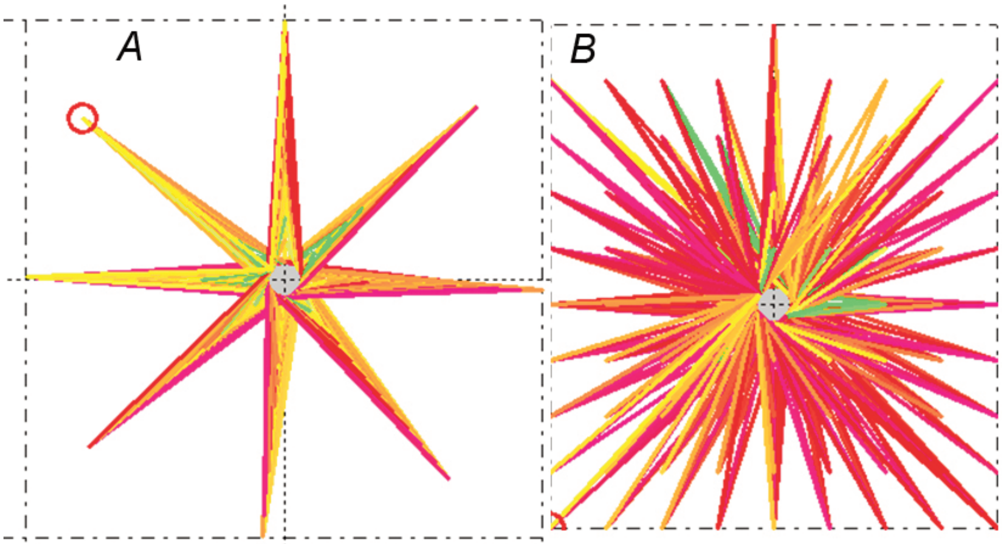

Figure 6. Arboradix graphical output. Each coloured line represents the connection between the tapping point and the tree, measured as sound velocity. Different colours represent different velocities. Tapping points are here arranged according to two different configurations: (a) star configuration where tapping points are displaced at a fixed distance from each other along radial directions in correspondence of every sensor on the stem base; (b) grid distribution where tapping points are at the crossing points of the lines of the grid.

The second method found in literature has been developed at the University of West Hungary is the combination of Root detector and ArborSonic3D® (Fakopp Enterprise Bt, Hungary). The main difference compared to Arboradix® is that the sound moves outward from the root flare to the surrounding soil rather than inward to the root flare. The instrument is composed by a transmitter (SD02 piezo sensor) which should be attached at the tree collar (the tapping point), a control unit (ArborSonic3D) and a receiving sensor (a high-frequency geophone) that should be driven into the soil (Buza and Goncz, 2015; Divos et al,. 2009; Proto et al., 2020). Upon the generation of short sound signal (an acoustic flash) at the root flare, the time of flight to the receiving sensor can be calculated.

3.5.2. Accuracy in root detection and limitation

The physical background of the measurement is the difference in sound conductivity between roots and the surrounding soil. Proto et al. (2020) found a significant correlation between sonic speed and root density. Authors also found a significant correlation, although poorly explanatory between sonic speed and root diameter (Proto et al., 2020). They suggest that sonic tomography detects root density more efficiently than root diameter. This is because in wood, the sonic wave moves through the wood grains and its direction and speed vary with grain angle. Moreover, the speed may increase with increasing wood density (g dry biomass cm^{-3}) and decreasing moisture content (Legg and Bradley, 2016; Proto et al., 2020).

The ability of the sonic root tomography to detect root is limited in depth at approximately 30 cm (Buza and Goncz, 2015; Divos et al., 2009; Proto et al., 2020; Rinn, 2016). The maximum horizontal distance at which root can be detected is more controversial. Using Root Detector technology, Proto et al. (2020) and Buza and Goncz (2015) found that root detection markedly decreased at an horizontal distance from the flare higher than 120 m, which corresponded to 6 times the diameter at breast height. Conversely, using Arboradix, Rinn (2016) could detect roots at more than 10 m horizontal distance from the tree. The minimum diameter detected from the root sonic tomography is approximately 3-4 cm

(Buza and Goncz, 2015; Divos et al., 2009; Rinn, 2016). Pioneer studies reported that sonic tomography may successfully detect individual roots if they are spaced at least 20 cm from the neighbouring roots (Divos et al., 2009).

It is relatively easy and fast to study roots using sonic tomography. More knowledge is needed, however, about the influence of soil compaction, soil cover materials, and moisture on sound speed, in order to make this method replicable (Rinn, 2016). This technique has a remarkable advantage compared to other non-invasive methods like GPR or ERT: only the roots of the measured tree are detected (Buza and Divos, 2016; Rinn, 2016) because they are the only ones mechanically connected to the stem. Anyway, authors found in the literature and that uses this technique, are only a few and other studies are needed to completely understand its capacity to study the root system and its accuracy.

4. Conclusions

In this review four different non-invasive root investigation techniques which may be suitable for root detection in the built environment were discussed: ground penetration radar (GPR), electric resistivity tomography (ERT), earth impedance methods (EIM) and sonic tomography (ST). Such methods have been proposed for the detection of spatial position, and for the measurement of root dimension, but their practical use is hastened by the limited body of scientific evidence about their applicability, accuracy, and reliability.

GPR has shown its capacity to adequately locate the position and the diameter of coarse roots, while fine absorbing roots are neglected. Root plate size and depth, and root number and density can be measured using GPR. This technique has several advantages: 1) it is applicable in paved sites, with no need of pavement displacement; 2) it relatively plastic in terms of depth of investigation, as antenna frequencies can be selected based on soil type and on the aim of the investigation. The soil can be easily scanned down to 90-100 cm with sufficient resolution, which allow the detection of a major portion of root system vertical profile. Major limits of this technology include: 1) the reliability greatly depends on algorithms implemented in the software for automatic root detection and/or on the personal ability of the operator to distinguish roots and non-root objects; 2) overlapping roots can hardly be distinguished from a single root. This may lead to an underestimation of root count. More importantly, it can be difficult to separate overlapping roots of neighbouring trees, making the measurement of the individual root system troublesome.

The ERT can allow the measurement of the coarse root biomass and root length density, although the latter has been successfully estimated only on herbaceous plants. ERT can also be used for root localization, since the distribution of ρ follows the spatial distribution of coarse roots. The main limitations to this method include: 1) it is not applicable to paved soil without displacing or augering the pavement, because electrodes must be placed in contact with the soil; 2) it is hardly applicable to sandy or excessively dry soils, because they lack enough difference in ρ as compared to roots to allow their detection.

With EIM is possible to quantify the amount of absorbing root area, but it ignores non-absorbing suberised root surfaces. The EIM, as the ERT, involves electricity enforcement into the soil-tree system and share its limitation in paved soil due to impossibility to place electrodes without augering. Only few authors have employed this method and the only validation has been done without root excavation. Further validation is required for this methods.

Sonic tomography can be used for the detection of root density more efficiently than for measuring root dendrometric traits. This technique is faster than the others for both data collection and interpretation, but its implementation for roots studies is still preliminary, due to some major limitations: 1) only roots with diameter larger than 3-4 cm can be detected; 2) the maximum depth of investigation is about 30 cm, much shallower than the tree root-system; 3) although this technique has already been used by professionals, its scientific validation has not been completed yet.

This review highlights that no conclusive and highly reliable non-invasive method for the detection of the whole root system (coarse + fine roots) in urban sites has been developed so far. Further research is needed to advance all methods towards higher replicability, accuracy and reliability. The combined use of different methods based on different principles may provide an interesting opportunity for further research and development.

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