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Technical notes

Tree root system imaging using Ground Penetrating Radar

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Abstract - Evaluating tree roots systems without compromising their environment with destructive and laborious methods is of crucial importance for preserving plant resources. Ground Penetrating Radar (GPR) technology applied to root and forest ecology studies is a key active remote sensing technology, based on the use of electromagnetic waves, providing unique, non-invasive resources to sample root biomass and spatial distribution. This paper reviews the use of GPR techniques, as near surface sensor radar scanning technology using a ground-coupled single-offset antenna configuration, to yield accurate tree roots system information. Based on the analysis of both geometric and general characteristics of underground soil layers, the GPR can be used as a rapid and high-spatial resolution tool for the analysis of roots distribution, morphology, orientation, and the occupied soil volume. Finally, this paper will give a brief description of a remote technique supporting silvicultural research in terms of application of radar technology to tree root systems.

Keywords - Ground Penetrating Radar; tree root systems; forest ecology

Introduction

Thanks to the latest advancements in geophysical research applied to forestry and agricultural issues, the accurate characterization of subsurface can be obtained using new spatial and temporal monitoring techniques. In particular, the application of Ground Penetrating Radar (GPR) has gradually increased in the last few years, mainly due to high-frequency antenna development (Allred et al. 2008).

In general, GPR can be used to determine physical parameters of both large-scale (km) and small-scale areas (cm), in rapid and non-destructive ways. The use of GPR to study plants, specifically tree root distribution, size, morphology and their biomass, has progressively received more attention for their valuable capability of providing *in situ* non-destructive high-precision measurements (Wu et al. 2014; Ferrara et al. 2014a; Butnor et al. 2008). Moreover, the usefulness of high-frequency GPR for monitoring spatial-temporal variation of tree root systems has become very valuable, given the importance of understanding carbon cycle balance between sources and sinks due to the increasing atmospheric carbon dioxide (CO2) levels and climate global changes (Danyagri and Dang 2013; Wielopolski et al. 2002; Stover et al. 2007).

Assessing tree health plays a key role in urban and peri-urban environments (Salvati 2014), tree roots are vital for plant healthiness and longevity as they play a fundamental role in water and nutrient intake and plant anchorage and their decline anticipates that of the whole plant (Barone et al. 2016). Tree roots are concentrated close to the trunk base and they are generally included into the canopy projection on the ground, although in some situations they reach a greater extension. In fact, their growth is not only based on the species characteristics, but also on the site-specific pedo-climatic conditions. The root system size can vary to ensure an adequate and constant energetic supply even in non-optimal soil conditions (Merlini and Corona 2007; Zucconi 2003).

GPR has a key role in this detecting, in real time, both vertical and horizontal dielectric anomalies associated with natural or manmade subsurface variability (Barone 2016; Perez-Gracia et al. 2010). Even if, in some cases, the successful application of GPR in root detection is site-specific and some factors can interfere with the root resolution (Hirano et al. 2009), the success of the recent GPR investigations of the tree root architecture is relevant and uncontested (Guo et al. 2013). The goals of this study were to test the feasibility of using GPR to describe root architecture, root orientation, and soil volume utilization in large urban parks and peri-urban/wildland fringe land, by means of a brief technical note on a procedure supporting silvicultural research in

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the northern Mediterranean region (Barbati et al. 2013; Ferrara et al. 2014b; Salvati 2015). In general, tree roots are difficult to assess and delineate without laborious and destructive excavations that are impossible in these places, for this reason, processing speed, repeatability and non-invasiveness of GPR measurements, main characteristics of these geophysical surveys, are valuable for urban forestry applications.

Materials and methods

The GPR technique is based on analysing the Two-Way Traveltime (TWT) of an electromag-netic pulse of a short duration (1-10 ns) and high frequency (MHz-GHz) sent into the ground, and its subsequent reflection. Injecting an electromagnetic (em) field in a non-homogeneous field, there will occur reflection and refraction phenomena, well-known in optics. Due to a contrast of dielectric properties between different materials, by exploiting electromagnetic (em) propagation principles, for each variation of the refractive index, associated with the wavelength of the radiation (1):

$$n(\lambda) = \frac{c}{v(\lambda)} \quad (1)$$

there is a partial reflection of the em waves, which can be intercepted and analyzed, identifying the position on the time scale (x-axis) and intensity (y-axis) of the reflected or refracted pulses (Annan 2004). The position on the time scale of a peak determines the distance between GPR antennas and the object that produces the spread. Assuming that the investigated medium is homogeneous, the propagation velocity v can be considered constant, so that the depth D of the target is calculated as (2):

$$D = \frac{t \cdot v}{2} \quad (2)$$

where the em waves velocity is (3):

$$v = \frac{1}{\sqrt{\varepsilon\mu}} \approx \frac{c}{\sqrt{\varepsilon_r}} \quad (3)$$

which varies depending on soil physical properties. The right expression, in which there are c, the speed of light, and ε_r, the dielectric constant of the material, is valid in the case of materials which are good dielectric, the conductivity, σ, is negligible (Jol 2009) and the magnetic properties are close to those of vacuum ($\mu = \mu_0$), or propagation occurs essentially without dispersion (Annan 2004). The reflection intensity depends both on the wave attenuation and the reflection coefficient, where the latter mainly depends on the contrast between the different dielectric properties of the medium in which the waves propagate and the investigated object (Barone 2016). Because of this em properties contrast, the GPR technique can determine the physical characteristics, and in particular the water content since the relative dielectric permittivity of water is approximately 80, an order of magnitude greater than that characterizing the soils (Ferrara et al. 2013; Ferrara et al. 2014a).

To measure the root morphology and distribution and to assess tree root concentrations GPR measurements have were carried out at in an urban park of Rome (Italy) dominated by sparse old *Pinus pinea* plants. The root systems of two pine trees were selected for GPR survey, where the GPR antennas are moved along the surface of the medium to be investigated, over straight lines, called profiles. The average dimensions characteristics of the considered pines are the diameter at breast height (DBH) that is 72.5 cm, the average tree height (H) that approaches 21.5 m and the average canopy radius that is about 8.5 m.

Finally, the data were collected using a bistatic 500 MHz antennas (FINDAR - Sensors & Software, Inc.) and an odometer. The basic Dewow time filter and Automatic Gain Control were applied to all radargrams. Then, to convert the TWT time into depth, a velocity analysis using the hyperbola calibration technique (Annan, 2004) was performed on all radar sections in which the hyperbolic events were well detectable, providing an average velocity of 0.10 m/ns.

Results and discussion

Through the acquired measures it is possible to built the so-called radargram, i.e. a two-dimensional reconstruction of the medium as if it were seen at different radiofrequencies, resulting from the envelope of the individual tracks acquired along the current profile. On each track the reflections that undergo the signal will be detectable, which may be due to both the different stratification in the soil or to well-defined objects.

During the GPR measurements, it is possible to notice a variation of em parameters in both trees, but the reflections produced are different. In the first case, a sub-horizontal reflector appears in the radargram, while the second displays a reflection hyperbola. This is due to the fact that as the radar is moved horizontally, the signal two-way travel time diffused by the same reflector has initially a descending trend, until the top, when the antennas are above

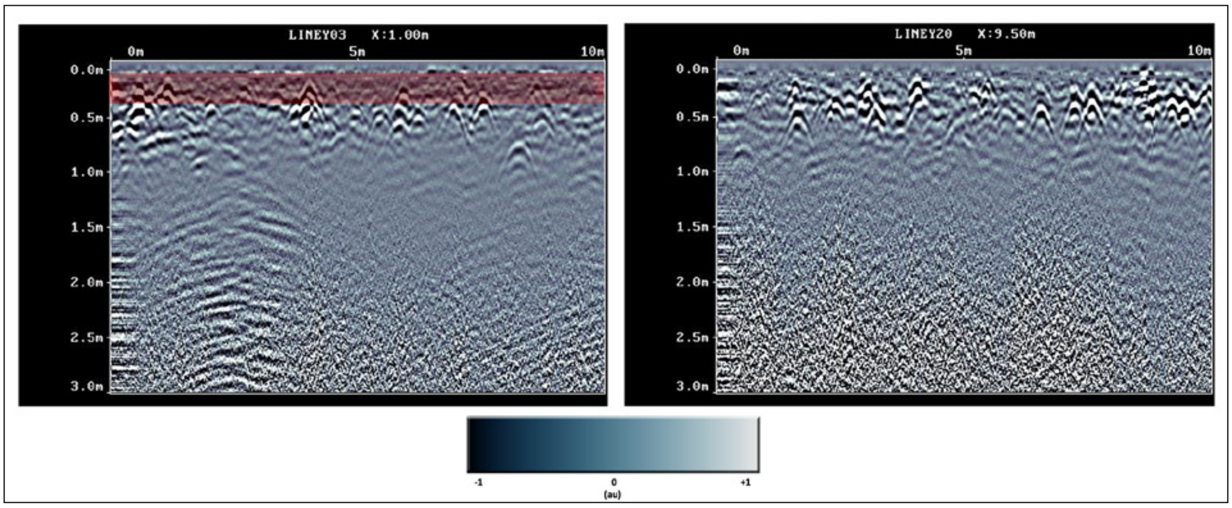

Figure 1 - GPR sections, where the vertical scale is depth (m) and the horizontal scale is the profile length (m). The tree roots of the two different pines are located in correspondence of the hyperbolas events between 0-0.45 m depth (highlighted in red). Note that the scale of values is related to the average envelope amplitude (arbitrary unit).

the target, and then increasing (Annan 2004; Jol 2009; Barone 2016). The radargrams reported in Fig. 1 show the GPR ability of detecting and precisely locating the tree roots, from the above-mentioned hyperbolas.

Furthermore, if the acquisitions have provided parallel profiles within a x-y grid, maps at different depths (depth-slices) can be obtained, displaying not only geometries of buried objects but also their size. Fig. 2 shows two different maps obtained using an envelope algorithm, known as average envelope amplitude (Annan 2004; Ferrara et al. 2013; Barone 2016), displaying the root system distribution.

In particular, the pines roots extend out from the trunk occupying to the fullest extent an area of approximately 100 m^2, where the roots orientation reproduces a peculiar star architecture. From radargram and depth slice analysis the maximum depth of the pine root system can be defined, which is 0.45 m, giving an occupied soil volume of 45 m^3.

The ratio between the canopy projection on the ground and the radial root area is an important indicator of soil fertility (Zucconi 2003), as tree roots tend to extend to compensate low resources availability.

The aim of the data collection was to obtain rapidly and in real time both a qualitative and brief quantitative on-site evaluation of the root architecture. Using different GPR systems, with different frequencies and different geophysical methods, it is possible to obtain more detailed information in a larger time-lapse (Rodríguez-Robles et al. 2017, and literature therein).

Conclusion

The spatial distribution of tree root architecture is of great importance for understanding its role in resource acquisition, storage and structural support. Unfortunately, tree roots are not easy to sample, and typical root detection methods, such as excavations and uprooting, require a large amount of labour and a destructive interference. This creates a limit to quantitative and repeated monitoring in long-term research.

Overall, the application of ground radar technol-

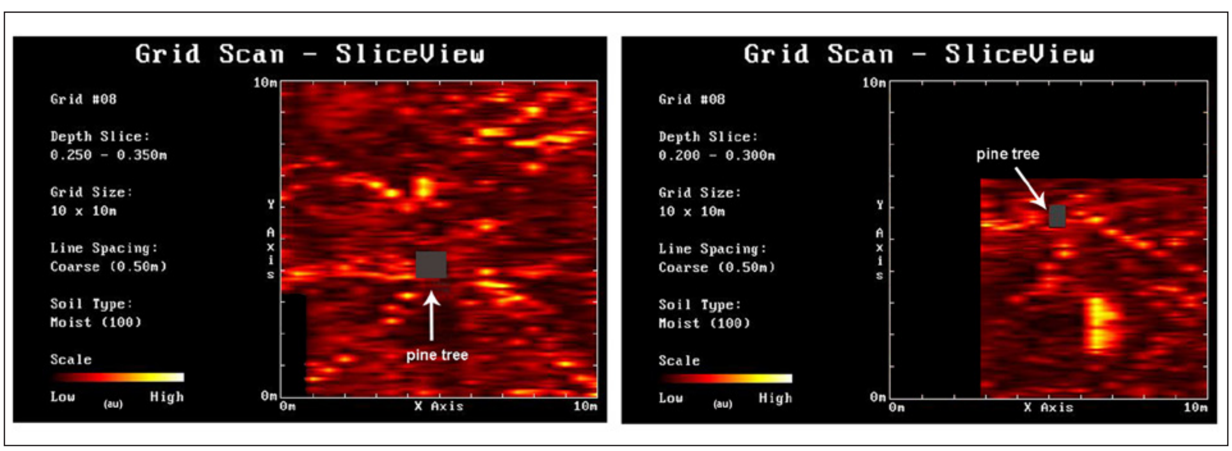

Figure 2 - GPR depth-slices. The tree roots star architectures of the two different pines are precisely mapped at a depth of about 0.30 m. Note that the scale of values is related to the average envelope amplitude (arbitrary unit).

ogy to root and urban forest ecology studies provides unique, non-destructive means to sample root spatial distribution. In this study, the GPR technique can be used as a non-invasive tool to precisely and rapidly quantify root architecture, root orientation and soil volume utilization, of pine trees. Compensatory tree root growth depending on soil mineral resources availability and the canopy/radical ratio is directly proportional to the soil fertility. Based on these information, it is possible to provide valuable support in the urban-forestry sector and in urban-parks management policies to preserve stability and healthiness of urban/forests environments.

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