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ABSTRACT

Ground Penetrating Radar (GPR) has been used extensively in near-surface studies to detect underground objects and features typically located within a few meters beneath the surface. In urban areas, GPR is widely used to study buried utilities such as pipes and cables. A more recent and unconventional application of GPR is the detection of tree roots, which can interact negatively with the human infrastructure in a number of ways. However, the geophysical study of tree roots has proven quite challenging and site-specific. Most tree roots (even coarse roots) have a small diameter and are hard to resolve through geophysical methods. In addition, the sheer amount of potential variability regarding the tree species, age, size, health, and the subsurface environment (e.g. soil or a man-made material such as concrete or asphalt) makes it very hard to implement a one-size-fits-all approach. This is where robust, easily customizable forward models can be of assistance, indicating the range of detectable geophysical contrast and the limitations of the method, as well as the suitable antenna frequencies. Here, a Vector Network Analyser (VNA) with a commercial open ended coaxial probe was used to take direct measurements of the relative permittivity of freshly cut tree root segments at frequencies from 50 MHz to 3 GHz. The results were used as inputs for GPR forward models using gprMax open source software, depicting various realistic

scenarios which could be encountered in real surveys. The developed models help better understand the applicability, potential, and limitations of GPR surveys for detecting tree roots in different environments, aiding the development of future surveys. The notable variability in the tree roots is a significant consideration for surveys and forward models.

INTRODUCTION

Trees are essentially ubiquitous in both rural and urban areas, where they provide a number of environmental and social services (Mcpherson, Doorn and Goede 2016; Gillner et al. 2015). Roots are a key structural component of trees, offering anchorage as well as water and nutrient absorption and distribution. However, tree roots can also destructively interact with human infrastructure, causing structural damage to roads, sidewalks, and buildings, and causing or enlarging pipe fissures (Mullaney, Lucke and Trueman 2015; Randrup, McPherson and Costello 2001). In urban areas, trees can pose significant risks, with the damage to infrastructure ranging from simple cracks or bumps to serious structural damage (Day 1991).

Roots are more difficult to study than the rest of the tree in situ since they are inaccessible and generally buried beneath the soil. Roots are also actively exchanging chemical substances with the surrounding soil (through absorption and respiration), which tends to mask their geophysical contrast. Along with their small size, this makes the in situ geophysical detection and study especially difficult.

Ground Penetrating Radar (GPR) is a potential method for detecting tree roots (Bassuk et al. 2011; Butnor et al. 2001). GPR is a non-destructive geophysical method which can be operated relatively fast and is generally well-suited for urban surveys. Studies have shown that coarse roots can be mapped in some cases (Guo et al. 2013; Butnor et al. 2003; Hruska, Cermák and Sustek 1999), but the extent to which smaller roots can be detected remains unclear and since past studies generally focus on individual case study scenarios, a certain degree of uncertainty exists even in the case of coarse root detection. The suitability of detecting different types of roots in different types of soils with GPR remains a matter of active research. Most studies have been carried out under controlled conditions or forest/orchard settings, and significant differences between these soils and urban soils can be expected (Lehmann and Stahr 2007), which could have important implications for the GPR detection of roots. However, it is in the urban areas where the interaction between roots and human infrastructure such as roads, pavements, buried utilities and buildings is more likely.

The usage of GPR in tree root detection has fundamental limitations (Hirano et al. 2009), and given the inherent variability of parameters in soils, roots, and environmental conditions, a signification variation in detection rates can be expected. Root orientation also affects the detection accuracy of GPR (Tanikawa, Hirano and Dannoura 2013), which adds another layer of uncertainty to surveys.

Several studies describe different scenarios in which tree roots have been detected using GPR, with varying degrees of success (Butnor et al. 2016; Zhu et al. 2014; Bassuk et al. 2011; Morelli et al. 2005; Butnor et al. 2003; Cermak at al. 2000). However, these usually focus either on experimental scenarios (Bassuk et al. 2011; Barton and Montagu 2004), or natural soil environments like a forest (Hirano et al. 2012; Morelli et al. 2005). Real-scenario studies in urban settings, which have differences to natural landscapes (more compaction, erosion, higher temperatures, potential elements of human infrastructure or other artefacts), have generally used relatively low frequencies of 400 (Zhu et al. 2014; Ow and Sim 2012) or 500 MHz (Nichols, McCallum and Lucke 2017), which can only resolve the coarsest roots. Notably, Yokota et al. (2011) found that even a frequency of 800 MHz has difficulties resolving roots with a diameter under 3 cm. However, the literature does not focus on the dielectric properties of the roots (for clarity, and hereafter, the term "permittivity" is used to refer to the real part of the relative permittivity). Furthermore, potentially unsuitable frequencies are still chosen in practice, leaving some roots outside of the detectability range. Hence, establishing a range of expected permittivity values and a generally detectable contrast could allow GPR operators to better design surveys by anticipating the limitations of different antenna frequencies (i.e. resolution and depth of penetration) and the contrast between roots and soil. A robust model in which parameters for local soil are introduced could provide an indication to what antenna is best suited for the survey. Similarly, developing robust forward models in which one needs only to insert the permittivity values of the root and the soil could help with the interpretation of often complex subsurface scenarios.

This paper presents direct permittivity measurements over a substantial range of root samples (and a few branch samples), from trees belonging to four common species: Sycamore (Acer pseudoplatanus), Pine (Pinus sylvestris), Ash (Fraxinus excelsior), and Oak (Quercus robur). These trees are commonly widespread in temperate climates in urban areas and are likely to be encountered by a surveyor in a real-life setting.

These experimental data are integrated into GPR forward models using gprMax, presenting several relevant scenarios, including the permittivity of common soil types and of the measured roots, potentially serving as a foundation for a better understanding of GPR tree root detection in urban areas. The geophysical mapping and characterization of these tree roots could be used to assess or predict interactions with human infrastructure, enabling city councils to make better urban planning decisions regarding trees. Ultimately, with sufficient development and increasing technological affordability, these measurements could be integrated in a smart city system, with sensors monitoring the potential interactions of tree roots and infrastructure.

This is a cross-disciplinary study with multiple considerations from biology, civil engineering, and geophysics. Special emphasis is given to the geophysical standpoint, though other implications are also considered.

METHODOLOGY

Sample collection

A great deal of emphasis was placed on the health and wellbeing of the trees. All the root samples were collected from mature, healthy trees, and only small segments were cut. Roots under 2 cm in diameter were selected and analysed, since the main purpose of the study was to assess roots that would be more difficult to detect. This also ensured that no structural damage was done to the tree by cutting any of its major roots. Root segments were collected close to their termination, so as not to disturb a longer segment of the root. All harvested roots were gathered from the shallowest part of the topsoil (depth <2 cm). The areas from which the roots were harvested were heavily shaded, with very few patches of sun, and no roots were taken from these sunny patches, to avoid a potential source of water content variation. Roots were harvested at a distance of 3-4 meters from the trunk.

All root samples were harvested from an urban area around Harborne, Birmingham (UK); freshly cut roots were labelled, placed in air-tight plastic containers, and quickly transported to the laboratory where measurements could be taken. The root is a living part of the tree. From the moment it is separated, it starts to undergo a series of changes. Significantly, it starts to slowly lose some of its water content. Since the measurements could not be carried out in situ, it was therefore imperative to perform them as quickly as possible, within 30-60 minutes.

Root samples were cut into segments approximately 10 cm long. Their shape was sometimes irregular which made measurements more difficult, so samples were cut into smaller segments, but never smaller than 5 cm.

Measuring permittivity

The permittivity measurements were carried out with a 85070E dielectric probe, an open-ended coaxial probe (Keysight Technology). The 85070E can measure complex permittivity over a broad range of frequencies. Most measurements were normally taken from 50 MHz to 3 GHz, and some times from 100 MHz to 3 GHz, which is a broad frequency range for GPR measurements.

While measuring, the transversal part of the root was firmly pressed on the probe surface. The transversal part was cut smoothly to minimize the presence of small pockets of air which would cause lower permittivity values to be measured.

To further reduce uncertainty, 40 individual measurements were taken for every sample, allowing any anomalous measurements (likely resulting from imperfect contact between the probe and the root segment) to be safely eliminated. In most instances, 40 satisfactory measurements were obtained, and in all occasions, at least 30 valid measurements were obtained for each root segment.

Initially, some measurements were taken as a proof-of-concept, as we wanted to assess the feasibility of the method and the potential of using branches as root substitutes for lab measurements (which turned out to not be the case). For subsequent measurements, samples were also weighed on a high-precision scale, placed into an oven at 105 °C for 24 hours, after which they were weighed again to calculate the water content.

Forward Models

The data obtained was introduced into forward models produced using the gprMax software; gprMax is an open-access software that simulates electromagnetic wave propagation, using the Finite Difference Time-Domain (FDTD) method.

Through its nature, gprMax encourages robust models, as key parameters (such as tree root permittivity, in this case) can be changed, often by modifying a single line of code. Its latest version (based on Python) makes it relatively easy to script more complex scenarios, although the models presented here are reasonably simplistic. Overall, given the inherent complexity of GPR data, developing forward models can be extremely challenging, but gprMax offers a readily available open-source software solution.

Generally, 3D model calculations are significantly more computationally-intensive, particularly for high resolution models involving GPR antennas operating at high frequencies. Hence, for the purpose of this study, only 2D models were developed, as the identification of tree roots is primarily done on GPR profiles.

Several variations of the initial models were carried out, highlighting the robustness of the models, which can be easily tweaked based on existing environmental and root conditions. Easily changeable parameters include the permittivity of the roots and surrounding soil, potential soil layers, root size, position, and shape, antenna frequency and waveform. Additionally, gprMax offers the possibility of designing a fractal box with a complex mixture of sand and clay with varying water contents.

Several simplifying assumptions were made. The roots were considered to be cylindrical; although they have irregularities, they still follow a cylindrical shape, and the irregularities are unlikely to have a significantly effect. All surfaces were considered to be flat and regular.

Two antenna frequencies were used for these models: 700 MHz and 1.5 GHz. These frequencies were selected as relevant to the practical applicability in GPR surveys and the potential of detecting roots. Both the depth of penetration and the resolution are governed by the GPR wavelength in a trade-off relationship: higher frequency means higher resolution and lower depth of penetration. For this type of study, the vertical and lateral resolution must first be considered.

In order for root detection to be possible, the vertical distance between two reflectors must be at least $1/8$ to $1/2$ of the wavelength λ (Møller and Vosgerau 2006). The two important parameters to consider here are wave frequency and velocity, the latter of which can vary significantly in different mediums. Wave theory indicates that the best vertical resolution can be achieved at one quarter of the dominant wavelength (Sheriff 1977). Applying this to clays with relative permittivities ranging between 5-40 will yield propagation speeds of 4.7-13 cm/ns (Overmeeren 1994), which for the two antennas yields vertical resolutions of 1.765- 4.5 cm and 0.77-1.97 cm respectively.

Of course, this theoretical range can be worsened in practice by many factors, such as scattering, energy losses, or the return centre frequency being typically lower than the nominal centre frequency due to greater attenuation of higher frequencies (Neal 2004). Given a reasonable velocity of 10 cm/ns, the theoretical vertical resolution for the 700 MHz and 1500 MHz antenna can be expected to be 3.5 cm and 1.6 cm respectively (Mancuso 2012).

Horizontal resolution, regarded as the minimum distance which should exist between two reflectors to allow detection, is more difficult to calculate, as it also depends on the trace interval, the beam width, the radar cross section of the reflector and the depth of the target (Rial et al. 2009). This horizontal resolution is also determined by the area illuminated by the GPR antenna, the so-called antenna footprint. It is typically worse than the vertical resolution as it includes the $\lambda/4$ factor as well as another factor dependent on depth. The most common approximation for the antenna footprint, which is used to define the horizontal resolution (Vega, Ramon and Di Capua 2008) is:

$$A = \frac{\lambda}{4} + \frac{h}{\sqrt{(\varepsilon + 1)}} \ ,$$

where h is depth and ε is the average relative permittivity to depth h.

This effect is diminished since with the exception of tap roots, the vast majority of roots are located within the first 20 cm, but is still significant. For the clay interval, considering a depth of 10 cm, this adds another 1.6 – 5 cm to the vertical resolution. The increase in lateral resolution with depth is an important factor in tree root study. Neal (2004) discusses the detailed aspects which can influence practical lateral resolution, including horizontal spacing between GPR profiles (which of course, is not considered on a single profile).

In theory, using higher frequency always seems desirable, but in practice this is not always the case as the depth of penetration is reduced to only a few centimetres due to high scattering in the topsoil. In the field, topsoil is a heterogeneous and lossy complex medium, with greatly varying dielectric properties (Zhu et al. 2014), which can create an unsuitable medium for very high frequency antennas (2 GHz and above).

The 700-1500 MHz interval range therefore seems like a realistic range for the study of coarse tree roots (thicker roots which have undergone secondary thickening and have a woody structure). While the 700 MHz antenna will be incapable of detecting thinner roots, it is still a frequency commonly used in practice (along with even lower frequencies), and the models highlight the limitations of these lower frequencies.

RESULTS

Experimental results

A set of initial measurements was carried out to assess the suitability of using branches instead of roots, which would have been more easily accessible. However, it was found that branches and roots have very different permittivity values (as illustrated in Figure 1), and therefor branches cannot be used as a proxy for roots.

Although there may well be a correlation between the permittivity of roots and branches (influenced by species, overall health and activity of the tree, or water content), results indicate that branches are not an accurate proxy for roots.

Figure 1 shows measurements on roots and branches approximately 1 cm in diameter from a mature Sycamore tree. The curves follow an expected shape, with permittivity values slowly declining with frequency.

[INSERT FIGURE 1]

The initial measurements also revealed two other aspects: firstly, a minority of the roots have a very low, almost negligible permittivity (<4). Although the water content was not measured for these first samples, they were visibly drier, and possibly diseased or inactive. Secondly, it was immediately visible that the root permittivity values were spread over a wider range and did not cluster around a single value.

There was also a large difference in permittivity between roots and branches of similar diameters, further suggesting that branches are not good substitutes for roots.

Several smaller-scale measurement campaigns were carried out, gathering 2-4 roots or 2-4 segments of the same root. Since this was time-consuming and logistically challenging, all surveys but one (describe in the following section) were carried out in this fashion. Additionally, since there is a reasonable reason to believe that environmental conditions such as soil moisture can change the permittivity of the roots, surveys conducted on different days were analysed separately.

A larger survey

The largest and most comprehensive survey was carried around the Harborne Walkway, in Birmingham, UK. A total of 20 root segments were successfully harvested and analysed (2 segments from 8 individual roots, 4 segments from one individual root). Another 4 segments from a different root yielded very low permittivity values and were discarded. This ensured that there was time to carry the measurement before the root samples start drying up. All samples were taken from the same soil unit (a wet clay), over a distance of under 1 km, with depths ranging from 0 to approximately 2 cm, from three species: Sycamore, Pine, and Oak. Roots were labelled from R1 to R10. Out of the samples, R5 segments were discarded as very dry and potentially diseased/inactive, and 4 segments were harvested from R6 (R6a, R6b, R6c, R6d). From all other roots, two segments were harvested (a and b). The diameter, weight, and dry weight were measured. It was attempted to harvest root segments both from the surface and right beneath the surface. All the "a" segments were visible on the surface. The "b" segments were on the same root section as the "a" segments, in their direct continuation, but right beneath the surface (<2 cm), which did not appear to have a consistent effect on permittivity. For the R6 root, only the "a" segment was partially visible on the surface.

Table 1 shows the characterisation parameters of the tree roots analysed in this study.

Segments from the same root tended to have more similar water content values, typically within 1-2%, although one sample varied by up to 4% (R6 in Table 1). Water content also did not appear to be correlated with diameter.

	R1a	R1b	R2a	R2b	R3a	R3b	R4a	R4b	R6a	R6b
Species	Syc	Syc	Syc	Syc	Syc	Syc	Oak	Oak	Oak	Oak
ø (mm)	8	8	9	9	10	10	9	9	8	7
Weight (g)	4.68	7.41	6.05	6.41	6.2	5.68	4.27	6.35	4.06	3.4
Dry W (g)	2.89	4.55	3.12	3.49	2.89	2.64	2.1	3.17	1.99	1.53
Water %	0.38	0.39	0.48	0.46	0.53	0.54	0.51	0.5	0.51	0.55
Perm 0.5GHz	15.1	14.5	12	13.5	15.3	17.8	25.1	18.1	28.4	33
Perm 1GHz	13.5	12.9	11	12.2	13.5	16	22.5	16.1	26.3	31.2
Perm 1.5GHz	13	12.4	10.6	12.1	13	15.3	21.6	15.5	25.6	30.5
	R6c	R6d	R7a	R7b	R8a	R8b	R9a	R9b	R10a	R10b
Species	Oak	Oak	Syc	Syc	Syc	Syc	Syc	Syc	Syc	Syc
ø (mm)	7	7	6	6	6	6	7	8	8	7
Weight (g)	3.61	3.33	3.04	3.08	2.72	2.45	4.62	3.8	4.54	4.15
Dry W (g)	1.73	1.56	1.56	1.53	1.34	1.2	2.5	2.09	2.19	1.97
Water %	0.52	0.53	0.49	0.5	0.51	0.51	0.46	0.45	0.52	0.53
Perm 0.5GHz	28.8	31.5	16.8	23.5	28.5	28.6	15	16.5	28.1	22.8
Perm 1GHz	26.9	29.2	15.1	21.6	26.2	26.8	13.3	14.7	26.2	21.3
Perm 1.5GHz	26.2	28.3	14.6	20.9	25.4	26.2	12.9	14.4	25.5	21

Table 1.General characteristics of the measured root segments, including the diameter (ø), wet weight (g), dry weight (g), and water content (%).

The range of frequencies over which the segments were measured was 50 MHz – 3 GHz, with measurements taken at 101 individual frequencies. The first and last five extreme measurements were eliminated, and the median value was calculated.

[INSERT FIGURE 2]

Figure 2 shows the median permittivity values for root segments R1-R10; the lack of smoothness in the curves is common when taking VNA measurements with open-ended coaxial probes and can be caused by imperfect contact between root sample and probe and possibly by suboptimal calibration of the probe (note that the measurements shown in Figure 2 were taken on the same day). However, because all the curves followed a similar shape, we interpret this to be an artefact of the probe measurement, and these irregularities do not affect the conclusion derived from the analysis.

The wide spread of the permittivity values is remarkable. At 1 GHz, permittivity values range from just over 10.9 to 31.1. This interval is significant because the permittivity of the soil is likely to be within this range (Curioni, Chapman and Metje 2017). If the permittivity of the soil is similar to the permittivity of the root, it is unlikely that GPR can detect it.

Similarly to the water content (see Table 1), the permittivity values show no correlation to the root diameter or tree species.

In most instances, different segments of the same roots had very similar values – but this was not always the case. Figure 3 shows the relationship between water content and permittivity at 1 GHz.

[INSERT FIGURE 3]

Although a positive relation exists, the data are spread out and do not appear to follow a predictable behaviour. This suggests that several different factors other than water content are affecting the permittivity value of the roots, producing a notable spread.

The trend did not become clearer when grouping the data points by diameter, tree species, or other available characterisation parameters. This suggests that unlike other materials (for example soils), tree root permittivity cannot be estimated based on water content alone, and other factors need to be considered.

However, a thorough explanation of this variability was not attempted here as it was not the primary objective of this study and is an area of interest for future work.

The root density and the electrical conductivity caused by sap flow at the time of the sampling are potential parameters which could have played a significant role in affecting the measured permittivity, as suggested by Cermak et al. (2000).

Forward models

The root permittivity values described in the previous section were inserted into the forward models using gprMax.

Two virtual 2D boxes of 0.8 x 0.3 m and 0.6 x 0.2 m respectively were constructed in gpr-Max.The antenna was not modelled, and a simple Tx-Rx system was used, as is readily available in gpr-Max (Warren, Giannopoulos and Giannakis 2016). Both the permittivity values of the roots and the soil can be changed with ease. Additionally, a complex and real-life mixture of clay and sand can be modelled as an existing feature of the software.

The soils from which the roots were harvested were loamy and clayey. The permittivity values for these soil were extracted from existing literature (Daniels 1996) and input into the models (Peplinski, Ulaby and Dobson 1995). Forward models were generated with a time window of 8 ns; discretization step (dx_dy_dz): 0.001; waveform: Ricker; spatial increment for sources and receivers: 0.001.

[INSERT FIGURE 4]

For simplicity, the modelled roots were kept horizontal, and most of the generated GPR profiles were kept perpendicular to the root. However, profiles along the direction of the root were also generated.

After the forward models were outputted, they were imported into ReflexW, where some filtering was applied. Since the data is synthetic, there was no need for processing steps like dewow or bandpass filters, but static corrections (moving start time), background removal (standard ReflexW settings), hyperbola-based migration, and Hilbert transforms (standard ReflexW envelope) were applied.

[INSERT FIGURE 5]

Figure 5 depicts how segments through R1a-R6b would generate a GPR response if placed next to each other, in the same soil type, at the same depth. The visual differences caused by a range of real, different permittivity contrasts are presented, using a common processing flow. If the contrast is strong enough, it overshadows the impact of root size, and if the contrast is low enough, detectability becomes much more difficult, and potentially impossible.

Some models were also developed with varying bark thickness (Figure 6). However, plausible bark thickness (around 1-2 mm) did not appear to have a major effect, though it did make the contrast slightly more pronounced. In a more realistic soil scenario (which is heterogeneous), data migration can become problematic, potentially causing unwanted effects (migration artefacts). For the practical purpose of a GPR survey, it seems that using non-migrated data may be more useful in the case of resolving tree roots.

[INSERT FIGURE 6]

As expected, models with a lower permittivity (which mimicked a drier soil) yielded an overall better quality. This was also visible in the Peplinski soil model in Figure 4: when the fraction of clay (especially wet clay) was higher, the quality of the data was reduced.

It is important to also note that urban soils also have a great variability in terms of permittivity. In addition to the root variation, soil variation is potentially equally significant. In Figure 7, a dry root is presented in different homogeneous soil conditions, mimicking a very dry clay, a very dry loamy soil, a fertile soil, and a wet clay.

The unlikely case of carrying out a GPR profile along the line of a tree root is depicted in Figure 8. Here, the heterogeneous soil is kept unchanged, and instead, the root permittivity value takes different values.

In both cases, when one member of the root-soil system changes permittivity values, the contrast becomes more pronounced as the difference increases. Tree roots can be detected if they have a permittivity contrast to the surrounding soil, regardless of whether it is a positive or negative contrast. In the absence of a permittivity contrast, even a large root can be difficult to detect.

[INSERT FIGURE 7]

Figure 7 shows that even a dry root, which a surveyor might believe to be easily detectable, is almost completely invisible in the case of very dry soils, though the contrast becomes evident in the case of soils with a higher permittivity. Strong permittivity contrasts (be they positive or negative) make tree root detection possible. In other words, it is the relative permittivity value (between the root and the soil) that enables GPR detection, not the absolute value. This is, of course, a fundamental principle of geophysics, but becomes particularly important here due to the range of permittivity of the target (tree root) and the environment (soil), which can have significant overlap.

[INSERT FIGURE 8]

Figure 8 shows the type of signal that can be expected in the case of a GPR profile carried in the line of a tree root which thins out towards its termination.

DISCUSSION

Tree roots are complex and highly variable. They exhibit a broad range of permittivity values, depending on factors that do not seem solely limited to water content. The permittivity contrast to the surrounding soil environment critically dictates the ability of GPR to detect tree roots, which is a practical concern.

Even within a single soil unit, in similar environmental conditions, root permittivity can be spread over a large interval. This permittivity interval has substantial overlap with that of many soil types and therefore there is a high chance that some of the roots will have a permittivity value close to that of the soil, making detection more difficult or, in some cases, impossible. This also explains why GPR seems “blind” to some roots, as the root permittivity is masked by that of the surrounding soil.

Root permittivity does not seem to be correlated with diameter. This suggests that in some scenarios, larger roots can be more difficult to detect than smaller roots, if their permittivity happens to be closer to that of the surrounding soil. Neighboring segments of the same root can also have varying permittivity values.

Permittivity values for branches show no correlation with permittivity values for roots. Appealing to this proxy is unreliable and not recommended.

The permittivity contrast between the root and the surrounding soil is the defining factor which impacts detectability. This contrast, defined by the permittivity values for the soil and the root, is the parameter which should be most carefully considered in the forward models. It is recommended that a range of permittivities be simulated. The diameter of the root should be considered for the selection of a suitable survey antenna. As expected, results suggest that the 1500 MHz is much better suited for studying finer tree roots, due to its higher resolution. This should also ensure a sufficient depth of penetration in most scenarios.

The root can exhibit a positive or a negative permittivity contrast to the surrounding soil. The positive or negative nature of the contrast does not have a strong impact on detectability, although in practice, a negative contrast suggests a higher soil permittivity, where GPR data tends to have lower quality.

The above does not necessarily hold true for paved surfaces, where it is possible to detect roots even when they exhibit similar permittivity values to the surrounding environment as they generate a system of small cracks and fissures which might be detected with GPR.

The presence of bark does not always ensure detectability. Roots with a thin bark (1-2 mm) are only slightly easier to detect, this effect being most significant in a higher-permittivity soil, which ensures a higher bark-soil permittivity contrast. If the bark is thin enough, some of the signal is reflected by the root, while some of it passes through the root, which is why sometimes, some roots exhibit a double hyperbola response.

Some roots (including diseased or inactive roots) have an extremely low permittivity (<5). This could be useful, for instance, in an orchard setting, to detect potential health problems of the roots and subsequently, the trees themselves.

Water content, while certainly an important parameter, is not the only influential factor responsible for tree root permittivity. Permittivity might also vary dynamically with water/nutrient uptake and sap flow. Hence, repeating a GPR survey at different times, or under different environmental conditions, could yield different results. A general correlation between the soil and the root permittivity can be assumed and with all things equal, wetter soils (with a higher permittivity) will generally contain wetter roots (also with a higher permittivity), though this does not appear to cancel out the root permittivity variability, just offset it.

The results presented in the study can give surveyors an awareness of the spread of permittivity values of tree roots, and a more realistic expectation of what can be detected, including the fact that some roots may remain undetected even in the case of a well-designed and carefully carried-out survey. This range of permittivity can be then input into forward models along with a predicted or measured value for the soil unit to aid in the understanding of the range of detectable contrasts and the overall expected signal (with the mention that models will provide an "optimistic" version of detectability; low contrasts barely distinguishable in the simplified forward models are unlikely to be detectable in a real-life scenario). This is an inexpensive, relatively easy way of improving a pre-survey assessment and overall survey design.

Tree root forward models can also aid in the interpretation of GPR data. The identification of tree roots on radargrams and differentiation from other subsurface reflectors relies on the root's continuity. However, permittivity variation within a single root could mask this continuity. This can be particularly impactful in surveys which map the proximity of tree root growth to elements of infrastructure such as pipes, one of the main objectives of the geophysical study of tree roots. The removal of such tree roots is an expensive and delicate intervention, and a thorough geophysical interpretation could assess whether such an intervention is necessary, saving costs and time. Ideally, pre-emptive surveys would be carried out enabling such interventions before any damage has been done.

Lastly, should all the underlying parameters determining root permittivity be determined, a simple, non-invasive radargram could reveal important aspects about these parameters and subsequently, about tree health. For instance, it is plausible that diseasesd tree roots have lower permittivity, and GPR could provide a relatively fast and non-invasive way to help assess the disease spread.

CONCLUSION

The GPR detection of tree roots remains a difficult and site specific task. A range of permittivity values for tree roots is introduced, and the impact on detectability is discussed.

This the first study to combine direct measurements of permittivity and GPR forward modelling techniques. Harvesting and measuring of tree root permittivity is possible, though the process is time-consuming and must be done carefully. The contact between root segment and probe remains a potentially problematic issue, although this can be overcome by collecting a large number of measurements and removing any potential outliers.

Tree root permittivity has a broad range of values, even in the same ground conditions. In one of the surveyed areas, the roots' relative permittivity varied between 10.9 and 31.5. Some roots will have a value closer to that of the surrounding soil, which makes detection much more difficult. This information is useful in several ways: it can help develop more realistic survey expectations, it can aid GPR data interpretation, and it can offer a better understanding of the root-soil system from the standpoint of a GPR surveyor.

Whilst the generated synthetic models here have featured a root-soil dynamic, the same type of models can be adapted with relative ease to depict tree root damage to man-made structures (such as concrete or sidewalks) and better understanding this potentially destructive interaction, or used to monitor trees in a controlled setting (such as an orchard).

This study can serve as a starting point for a more thorough understanding of the biophysical parameters of tree roots, which can in turn affect their geophysical detection and characterization. The permittivity variation between the same root segment remains an intriguing find which warrants further exploration.

The imaginary part of permittivity, not analysed here, warrants its own investigation, to see whether it follows the trends of the power law described by Jonscher (1977).

Future research should focus on including more complex models that resemble reality, for example by including more complex root structures and man-made structures in addition to soil. Additional experimental studies and the collection of real data are needed to confirm the findings of this research and shed light on the reasons why tree roots exhibit the large variability measured here, ultimately providing a more effective guidance for tree root detection using GPR.

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LIST OF FIGURES

others, depending on the permittivity contrast. Notably, size plays a secondary role -- roots with a larger diameter are not easier to detect if the permittivity contrast is not strong. No type of noise was added, thus all results can be considered an ideal case for GPR detectability.

Figure 6. A forward model simulation in a 0.6 x 0.2 m virtual box for three roots with varying permittivity values (R3a, R6a, R10b) in a wet clay with a permittivity of 20 (radar frequency: 1.5 GHz). Results show a homogenous root (a) and a root with a 1 mm bark (b), in unmigrated (top) and migrated (bottom) form.

Figure 7.A dry root (permittivity value 3) is presented in 4 different soils, with different permittivity values (2, 3.5, 10, 20 for a, b, c, d, respectively). Radar frequency is

700 MHz.

Figure 8. A mixture of sand and clay and a simplified root, which grows thinner from the tree to its termination (a). Different permittivity values are given to the root (12, 16, 20, 24 for b, c, d, and e respectively). Radar frequency is 700 MHz.