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Recent advances in tree root mapping and assessment using non-destructive testing methods: a focus on ground penetrating radar

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### **Rights Retention Statement:**

1 **Recent Advances in Tree Root Mapping and Assessment using Non-**  
2 **Destructive Testing Methods: a Focus on Ground Penetrating Radar**

3

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8

9 **Abstract**

10 This paper provides an overview of the existing literature on the subject of assessment  
11 and monitoring of tree roots and their interaction with the soil. An overview of tree root  
12 systems architecture is given, and the main issues in terms of health and stability of  
13 trees, as well as the impact of trees on the built environment, are discussed. An overview  
14 of the main destructive and non-destructive testing (NDT) methods is therefore given.  
15 The paper also highlights the lack of available research based outputs in the field of tree  
16 roots and soil interaction, as well as of the interconnectivity of tree roots with one  
17 another. Additionally, the effectiveness of non-destructive methods is demonstrated, in  
18 particular ground penetrating radar, in mapping tree root configurations and their  
19 interconnectivity. Furthermore, the paper references recent developments in  
20 estimating tree root mass density and health.

21 **Keywords:** assessment of tree roots; destructive testing methods; non-destructive  
22 testing methods; ground penetrating radar (GPR); tree root interconnectivity; tree root  
23 mass density.

24

## 25        **1. Introduction**

26        The earliest identified fossil tree, from over 385 million years ago, was found in the New  
27        York State, USA in 2007. Trees and plants have always been part of life on planet Earth.  
28        The impact of trees and their value to human life and the environment have been  
29        discussed in numerous publications for decades, even centuries, as suggested in  
30        <https://www.savatree.com/whytrees.html>. In more detail, the value of trees within the  
31        context of modern life could be considered under the following areas:

- 32        • Ecological and environmental
- 33        • Community and social
- 34        • Aesthetics
- 35        • Commercial and economic

36        Trees and forests are every society's asset and must be looked after and cherished. The  
37        contribution of trees and their importance to environmental sustainability are so vast  
38        that they can only be compared to the existence of icebergs and our oceans. Prevention  
39        from destruction of trees and plants by cutting them at alarming rate for materialistic  
40        reasons (i.e. creating wealth in different shapes and forms) are vital to the preservation  
41        of life, both for humans and animals, on the planet Earth.

42        Likewise, safeguarding and having planned health monitoring and assessment of the  
43        existing trees and plants are equally important. Within this context, the understanding  
44        of the health of tree roots and plants (i.e. growth, architecture and interaction with the  
45        soil and other tree roots) are of paramount importance.

46        Appropriately managing and caring for natural heritage is more important than ever  
47        today (Innes, 1993), and there is a growing awareness of the need to protect the  
48        environment. In particular, the preservation of veteran or ancient trees presents a series  
49        of conservation challenges that differ from standard arboricultural practices.

50        Among all the tree organs, roots are of vital importance because they have crucial  
51        functions in plants and ecosystems: they provide anchorage, supply soil-borne resources  
52        and modify soil properties. However, even if roots account for between 10% and 65% of

53 a tree's total biomass, they typically lie below the soil surface, which in turn has limited  
54 our understanding of tree root system development and their interaction with the  
55 surrounding environment.

56 Various methods have been used to study the root systems of plants. Such investigations  
57 are usually carried out using destructive methods, such as excavation or uprooting.  
58 Although these techniques can provide direct measurements of the roots, they are  
59 onerous, time-consuming and above all destructive. The damage that these techniques  
60 inflict on trees leads to a reduction in the number of measurements which can be carried  
61 out in the future, making it impossible to assess the status of the roots during a given  
62 period. Also, root systems are often destroyed by these inspection methods, thus  
63 becoming susceptible to infections and diseases which can lead to the death of the tree.

64 The use of non-destructive techniques for root inspection and analysis has gained  
65 popularity in recent years, as this method can provide information about tree root  
66 architecture without harming the tree. It also enables long-term monitoring of tree root  
67 systems, as no disturbance is caused to their development by the application of these  
68 techniques.

69 In this framework, ground penetrating radar (GPR) is widely acknowledged to be a  
70 powerful geophysical non-destructive tool, useful in locating buried objects such as  
71 bedrocks, artefacts, utilities infrastructure and objects, voids and sub-surface water  
72 levels. Recently, several studies have been carried out about the use of GPR for root  
73 detection and mapping, as well as for the estimation of root biomass and diameter. This  
74 technique has shown great potential due to the reliability of the results and its ease of  
75 use. However, some research has led to contradictory results, due probably to  
76 difficulties in surveying a non-homogeneous medium such as the soil-root system. For  
77 this reason, gaining comprehensive knowledge about tree root systems is advisable in  
78 order to improve the use of GPR in this field and the understanding of achieved results.

79 Hence, this review aims to evaluate state of the art in tree root system investigation,  
80 from the beginning to the most recent achievements in the non-destructive techniques  
81 field. To this purpose, a brief introduction on tree root system architecture is presented,

82 to broaden the understanding of root growth, development and structure, as well as the  
83 root system's dependence on the environment and the characteristics of the soil.  
84 Following this, the main concerns regarding roots are defined and discussed, divided  
85 into health problems which could affect roots and the damage that roots can cause to  
86 the environment. The principal techniques for tree root system investigation are listed  
87 and examined, from the destructive methods to the non-destructive techniques. The  
88 main achievements and limitations of each method are thus discussed.

89 Finally, a comprehensive review of GPR applications to root detection and root index  
90 quantifications is carried out, in a section organised as follows:

- 91 • GPR operating principles and signal processing techniques are outlined;
- 92 • The current state of knowledge about GPR use in tree root systems investigations  
93 is reviewed;
- 94 • Limiting factors to root surveys using GPR are outlined;
- 95 • Future perspectives are discussed.

96

## 97        **2. Tree root systems architecture**

98        Tree roots are responsible for water and mineral uptake, carbohydrate storage and  
99        hormonal signalling (Pallardy, 2008), as well as for providing support and anchorage in  
100       the ground (Coutts, 1983). Thus, the health of the root system, and as a consequence  
101       the health of the tree, is closely linked to the soil conditions (Gregory, 2006).

102       Tree roots are usually composed of complex structures, and they can be divided into  
103       two main groups:

- 104        • Woody roots: roots that have gone through secondary growth, resulting in a  
105        more rigid structure. Such roots have a structural role, as they are essentially  
106        responsible for anchoring the tree in the ground, and their lifespan is perennial  
107        (Pallardy, 2008). Wilson (1964) observed that woody roots that are located  
108        within one or two meters of the stem, the so-called zone of rapid taper, have  
109        different features from the roots that are located beyond this area, as the former  
110        often exhibit considerable secondary thickening. If the thickening is along the  
111        vertical plane, they are called buttress roots, the presence of which has been  
112        associated with soils that offer poor anchorage (Henwood, 1973). Beyond the  
113        zone of rapid taper emanates a framework of woody structural roots that gather  
114        water and nutrients from long distances to the trunk: their size is often  
115        influenced by mechanical stresses such as the wind load (Stoke, 1994).
- 116        • Non-woody roots: also known as fine or absorbing roots, they are responsible  
117        for the absorption of water and nutrients (Pallardy, 2008), the synthesis of  
118        rooting hormone, root exudation, and symbiosis with soil microorganisms. As  
119        the name suggests, they do not undergo secondary thickening, are generally  
120        small in diameter (<2 mm) and their lifespan ranges from days to weeks,  
121        depending on soil conditions and temperature (Pallardy, 2008).

122        Root architecture is quite complex and varies between and within plant species  
123        (Gregory, 2006). As far as rooting depth is concerned, it is influenced not only by the  
124        tree species but also by the type and conditions of the soil (Stone & Kalisz, 1991): in fact,  
125        the downward penetration of roots can be impeded by soils that are poorly aerated or

126 too dense, and by the presence of rock layers or by low soil temperatures. Stone and  
127 Kalisz (1991) carried out an extensive study on tree roots, reviewing the existing  
128 literature and performing on-site surveys on a wide variety of tree species,  
129 demonstrating that root extent is strictly related to site conditions. Indeed, evidence has  
130 been found that many species can reach considerable depths if not limited by soil  
131 characteristics. According to Jackson et al. (1996), there can be significant differences in  
132 rooting depths, depending on the features of the surrounding environment: rooting  
133 profiles are shallowest in boreal forests, temperate grasslands, and tundra, due not only  
134 to the convenient characteristics of soil moisture and aeration but also the presence of  
135 physical barriers to root vertical growth, such as permafrost in tundras and some boreal  
136 forests (Bonan, 1992). On the other hand, root distribution is deeper in deserts and xeric  
137 shrublands, as the lack of water and nutrients in the shallow subsurface, together with  
138 extreme soil surface temperatures, inhibits root development in the upper soil layers  
139 (Nobel, 2003) and forces them to grow deeper. Regardless, there is undoubtedly a  
140 tendency for tree roots to be concentrated in the surface soil (Wilson, 1964) (Wang, et  
141 al., 2006), as it is usually better aerated and moist, it contains a higher concentration of  
142 minerals than the deeper layers. Pallardy (2008) states that root density is often higher  
143 in the first 30 cm below the soil surface.

144 On the other hand, root spread seems to be less closely related to soil temperature and  
145 characteristics (Strong & La Roi, 1983). The extent of root development seems to rely  
146 upon the tree species, but also upon the stand density (Stone & Kalisz, 1991) and the  
147 presence of competing species (Shainsky & Radosevich, 1992). Many rules of thumb  
148 have been presented for estimating root spread, the most common of which is a relation  
149 between root extent and canopy diameter (Tubbs, 1977); however, Stone and Kalisz  
150 (1991) reported many examples of a maximum lateral root extent of more than 30m  
151 from the trunk, and in some cases more than 50m. This seems to demonstrate that roots  
152 tend to explore the largest soil area possible, in order to exploit its resources and provide  
153 anchorage and stability. These estimates commonly assume that there are few  
154 significant physical impediments to root extent; moreover, not much is known about

155 how different trees compete for water and mineral uptake when root systems come in  
156 contact with one another.

### 157 **3. Main issues**

#### 158 **3.1. Health and stability of the tree**

159 Tree diseases are an integral part of natural ecosystems, as they regulate the  
160 development of forests (Hansen & Goheen, 2000). The coexistence of plants and  
161 pathogens is therefore necessary for the survival of both. However, human activities  
162 have often altered the natural balance, breaking down the geographical barriers that  
163 had preserved the ecosystems and allowing the movement of wild species (Richardson,  
164 et al., 2001). As a consequence of the increase in the global trade of plants, alien  
165 pathogens and fungi have invaded entire regions (Santini, et al., 2012) (Liebhold, et al.,  
166 2012), sometimes with devastating consequences, as in the Dutch elm disease (Gibbs,  
167 1978) and the chestnut blight (Anagnostakis, 1987) cases. Such diseases not only have  
168 severe ecological consequences, but they can also have economic repercussions  
169 (Aukema, et al., 2011).

170 Fungal infections are one of the main causes of root disease, as fungi are natural  
171 components of forests (Hansen & Goheen, 2000). These typically contaminate trees  
172 which have already been weakened by other factors, such as other pests or climatic  
173 changes (Williams, et al., 1986), and they usually spread from the roots of dead or  
174 uprooted trees (Rishbeth, 1972). Fungi penetrate the bark and initiate decay in roots,  
175 inducing root rot and infecting coarse roots and the lower stems of trees (Figure 1).



176

177 **Figure 1: Roots and lower stem of a tree infected by *Armillaria root rot* fungi (Canadian Forest Service, 2015)**

178 Plants can live for a long time even if sick, as they continue to collect water and nutrients  
179 from healthy roots. Within this time, the infection can spread to other trees through  
180 root contact (Hansen & Goheen, 2000). Eventually, rotten roots will not be able to  
181 provide anchorage and sustenance, and the contaminated tree will die either by wind-  
182 throw or disease (Rishbeth, 1972).

183 The recognition of root diseases is difficult, as fungal infections do not show visible  
184 symptoms. Manifestations of diseases can include the production of mushrooms around  
185 the tree base, foliage discolouration and reduced growth (Williams, et al., 1986).

186 However, these symptoms can take several years to materialise if the tree is large or old,  
187 and by the time the disease is recognised, it is often too late for any interventions.

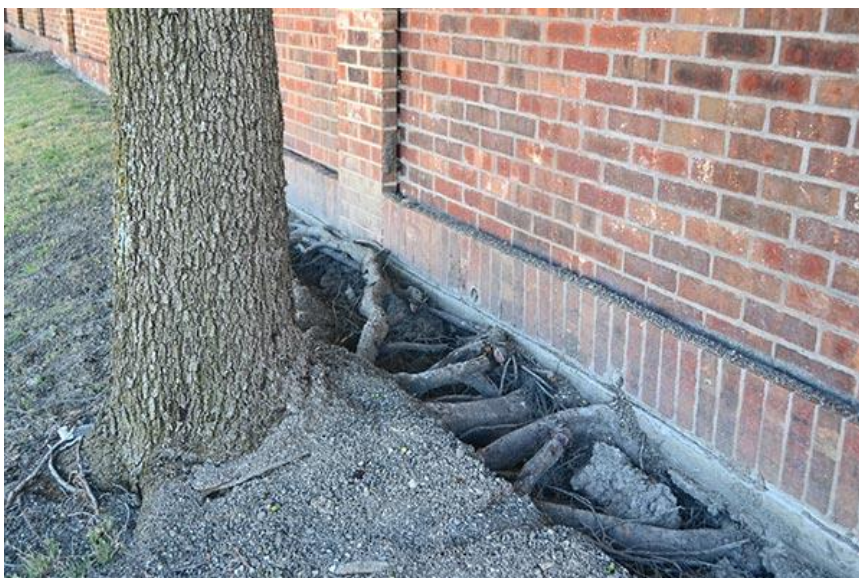
188

189        **3.2. Built environment**

190        **3.2.1. Buildings**

191        Despite being an essential presence in urban and archaeological sites, trees can also  
192        cause damage to structures and buildings. Damage can occur through direct contact  
193        with tree roots (Satriani, et al., 2010), as their growth can cause structures to uplift. This  
194        is more likely to take place near the tree trunk, as the pressure exerted by roots  
195        decreases rapidly with distance (MacLeod & Cram, 1996). This usually occurs when trees  
196        are allocated an inadequate space: as the tree grows up, the roots start spreading and  
197        making their way underneath buildings (Day, 1991). The pressure that roots are capable  
198        of exerting is fairly weak and is further diminished by urban soil compaction (Roberts, et  
199        al., 2006). Moreover, modern building foundations are designed to withstand root-  
200        induced movement.

201        Indirect damage is a more common cause of disturbance to structures, especially the  
202        shrinkage of expansive soils (Driscoll, 1983). Roots belonging to trees growing close to  
203        buildings tend to develop under the foundations, as the moisture content there tends  
204        to be higher than in the surrounding soil (Figure 2). The extraction of water by roots  
205        creates a reduction in soil volume, resulting in subsidence and cracks in the structures  
206        (Day, 1991).



207

208

**Figure 2: Tree roots growing under foundations**

209 Cutler and Richardson (1981) and Biddle (2001) have reviewed several cases of damage  
210 to buildings, producing an extensive analysis of how tree root interaction with the  
211 surrounding environment can damage buildings. Regarding damage to ancient  
212 structures, Caneva, Ceschin and De Marco (2006) have carried out a risk evaluation of  
213 root-induced damage which archaeological sites are exposed to, while Caneva et al.  
214 (2009) have surveyed the archaeological site of Villa Torlonia in Italy, investigating the  
215 root expansion and evaluating the tendency of various species to harm ancient  
216 monuments.

### 217 **3.2.2. Utilities**

218 Underground services, especially sewers, are frequently obstructed or damaged by the  
219 growth of roots. This damage usually occurs in old systems (Randrup, et al., 2001), as  
220 these were built with materials which could deteriorate with time, such as bricks or  
221 concrete. Moreover, roots are attracted by the presence of moisture around pipes,  
222 which are commonly cooler than the surrounding soil (Brennan, et al., 1997) and tend  
223 to grow around the pipe (Figure 3).



224

225

Figure 3: Roots growing around a pipe

226

227 Modern sewers are made of plastic, iron or reinforced concrete, which are unlikely to  
228 be damaged by root growth pressure. Potential leakages due, for example, to a broken  
229 joint (Schrock, 1994) or poor construction (Sullivan, et al., 1977) (Brennan, et al., 1997)  
230 can lead to roots penetrating the pipe, and eventually blocking it.

231 **3.2.3. Roads and pavements**

232 Urban trees provide several environmental, social and economic benefits, but they can  
233 also cause extensive damage to road infrastructures. Root development can cause  
234 disruptions to road surfaces, such as cracking or uplifting (Francis, et al., 1996) (Figure  
235 4). This damage can have serious consequences (Tosti, et al., 2018a), leading to  
236 additional pavement maintenance or repair and interventions on the tree (Mullaney, et  
237 al., 2015).



238

239 **Figure 4: Damages to road pavement due to tree roots**

240 One of the principal causes of conflict between roots and infrastructures seems to be  
241 the limited space provided for the development of trees (Barker, 1983) (Francis, et al.,  
242 1996). Tree size at maturity should be considered when choosing tree species to plant,  
243 as it will influence the necessary volume of soil (Trowbridge & Bassuk, 2004). Such  
244 amounts of soil are not typical of urban environments, and trees are usually confined to

245 tree lawns, which restrict not only the roots but also the branch and canopy  
246 development (Pokorny, et al., 2003). Also, trunk flare and root buttresses are associated  
247 with road infrastructure damages (Wagar & Barker, 1983), and the tendency of species  
248 to develop them should be considered when choosing which tree to plant (Costello &  
249 Jones, 2003). Finally, when large trees are planted in cities, there is a significant danger  
250 of wind-throw, as tree roots are often cut during pavement repairs and therefore cannot  
251 offer sufficient resistance to wind load (Pokorny, et al., 2003). Therefore, a selection of  
252 species adequately matched to the site conditions is advisable (Costello & Jones, 2003),  
253 as this can lead to a significant reduction of hazards; however, McPherson and Peper  
254 (2000) state that this resolution would reduce the benefits gained from larger trees.

255 Another factor which limits root development is soil compaction, as it decreases soil  
256 aeration, restricts air and water movement, limits water-holding capacity and impedes  
257 root penetration (Boyer, 1995). This is a significant issue in urban areas, as it conflicts  
258 with road engineering specifications, which require a load-bearing base to support  
259 pavement loading (Grabosky, et al., 1998). The essential requirement is to increase soil  
260 compaction in order to reduce cavities and increase contact between the grains, thus  
261 giving the lithic structure a high frictional resistance. Moreover, this minimises deferred  
262 subsidence, providing greater functionality and security to the infrastructure. The  
263 resulting level of compaction produces unbearable conditions for root growing (Blunt,  
264 2008) (Grabosky, et al., 2009) as it limits access to oxygen, water and nutrients (Loh, et  
265 al., 2003) (Lucke, et al., 2011) (Tracy, et al., 2011). Table 1 compares the prescriptions  
266 for bulk densities of soils based on the Proctor Compaction Test (ASTM D698/AASHTO  
267 T99) with the maximum level of compaction, which inhibits root penetration.

268

Bulk density of soils at 70 - 95% relative compaction						
		Landscape		Paving		Critical bulk density
		70%	85%	90%	95%	
Soil type	Loamy sand (WG)	1.52	1.85	1.96	2.07	1.75
	Sandy loam (WG)	1.43	1.74	1.85	1.95	1.70
	Sandy loam (MG)	1.35	1.64	1.74	1.83	1.70
	Sandy silty clay	1.29	1.56	1.66	1.75	1.50
	Silt	1.19	1.45	1.53	1.62	1.40
	Silty clay	1.22	1.49	1.58	1.66	1.40
	Clay	1.15	1.40	1.49	1.57	1.40

269 Table 1: Information on the critical bulk density for soils of differing textures (ASTM D698/AASHTO T99). Critical  
270 bulk density is the level of compaction at which the roots are no longer able to penetrate the soil. Units are given  
271 as dry bulk density in grams per cubic centimetre (gm/cc). WG is with gravel; MG is minus gravel (Lindsey & Barlow,  
272 1994)

273 Such levels of compaction cause roots to develop at the interface between the  
274 pavement and soil, where nutrients and moisture are available (Kopinga, 1994)  
275 (Randrup, et al., 2001) (Wagar & Franklin, 1994). The favourable conditions that roots  
276 find at the interface between the surface layer and the sub-base make them grow faster,  
277 resulting in accelerated secondary thickening that can cause damage to the road surface  
278 (Nicoll & Armstrong, 1998).

279 Other issues that can interfere with root growth in urban environments and lead to road  
280 infrastructure damage are waterlogging (Boyer, 1995) (Pokorny, et al., 2003) and severe  
281 water deficiency (Boyer, 1995) (Mullaney, et al., 2015). In the former case, soil  
282 saturation displaces air, making soil aeration more restrictive as depth increases and  
283 therefore forcing roots to grow within the soil surface; these conditions encourage the  
284 development of root pathogens. In the latter case, water deficit causes trees to slow  
285 down their leaf growth, resulting in a surplus of carbohydrates, which then become  
286 available for root growth. The immediate consequence, therefore, is that the root  
287 dimensions of water-stressed plants are higher than average.

288

## 289        **4. Detection and Mapping of Tree Root Systems**

290        Locating tree roots and estimating their depth and spread is a significant challenge, and  
291        a necessary condition for several practices, ranging from tree health preservation to  
292        safety assessment in urban areas. There are several methods for studying roots  
293        available, which can be divided into destructive or non-destructive techniques.

### 294        **4.1. Destructive testing methods**

295        Destructive testing methods allow for the investigation of root systems at the time of  
296        sampling. Therefore, they are of limited value for investigating developmental  
297        processes. Moreover, these techniques are not only destructive to the root system itself  
298        and its immediate environment (Taylor, et al., 1991), but are also expensive, time-  
299        consuming and laborious (Krinskyukov & Lyaksa, 2016). Given root system architecture  
300        variability, several replicated samples are needed to precisely assess root parameters,  
301        but this practice destroys the roots and exposes the tree to diseases and infections that  
302        can lead to its death (Smit, et al., 2013). However, these techniques are still widely used,  
303        as they provide reliable quantitative results.

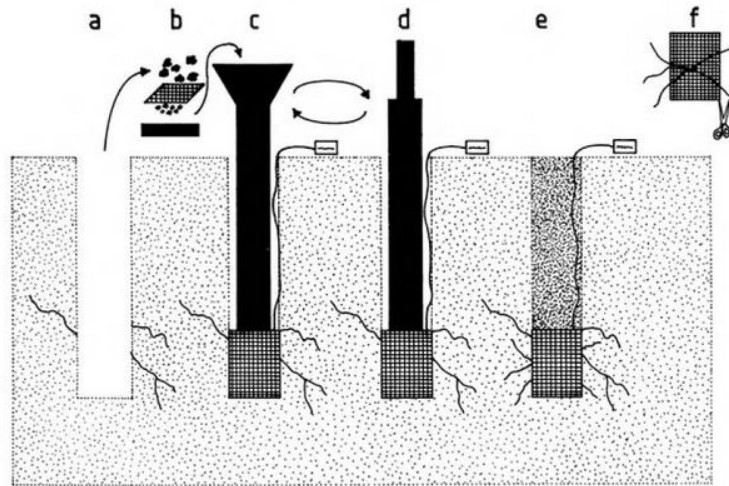
304        The main destructive techniques are:

- 305        •        Ingrowth core;
- 306        •        Auger method;
- 307        •        Monolith method.

#### 308        **4.1.1. Ingrowth core**

309        Ingrowth cores are commonly used to quantify fine root production and to estimate the  
310        rate of growth during a given period (Smit, et al., 2013). They are also adopted to  
311        examine the effect of experimental manipulation on root growth (Majdi, et al., 2005).  
312        The operating principle of this technique is to replace a volume of soil (as it is) with the  
313        same volume of root-free soil, enclosed in a mesh bag, which is resampled after a  
314        determined period (Figure 5). This method is widely acknowledged to be straightforward  
315        and inexpensive, and it illustrates how long it takes for roots to develop in a particular  
316        soil. However, it can lead to misinterpretation, as the soil structure is altered when the

317 mesh bags are introduced into the cores (Smit, et al., 2013) and this can affect root  
318 growth rates. Moreover, since roots are damaged by the initial coring, their  
319 development into the root-free samples can be unnatural (Majdi, et al., 2005).



320

321 **Figure 5: Procedure for installing the mesh bags for the root ingrowth core technique (Smit, et al., 2013).** a) a core  
322 of soil is removed and b) the soil is sieved to remove the roots; c) a mesh bag is placed in the hole, which is filled  
323 with the sieved soil; d) the soil is packed to the original bulk density by means of a pestle; e) the mesh bag is left  
324 in place for a determined period of time, after which it is recovered and f) non-woody roots are trimmed.

#### 325 **4.1.2. Auger method**

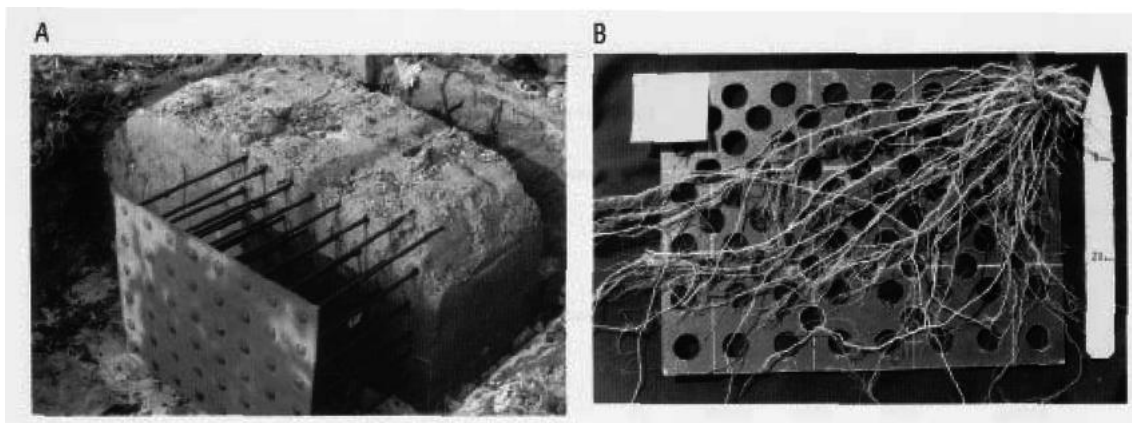
326 The auger method is the most convenient for investigating root density. It involves  
327 taking soil samples from the field, which are then washed to separate roots from the soil  
328 (Bohm, 2012) (Smit, et al., 2013). The soil core extraction can be made using either a  
329 hand-operated or a mechanical sampler, depending on the hardness of the investigated  
330 soil. The former is faster to use, being a cylindrical tube 15 cm long with an inside  
331 diameter of 7 cm, equipped with a T-handle at the top that simplifies the penetration  
332 into the soil by rotation. However, if core samples need to be taken from hard soil or  
333 considerable depths, the auger is driven into the soil by a motorised dropping hammer,  
334 and then pulled back using a screw-jack (Smit, et al., 2013).

335 There exists uncertainty about the frequency of samples required in order to obtain  
336 reliable results (Bohm, 2012), however, increasing the number of samples will lower the  
337 uncertainty and improve the variability of data collected (Smit, et al., 2013).  
338 Consequently, this technique is time-consuming (Majdi, 1996) and the large number of

339 replicates required harms a considerable part of the investigated root system (Smit, et  
340 al., 2013). Moreover, the type of soil can prevent the sampler from being inserted, such  
341 as in stony or dry clay soils (Smit, et al., 2013).

#### 342 **4.1.3. Monolith method**

343 The monolith method requires large blocks of soil to be removed and washed out, in  
344 order to separate the roots from the soil (Boyer, 1995) (Bohm, 2012). Contrary to the  
345 auger method, which requires just the root volume to be quantified, in this technique  
346 roots are washed without displacing them from their original position (Weaver & Voigt,  
347 1950). This is possible thanks to the use of special boards covered with spikes, called  
348 pinboards, which are driven into the soil to preserve the root architecture while the soil  
349 is washed away (Boyer, 1995) (Figure 6).



350

351 **Figure 6: Metallic monolith pinboard used for excavating the soil-root samples (left) and roots after extraction**  
352 **and washing from the soil (right) (Leskovar, et al., 1994)**

353 This technique provides useful information, as it is possible to have a general view of the  
354 root system architecture (Smit, et al., 2013). On the other hand, the collection of the  
355 samples requires great skill in order not to displace the roots, so the pinboards are  
356 usually of limited dimensions; additionally, the washing process can introduce biases, as  
357 significant losses of fine roots can occur (Smit, et al., 2013). Finally, this method is often  
358 non-repeatable, as the hole will be filled up with new soil that could lead the roots to  
359 develop differently, affecting the results of a second inspection (Schuurman &  
360 Goedewaagen, 1965).

361

362        **4.2. Non-destructive testing methods**

363 Non-destructive evaluations are acknowledged as being effective in investigating  
364 different materials, without harming or damaging them (Buza & Divos, 2016).  
365 Furthermore, these techniques are easily repeatable, which means that long-term  
366 investigation and monitoring of trees can be achieved (Buza & Divos, 2016).

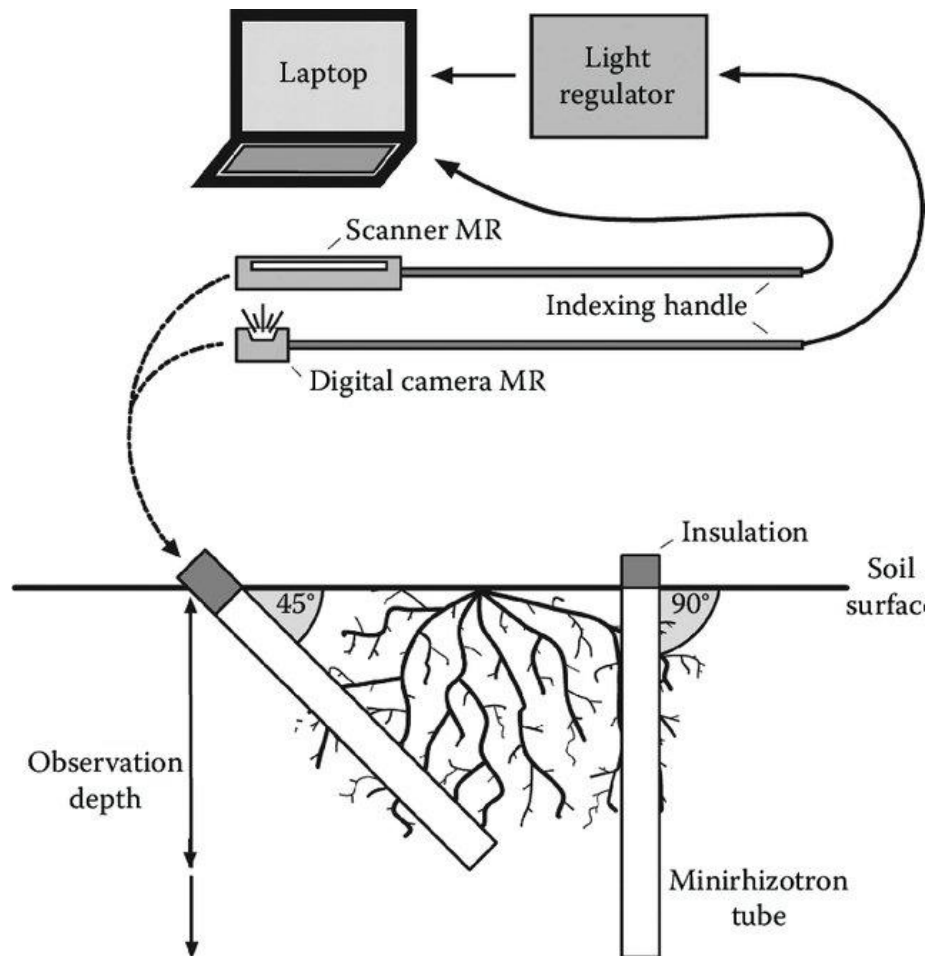
367 The main non-destructive techniques applied in root system investigations are:

- 368        • Rhizotrons and minirhizotrons;
- 369        • Pulling test;
- 370        • Electrical resistivity tomography (ERT);
- 371        • Acoustic detection;
- 372        • X-ray computed tomography (CP);
- 373        • Ground penetrating radar (GPR).

374        **4.2.1. Rhizotrons and minirhizotrons**

375 One of the first NDT methods for tree root system observations was to put glass plates  
376 into the soil, so that it was possible to observe root development and growth against  
377 them. This method has evolved into the modern rhizotron, namely an underground  
378 chamber equipped with glass walls (Boyer, 1995).

379 This technique provides repeated and non-destructive access to soil and roots, allowing  
380 for a better understanding of underground processes as they are in nature.  
381 Nevertheless, since such an instalment is impossible to set up for assessment of urban  
382 trees, minirhizotrons have become increasingly popular. These instruments consist of  
383 small plastic tubes (about 5 cm in diameter and 2 to 3 m long), which can be driven into  
384 the ground at different angles (Majdi, 1996). A fibre optic light and a camera are then  
385 lowered down the tube, in order to observe the roots' developmental process over time  
386 (Boyer, 1995), sometimes in combination with dedicated image processing software  
387 (Majdi, 1996) (Figure 7).



388

389 **Figure 7: Minirhizotron typical setups (diagonal and vertical installation) (Eshel & Beeckman, 2013)**

390 This method is commonly used for quantitative investigations on root length production,  
 391 root length mortality, longevity, rooting density and root diameter, as well as to achieve  
 392 qualitative information about root colour, branching and decomposition (Majdi, 1996).

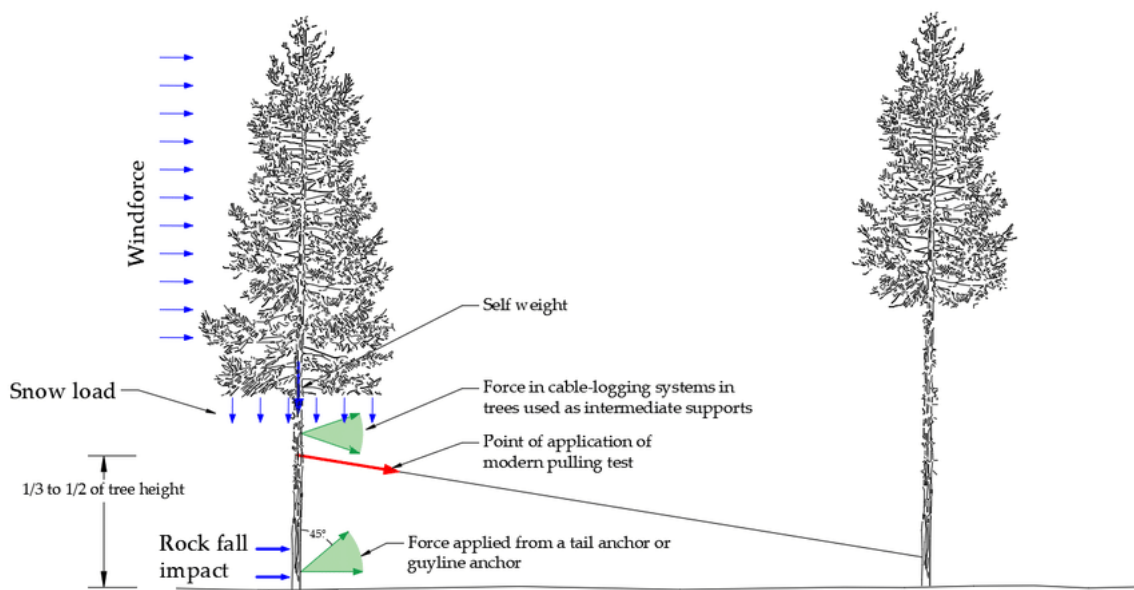
393 The main limitations of this technique are linked to its installation in hard or stony soils  
 394 (Majdi, 1996). Moreover, the viewing window is static, providing only a limited, 2-D  
 395 visualisation that is unrepresentative of the architecture of a tree root system (Mooney,  
 396 et al., 2012). Another limitation arises from the fact that rhizotrons are not totally non-  
 397 invasive, as they may create an altered soil-root interface that could affect root growth  
 398 (Amato, et al., 2009) (Neumann, et al., 2009). Finally, the effectiveness of minirhizotrons  
 399 as opposed to other techniques, especially when used in the shallow subsurface, is still  
 400 an object of discussion (Heeraman & Juma, 1993).

401

402       **4.2.2. Pulling test**

403       The pulling test is principally applied to test the root system anchorage to the soil. Its  
404       primary application is the assessment of the reaction of the tree to a determined load,  
405       especially the one caused by the wind (Buza & Divos, 2016), in terms of the resulting  
406       bending of the stem and the inclination of the root plate (Fay, 2014).

407       During a pulling test, a load is applied to the subject tree by securing a cable to the tree  
408       trunk. The pulling force applied using a load cell or force meter is measured, and factors  
409       such as the inclination, elongation and dislocation of the ground are monitored (Buza &  
410       Divos, 2016) (Marchi, et al., 2018). In order to evaluate the risk of tree uprooting, an  
411       inclinometer is applied to the trunk close to the ground. Depending on the tree species  
412       and conditions, limits are placed on the possible inclination of the tree, in order to  
413       prevent damage to tree roots. Destructive pulling tests were conducted in several  
414       studies (Coutts, 1983) (Brudi & Wassenaer, 2002) (Lundström, et al., 2007), which report  
415       root failure models and maximum inclination values for different tree species.



417       **Figure 8: Schematic representation of a pulling test (Marchi, et al., 2018)**

418       The primary output of a pulling test is a safety factor, which is given by the ratio between  
419       the tree capacity and the calculated load (Buza & Divos, 2016). According to field studies  
420       (Fay, 2014), a tree is considered stable when its safety factor is greater than 1.5.

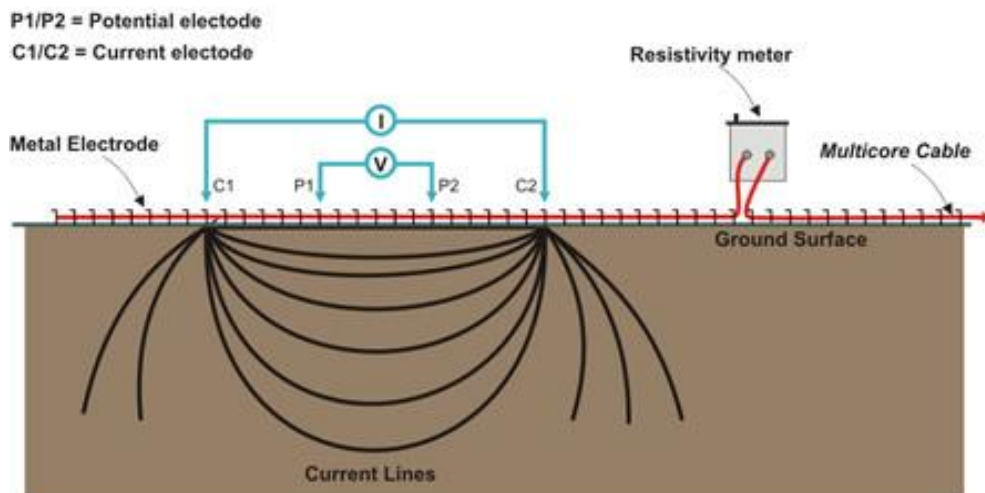
421 The pulling test provides useful information on the stability of trees, evaluating their  
422 resistance to external loads. It can be performed not only to assess the tree root plate  
423 conditions, but also the status of the trunk in terms of maximum bending moment (Fay,  
424 2014). However, the main limitation of this method is that it is not completely non-  
425 invasive, as both the trunk and the roots can be damaged when the pulling force is  
426 applied (Marchi, et al., 2018).

427 Other limitations to this methodology arise from the fact that the applied load cannot  
428 represent the complex action of the wind, but can only cause a reaction in the tree which  
429 can be compared to the one produced by the wind load (Fay, 2014). Moreover, the test  
430 could be affected by factors such as the temperature conditions of both the soil and the  
431 tree (Buza & Divos, 2016). Finally, the pulling test cannot predict the moment or the  
432 conditions under which the tree will fail (Fay, 2014), but can only assess the conditions  
433 of the tree at the time of testing.

#### 434 **4.2.3. Electrical resistivity tomography**

435 Electrical resistivity tomography (ERT) is a geophysical technique used for the calculation  
436 of the subsurface distribution of soil electrical resistivity (Zenone, et al., 2008). Electrical  
437 resistivity ( $\rho$ ) is defined as the electrical resistance through a uniform body of unit length  
438 and unit cross-sectional area and represents a measure of the ability of materials to limit  
439 the transfer of electrical current. This method has been extensively used for the  
440 characterisation of soil heterogeneity.

441 Soil resistivity is measured by applying electric currents through at least two conductors  
442 (current electrodes) and measuring the resulting differences in electric potential  
443 (voltage) on at least two separate conductors (potential electrodes). There are different  
444 possible geometric configurations for electrodes. The potential electrodes could be  
445 placed between the current electrodes (Wenner array, Figure 9) or consecutive to them  
446 (dipole-dipole configuration). The investigation depth relies on the configuration choice,  
447 and increases with the spacing between electrodes (Amato, et al., 2009).



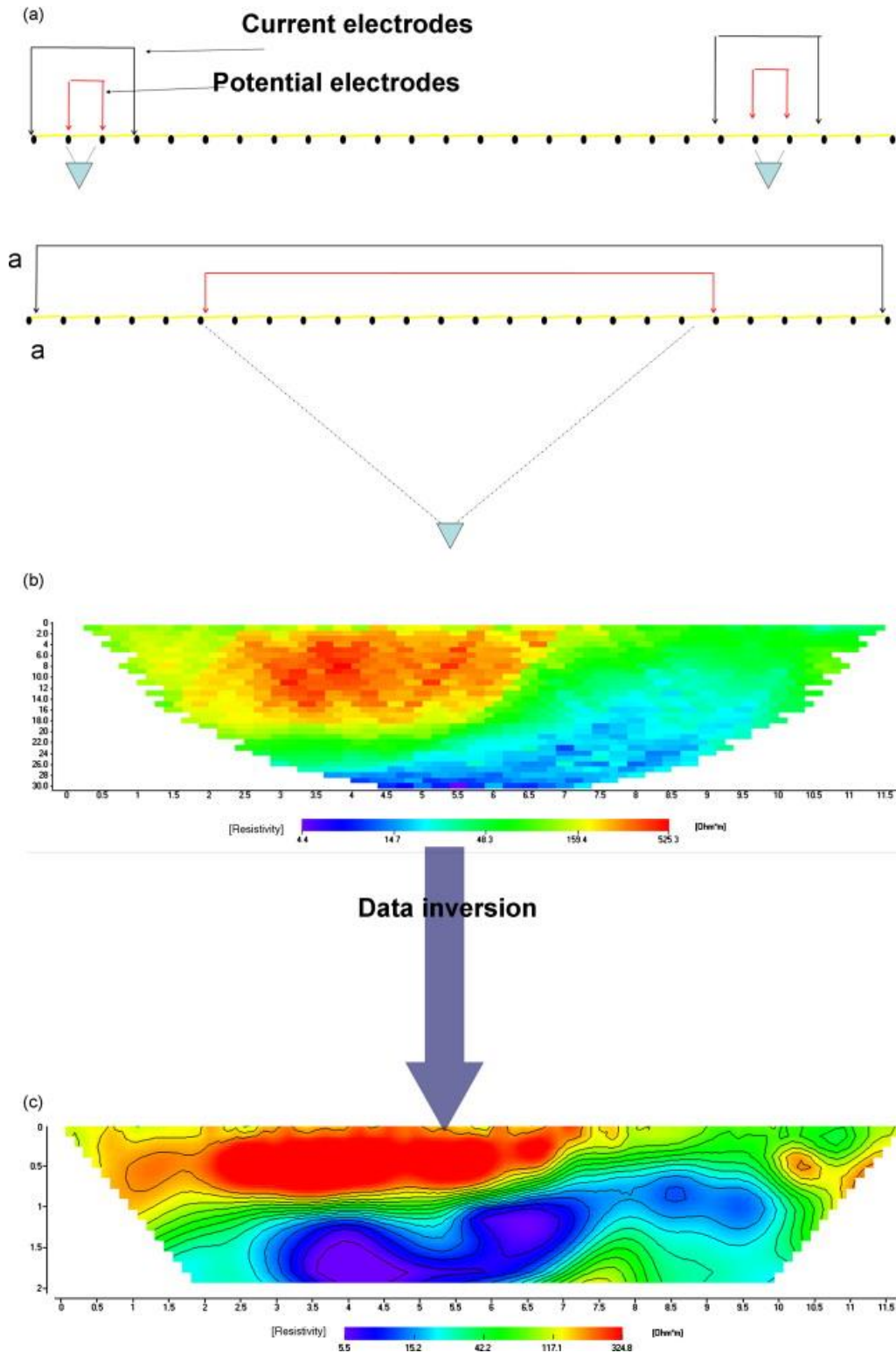
448

449

Figure 9: General ERT operating principles for a Wenner array configuration

450 The voltage distribution in space is a function of the different resistivity of soil volumes  
 451 (Kearey, et al., 2013).

452 Geophysical surveys performed using electrical exploration have qualitative purposes,  
 453 and are based on the contrast between the resistivity of different soil layers or the  
 454 heterogeneous materials within each layer. In heterogeneous media, the current flow  
 455 lines are deformed and tend to be concentrated in conductive volumes. Resistivities are  
 456 first calculated according to the theoretical flow-line distribution in isotropic media and  
 457 are called apparent resistivity values. These are attributed to soil coordinates  
 458 corresponding to the hypothesis of homogeneous current distribution and arranged in  
 459 a pseudosection. In order to obtain real resistivity values, correctly positioned in space  
 460 (true section), a procedure called inversion is applied. The investigated soil domain is  
 461 divided into elementary cells, and resistivity data are imaged by attributing values  
 462 corresponding to each elementary soil volume to a point corresponding to the  
 463 intersection of two lines conducted through the centres of the quadrupoles (Figure 10)  
 464 (Amato, et al., 2009).



465

466 Figure 10: Data acquisition and processing in ERT; (a) a linear array of electrodes with two quadrupoles at minimum  
 467 spacing (top) and one quadrupole at maximum spacing (bottom). Dots represent electrodes and full triangles  
 468 represent the centre of soil volumes measured by the corresponding quadrupole; (b) soil apparent resistivity 2D  
 469 pseudosection obtained after data acquisition; (c) soil resistivity 2D section obtained after data inversion with  
 470 numerical modelling (Amato, et al., 2009)

471 ERT has been widely applied for detecting soil compaction (Besson, et al., 2004), water  
472 content and flow in soil and plants (Loperte, et al., 2006), soil cracks (Samouelian, et al.,  
473 2005) and tillage effects (Basso, et al., 2010). The plant root zone shows variations in soil  
474 electrical resistivity (Panissod, et al., 2001), and resistive soil volumes have been  
475 correlated to large tree root structures (Amato, et al., 2008) (Zenone, et al., 2008).

476 Amato, et al (2008) conducted research in which the root biomass of alder trees was  
477 accurately mapped in 2D. This study demonstrated that the use of ERT for the non-  
478 destructive characterisation of root systems' spatial structure could reduce the  
479 coefficient of variability of root measurements, which is more significant than that of  
480 above-ground plant parts (Amato & Ritchie, 2002).

481 A quantitative relationship between the electrical resistivity of the soil and the biomass  
482 of the roots has been widely demonstrated (Loperte, et al., 2006) (Amato, et al., 2008).  
483 However, in the case of low root biomass densities, the electrical response of the roots  
484 is indistinguishable from the background noise. In fact, it is assumed that it is of the same  
485 order of magnitude as the response coming from the other characteristics of the soil,  
486 and consequently too weak to be detected (Amato, et al., 2009).

487 The main advantage of this technique is that it is totally non-destructive, as it does not  
488 disturb the structure nor the functioning of soil. Subsurface heterogeneities can be  
489 determined, in one, two or three dimensions, both non-invasively and dynamically  
490 (Samouelian, et al., 2005). Variations in time of root systems can be obtained, and  
491 different and more detailed information can be obtained by varying the operating  
492 configurations or the distance between the electrodes, depending on soil properties.  
493 Furthermore, this methodology has a low application cost, and can be applied on a large  
494 scale.

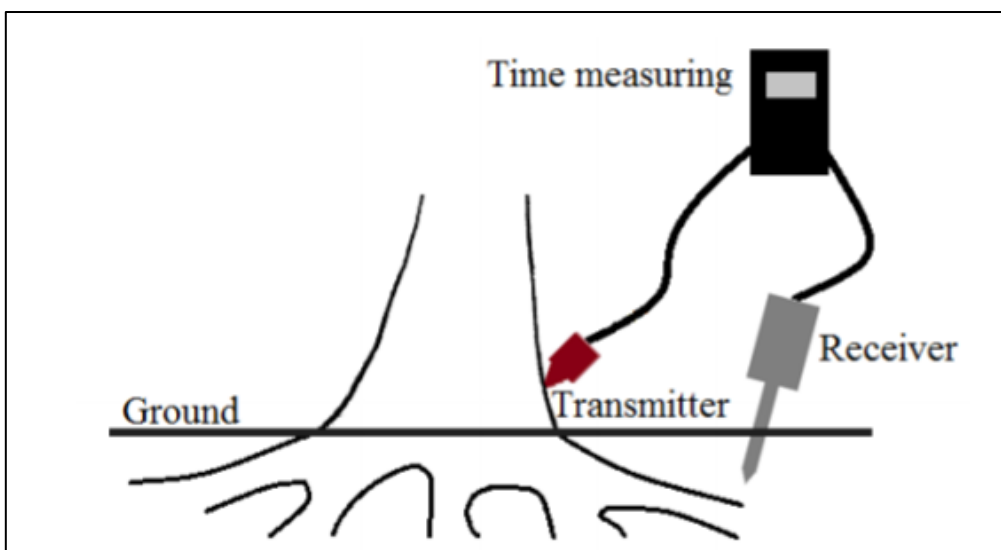
495 However, this investigation technique can be influenced by several factors, which could  
496 potentially act at the same time, making interpretation of the results difficult.  
497 Systematic errors can result from poor electrode contact or noise averaging, although  
498 these can be avoided by carrying out replicated and reciprocal measurements (positive  
499 and negative current and potential electrodes reversed) (Samouelian, et al., 2005).

500 Moreover, ERT field investigations should be coupled with laboratory studies, to  
501 calibrate the resistivity against different soil conditions. (Samouelian, et al., 2005).

#### 502 **4.2.4. Acoustic detection**

503 The acoustic detection of wood is widely used for tree investigations, ranging from the  
504 detection of decay, cracks, hollows or holes (Buza & Goncz, 2015) (Wang, et al., 2007)  
505 (Grabianowski, et al., 2006) to material characterisation for wood evaluation and quality  
506 assessment (Bucur, 2006). Therefore, the acoustic detection of roots has been tested,  
507 based on the difference of velocity in wood and soil. In fact, the velocity of the acoustic  
508 signal in soil is between 250 – 400 m/s, depending on soil type and moisture content,  
509 while the velocity in wood is between 2000 and 4000 m/s (Bucur, 2006) (Buza & Goncz,  
510 2015).

511 The device for acoustic measurements consists of a transmitter, a receiver, and a time-  
512 measuring component. The transmitter is needle-like and must be placed onto the trunk  
513 at ground level, while the receiver is a long metal spike (30 cm or longer), which has a  
514 suitable coupling for the soil (Figure 11) (Buza & Goncz, 2015). During an investigation,  
515 the transmitter sends a very short signal, which is then reflected and read by the  
516 receiver. The presence of roots decreases the travel time significantly, making it possible  
517 to locate them.



518

519

Figure 11: Device for acoustic detection of roots (Buza & Goncz, 2015)

520 Using this technique, it is possible to identify roots with a diameter of 4 cm upwards,  
521 with a maximum depth of investigation of 50 cm. Furthermore, it is possible to separate  
522 two roots from each other if they are at least 20 cm apart (Buza & Divos, 2016). These  
523 achievements are limitations as well, as the detection of small or deep roots is not  
524 possible. Furthermore, research carried out by Iwase, et al. (2015) demonstrated that  
525 the signal is highly sensitive to water content. Finally, other buried objects, such as rocks,  
526 can disguise the signal, making it difficult to recognise root system architecture correctly  
527 (Divos, et al., 2009). Given that this methodology, despite the promising results, is still  
528 in its infancy, it is often coupled with other NDT methods, in order to further investigate  
529 its potential (Buza & Goncz, 2015).

#### 530 **4.2.5. X-ray computed tomography**

531 X-ray computed tomography (CT) is a non-destructive, non-invasive technique that can  
532 be used to visualise the interior of objects in 2D and 3D based on the principle of  
533 attenuation of an electromagnetic wave. X-ray CT has been repeatedly demonstrated to  
534 be an efficient methodology for imaging and studying soil systems. CT uses X-rays to  
535 obtain cross-sectional images of an object, which contain information regarding the  
536 attenuation of the X-rays, a function of the density of the sample material (Mahesh,  
537 2002). These slices are then reconstructed to provide a 3-D visualisation of the sample  
538 volume.

539 During CT acquisition, X-rays are produced in a highly evacuated tube, which contains  
540 an anode, usually platinum or tungsten, and a cathode (Wildenschild, et al., 2002). When  
541 a high voltage is applied across these electrodes, accelerated electrons produce X-rays  
542 as they strike the anode. As the X-ray beams pass through a sample, the object itself  
543 becomes a secondary source of X-rays and electrons. A portion of the primary incident  
544 beam is therefore absorbed or scattered. This reduction in intensity of the X-ray as it  
545 passes through the investigated object is called attenuation. The beam is projected onto  
546 the detector, which measures the change in energy intensity (Mooney, et al., 2012).

547 X-ray CT offers great potential for examining undisturbed root systems architecture in  
548 soils, and its potential has been widely investigated within the last decades (Heeraman,

549 et al., 1997) (Gregory, et al., 2003). The imaging of plant roots in soil using X-ray CT relies  
550 on sufficient contrast in X-ray attenuation between growth medium solids, air-filled  
551 pores, soil water, plant material and organic matter. The attenuation of these materials  
552 varies with several factors including soil type, soil moisture content, the proximity of  
553 roots to organic matter or air-filled pores and root water status (Kaestner, et al., 2006).

554 The limitations of this technique are the overestimation of root diameter during image  
555 analysis due to the proximity of water and air within the soil (Perret, et al., 2007), and  
556 the underestimation of root length and number of lateral roots due to the fact that root  
557 material cannot be easily distinguished from other soil components. To minimise the  
558 effects of similar attenuation between the soil and plant fractions, researchers have  
559 focused on plants with coarse roots (Hargreaves, et al., 2009), artificial soil systems  
560 (Perret, et al., 2007), manipulating the water content of the sample and undertaken  
561 convoluted image processing to enhance contrast. Still, it is difficult to distinguish the  
562 boundaries between adjacent structures (Mooney, et al., 2012).

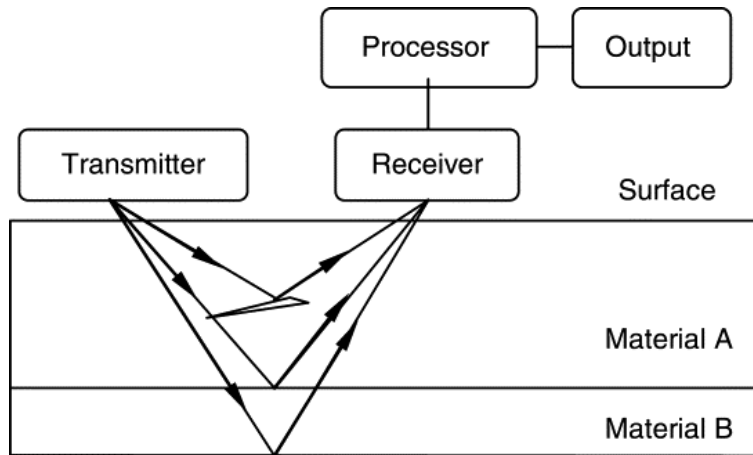
563 Advancements in CT technology include a reduction in scan and reconstruction times by  
564 at least an order of magnitude, automated algorithms to remove artefacts and more  
565 sophisticated detectors that have significantly increased the raw scan image quality  
566 (Mooney, et al., 2012). Research is now focused on investigating this technique's future  
567 potential in terms of the interaction between roots and their soil environment (Tracy, et  
568 al., 2010).

## 569        **5. Ground Penetrating Radar**

570        Ground penetrating radar (GPR) is a non-destructive testing method used to detect  
571        changes in physical properties within the shallow subsurface (Daniels, 1996). The  
572        operating principles of a GPR system are based on the theory of electromagnetic (EM)  
573        fields, which is described by Maxwell's equations (Jol, 2008). In addition, GPR  
574        effectiveness relies on the response of the investigated materials to the EM fields, which  
575        is ruled by the constitutive equations (Jol, 2008). Therefore, the combination of the EM  
576        theory with the physical properties of the material is essential for a quantitative  
577        description of the GPR signal.

### 578        **5.1. GPR theoretical background**

579        A standard GPR system consists of three essential components: a control unit (including  
580        a pulse generator, computer, and associated software), antennas (including paired  
581        transmitting and receiving antennas), and a display unit (Guo, et al., 2013) (Figure 12).  
582        During a GPR investigation, the transmitting antenna generates short impulses of EM  
583        energy, which are launched into the investigated medium where they propagate as  
584        waves (Daniels, 1996). When these waves hit a target with different electrical or  
585        magnetic properties, reflections are generated, which are then diffracted back towards  
586        the surface and recorded by the receiving antenna. The remaining energy, conversely,  
587        continues to travel into the medium until it is completely attenuated (Daniels, 1996).  
588        The control unit samples and filters the collected information, and then combines it into  
589        a reflection trace (also named A-scan), recording the time between the emission of the  
590        reflected signal and its reflection on the vertical axis and the amplitudes of the received  
591        signals on the horizontal axis (Daniels, 2004). Being an individual trace, the A-scan  
592        provides punctual information about the subsurface configuration (Benedetto, et al.,  
593        2017).



594

595

Figure 12: GPR operating principles

596 The depth of a target can be derived from the propagation velocity ( $V$ ), as follows  
 597 (Daniels, 1996):

$$D = \frac{V \times t}{2} \quad (1)$$

598 where  $D$  is the depth and  $t$  is the two-way travel time. Instead, wave velocity can be  
 599 calculated from the following equation (Lorenzo, et al., 2010):

$$V = \frac{1}{\sqrt{\frac{\mu\varepsilon}{2} \left( \sqrt{1 + \left( \frac{\sigma}{\omega\varepsilon} \right)^2} \right) + 1}} \quad (2)$$

600 where

- 601 •  $\mu$  is the magnetic permeability;
- 602 •  $\sigma$  is the electrical conductivity;
- 603 •  $\varepsilon$  is the dielectric permittivity;
- 604 •  $\omega$  is the angular frequency ( $\omega = 2\pi f$ , where  $f$  is frequency) of the emitted  
 605 pulse.

606 A formula for the estimation of propagation velocity for low conductive and  
 607 nonmagnetic materials ( $\sigma \ll \omega\varepsilon$  and  $\mu_r = 1$ , where  $\mu_r$  is the relative magnetic  
 608 permeability) has also been proposed (Jol, 2008) (Daniels, 2004):

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

609 where

- 610 •  $c$  is the speed of light in vacuum (0.2998 m per nanosecond);
- 611 •  $\varepsilon_r$  is the relative dielectric permittivity.

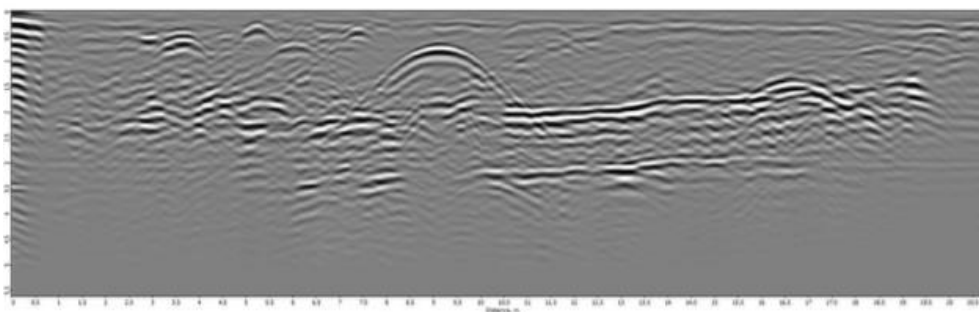
612 The reflected energy amplitude at an interface between two materials depends on the  
 613 reflection coefficient  $R$  (al Hagrey, 2007):

$$R = \frac{\sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}}}{\sqrt{\varepsilon_{r1}} + \sqrt{\varepsilon_{r2}}} = \frac{V_2 - V_1}{V_1 + V_2} \quad (4)$$

614 where

- 615 •  $\varepsilon_{r1}$  is the relative dielectric permittivity of the overlying material;
- 616 •  $\varepsilon_{r2}$  is the relative dielectric permittivity of the underlying material;
- 617 •  $V_1$  is the propagation velocity in the overlying material;
- 618 •  $V_2$  is the propagation velocity in the underlying material.

619 During a survey, GPR is moved along a detection transect, and EM pulses are generated  
 620 at a specified interval of time or distance. As reflected signals are recorded, traces can  
 621 be integrated into a radargram (also called B-scan) that allow for a 2D representation of  
 622 the subsurface (Figure 13). The B-scan mode is a widely used imaging methodology, as  
 623 it permits to visualise the presence of buried objects (Bianchini Ciampoli, et al., 2019).



624

625

Figure 13: A typical radargram or Bscan

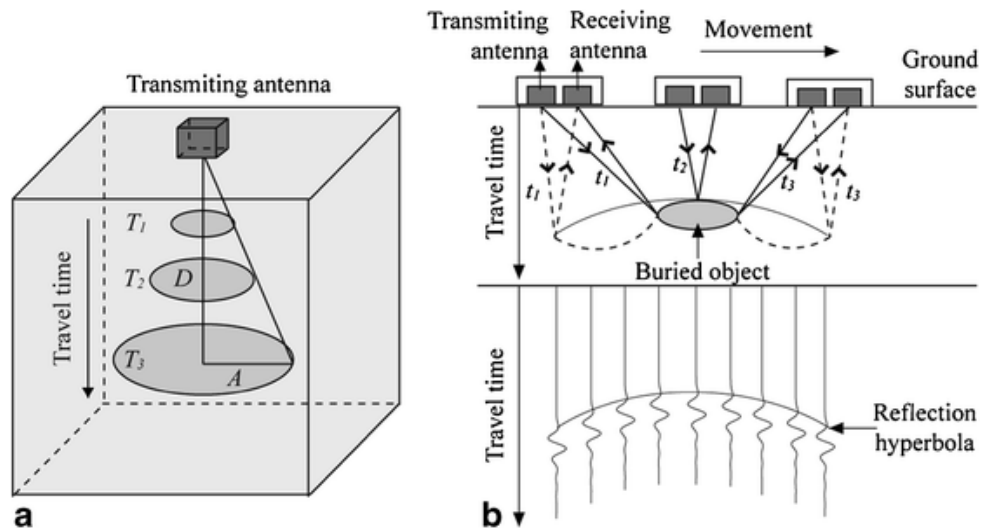
626 The GPR transmitting antenna produces energy in the form of a beam that penetrates  
627 into the ground in the form of an elliptical cone. As the propagation depth increases, the  
628 cone radius also expands, resulting in a larger footprint scanned beneath the antenna  
629 (Figure 14a). The footprint area can be approximated by the formula (Conyers, 2002):

$$A = \frac{\lambda}{4} + \frac{D}{\sqrt{\epsilon_r + 1}} \quad (5)$$

630 where

- 631 •  $A$  is the long dimension radius of footprint;
- 632 •  $\lambda$  is the centre frequency wavelength of radar energy;
- 633 •  $D$  is the depth from the ground surface to the reflection surface;
- 634 •  $\epsilon_r$  is the average relative dielectric permittivity of scanned material from the  
635 ground surface to the depth of reflector ( $D$ ).

636 Based on this feature of propagating waves, radar energy will therefore be reflected  
637 before and after the antenna is positioned above a buried object. As the antenna moves  
638 closer to the object, the recorded two-way travel time decreases, while when the  
639 antenna moves away from it, the same phenomenon is repeated conversely, generating  
640 a reflection hyperbola, the apex of which indicates the exact location of the buried  
641 object (Guo, et al., 2013) (Figure 14b).



642

643 **Figure 14: Schematic illustration of the conical radiating pattern of GPR waves and generation of a reflection**  
 644 **hyperbola (Guo, et al., 2013): a) development of a footprint with increasing travelling time; b) detection of a**  
 645 **buried object with the creation of a reflection hyperbola**

646 The GPR resolution, and therefore its capability to discriminate between two closely  
 647 spaced targets as well as the minimum size detectable, correlates negatively with the  
 648 footprint area. GPR detection resolution depends on the antenna frequency, the EM  
 649 properties of the medium, and the penetrating depth (Hruska, et al., 1999). Therefore  
 650 in a survey, the selection of the appropriate GPR features, including frequency  
 651 operations, the type of antenna or its polarization rely on a number of factors, such as  
 652 the size and shape of the target and the transmission properties of the investigated  
 653 medium, as well as the characteristics of the surface (Daniels, 2004).

654 Advances in GPR data processing and visualisation software have allowed for the  
 655 creation of 3D pseudo-images (also called C-scans) of the subsurface, obtained by  
 656 interpolating multiple 2D radargrams. A C-scan provides an amplitude map at a specific  
 657 time (or depth) of collection (Benedetto, et al., 2017), and is therefore helpful in  
 658 visualising a trend of the amplitude values all over the investigated domain.

659 In regard to GPR data processing and analysis, appropriate signal processing techniques  
 660 are needed to provide easily interpretable images to operators and decision-makers  
 661 (Daniels, 2004). Most of the techniques that are applied today originate from seismic  
 662 theory (Benedetto, et al., 2017), as both disciplines involve the collection of pulsed  
 663 signals in the time domain. It is not possible to establish a unique methodology, as it

664 depends on the purpose of the survey, the features of the used radar and the conditions  
665 of the investigated medium. Furthermore, the analysis of GPR data is a challenging issue,  
666 as the interpretation of GPR data is generally non-intuitive and considerable expertise is  
667 therefore needed.

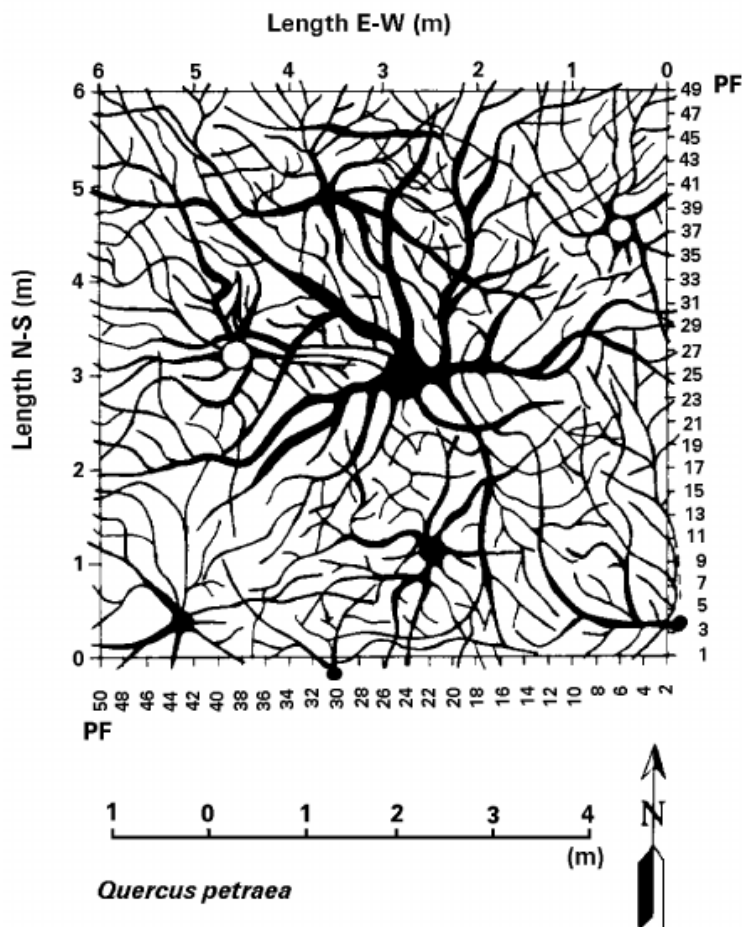
## 668 **5.2. GPR applications in the assessment of tree root systems**

669 GPR has been employed for many applications and in several disciplines, such as  
670 archaeological investigations (Goodman, 1994), bridge deck (Alani, et al., 2013) and  
671 tunnel analyses (Alani & Tosti, 2018), the detection of landmines (Potin, et al., 2006),  
672 civil and environmental engineering applications (Tosti et al., 2018b) (Benedetto, et al.,  
673 2017) (Benedetto, et al., 2015) (Loizos & Plati, 2007), and planetary explorations (Tosti  
674 & Pajewski, 2015), for about forty years.

675 Although GPR has commonly been used to characterise soil profiles (Lambot, et al.,  
676 2002) (Huisman, et al., 2003), roots have often been considered an unwanted source of  
677 noise that usually complicates radar interpretation (Zenone, et al., 2008). However, over  
678 the past decade, GPR has been increasingly used for tree root assessment and mapping,  
679 as it is completely non-invasive and does not disturb the soils or bring harm to the  
680 examined trees or the surrounding environment. For these reasons, repeated  
681 measurements of root systems are possible, allowing for the study of the roots'  
682 developmental processes.

683 The first application of GPR that relates to the mapping of tree root systems dates back  
684 to 1999 (Hruska, et al., 1999). In this study, a GPR system with a central frequency of  
685 450 MHz was employed to map the coarse roots of 50-year-old oak trees, and  
686 measurements were made in two directions within a 6 m by 6 m square, with a 0.25 m  
687 x 0.25 m profile grid, at 0.05 m intervals. After data processing, the root system of the  
688 large oak tree was analysed in detail by applying depth correlations of GPR indications  
689 from single profiles to develop a 3D picture. Additionally, the root system was excavated  
690 and photographed, and root lengths and diameters were measured to verify the radar  
691 data. The researchers confirmed that the resolution of the GPR system was sufficient to  
692 distinguish the roots that were 3 cm to 4 cm in diameter. Diameters of roots detected

693 by the GPR system corresponded to measured diameters of excavated roots with an  
 694 error of between 1 and 2 cm. The GPR system determined the length of individual roots,  
 695 from the stem to the smallest detectable width, with an error margin of about 0.2 dm  
 696 to 0.3 dm. Higher frequencies together with smaller measurement intervals were  
 697 applied, and this method improved the resolution and accuracy to less than 1 cm. In  
 698 conclusion, the researchers claimed to have successfully tested GPR in a forest and  
 699 woodland environment, where the soil is relatively homogenous. The output of this  
 700 study was criticised several years later (Guo, et al., 2013), because the 3D views of the  
 701 coarse root system were redrawn manually based on the GPR radargram, but no specific  
 702 information was provided regarding how it had been done (Figure 15). Assuming that  
 703 the maps were redrawn arbitrarily according to the operator's personal experience, bias  
 704 may therefore have been introduced.



705

706  
707

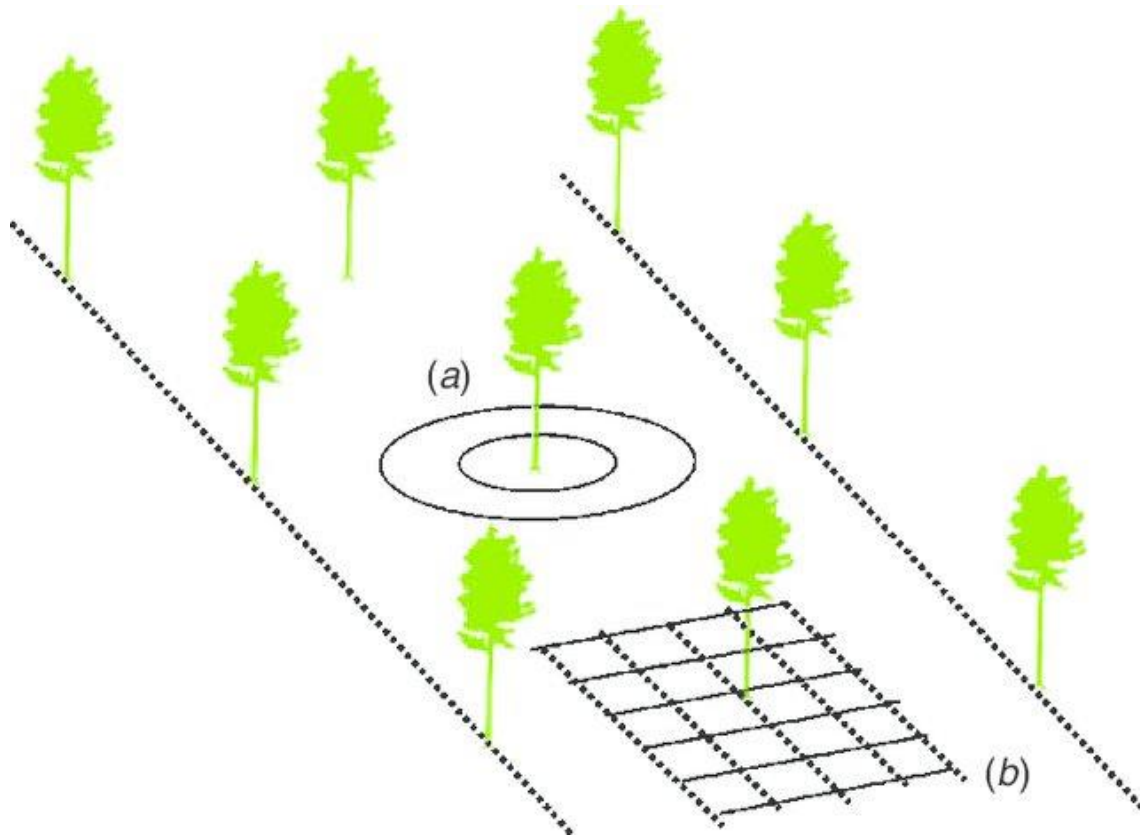
Figure 15: Hand-drawn reconstruction of a tree root system based on the analysis of GPR data (Hruska, et al., 1999)

708 Attempts to map tree root systems have continued throughout the years (Sustek, et al.,  
709 1999) (Cermak, et al., 2000) (Wielopolski, et al., 2000), with alternate and controversial  
710 results. The most significant barrier to mapping complete root systems with GPR is the  
711 inability to distinguish individual roots when tight clusters of roots are encountered, as  
712 they give one only large parabolic reflection (Butnor, et al., 2001). Furthermore, many  
713 pieces of research were carried out under controlled conditions (Barton & Montagu,  
714 2004), therefore limiting the significance of the results for in situ tree root mapping.  
715 Moreover, the minimum detectable size for tree roots is still a subject of discussion. In  
716 fact, tests conducted under controlled conditions confirmed that it was possible to  
717 detect fine roots (0.5 cm in diameter or less) (Butnor, et al., 2001), while tests carried  
718 out in the field demonstrated that only coarse roots with diameters greater than 5 cm  
719 could be identified (Ow & Sim, 2012).

720 Furthermore, research has concentrated on the use of GPR as an appropriate tool for  
721 use on valuable trees, or trees in situations where excavation is not possible, such as  
722 growing near pavements, roads, buildings or on unstable slopes (Stokes, et al., 2002).  
723 GPR data were able to reliably locate roots under pavements and provided a reasonably  
724 accurate root count in the compacted soil under concrete (Bassuk, et al., 2011) and  
725 asphalt (Cermak, et al., 2000). This is possible thanks to the difference in water content  
726 between roots and soil, which can provide the necessary permittivity contrast and  
727 therefore allow root detection by GPR (Wielopolski, et al., 2000). Also, it facilitates the  
728 distinction between roots and buried utilities (i.e. cables and pipes), which could  
729 otherwise generate signal interference, affecting the GPR survey (Ow & Sim, 2012).

730 Another testing issue that has been investigated is the survey methodology. Two  
731 experimental sites situated in Italy, subject to different climates and hydrological  
732 conditions, were investigated for this purpose (Zenone, et al., 2008). In this study, GPR  
733 measurements were taken using antennas of 900 and 1500 MHz applied in square and  
734 circular grids (Figure 16): even though square grids are preferable for GPR lines, results  
735 obtainable with circular transects (created by rotating the GPR around the tree, keeping  
736 a constant radial distance) were tested to ensure a quasi-perpendicular scanning of root

737 systems. The major difficulty in this setup, however, arose from soil unevenness, as it  
738 was challenging to push a radar system in circles over roots and stones.

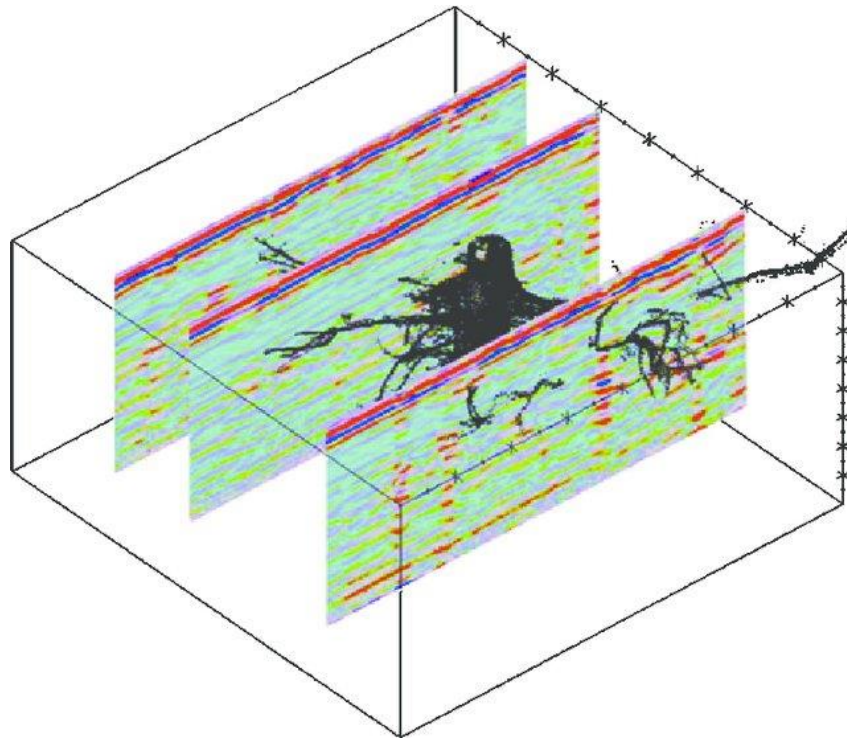


739

740 Figure 16: GPR setups for tree root system survey using a) circular transects and b) square grids (Zenone, et al.,  
741 2008)

742 Most of the aforementioned methodologies tested the reliability of their results by  
743 digging or uprooting the investigated trees. Zenone, et al. (2008) excavated the root  
744 system with an air-spade and pulled it out using a digger; a laser measurement system  
745 was then applied in order to create a scan, and the 3D root system architecture was  
746 reconstructed.

747 A comparison between the laser scan point cloud and the sections of GPR scans (Figure  
748 17) returned a limited grade of correspondence, and the authors stated that this might  
749 be due to an alteration of the root system architecture that occurred during the  
750 excavation. Nevertheless, the use of GPR for 3D coarse root system architecture  
751 reconstruction was further criticised (Guo, et al., 2013).



752

753 **Figure 17: Comparison between 3D rendering from a laser scanner and GPR Bscans (Zenone, et al., 2008)**

754 Set aside the recognition and mapping of tree roots, a challenge that is still object of  
 755 discussion is the quantification of the biomass of tree roots. As it is widely  
 756 acknowledged, the estimate of tree root mass density is crucial for the evaluation of the  
 757 health status of the tree, for the stability of the tree itself and the stability of the soil, as  
 758 tree roots are used for the reinforcement of slopes. Not least, root mass evaluation is  
 759 essential for understanding the storage of carbon in the ecosystem (Stover, et al., 2007).

760 Traditional methods for estimating root biomass are usually destructive, time-  
 761 consuming and expensive, as well as often inaccurate (Birouste, et al., 2014). The  
 762 application of NDT methods in this research area is still at the early stage, and the  
 763 achieved results are still not accurate enough (Aulen & Shipley, 2012).

764 GPR has proven to be efficient in the estimation of coarse root biomass (Guo, et al.,  
 765 2013). Several studies have been conducted so far in field conditions (Butnor, et al.,  
 766 2001) (Butnor, et al., 2003) (Stover, et al., 2007) (Butnor, et al., 2008) (Samuelson, et al.,  
 767 2008) (Borden, et al., 2014) and in laboratory environment (Cui, et al., 2011). GPR has  
 768 shown potential for root quantification, as coarse root biomass has been assessed with

769 reasonably good accuracy (Guo, et al., 2013). However, uncertainty still affects the  
770 precision of the existing methodologies. Currently, a limiting factor for a correct root  
771 density estimation is the root water content which, if too low, can lead to an  
772 underestimation of root biomass (Guo, et al., 2013).

773 In conclusion, all the above-mentioned NDT methods have proven viability in the  
774 assessment of tree root systems. However, the knowledge of the application of some of  
775 these techniques in tree assessment is still in its infancy. Moreover, their employment  
776 can be troublesome, as the required equipment is often difficult to operate. In addition,  
777 the application of these methods can often be very expensive. On the other hand, GPR  
778 is gaining attention in view of the high versatility, the rapidity of its data collection and  
779 the provision of reliable results at relatively limited costs. It has also proven to be a  
780 reliable instrument for the assessment of tree root systems. The advantages and  
781 limitations of the aforementioned ND techniques in the assessment of tree root systems  
782 are summarised in Table 2.

**Table 2: Non-destructive testing methods for the assessment of tree root systems**

Working principle	Method	Characteristics	Applications	Advantages	Limitations
Imaging	<b>(Mini)Rhizotrons</b>	Non-destructive Slightly invasive	Quantification of fine root growth	<ul style="list-style-type: none"> <li>High-resolution imaging</li> <li>Frequent inspections</li> </ul>	<ul style="list-style-type: none"> <li>Modification of soil hydrology and physics</li> <li>Only small portions of the root system can be observed</li> <li>Disparity in results obtained from different image processing methods</li> <li>Cost of installation</li> <li>Expensive equipment</li> <li>Impossible to install in certain environments (i.e. urban trees)</li> </ul>
Mechanical	<b>Pulling test</b>	Non-destructive Invasive	Assessment of tree root plate stability	<ul style="list-style-type: none"> <li>Provides a safety factor for tree stability</li> <li>Test of the elastic response of the tree trunk</li> </ul>	<ul style="list-style-type: none"> <li>Invasive</li> <li>Not completely realistic (i.e. cannot simulate wind effects)</li> <li>Affected by temperature conditions</li> <li>Not useful for understanding the causes of tree instability</li> </ul>
Electrical	<b>ERT</b>	Non-destructive Non-invasive	Detection of root distribution Quantification of root biomass	<ul style="list-style-type: none"> <li>Easiness of data collection</li> <li>Suitable for measurements repeated over time</li> <li>Various scales application</li> <li>Possibility of 1D, 2D and 3D surveys</li> <li>Depth of detection</li> </ul>	<ul style="list-style-type: none"> <li>Systematic errors due to poor electrode contact</li> <li>Long measurement times</li> <li>Laboratory calibration phase needed</li> <li>Non-uniqueness of the solution in the inversion scheme</li> <li>Difficult to discern the effect of roots from the background noise for low root biomass</li> </ul>
Acoustic	<b>Acoustic detection</b>	Non-destructive Slightly invasive	Detection of roots	<ul style="list-style-type: none"> <li>Successful detection of coarse roots</li> </ul>	<ul style="list-style-type: none"> <li>Small roots (diameter &lt; 4 cm) are not detected</li> <li>Superficial depth of detection (&lt; 50 cm)</li> <li>High sensitivity to water content</li> <li>Difficult to discern roots from other buried objects</li> </ul>
Electromagnetic	<b>X-ray CT</b>	Non-destructive Non-invasive	3D mapping of roots Quantification of root length and diameter	<ul style="list-style-type: none"> <li>High-resolution imaging</li> <li>Suitable for measurements repeated over time</li> <li>Detection of fine roots</li> </ul>	<ul style="list-style-type: none"> <li>Difficulty in distinguishing the boundary between roots and other materials</li> <li>High dependence on soil-related factors (i.e. soil type, soil moisture content, presence of organic matter or air-filled pores, root water status)</li> <li>Overestimation of root diameter</li> <li>Underestimation of root length</li> <li>Complex image processing</li> </ul>

	<b>GPR</b>	Non-destructive Non-invasive	3D mapping of roots Quantification of root length Dielectric properties measurements	<ul style="list-style-type: none"> <li>• Totally non-invasive</li> <li>• Easy to use</li> <li>• High-resolution imaging</li> <li>• Suitable for measurements repeated over time</li> <li>• Different frequencies for different objectives</li> <li>• Can be used on valuable trees</li> <li>• Capable of finding roots under pavements</li> </ul>	<ul style="list-style-type: none"> <li>• Difficulty of data interpretation</li> <li>• Fine roots are not detected</li> <li>• Impossible to distinguish clusters of roots</li> </ul>
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785        **6. New methodological and data processing prospects for the**  
786            **assessment of tree root systems architecture using Ground**  
787            **Penetrating Radar: a case study**

788        Recent advances in tree root mapping using GPR have led to the reconstruction of root  
789        system geometry using correlation analysis in the 3D domain (Alani, et al., 2018). In this  
790        study, two trees of different species, fir and oak, were investigated using circular and  
791        semi-circular scanning configurations, in order to test the viability of a novel technique  
792        for the creation of a three-dimensional root system model.

793        This study was further developed by Lantini, et al. (2018), with the aim of assessing  
794        interactions between different tree root systems. Interconnections between different  
795        root systems allow the transmission of pathogenic diseases and fungi. Research into  
796        how these roots interact with each other and with the surrounding environment is  
797        essential for the achievement of effective containment practices. To achieve this aim,  
798        this pilot research study focused on the estimate of root mass density, and this objective  
799        was addressed by evaluating the total root length per reference unit. Promising results  
800        were obtained, demonstrating that local increases in density occur in the area where  
801        interconnections are supposed to happen.

802        Further research, which includes advanced signal processing, is now under  
803        development, with the aim of reducing uncertainty and false alarms in root detection.  
804        To this extent, a case study is presented, in which a dedicated data processing  
805        methodology, based on three main chronological stages, is applied to GPR data. An  
806        improved pre-processing algorithm is proposed, with the aim of reducing clutter in raw  
807        GPR data, improve target detection and increase deeper reflections which are likely to  
808        be related to deep root systems but have been attenuated due to increasing depths or  
809        highly conductive materials. Furthermore, advanced signal processing techniques are  
810        applied, in an effort to remove ringing noise from GPR data and focus on the response  
811        from the target. Subsequently, an iterative procedure for tree root recognition and  
812        tracking and root system architecture reconstruction in a 3D domain is implemented,  
813        based on a correlation analysis between identified targets. Lastly, the domain is divided

814 into reference volume units and root density maps are produced. This approach has  
815 given promising results, proving that GPR has the potential to identify both the shallow  
816 (within the first 25 cm of soil) and the deep (more than 25 cm from the soil surface) root  
817 systems, and find viable root paths, allowing for the construction of three-dimensional  
818 models of root systems for different species of trees.

## 819 **6.1. Materials and methods**

### 820 **6.1.1. The survey technique**

821 The survey was carried out in Walpole Park, Ealing, London (United Kingdom). The soil  
822 around a mature tree (trunk circumference at ground level of 3.83 m and radius of 0.61  
823 m) was investigated (Figure 18). 24 circular scans were performed on the soil around the  
824 tree trunk, starting 0.50 m from the bark and then 0.30 m apart from one another. Thus,  
825 an overall area of 197.69 m<sup>2</sup> was examined.



826

827

828

**Figure 18: The investigated area**

829        **6.1.2. The GPR equipment**

830        The survey was performed using a ground-coupled GPR system (Opera Duo, IDS  
831        GeoRadar (Part of Hexagon)), equipped with 700 MHz and 250 MHz central frequency  
832        antennas (Figure 19). Data acquisition was performed using a time window of 80 ns and  
833        512 samples. The horizontal resolution was set to  $3.2 \times 10^{-2}$  m. For this study, only data  
834        from the 700 MHz frequency antenna were analysed, as these provide the highest  
835        effective resolution (Benedetto, et al., 2011) (Benedetto, et al., 2013).



836

837

838

**Figure 19: Opera Duo GPR system**

839       **6.1.3. Signal processing methodology**

840       As previously stated, the data processing methodology is divided into three main stages.  
841       A pre-processing stage was envisaged, aiming to eliminate clutter-related signal and  
842       increase the signal-to-noise ratio (SNR). To this purpose, advanced signal processing  
843       techniques were implemented. Moreover, in order to achieve information about the  
844       architecture of the entire tree root system, reflections from deeply localised targets  
845       were amplified.

846       **6.1.3.1. Pre-processing stage**

847       The need for a pre-processing stage arises from the fact that raw GPR data are often  
848       corrupted by clutter. This can make the data interpretation difficult, as the response  
849       from the real targets can be disguised. In order to ensure the widest possible  
850       applicability of the proposed methodology, basic signal processing techniques were  
851       considered. Thus, a sequential use of a) zero-offset removal, b) zero correction, c)  
852       bandpass filtering and d) time-varying gain was performed.

853       Nevertheless, the application of the aforementioned techniques does not help with the  
854       removal of ringing noise, which is a repetitive type of clutter and can appear as  
855       horizontal and periodic events. When present, ringing noise can conceal the real target  
856       of the investigation, with resulting misinterpretation of results. One of the most  
857       effective techniques for ringing noise removal, the Singular Value Decomposition (SVD),  
858       was therefore implemented in this stage.

859       The concept behind the SVD filter is that a GPR image can be divided into several sub-  
860       images (eigenimages), each of which contains some of the information relating to the  
861       original image. Since components such as ringing noise are highly correlated, it is  
862       possible to separate their response from the one given by the real target of the  
863       investigation, thus eliminating the clutter to enhance the SNR.

864       Another important advancement in the signal processing stage arises from the need to  
865       have information on the real position of the target. As previously stated, the response  
866       from a target in a GPR survey is given by a reflection hyperbola, the apex of which  
867       corresponds to the position of the buried object. This concept is acceptable for a simple

868 location of a target. However, automatic mapping of a tree root system architecture in  
869 a 3D domain requires the target to be concentrated in a single point. This will avoid false  
870 alarms for root identification. To this effect, a frequency-wavenumber (F-K) migration  
871 was applied to GPR data, assuming a constant velocity of the medium and estimating it  
872 through an iterative procedure. This allowed to find the permittivity value that best fit  
873 the data.

#### 874 **6.1.3.2. Tree root tracking algorithm**

875 The implementation of the algorithm for the automatic reconstruction of the tree root  
876 system geometry consists of two main parts. In the first part, the main settings, based  
877 on fundamental set up hypotheses, are defined (i.e. the outcomes of the previous pre-  
878 processing phase, matrix dimensions, and GPR data acquisition settings). In addition,  
879 other important variables (i.e. the data acquisition method and the dielectric properties  
880 of the medium) are initialised.

881 Subsequently, the pre-processed GPR data undergo an iterative procedure, in order to  
882 find a correlation between the amplitude values in different positions of the 3D domain.  
883 The steps of the procedure are the following:

- 884 • *Detection of the target*: each amplitude value in the data matrix is compared with  
885 a predefined threshold value, in order to identify the reflections that are more  
886 likely to belong to tree roots.
- 887 • *Correlation analysis*: a spatial correlation analysis is carried out between the  
888 identified reflections.
- 889 • *Root tracking*: where a correlation is found, targets are assembled into vectors  
890 which represent the spatial coordinates of the identified root.
- 891 • *Reconstruction of root system architecture in the 3-D domain*: all the vectors are  
892 positioned in a 3D environment, based on the previously identified coordinates,  
893 to recreate a rendering of the tree root system.

894

895        **6.1.3.3. Root density evaluation**

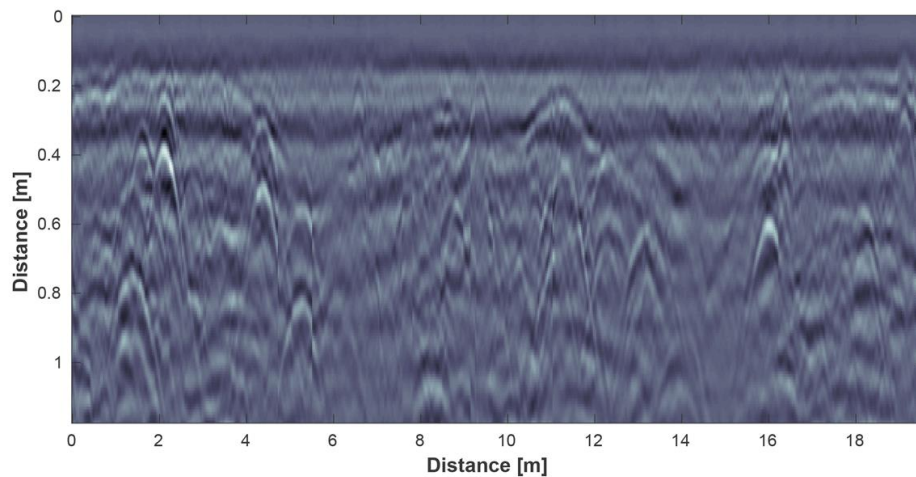
896        In this final step, root density is evaluated based on the position and length of the roots  
897        obtained in the previous phase. Through the application of a polynomial fitting function,  
898        the roots' path was better approximated in a continuous domain, thus allowing for the  
899        estimation of the length of each root. Based on this, the volume in which the tree root  
900        system resides was divided into reference volumes, and the length of the roots enclosed  
901        in each volume was evaluated as follows:

$$d = \frac{\sum_{i=1}^n L_i}{V} \quad (6)$$

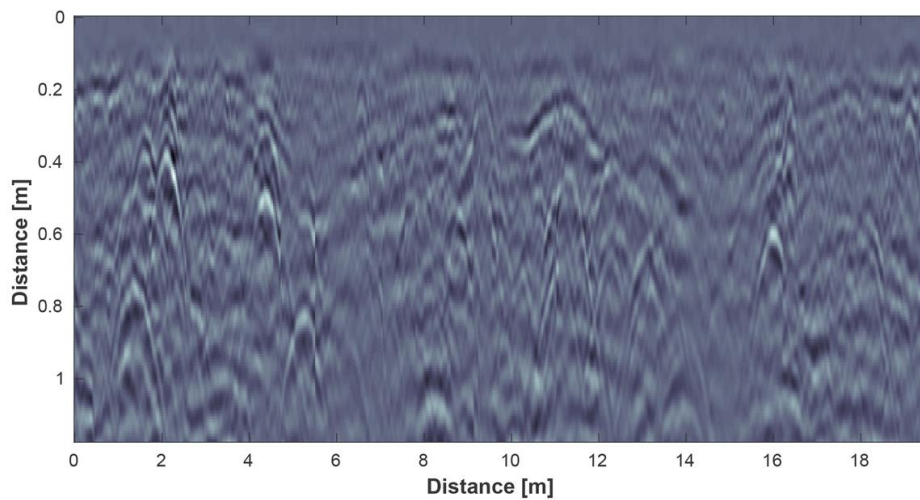
902        where  $d$  is the density [ $\text{m}/\text{m}^3$ ],  $n$  is the number of roots contained in a reference unit of  
903        volume [ $\text{m}^3$ ] and  $L_i$  is the length of the root [ $\text{m}$ ].

904        **6.1.4. Results and discussion**

905        The advances made here to the GPR data pre-processing phase have allowed a more  
906        effective identification of the tree roots, significantly reducing the margin of error. In  
907        fact, they made it possible to remove horizontal layers and repeated reflections given  
908        by ringing noise through the application of the SVD filter. Figure 20 shows an example  
909        of B-scan before (a) and after (b) the application of the SVD filter, from the analysis of  
910        which it is clear that the effect of noise-related features is considerably mitigated.



(a)



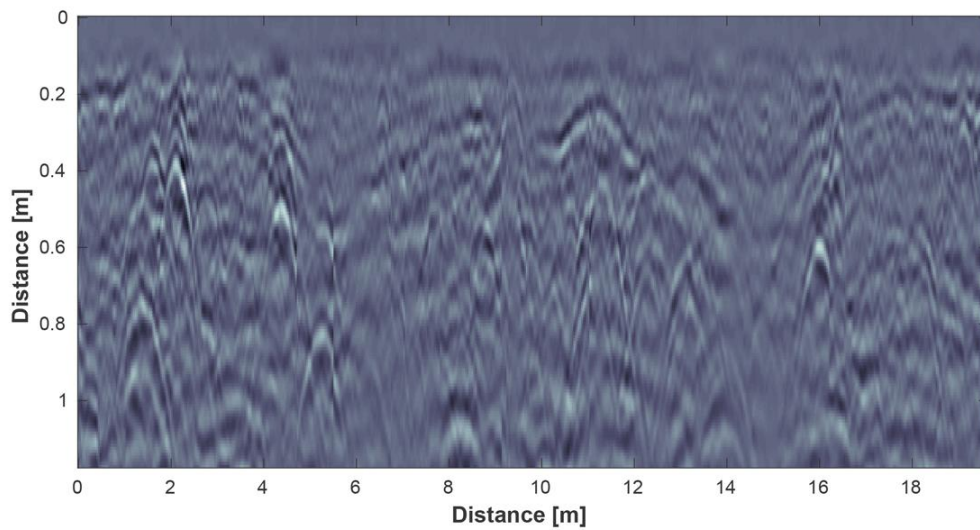
(b)

911

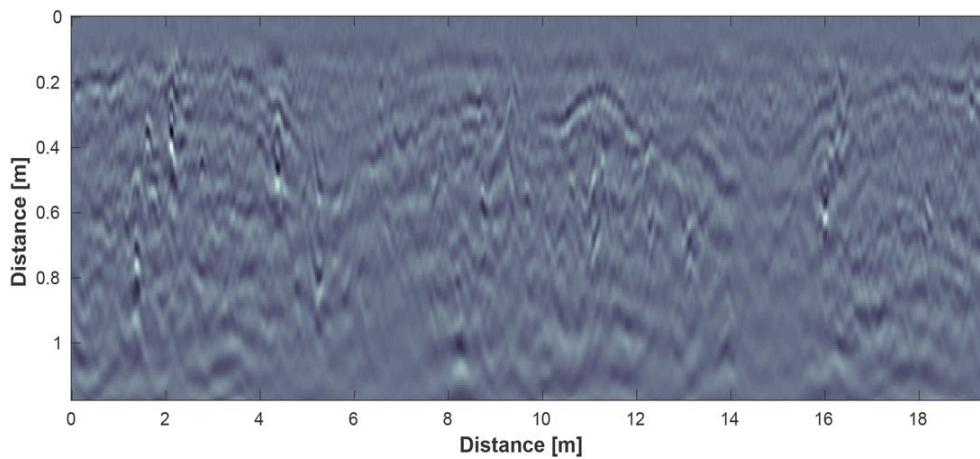
912

**Figure 20: Bscan before (a) and after (b) the application of the SVD filter**

913 Moreover, the application of F-K migration significantly improved the effectiveness of  
 914 the subsequent phases of the algorithm, as the margin of error in identifying the true  
 915 position of the roots was significantly reduced. In fact, the tails of the hyperbole made  
 916 accurate target detection difficult, as not infrequently points far from the apices (i.e. the  
 917 real location of the target) were higher than the set threshold. Thus, the migration  
 918 process increased the reliability of the subsequent steps. Figure 21 shows a comparison  
 919 between a B-scan before (a) and after (b) the application of the F-K migration. It is  
 920 evident how the hyperbolic response of the targets has become a single focused point,  
 921 which corresponds to the target's real position.



(a)



(b)

922

923

**Figure 21: Bscan before (a) and after (b) the application of F-K migration**

924

Subsequently, the application of the root tracking algorithm to the processed data

925

allowed for the reconstruction of the tree root system architecture in a three-

926

dimensional environment. Figure 22 shows the result of this procedure in a 2D planar

927

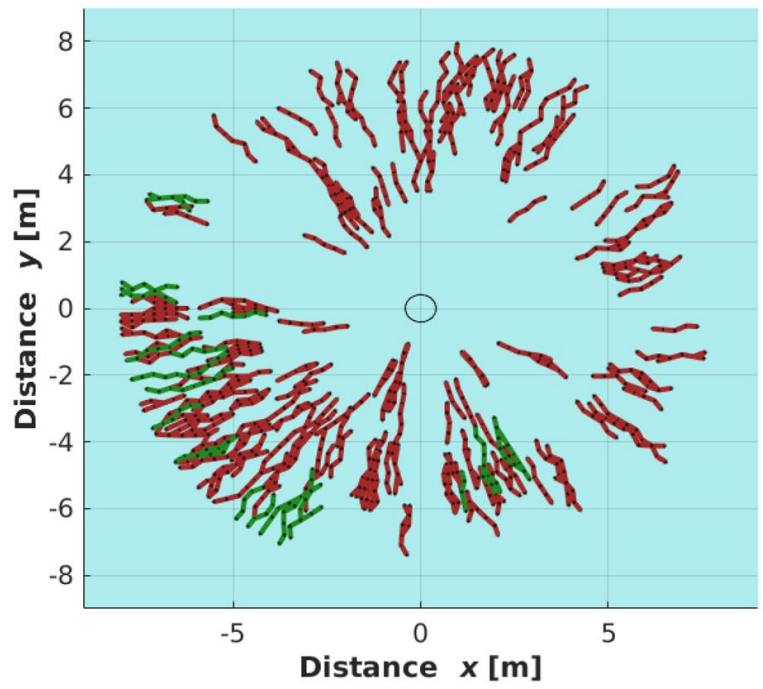
view (a) and in a 3D environment (b). To make interpreting the results easier, shallow-

928

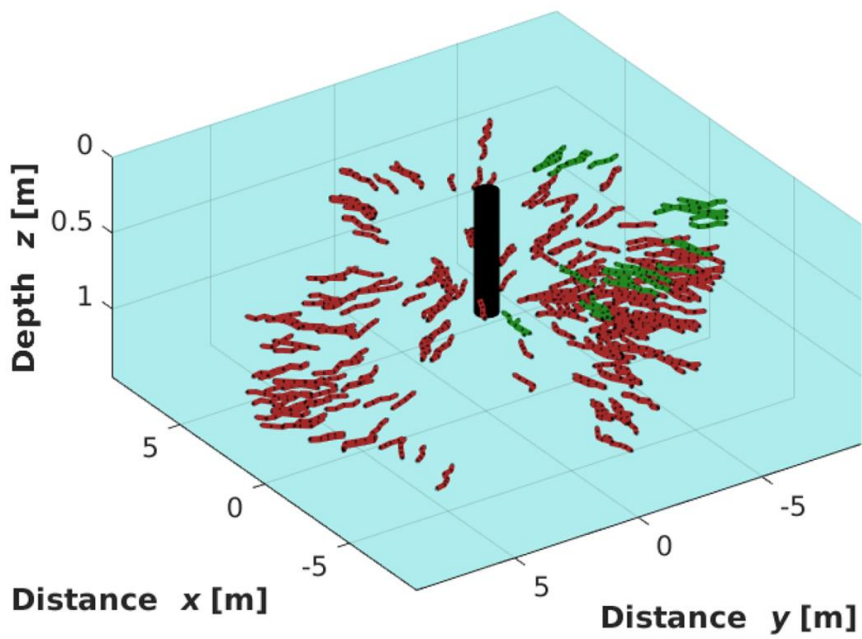
buried roots (i.e. within the first 25 cm of soil) have been represented with a different

929

colour than deeper roots.



(a)



(b)

930

931

Figure 22: 2D planar view (a) and 3D rendering (b) of the investigated root system

932 Results have proven the potential of the algorithm in identifying consistent root paths.  
933 Points belonging to the roots were successfully identified and linked together, based on  
934 a spatial correlation analysis.

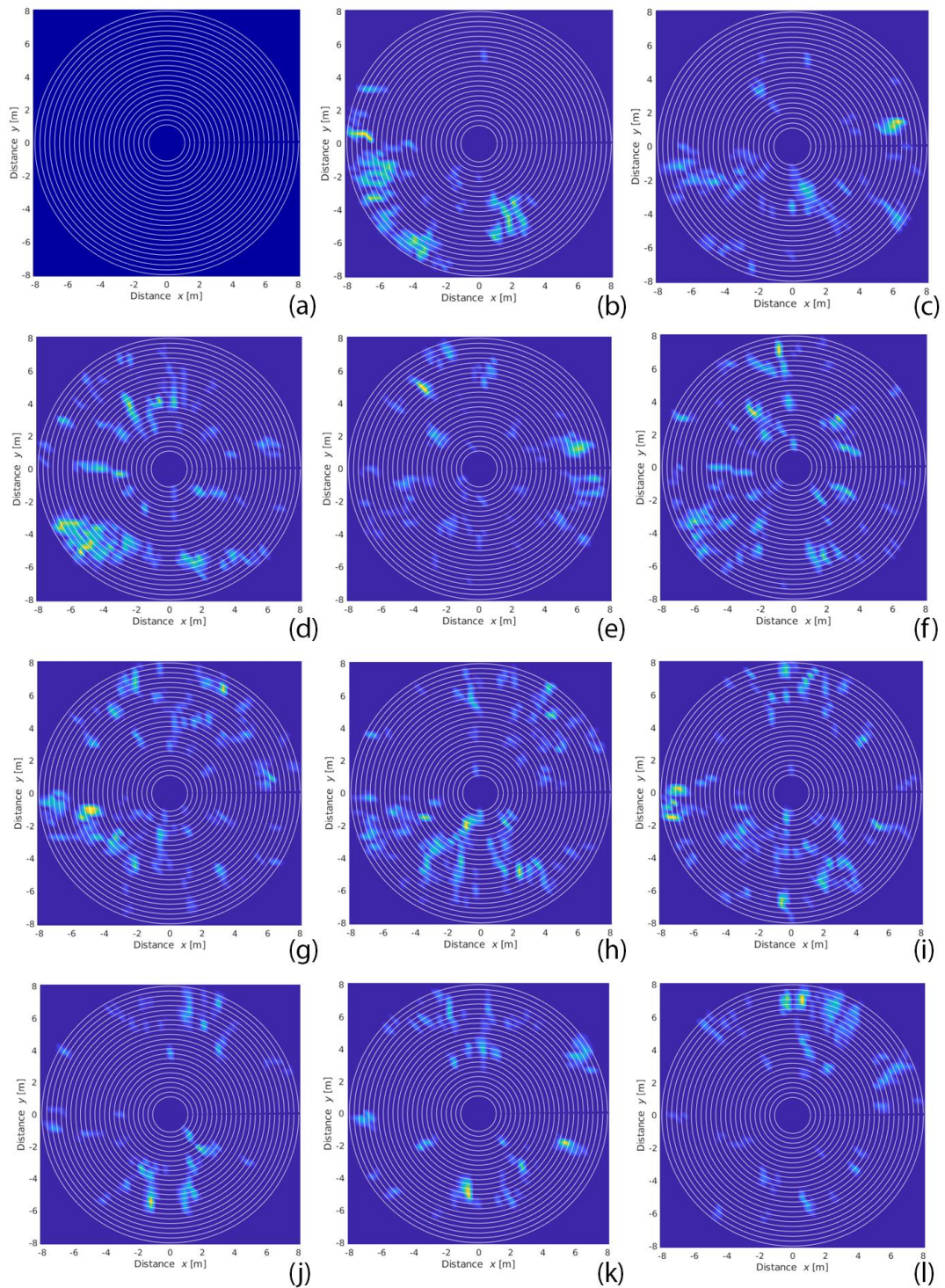
935 From the analysis of B-scans, the strongest reflections resulted to be located within the  
936 first 80 cm of soil. Nevertheless, the application of the time-varying gain function  
937 allowed the detection of deeper targets, up to a maximum depth of 1.20 m. This result  
938 is in line with what was expected, as generally tree root systems develop in the first 2 m  
939 of subsoil, with the 90% to the 99% of roots occurring in the first meter (Crow, 2005).

940 As depicted in Figure 22, root discontinuity is visible in certain areas. Possible  
941 explanations for this could be:

- 942 • Presence of a higher moisture content (Ortuani, et al., 2013) or a high  
943 concentration of clay in certain areas of subsoil (Patriarca, et al. 2013; Tosti, et  
944 al., 2016).
- 945 • Propagation of tree roots vertically downwards within the soil matrix

946 Furthermore, in order to avoid the inclusion of non-root targets within the soil (cobbles  
947 and utility futures), the algorithm is programmed to discard shorter roots.

948 The architecture of the root system was then further investigated through the  
949 evaluation of root density at different depths, using the proposed equation (Equation  
950 6). The domain investigated was divided into reference volumes of 0.3 m × 0.3 m × 0.1  
951 m and thus analysed to determine the total root length per reference unit. Figure 23  
952 presents the outcomes of this data processing stage. Several areas with a high density  
953 of roots can be identified, as shown in Table 3.



954

955 **Figure 23: GPR-derived root density maps, related to the following depths: a) from 0 m to 0.10 m; b) from 0.10 m**  
 956 **to 0.20 m; c) from 0.20 m to 0.30 m; d) from 0.30 m to 0.40 m; e) from 0.40 m to 0.50 m; f) from 0.50 m to 0.60 m;**  
 957 **g) from 0.60 m to 0.70 m; h) from 0.70 m to 0.80 m; i) from 0.80 m to 0.90 m; j) from 0.90 m to 1.00 m; k) from**  
 958 **1.00 m to 1.10 m; l) from 1.10 m to 1.20 m;**

Table 3: Zones of increased root density for the investigated tree

Zones of increased density					
Depth [m]	x		y		Maximum values [m/m <sup>3</sup> ]
	From [m]	To [m]	From [m]	To [m]	
0.10 - 0.20	-6.30	-7.20	0.00	0.60	1.25
	-6.30	-6.60	-3.30	-3.60	1.08
	2.10	2.40	-3.60	-3.90	1.03
0.20 - 0.30	5.70	6.90	0.90	1.50	2.05
	0.60	1.20	-2.40	-3.00	1.14
	6.30	6.60	-4.20	-4.50	1.11
	-6.30	-6.60	-1.20	-1.50	1.11
	-4.20	-4.50	-2.10	-2.40	1.11
	0.00	0.30	-3.60	-3.90	1.05
0.30 - 0.40	-2.40	-6.90	-3.30	-5.70	1.85
	-0.60	0.60	3.90	4.20	1.55
	-1.80	-2.40	3.00	3.90	1.49
	-2.70	-4.20	0.00	-0.60	1.48
	0.90	2.10	-5.40	-6.00	1.28
	-6.30	-6.60	2.70	3.00	1.11
0.40 - 0.50	-3.00	-3.60	4.50	5.10	2.49
	5.40	6.90	0.60	1.80	1.84
	6.90	7.50	-0.60	-1.80	1.50
	-1.50	-1.80	6.60	6.90	1.20
	-2.40	-2.70	1.80	2.10	1.09
0.50 - 0.60	-0.60	-0.90	6.60	7.50	1.88
	-2.10	-2.70	3.00	3.60	1.79
	2.40	3.00	2.40	3.00	1.67
	-5.70	-6.00	-3.30	-4.50	1.48
	1.80	2.10	-5.40	-5.70	1.33
	3.30	3.60	-1.50	-1.80	1.33
	3.00	3.30	0.90	1.20	1.32
	-1.80	-2.10	-3.60	-3.90	1.12
	1.50	1.80	-1.80	-2.10	1.05
	-3.60	-3.90	-3.30	-3.60	1.04
-6.60	-6.90	2.70	3.00	1.00	
0.60 - 0.70	-4.20	-5.40	-0.90	-1.80	2.20
	3.30	3.60	6.00	6.60	1.94
	-2.70	-4.50	-2.40	-3.30	1.66
	-1.80	-2.10	-4.20	-4.80	1.53
	-1.80	-2.10	6.30	7.20	1.48
	6.30	6.60	0.60	0.90	1.46
	-3.00	-3.60	4.50	5.10	1.26
	-6.60	-7.50	0.00	-0.90	1.17
	-0.30	-0.60	-2.40	-3.00	1.15
-1.80	-2.10	3.30	3.60	1.04	
0.70 - 0.80	-0.30	-3.60	-1.50	-5.10	2.25

	2.40	2.70	-4.50	-5.40	1.94
	1.50	1.80	-1.80	-2.10	1.60
	4.20	4.80	4.50	4.80	1.55
	4.20	4.50	6.00	6.60	1.49
	1.50	1.80	-4.80	-5.10	1.33
	3.60	3.90	-4.50	-4.80	1.33
	-5.10	-5.40	-1.20	-1.50	1.29
	0.00	-0.60	5.10	6.00	1.18
	4.80	5.10	2.40	2.70	1.06
	-6.60	-6.90	-0.30	-0.60	1.05
	-6.30	-6.90	-2.40	-3.60	1.04
<b>0.80 - 0.90</b>	-6.60	-7.50	0.30	-1.80	1.74
	-0.30	-0.60	-6.60	-7.20	1.36
	5.40	5.70	-2.10	-2.40	1.27
	0.90	1.50	6.60	7.20	1.21
	4.50	4.80	3.00	3.30	1.16
	0.00	-0.30	7.20	7.50	1.14
	1.80	2.10	-5.40	-5.70	1.10
	0.00	-0.30	-1.50	-1.80	1.03
<b>0.90 - 1.00</b>	-0.90	-1.80	-3.30	-6.00	2.22
	1.20	2.10	-1.20	-5.40	1.65
	3.00	3.30	6.60	6.90	1.24
	2.10	2.40	5.10	5.70	1.20
	3.00	3.30	3.90	4.20	1.06
<b>1.00 - 1.10</b>	5.10	6.00	-1.80	-2.10	2.43
	-0.30	-0.90	-4.20	-5.40	2.25
	2.70	3.00	-3.00	-3.60	1.64
	0.30	0.60	3.60	4.20	1.39
	-3.00	-3.60	-1.80	-2.40	1.39
	6.00	6.90	3.30	3.90	1.27
	-1.50	-1.80	5.70	6.60	1.26
	-6.30	-7.20	-0.30	-0.60	1.19
	1.50	1.80	-1.80	-2.10	1.13
-1.20	-1.50	2.70	3.30	1.11	
<b>1.10 - 1.20</b>	-0.60	1.20	6.30	7.20	2.29
	2.40	2.70	5.70	6.90	1.26
	0.60	0.90	4.20	4.50	1.24
	3.90	4.20	-3.30	-3.60	1.15
	2.10	2.40	2.70	3.00	1.03

960 From the analysis of the results, it can be noticed that there is a high density of roots in  
961 the south-west quadrant, at a depth between 0.10 m and 1.10 m. This result could be  
962 due to the peculiar location of the investigated tree in the park. In fact, the tree is  
963 confined to the north by the presence of a pathway, which requires a higher compaction  
964 level than the undisturbed soil. Moreover, root development is not limited to the south-

965 west direction, as there are no other trees which could compete for the exploitation of  
966 soil resources. Nevertheless, we can note the presence of areas of high root density in  
967 the east direction, between 0.30 m and 0.50 m deep and at a great distance from the  
968 trunk. This could be due to the close proximity of another tree, which roots are  
969 interconnected with the ones of the investigated system. In fact, in that direction root  
970 density gradually decreases, to then increase again towards the limit of the surveyed  
971 area, bordering the area potentially affected by the roots of the adjacent tree. Such an  
972 outcome is in line with the results provided by Lantini, et al. (2018).

973 The evaluation of tree root density in soil has therefore proven to be an effective tool  
974 for the assessment of the root system conditions. Variations in time of root density,  
975 obtained by repeating GPR tests at appropriate intervals, could help in the assessment  
976 of the root system health. In fact, sudden reductions in root density could be due to the  
977 occurrence of diseases or fungal attacks. Thus, acknowledging the problem at its early  
978 stage could allow the application of appropriate remedial actions, in order to save the  
979 tree and prevent infection from spreading to other trees.

980

## 981        **7. Conclusion**

982        In this review paper, the authors have presented a significant proportion of the existing  
983        literature within the subject area of assessment and monitoring of tree roots and their  
984        interaction with the soil. To that effect the nature of tree root systems, their architecture  
985        and the factors affecting their development have been covered. Emphasis was paid to  
986        establishing the reasons behind the increasing importance of assessment and health  
987        monitoring of tree roots and their relationship with the health of trees.

988        An emphasis is given to the major destructive methods for tree root detection and  
989        mapping, followed by a section presenting a summary of the main non-destructive  
990        testing methods and the research outputs based on their application for tree root  
991        system evaluation. The paper also clearly demonstrated that the investigation of tree  
992        root systems using non-destructive testing (NDT) methods is effective and is gaining  
993        momentum. As the awareness of the importance of the world's natural heritage is  
994        growing, hopefully more desperately needed research and development work will be  
995        carried out and efforts will be devoted to this vitally important area of endeavour.

996        Due to its ease of use, its non-intrusiveness nature and its relatively low costs, Ground  
997        Penetrating Radar (GPR) was found to be one of the most reliable tools for root  
998        inspection. Recent research has focused on root detection and three-dimensional  
999        mapping of tree root systems architecture and root diameter, and the evaluation of root  
1000        diameter in complex urban areas. New research is now focusing on tree root and soil  
1001        interactions, as well as the interconnectivity of tree roots with one another.  
1002        Furthermore, it is important to report that the authors are currently engaged with  
1003        research involving novel survey methodologies and data acquisition techniques which  
1004        in turn have been applied in assessing a variety of tree species. Promising results have  
1005        been obtained within the context of tree roots variations as well as the soil  
1006        characterisations.

1007        Advancements in GPR signal processing for tree root assessment and mapping are also  
1008        under development. To that effect, a case study was presented, focusing on the removal

1009 of noise-related information for an improved automatic recognition and mapping of tree  
1010 roots in a 3D environment.

1011 Regarding the assessment of the root mass density, it is important to conclude that, at  
1012 the present time, existing assessment methods are unable to provide accurate  
1013 estimations. As has been pointed out earlier, the importance of assessing tree root  
1014 density is vital for several purposes, ranging from the health of the tree to the safety of  
1015 the surrounding environment (including buildings and infrastructure). It was noted that  
1016 a definitive approach is difficult to achieve, as the estimation of root density is an  
1017 indirect output of the compiled GPR data. Within this framework, the authors have  
1018 proposed a new emerging approach, based on the evaluation of a novel root density  
1019 index. Root density is evaluated based on the position and length of the roots, as it is  
1020 obtained from the modelling phase of the root mapping algorithm. Results have given  
1021 encouraging outcomes, showing that a more reliable estimation of tree root density can  
1022 be achieved. More research is now under development, in order to demonstrate the  
1023 viability of the proposed algorithm. To this extent, tests on several species of trees, using  
1024 different antenna systems (frequencies and type) and survey conditions, are under  
1025 development.

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1032        **9. References**

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