

1

2 Article

3 An Enhanced Data Processing Framework for 4 Mapping Tree Root Systems using Ground 5 Penetrating Radar

6 Livia Lantini ^{1,*}, Fabio Tosti ¹, Iraklis Giannakis ¹, Lilong Zou ¹, Andrea Benedetto ² and Amir M.
7 Alani ¹

8 ¹ School of Computing and Engineering, University of West London (UWL), St Mary's Road, Ealing,
9 London W5 5RF, UK; Livia.Lantini@uwl.ac.uk, Fabio.Tosti@uwl.ac.uk, Iraklis.Giannakis@uwl.ac.uk,
10 Lilong.Zou@uwl.ac.uk, Amir.Alani@uwl.ac.uk,

11 ² Department of Engineering, Roma Tre University, Via Vito Volterra 62, 00146 Roma, Italy;
12 andrea.benedetto@uniroma3.it

13 * Correspondence: Livia.Lantini@uwl.ac.uk; Tel.: +44-(0)-20-8280-0258

14 Received: date; Accepted: date; Published: date

15 **Abstract:** The preservation of natural assets is nowadays an essential commitment. In this regard,
16 root systems are endangered by fungal diseases which can undermine the health and stability of
17 trees. Within this framework, Ground Penetrating Radar (GPR) is emerging as a reliable non-
18 destructive method for root investigation. A coherent GPR-based root-detection framework is
19 presented in this paper. The proposed methodology is a multi-stage data analysis system that is
20 applied to semi-circular measurements collected around the investigated tree. In the first step, the
21 raw data are processed by applying several standard and advanced signal processing techniques,
22 to reduce noise-related information. In the second stage, the presence of any discontinuity element
23 within the survey area is investigated by analysing the signal reflectivity. Then, a tracking algorithm
24 aimed at identifying patterns compatible with tree roots is implemented. Finally, the mass density
25 of roots is estimated by means of continuous functions, to achieve a more realistic representation of
26 the root paths and to identify their length in a continuous and more realistic domain. The method
27 was validated in a case study in London (UK), where the root system of a real tree was surveyed
28 using GPR and a soil test pit was excavated for validation purposes. Results support the feasibility
29 of the data processing framework implemented in this study.

30 **Keywords:** Assessment of Tree Roots; Ground Penetrating Radar (GPR); Tree Root Mapping; Tree
31 Root Mass Density; Multi-stage Data Processing Framework

32

33 1. Introduction

34 Trees and forests are valuable resources to humankind and the nature. Trees are essential for
35 life, as they provide oxygen, store carbon, stabilise the soil, protect the land from erosion and provide
36 food and habitats for wildlife [1]. There is scientific evidence regarding the effects that trees and
37 forests have on human health [2, 3], as they contribute to the reduction of pollution [4, 5] and noise,
38 [6], provide food and medical substances [7], and serve as a source of essential products, including
39 timber, fuel, waxes, oils, gums, and resins [1]. Trees and forests provide much needed resources and
40 protection for different species. They protect buildings, infrastructures and crops from sunlight,
41 winds, and flooding [7], and reduce energy consumption for heating and cooling of buildings [8].
42 Finally, trees also have a significant social and economic value, as they provide a pleasant
43 environment for recreational activities [1, 9], contribute in increasing social interaction [10], and

44 increase business income and property values in urban environments [11]. For the reasons mentioned
45 above, the safeguarding, health monitoring and assessment of trees, forests and woodland are of
46 paramount importance.

47 Among all the tree organs, roots are of vital importance because of their critical functions in
48 health of trees and plants. In fact, they provide anchorage and support [12], absorb minerals and
49 water from the soil, store carbohydrates and synthesise hormones [1]. The typical tree root system is
50 composed of two main root types, namely the woody roots and the non-woody (or fine) roots [13].
51 The first group is composed of more prominent and more rigid roots, which have undergone
52 secondary growth and have an eternal lifespan. These roots form a structure which is responsible for
53 the anchorage of the tree in the ground [1]. On the other hand, fine roots absorb water and nutrients
54 from the soil [1], synthesise the rooting hormone, and are accountable for root exudation and
55 symbiosis with soil microorganisms. As suggested by their name, fine roots usually are small in
56 diameter (<2 mm) and are not subject to secondary thickening. Besides, their lifespan does not exceed
57 some weeks, depending on soil conditions and temperature [1].

58 However, even if roots can be up to 65% of a tree's total biomass [14], they are essentially found
59 below the soil surface, which results in a limited understanding of the tree root system architecture
60 and development, as well as of their interaction with the surrounding environment [13]. This carries
61 several problems, especially concerning the health of the plant itself. In fact, fungal infections of roots
62 are among the main causes of trees' diseases [15]. Fungi usually spread from the roots of dead trees
63 [16] and infect trees that have been weakened by other factors, such as climatic changes or other types
64 of disease [17]. The infection then induces root rotting and moves to the lower stem of the tree, until
65 no anchorage or sustain is provided anymore, and the tree dies either of disease or by wind-throw
66 [16].

67 Within this context, it is evident that the understanding of a tree's state of health is very
68 dependent on the assessment of its root system. Locating tree roots and evaluating their extension
69 and depth, is an essential and necessary task for a number of reasons, ranging from the conservation
70 of the natural heritage to the provision of safety conditions in urban areas. Various methodologies
71 are available to map the structure of a tree root system, and these can be divided into destructive and
72 non-destructive testing (NDT) methods. Destructive methods include excavation, uprooting and the
73 profile wall technique [18]. These methods are unpractical and unsuitable for large-scale forestry
74 applications and, above all, they can also cause irreversible damage to trees [18-20]. Not last,
75 destructive testing methods allow for the investigation of root systems only at the time of sampling,
76 and therefore are of limited value for investigating roots' development or the progress rate of a fungal
77 infection.

78 On the other hand, NDT methods are increasingly being acknowledged as effective for the
79 investigation of root systems without harming or causing irreversible damage to the tree. Various
80 NDT methods have been tested for root mapping, including X-ray tomography, nuclear methods and
81 magnetic resonance [21-23], acoustic methods and electrical resistivity tomography [24]. Among
82 these, ground-penetrating radar (GPR) is a fast, reliable [25] and cost-effective [26, 27] non-destructive
83 method used to detect changes in the physical properties within the shallow subsurface [28]. A GPR
84 system's transmitting antenna emits electromagnetic (EM) pulses that propagate into the investigated
85 medium in the form of waves [28]. When encountering a dielectric contrast, a part of the energy is
86 back-reflected and recorded by a receiving antenna. Once collected, GPR data can be displayed in
87 different ways, allowing for a representation of the subsurface in both two and three dimensions.

88 GPR has been extensively employed in a wide range of applications and several disciplines, such
89 as archaeological investigations [29], bridge deck inspections [30], landmines' detection [31], and
90 civil and environmental engineering applications [32, 33] for decades. Regarding the use of GPR for
91 tree root systems' investigations, until about twenty years ago roots were considered as an unwanted
92 source of noise, i.e., an obstacle that complicated the EM characterisation of soil profiles [34, 35].
93 According to the literature, GPR has been used for mapping tree root systems since 1999 [36]. From
94 that time onward, GPR use in this area has increased [14, 38], due to its non-invasiveness and the
95 rapidity of data collection. Most importantly, measurements can be easily repeated on a routine base,

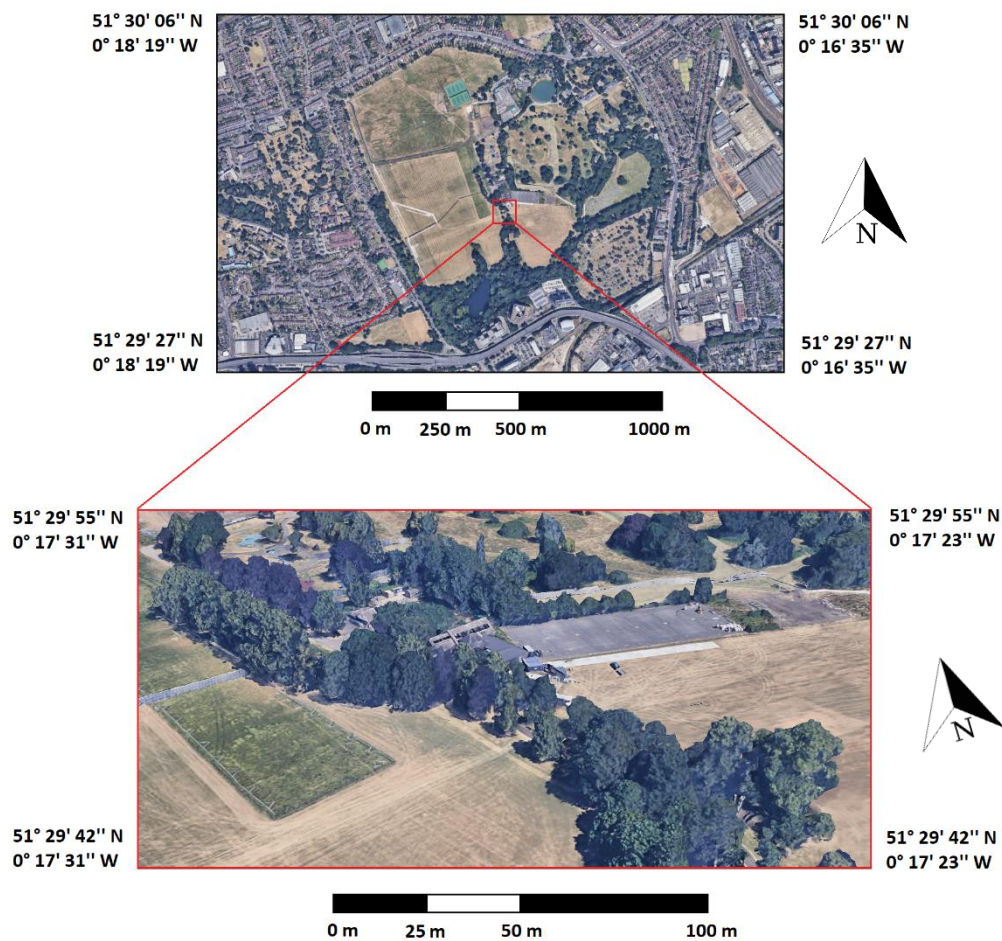
96 thereby allowing for a more comprehensive monitoring of the roots' growth process. Recent studies
 97 have focused on the use of GPR for large-scale investigations in forestry engineering and many efforts
 98 have been spent on the mapping of the tree root systems' architecture [39]. More specifically, these
 99 studies were focused on the assessment of the roots' interconnections with root systems belonging to
 100 nearby trees [40], the estimation of the tree root systems' mass density and the improvements of the
 101 roots' detection by advanced GPR signal processing techniques [13].

102 The present work reports the results of an experimental campaign conducted on a test site
 103 located in an urban park in London, United Kingdom. In particular, a GPR-based root-detection
 104 framework was tested on a diseased tree. The main aim of this research is to demonstrate the
 105 capability of mid-range frequency GPR antenna systems in efficiently reconstructing the architecture
 106 of tree root systems. To achieve this aim, the objective of this study are as follows: i) to provide root
 107 density maps at different depths, in order to interpret local variations of the root concentration; ii) to
 108 prove the feasibility of the proposed method by way of comparison between the results achieved and
 109 ground-truth information collected by soil excavation.

110 2. Materials and Methods

111 2.1. The Test Site

112 The survey was carried out in Gunnersbury Park, Ealing, London (United Kingdom) (Figure 1).
 113 The tree under investigation, a sycamore (*Acer pseudoplatanus*), was identified for this study by the
 114 London Borough of Ealing's Tree Service. This tree is located along a tree-lined avenue inside the
 115 park, at a distance of ~ 10 m from the adjacent trees.



116
 117

Figure 1. Study site for the GPR investigation (Map data: Google, Landsat/Copernicus).

118 The concerned tree was under observation since 2010, according to the "Friends of Gunnersbury
 119 Park and Museum" registered charity, as "a significant cavity of over 10% of the stem was present" [41].

120 Over the past decade, tree's conditions had deteriorated, as significant levels of rot and decay were
121 found, creating hazards to local residents and users of the park. To this effect, a decision was made to
122 cut the tree down and GPR investigations were carried out before falling the tree.

123 On the survey day, the weather was sunny, with temperatures between 19° and 21° Celsius and a
124 humidity of 39%. Furthermore, it is important to note that the last episode of light rain occurred ten
125 days before the survey [41].

126 2.2. The GPR Survey Technique

127 The survey technique followed a circular GPR acquisition method, as described in [38]. This survey
128 methodology was chosen due to the particular configuration of a typical root system, which expands
129 radially from the trunk of the tree outwards [42, 43]. In fact, GPR surveys carried out around the trunk
130 with constant radial distance have proven capable of providing a quasi-perpendicular scanning of the
131 root systems [13].

132 Also, the investigation was carried out on the portion of the tree root system developing below the
133 natural soil, excluding the area covered by an adjacent asphalt pavement (i.e. performing the scans
134 along semi-circular transects) (Figure 2).

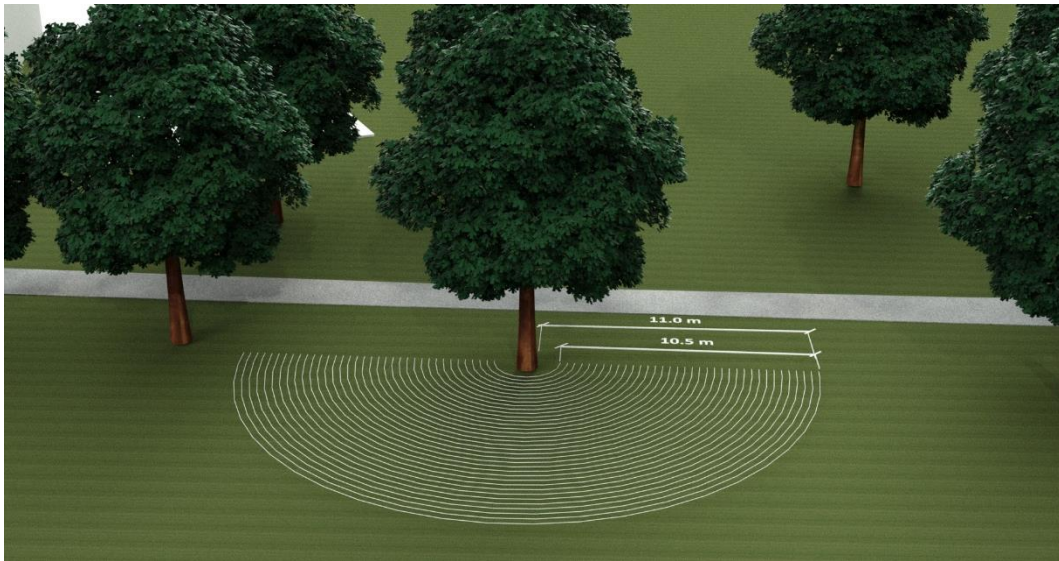


135

136

Figure 2. Detail of the survey setup.

137 A set of 36 semi-circular scans were performed around the investigated tree. The first survey
138 transect was positioned 0.50 m from the bark, in order to allow enough space for the GPR equipment
139 to manoeuvre around the tree trunk. Subsequently, the spacing between the lines of the scan was set to
140 0.30 m. Consequently, an overall area of 218.04 m² was surveyed around the tree, with an outer radius
141 of 11.86 m and an inner radius of 1.36 m. Figure 3 shows a rendering of the GPR survey setup's main
142 characteristics.



143

144

Figure 3. Rendering of the GPR survey setup.

145

2.3. The GPR Equipment

146

The Opera Duo ground-coupled GPR system, manufactured by IDS GeoRadar (part of Hexagon) was employed for testing purposes [44, 13]. The system includes two mono-static antennas of 700 MHz and 250 MHz central frequency. Data were collected using a time window of 80 ns, discretised across 512 samples. The horizontal resolution was set to 3.06×10^{-2} m. For the purposes of this study, only data collected using the 700 MHz antenna were analysed, in order to provide the highest effective resolution of the deepest layers of the root system.

149

152

2.4. The Excavation for Validation Purposes

153

In order to validate the results obtained through the processing of the GPR data (described in detail in the following paragraphs), an excavation was carried out near the investigated tree. The exact location of the excavation area was determined a-posteriori based on the results obtained, in order to be able to dig a defined area where the preliminary data analysis had highlighted the presence of potential targets.

154

158

The excavation took place about three months after the GPR survey. In the meantime, the tree was felled as planned, and it was necessary to wait for the technical time of the trunk removal from the investigation area. The whole activity, including finding the area coordinates, excavation, roots' measurements and excavation coverage, was completed in three days.

159

162

An area of 4 m per side was accurately identified (Figure 4), based on the coordinates of the GPR survey (see Subsection 3.5). The excavation was then carried out by removing layers of ~ 0.10 m of soil at a time.

163

164



165

166 **Figure 4.** Verification of the accuracy of the excavation area's coordinates. Note that the tree was felled
 167 before the excavation stage (the trunk base is visible on the left-hand side of the picture).

168 2.5. The Data Processing Framework

169 2.5.1. Preliminary Signal Processing Stage

170 The primary purpose of this stage is to reduce noise-related information from the GPR data, as
 171 well as to achieve quantitative information and easily interpretable images for the data analysis and
 172 interpretation stage. A signal processing methodology was implemented, based on a combination of
 173 standard and more advanced techniques [45, 46], which can be applied to any GPR root system's
 174 investigation. The raw data were therefore processed based on the following sequence of processing
 175 steps:

176 • *Zero-offset removal:* GPR signal can be distorted by low-frequency signal trend (known as "wow")
 177 or initial direct current (DC) shifts, which can conceal the actual EM reflections. The result is a GPR
 178 trace with an average amplitude different from zero, which could affect the results of further signal
 179 processing steps. The application of a dewow filter allows to obtain GPR traces with a mean value equal
 180 to zero.

181 • *Time-zero correction:* in order to compare the reflection time and consequently the depth of the
 182 buried targets, it is necessary to set a unique time-zero point for the GPR data. However, due to factors
 183 such as the air gap between the transmitting antenna and the soil surface or the ground-level
 184 inhomogeneities, the position of the air-ground surface reflection could vary across the different A-
 185 scans. To this extent, the air layer between the signal source point and the ground was eliminated across
 186 the whole sequence of A-scans.

187 • *Time-varying gain:* the GPR signal rapidly attenuates when it propagates through the investigated
 188 media. This is due to the dispersive nature of the EM waves, which relates to the electrical properties of
 189 the medium. For this reason, the response from deep targets can be hardly detected, especially in case
 190 of lossy materials. The application of a time-varying gain to each GPR trace compensates for the rapid
 191 fall of the signal, equalising the amplitudes and making the response from deeper targets more clear.
 192 In the present study, a spherical and exponential (SEC) function was employed to compensate the
 193 energy loss by applying a linearly increasing time gain combined with an exponential increase.

194 • *Singular Value Decomposition (SVD)* [47]: the SVD filter aims to reduce the ringing noise, i.e., a
195 repetitive type of clutter with a high correlation between traces, which can easily lead to data
196 misinterpretation. On the other hand, reflections due to potential targets are more random and
197 scattered, and therefore less correlated. The SVD filter operates by decomposing an image into a set of
198 different sub-images, each of which contains features with a gradually increasing correlation. With this
199 approach, ringing noise can be separated from the real response of the targets.

200 • *Frequency-wavenumber (F-K) migration* [47]: in a GPR investigation, the response of a target is
201 associated with a hyperbolic feature. This is caused by the difference in the travel time of the EM waves,
202 while the antenna is moved along the scanning transect. Although this output is acceptable for target
203 identification, the tracking of an object (e.g. tree roots) across several B-scans requires a more focused
204 and accurate localisation. The F-K migration transforms an unfocused space-time GPR image into a
205 focused image showing the object's true location and size with the corresponding EM reflectivity. The
206 velocity of the host medium in this paper is assumed as constant and it was estimated by means of a
207 trial and error procedure between permittivity values over-migrating and under-migrating the data.

208 2.5.2. Analysis of Discontinuity Elements

209 The presence of elements of discontinuity (e.g., manmade subsurface features such as pipes,
210 conduits or the multi-layered structure of a road pavement) in a dataset including a tree root system
211 architecture are regarded as a potential disruptive factor for the correct execution of the data processing
212 methodologies presented in this paper.

213 In this specific case study, the presence of a transversal element in the investigated area, such as a
214 road pavement and an underground pipe, interrupts the continuity of the data and creates the
215 conditions for the generation of false alarms in the mapping process of the roots. The potential presence
216 of these disturbing elements must therefore be identified before the application of the main tree root
217 tracking algorithm. For this purpose, a processing algorithm based on the methodology proposed in
218 [48] is introduced in the main data processing framework. An analysis of the data reflectivity is carried
219 out, in order to clearly identify the presence of features not related to roots. If present, these
220 inhomogeneities are subsequently reprocessed with dedicated signal processing techniques (e.g. in the
221 case of a road pavement structures [48]), or their reflections are simply removed from the GPR data (e.g.
222 in the case of pipes or other similar manmade buried features).

223 2.5.3. Tree Root Tracking Algorithm

224 This stage of the methodology is adapted from [38] and is composed of two main parts. First, the
225 initial hypotheses (the data acquisition method and the dielectric properties of the medium), and the
226 data input settings (the outcomes of the pre-processing algorithm, the matrix dimensions and the GPR
227 data acquisition settings) were outlined.

228 Following this, an iterative procedure was executed in order to analyse the output of the pre-
229 processing stage. The methodology was based on the comparison of the amplitude values, in a random
230 position of the 3D domain, with a given threshold. The following steps were then performed:

231 • *Preliminary hypotheses*: the proposed model is based on two main hypotheses regarding:

232 o the data acquisition method (longitudinal or circular transects)

233 o the dielectric properties of the investigated medium

234 The acquisition method was performed by rotating the GPR antenna around the tree with a
235 constant radial distance. As it was already stated, this was due to the radial distribution of roots
236 around a tree trunk, and the necessity to achieve a quasi-perpendicular scanning of the targets.

237 The algorithm has therefore been developed with reference to a three-dimensional system of
 238 cylindrical coordinates, in which the vertical axis is identified by the axis of the tree trunk and the
 239 origin is positioned at its intersection with the plane matching the ground level. The coordinates
 240 of the system are the depth z , the angular coordinate θ and the radial coordinate ρ .

241 In regard to the relative dielectric permittivity of the medium ϵ_r , this was calculated using a
 242 hyperbolic velocity analysis method. This compares the observed reflection hyperbolas with the
 243 velocity-specific hyperbolic functions, in order to find the function that best fits the data [46]. For
 244 the purpose of this application, the wave propagation velocity v in the medium was taken as the
 245 average value of velocities, estimated by the application of the hyperbola fitting method to several
 246 roots' reflections evenly picked up across the entire survey area.

247 • *Data input*: the algorithm expands upon GPR data from the pre-processing phase, in the form of a
 248 three-dimensional matrix of real numbers $\mathbf{A}(I, J, K)$, composed by the signal amplitude values in
 249 a random point of coordinates (i, j, k) . The index i indicates the number of GPR scans, limited to
 250 I , the index j corresponds to the scan direction, limited to J , and k is the vertical coordinate going
 251 into the ground, limited to K . According to a reference polar coordinate system, the coordinates
 252 of a random point (i, j, k) can be expressed as follows:

$$x = \rho(i) \cdot \cos\vartheta(j) \quad (1)$$

$$y = \rho(i) \cdot \sin\vartheta(j) \quad (2)$$

$$z = z(k) \quad (3)$$

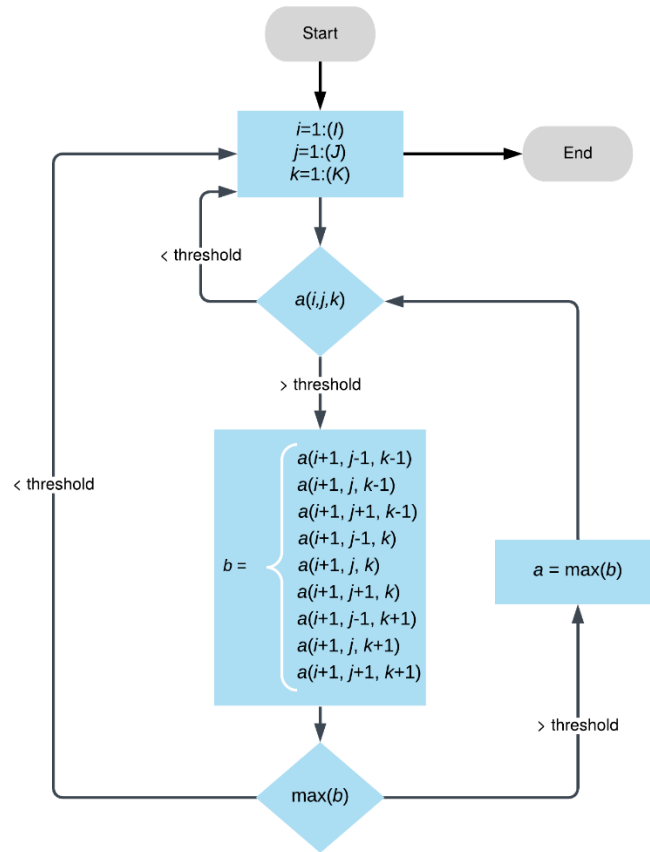
253 • *Iterative procedure*: the aforementioned assumptions and input information are essential to develop
 254 an iterative procedure for the tracking of a root system. Figure 5 shows a flowchart of the
 255 methodology followed in this stage.

256 o *Target identification*: the algorithm evaluates the amplitude values in a random position of the
 257 3D domain. In order to filter out the amplitude values that did not likely relate to tree roots, a
 258 threshold was set. This threshold value is established a-priori based on a preliminary analysis of
 259 the data collected, in an effort to isolate as many hyperbolas as possible. Hence, the algorithm is
 260 set to analyse the domain until a signal amplitude value greater than the threshold is found. This
 261 step is necessary to identify the apices of the reflection hyperbolae (i.e. the apices of the roots) and
 262 filter out amplitude values unrelated to candidate root targets.

263 o *Correlation analysis*: this step is focused on the investigation of further vertices in the closest
 264 vicinity of those identified at the target identification stage. This is preformed to pinpoint other
 265 potential amplitude values greater than the threshold. This analysis has been improved in the
 266 present study compared to the original version presented in [38], as the area in which the
 267 correlation is sought has been extended to four further points within the 3D domain, i.e., $a(i+1, j-1,$
 268 $k-1)$, $a(i+1, j+1, k-1)$, $a(i+1, j-1, k+1)$, $a(i+1, j+1, k+1)$ (see Figure 5). This improvement allows to smooth
 269 the correlation analysis process, including all the points of the 3D domain that could ideally belong
 270 to the development of a root.

271 o *Tracking of the root*: the algorithm isolates correlated points, creating a vector for the mapping
 272 of individual roots.

273 o *Reconstruction of the root system architecture in a 3D domain*: vectors identified at the previous
 274 step are positioned in a 3D environment in order to represent the geometry of the tree root system.



275

276

Figure 5. Flowchart of the tree root tracking algorithm's iterative procedure.

277

278

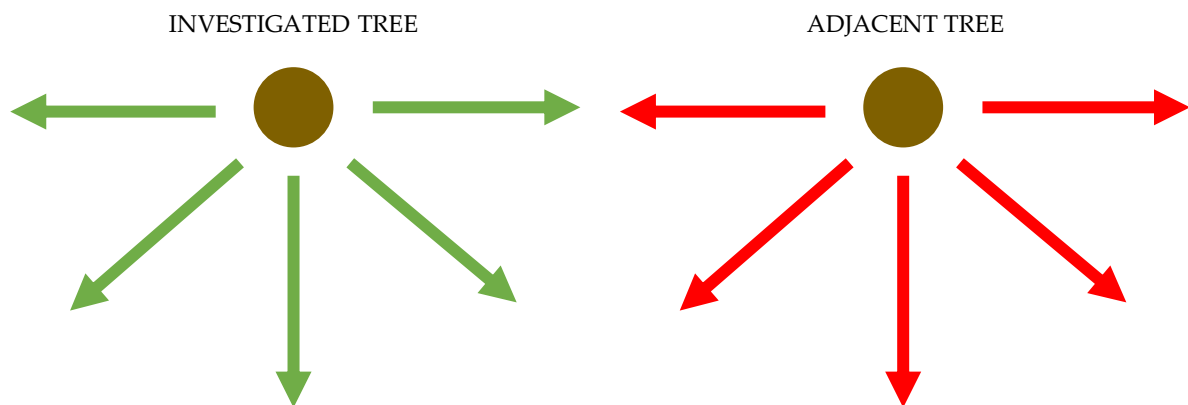
279

280

281

282

It is important to point out that in order to avoid the inclusion in the map of roots not belonging to the investigated tree, the root mapping algorithm is designed to perform a spatial correlation that follows the most likely directions of roots (i.e. from the trunk - source point - outwards). Therefore, the resulting renderings are only related to the examined tree, and do not include any potential root belonging to adjacent trees (Figure 6). If present, these will result as uncorrelated with the mapping process and, hence, will be excluded by the algorithm.



283

284

285

286

Figure 6. Layout of the roots' main directions in the case of two adjacent trees. Directions of roots of a reference tree (e.g., the tree under investigation in this study) (in green) are not compatible with the roots' directions of a nearby adjacent tree (in red).

287 2.5.4. Root Mass Density Estimation

288 At present, the quantification of the tree roots mass density is considered a controversial task. In
 289 this regard, it should be specified that most of the studies deal with the quantification of tree root's
 290 biomass, which is an indirect output of GPR data [19]. Several studies have been carried out on this
 291 topic, both in field conditions [37] and in controlled environment [49], achieving reasonably good
 292 results. However, the accuracy of current methodologies still is limited. At present, the limiting factor
 293 for a correct root density estimate is the root water content that, if too low, can lead to a sub-estimation
 294 of root biomass. It should be concluded that existing evaluation methods are currently unable to
 295 provide reliable estimates. In this context, the novelty of the presented methodology lies in a new
 296 root density index evaluation, based on root location and length as obtained from the root mapping
 297 algorithm modelling process. The following stage of the presented methodology is therefore developed
 298 to provide a representation of the density of roots in the investigated area, with the main aim of
 299 identifying local changes of density.

300 First, best-fitting functions were used to better approximate root paths in the 3D domain, as well
 301 as to identify the length of each root in a continuous domain. Before evaluating the length of the roots
 302 in a specified domain, it is necessary to express these in an analytical form. Each root is a 3D curve with
 303 a radial expansion that starts from the centre of the tree trunk. The only way to express 3D curves is
 304 through parametric equations or positional vectors [50]. As an example, a 3D curve can be expressed
 305 either as:

$$x = f(t) \quad (4)$$

$$y = g(t) \quad (5)$$

$$z = q(t) \quad (6)$$

306 or as:

$$\vec{F} = \langle f(t), g(t), q(t) \rangle \quad (7)$$

307 where $\{t \in R | 0 \leq t \leq 1\}$ is the parametric variable between zero and one that is chosen arbitrarily. To
 308 fit a parametric curve on a given set of 3D points, a polynomial function of n^{th} order is used to
 309 approximate each of the parametric functions [50]

$$x = \sum_{i=0}^n a_i t^i \quad (8)$$

$$y = \sum_{i=0}^n b_i t^i \quad (9)$$

$$z = \sum_{i=0}^n c_i t^i \quad (10)$$

310 The coefficients a_i, b_i, c_i are evaluated using least squares [51]:

$$\mathbf{A} = (\mathbf{W}^T \mathbf{W})^{-1} \mathbf{W}^T \mathbf{X} \quad (11)$$

$$\mathbf{B} = (\mathbf{W}^T \mathbf{W})^{-1} \mathbf{W}^T \mathbf{Y} \quad (12)$$

$$\mathbf{C} = (\mathbf{W}^T \mathbf{W})^{-1} \mathbf{W}^T \mathbf{Z} \quad (13)$$

311 where \mathbf{A} , \mathbf{B} and \mathbf{C} are vectors $\{A, B, C \in R^n\}$ that contain the coefficients a_i, b_i, c_i . The matrices \mathbf{X} , \mathbf{Y}
 312 and \mathbf{Z} are column vectors $\{X, Y, Z \in R^s\}$ that contain the predicted x, y, z coordinates using the root
 313 detection algorithm. The number of measurements is denoted with the letter s . Notably, when $n > s$,
 314 the system becomes underdetermined and no solution without constraints can be obtained. Thus, the
 315 number of measurements must always be greater than or equal to the order of the chosen polynomial.
 316 Lastly the matrix \mathbf{W} $\{\mathbf{W} \in R^{n \times s}\}$ is:

$$\mathbf{W} = \begin{bmatrix} t_1^n & \cdots & t_1^0 \\ \vdots & \ddots & \vdots \\ t_s^n & \cdots & t_s^0 \end{bmatrix} \quad (14)$$

317 where $t_1, t_2 \dots t_s, \{t \in R | t_{i+1} - t_i = \frac{1}{s}\}$ are a set of equidistant points defined in the closed interval $[0,$
 318 $1]$.

319 Knowing the analytical expression of the vector \vec{F} makes it possible to evaluate its length for a
 320 given sample. The length of vector \vec{F} with respect to t equals with [50]:

$$L(t) = \int_0^t \left\| \frac{d\vec{F}}{dt} \right\| dt \quad (15)$$

321 The derivative of the vector \vec{F} with respect to t , equals with the derivative of its components:

$$\frac{dx}{dt} = \sum_{i=1}^n i a_i t^{i-1} \quad (16)$$

$$\frac{dy}{dt} = \sum_{i=1}^n i b_i t^{i-1} \quad (17)$$

$$\frac{dz}{dt} = \sum_{i=1}^n i c_i t^{i-1} \quad (18)$$

322 Therefore, the integral in (15) can be rewritten as [50]:

$$L(t) = \int_0^t \sqrt{\left(\sum_{i=1}^n i a_i t^{i-1} \right)^2 + \left(\sum_{i=1}^n i b_i t^{i-1} \right)^2 + \left(\sum_{i=1}^n i c_i t^{i-1} \right)^2} dt \quad (19)$$

323 The integral above is evaluated using numerical methods (Simpson's rule, Gaussian quadrature)
 324 [52]. The length L is related to t , thus it can be calculated for a given segment, giving us the ability to

325 map the length of the roots in a specified domain. The degree of the polynomial n should be chosen
326 with caution since large values can give rise to over-fitting, resulting in poor generalisation capabilities
327 of the fitted polynomial, whereas small values can decrease the overall resolution. As a rule of thumb,
328 the order of the polynomial should be less than half the number of measurements $n < s/2$.

329 Once the length of the root was known, the domain was partitioned into reference volume units,
330 the dimensions of which depend on the circular scan spacing and the depth resolution required for the
331 density investigation. The length of roots contained in the reference volume was then evaluated as
332 follows:

$$d = \frac{\sum_{i=1}^n L_i}{V} \quad (20)$$

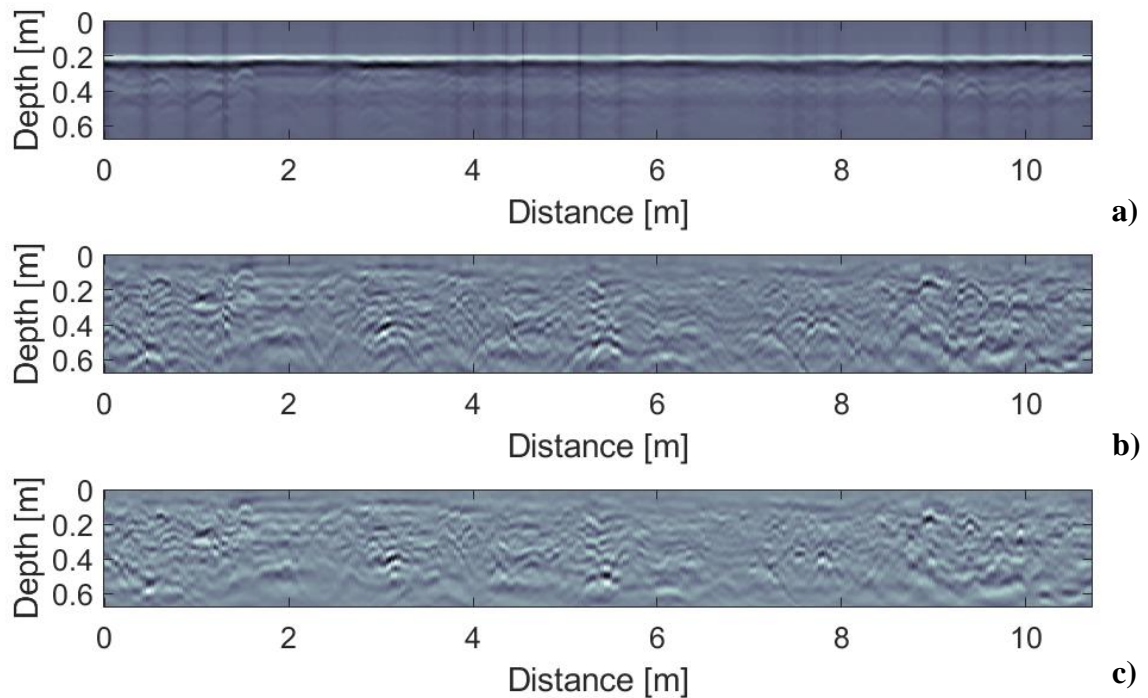
333 where d is the density [m/m^3], n is the number of roots contained in a reference unit of volume
334 V [m^3] and L_i is the length of the root [m].

335 3. Results

336 3.1. Preliminary Signal Processing Stage

337 The use of a pre-processing phase on the GPR data allowed to achieve a more effective detection
338 of targets with a significant reduction of noise-related features. To elaborate, the application of the
339 SVD filter has reduced the effect of reflections from the horizontal layers as well as the multiple
340 reflection patterns caused by ringing noise. Figure 7 shows the result of the application of the
341 discussed signal processing steps. Figure 7(a) and Figure 7(b) clearly show the application of the
342 standard processing techniques and the SVD filter. In particular, the latter has proven effective in
343 significantly removing noise-related features.

344 Moreover, the application of the F-K migration filter allowed to obtain a more focused
345 representation of the hyperbolic targets, including the roots, hence contributing to improve the
346 effectiveness of the proposed algorithm in the next phase. It is in fact fair to comment that, without
347 the application of this particular filter, it was frequent to have false alarms, i.e. points belonging to
348 the tail of the hyperbolas (therefore not representing the actual position of the target) with amplitude
349 values satisfying the threshold value conditions. These points were not discarded by the algorithm
350 and generated false positives. Thus, the application of the migration process has proven to increase
351 the reliability of the algorithm for the detection and tracking of roots in the subsequent steps. Figure
352 7(c) shows the result of the F-K migration to the pre-processed data. It is possible to notice how the
353 tails of the hyperbolas have retracted towards the apexes (i.e. the real position of the targets), forming
354 unique focused points. In addition to this, it is important to observe that the migration provided an
355 estimation for the value of the permittivity equal to 12, which corresponds to a velocity of the
356 electromagnetic wave equal to $4.33\text{e}+7$ m/s.



357

358

359

Figure 7. B-scan (a) before the application of the preliminary signal processing stage, (b) after the application of standard signal processing and SVD filter, and (c) after the application of the F-K migration.

360

3.2. Analysis of Discontinuity Elements: the Detection of a Buried Structure

361

362

363

364

365

366

367

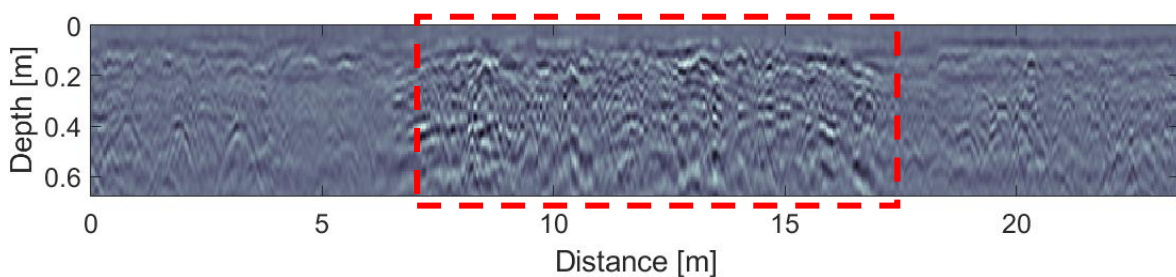
368

369

370

371

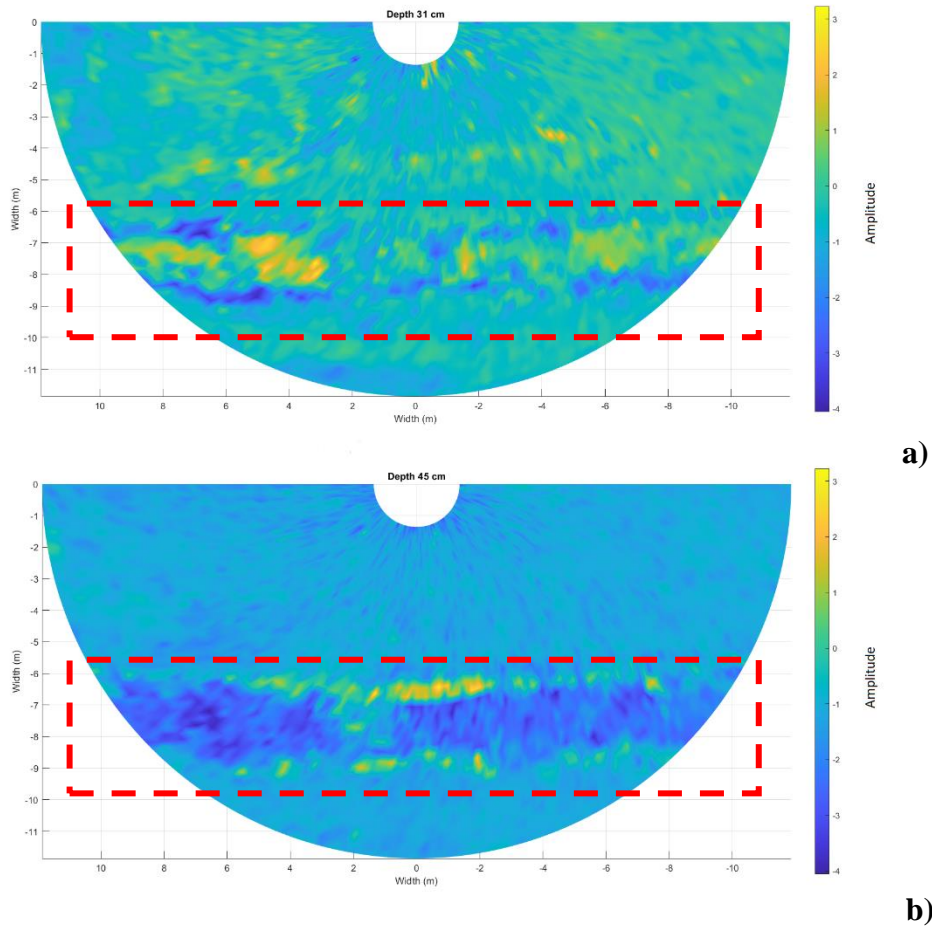
An in-depth analysis of potential elements of discontinuity across the collected set of B-scans – as per the requirements discussed in Section 2.5.2 - revealed the presence of a buried structure, recurring from scan 17 onwards (Figure 8). In order to better understand the nature of such a feature, a tomographic approach was followed to allow for a more comprehensive analysis of the investigated area. For this purposes, C-scans [45] were created at different depths, which highlighted the presence of a subsurface linear structure, approximately 2 m wide and 5 m distant from the tree, crossing the investigation area (Figure 9). The analysis of both B-scans and C-scans suggests the presence of a reinforced concrete structure, as hyperbolic and evenly spaced reflections, potentially attributable to reinforcement bars, can be observed. Considering the layout of the site and the characteristics of the feature (i.e., estimated dimensions and construction materials), the latter was interpreted to be a conduit, serving an artificial lake located in the vicinity of the survey area.



372

373

Figure 8. A B-scan showing the presence of a buried structure (highlighted by the red dashed square).



374

375
376

Figure 9. C-scans of the investigated area at (a) 0.31 m of depth and (b) 0.45 m of depth. The red dashed areas clearly show the presence of a buried structure.

377
378
379
380
381
382

In addition to the above, it is important to note that a difference in the appearance of the ground was noticed, based on a visual inspection carried out on the study area. This feature was observed exactly at the location coordinates of the identified structure (Figure 10). It is therefore reasonable to assume that a conduit was introduced in relatively recent times, and that the required excavation and groundwork have interfered with the existing root system, cutting off roots and undermining the already decayed conditions of the tree.

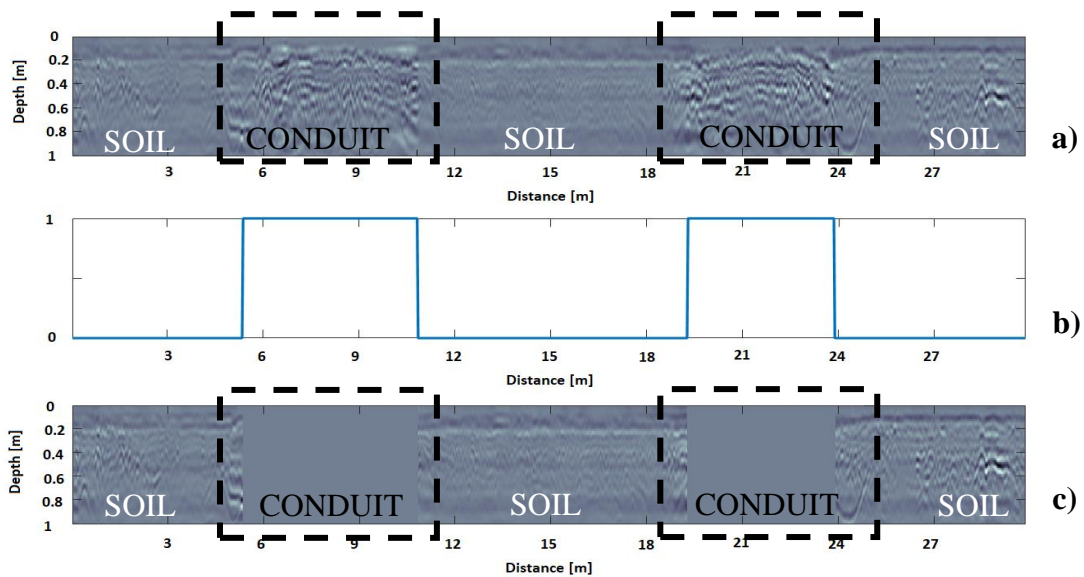


383

384
385

Figure 10. Aerial view of the investigated area. The red dashed area highlights a difference in the ground appearance matching the identified location of the discontinuity feature.

386 In terms of the data processing, the presence of this particular feature interferes with the
 387 application of the tree root tracking algorithm in the following stages. In addition, it implies that no
 388 roots are present within the volume occupied by the identified underground structure. For the
 389 purposes of this study, it was therefore decided to remove the reflections related to this particular
 390 type of discontinuity feature. A processing framework based on the methodology introduced in [48]
 391 was hence followed. The analysis of the data reflectivity was carried out to quantitatively locate the
 392 buried structure and eliminate the related reflections from the B-scans. Figure 11 shows the
 393 application of this processing scheme, proving that analysing the signal reflectivity is a valid tool to
 394 achieve an accurate detection of major elements of discontinuity.



395

396 **Figure 11.** An example of the GPR reflectivity analysis. (a) B-scan after the preliminary signal processing
 397 stage, (b) analysis of the signal reflectivity, showing a maximum value at the section coordinates of the
 398 identified buried feature, and (c) B-scan after a targeted trace removal.

399 3.3. Tree Root Tracking Algorithm

400 Following the application of the preliminary signal processing stage and the analysis of the
 401 signal discontinuity, the tree root tracking algorithm was applied for the reconstruction of the root
 402 system architecture in a three-dimensional environment. Figure 12 shows the outcome of this
 403 procedure, that is a 2D planar view (a) and a 3D view (b and c) of the reconstructed root system
 404 architecture. To aid with the interpretation of results, shallow-buried roots (i.e. within the first 25 cm
 405 of soil) and deeper roots (i.e., below the first 25 cm of soil) have been represented with different
 406 colours.

407 The analysis of the results showed that reflections were located within the first 0.70 m of soil.
 408 This is apparently not in line with the expectation for the root system of sycamore trees, as their roots
 409 can reach a depth of approximately 1.40 – 1.50 m [53, 54]. Nevertheless, Crow [54] reports that 90%
 410 to 99% of tree roots are usually found within the first metre of soil. The absence of reflections from
 411 deeper roots could be linked to the presence of death roots, having a value of dielectric permittivity
 412 close to that of the soil. Similarly, as shown in Figure 12, a discontinuity of the root system is visible
 413 in certain areas, mainly in the central region of the investigated soil. This could be likely an effect of
 414 the conduit installation, which may have interfered with the original structure of the root system and
 415 caused irreversible damage.

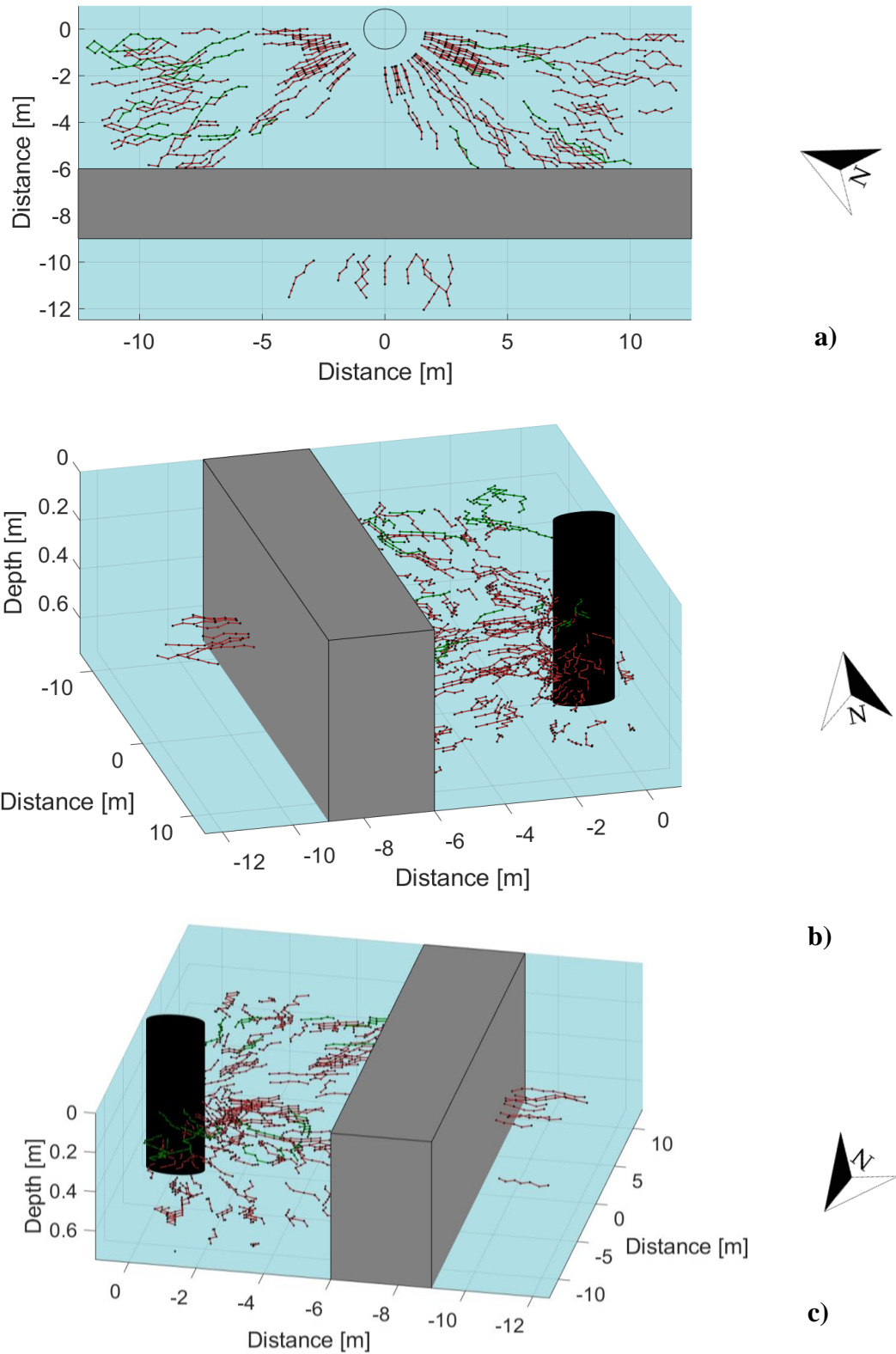
416 Finally, it is worth noting that the algorithm is designed to discard shorter segments, which
 417 might relate to non-root targets (e.g. boulders). The results achieved at this stage of the data
 418 processing are consistent with this particular algorithm feature.

419 3.4. *The Root Mass Density Maps*

420 The architecture of the root system was then further investigated through the evaluation of the
421 root density at different depths (Eq. 20). The investigated domain was divided into reference volumes
422 of $0.30\text{ m} \times 0.30\text{ m} \times 0.10\text{ m}$, where the dimension 0.30 m was chosen for consistency with the spacing
423 between the scans, and the depth dimension 0.10 m was selected for consistency with the excavation
424 steps performed at the validation stage. Hence, the domain was analysed to determine the total root
425 length per reference unit.

426 Figure 13, Figure 14 and Figure 15 show the outcomes of this processing stage, where several
427 areas with a high density of roots can be identified. In order to further analyse the density variations,
428 the maps were divided into homogeneous zones, as shown in Table 1. The minimum and maximum
429 density values, the average density and standard deviation were calculated at every identified area.

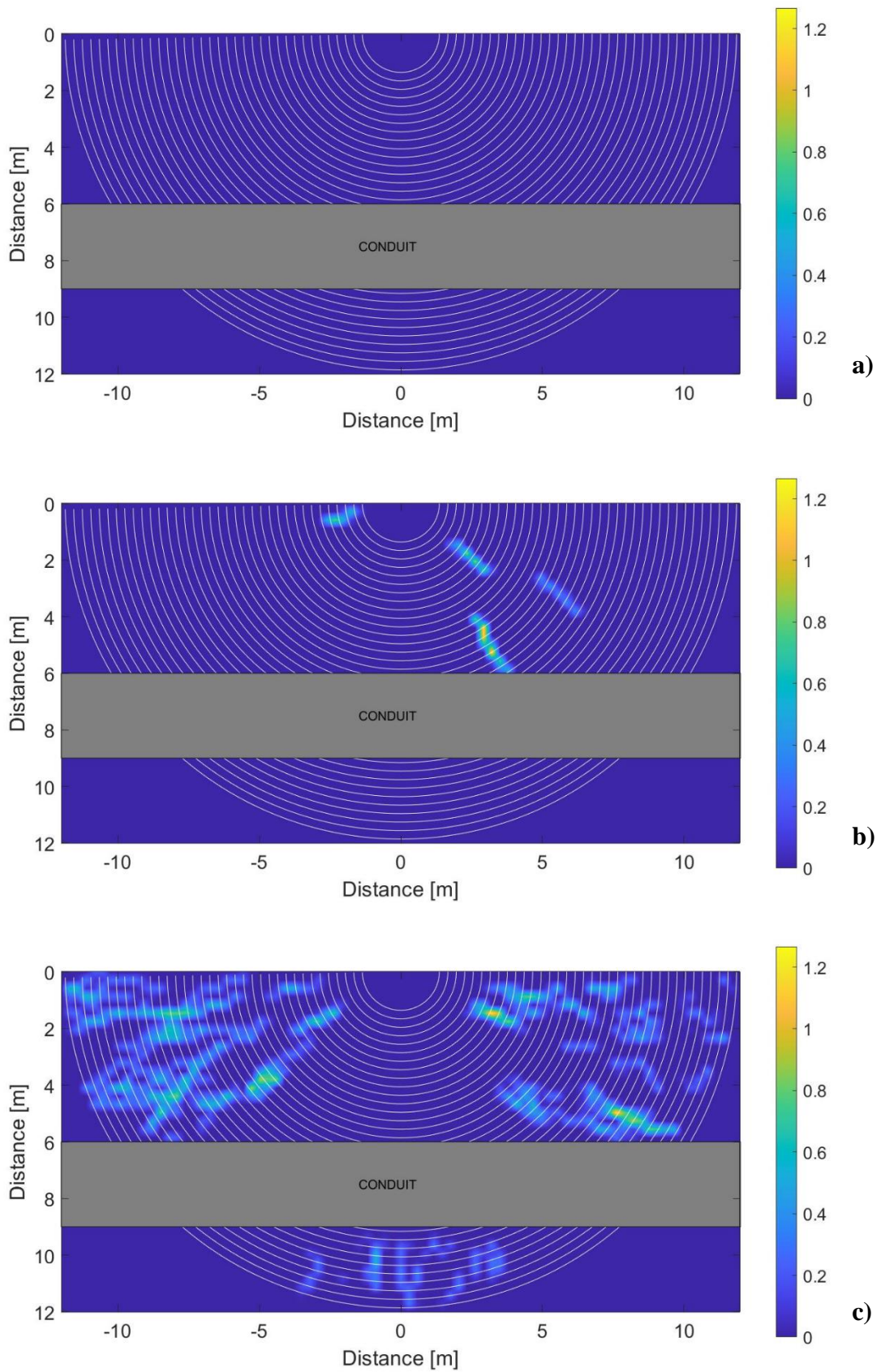
430 From the analysis of the density maps, the domain portion with a greater root mass density is
431 from a depth of 0.20 m to a depth of 0.60 m (Figure 13(c) and Figure 14). This is also supported by the
432 analysis of the maximum values reported in Table 1 for these depths. More specifically, the left
433 quadrant of the investigated domain presents a greater density of roots between 0.20 m and 0.30 m
434 of depth, with maximum values ranging from 0.88 m/m^3 to 1.05 m/m^3 (Table 1 - x coordinates -12.60
435 m to 0.00 m , y coordinates 0.00 m to 4.20 m) (Figure 13(c)), and between 0.50 m and 0.60 m of depth,
436 with maximum values between 1.00 m/m^3 and 1.11 m/m^3 (Table 1 - x coordinates -12.60 m to 0.00 m ,
437 y coordinates 0.00 m to 4.20 m) (Figure 14(c)). On the other hand, the right quadrant presents higher
438 values of root density between 0.20 m and 0.40 m , with peaks up to 1.44 m/m^3 (Table 1 - x coordinates
439 0.00 m to 4.20 m , y coordinates 0.00 m to 4.20 m , depth $0.20\text{ m} - 0.30\text{ m}$) (Figure 13(c) and Figure
440 14(a)). A higher root density on the left and the right quadrants can be likely interpreted as an indirect
441 consequence of the root system's interconnection with two adjacent trees, located respectively on the
442 North-West and the South-East directions from the investigated one. In fact, it is reasonable to assume
443 that the root density of a specific tree could be higher at root interconnection areas, as roots of
444 individual trees tend to have a closer arrangement between themselves, due to their own interaction
445 with the root systems of adjacent trees. Finally, it should be emphasised that, although the
446 aforementioned high root density concentrations are present, the average density values are still low
447 across the overall investigation area. This confirms that, for each homogeneous area identified, an
448 important amount of areas with very low or zero density can be found.



449

450
451
452

Figure 12. Reconstructed map of the tree root system architecture: (a) 2D planar view, (b) 3D view from South-West, and (c) in a 3D view from North-West. The grey block represents the volume occupied by the buried feature.

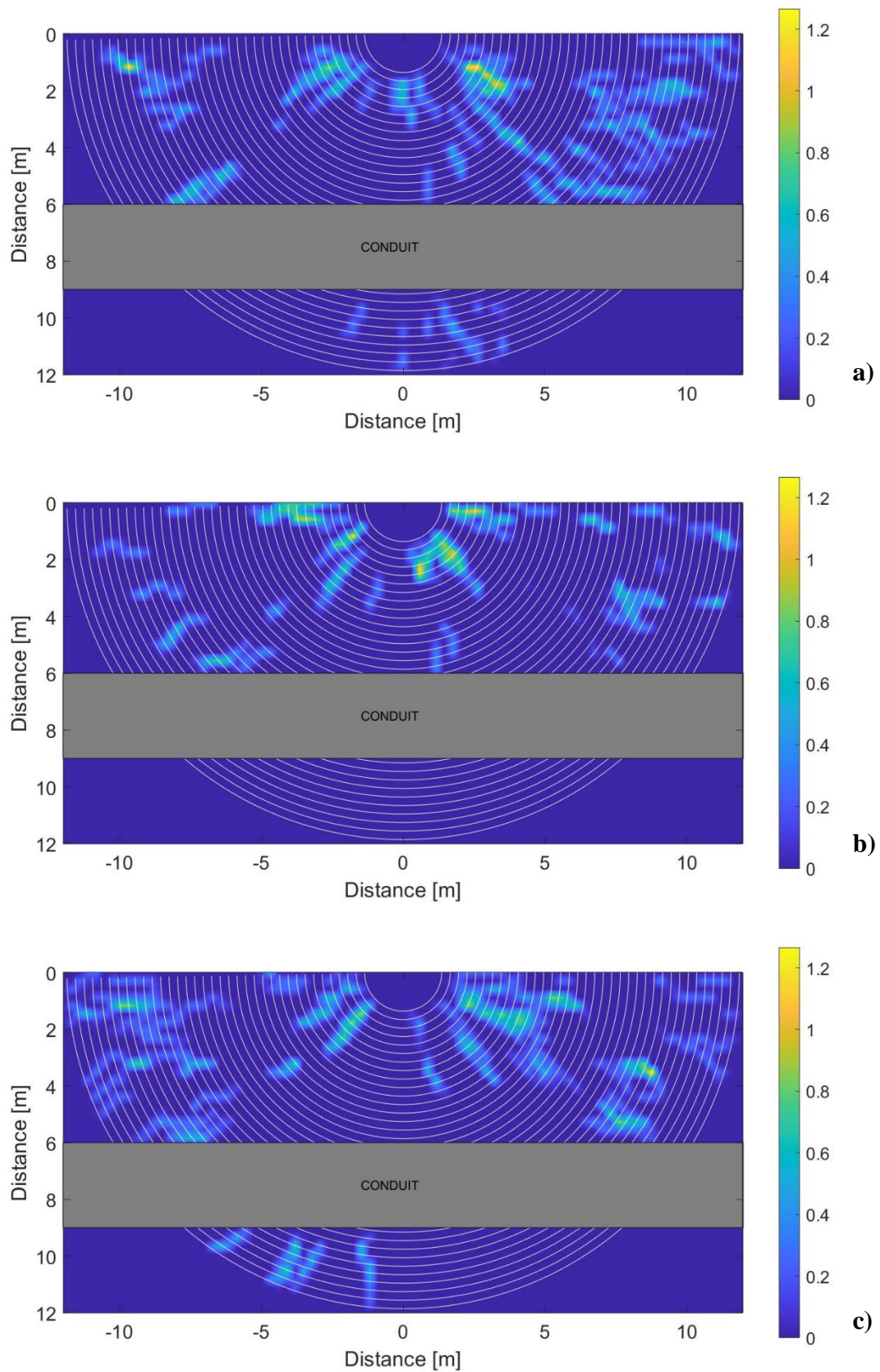


453

454

455

Figure 13. Root mass density maps at different depths. a) from 0 m to 0.10 m, b) from 0.10 m to 0.20 m, and c) from 0.20 m to 0.30 m.

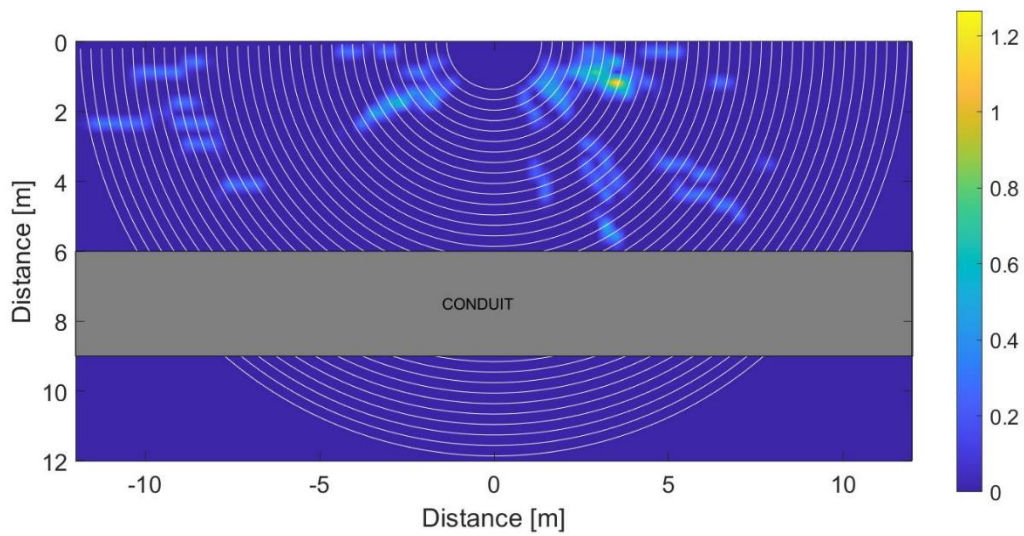


456

457

458

Figure 14. Root mass density maps at different depths. a) from 0.30 m to 0.40 m, b) from 0.40 m to 0.50 m, and c) from 0.50 m to 0.60 m



459

460

Figure 15. Root mass density map from 0.60 m to 0.70 m

461

Table 1. Root mass density zoning for the investigated tree.

| Root Mass Density Zoning | | | | | | | | |
|--------------------------|----------|--------|----------|--------|-----------------------------------|-----------------------------------|-----------------------------------|--|
| Depth [m] | x | | y | | Minimum value [m/m ³] | Maximum value [m/m ³] | Average value [m/m ³] | Standard deviation [m/m ³] |
| | From [m] | To [m] | From [m] | To [m] | | | | |
| 0.10 - 0.20 | -12.60 | -8.40 | 0.00 | 4.20 | 0.00 | 0.00 | 0.00 | 0.00 |
| | -8.40 | -4.20 | 0.00 | 4.20 | 0.00 | 0.00 | 0.00 | 0.00 |
| | -4.20 | 0.00 | 0.00 | 4.20 | 0.00 | 0.67 | 0.01 | 0.08 |
| | 0.00 | 4.20 | 0.00 | 4.20 | 0.00 | 0.76 | 0.02 | 0.10 |
| | 4.20 | 8.40 | 0.00 | 4.20 | 0.00 | 0.35 | 0.01 | 0.05 |
| | 8.40 | 12.60 | 0.00 | 4.20 | 0.00 | 0.00 | 0.00 | 0.00 |
| | -12.60 | -8.40 | 4.20 | 8.40 | 0.00 | 0.00 | 0.00 | 0.00 |
| | -8.40 | -4.20 | 4.20 | 8.40 | 0.00 | 0.00 | 0.00 | 0.00 |
| | -4.20 | 0.00 | 4.20 | 8.40 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 0.00 | 4.20 | 4.20 | 8.40 | 0.00 | 1.05 | 0.03 | 0.15 |
| | 4.20 | 8.40 | 4.20 | 8.40 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 8.40 | 12.60 | 4.20 | 8.40 | 0.00 | 0.00 | 0.00 | 0.00 |
| | -12.60 | -8.40 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 |
| | -8.40 | -4.20 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 |
| | -4.20 | 0.00 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 0.00 | 4.20 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4.20 | 8.40 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 8.40 | 12.60 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 | |

462

| | | | | | | | | |
|-------------|--------|-------|-------|-------|------|------|------|------|
| 0.20 - 0.30 | -12.60 | -8.40 | 0.00 | 4.20 | 0.00 | 0.91 | 0.15 | 0.21 |
| | -8.40 | -4.20 | 0.00 | 4.20 | 0.00 | 1.05 | 0.15 | 0.23 |
| | -4.20 | 0.00 | 0.00 | 4.20 | 0.00 | 0.88 | 0.04 | 0.13 |
| | 0.00 | 4.20 | 0.00 | 4.20 | 0.00 | 1.44 | 0.06 | 0.19 |
| | 4.20 | 8.40 | 0.00 | 4.20 | 0.00 | 0.91 | 0.09 | 0.18 |
| | 8.40 | 12.60 | 0.00 | 4.20 | 0.00 | 0.58 | 0.05 | 0.12 |
| | -12.60 | -8.40 | 4.20 | 8.40 | 0.00 | 0.91 | 0.07 | 0.17 |
| | -8.40 | -4.20 | 4.20 | 8.40 | 0.00 | 1.07 | 0.06 | 0.17 |
| | -4.20 | 0.00 | 4.20 | 8.40 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 0.00 | 4.20 | 4.20 | 8.40 | 0.00 | 0.75 | 0.01 | 0.07 |
| | 4.20 | 8.40 | 4.20 | 8.40 | 0.00 | 1.41 | 0.10 | 0.21 |
| | 8.40 | 12.60 | 4.20 | 8.40 | 0.00 | 0.92 | 0.03 | 0.14 |
| | -12.60 | -8.40 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 |
| | -8.40 | -4.20 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 |
| | -4.20 | 0.00 | 8.40 | 12.60 | 0.00 | 0.65 | 0.04 | 0.10 |
| | 0.00 | 4.20 | 8.40 | 12.60 | 0.00 | 0.36 | 0.04 | 0.09 |
| 4.20 | 8.40 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 8.40 | 12.60 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 0.30 - 0.40 | -12.60 | -8.40 | 0.00 | 4.20 | 0.00 | 1.27 | 0.05 | 0.15 |
| | -8.40 | -4.20 | 0.00 | 4.20 | 0.00 | 0.57 | 0.03 | 0.09 |
| | -4.20 | 0.00 | 0.00 | 4.20 | 0.00 | 0.86 | 0.10 | 0.20 |
| | 0.00 | 4.20 | 0.00 | 4.20 | 0.00 | 1.27 | 0.14 | 0.24 |
| | 4.20 | 8.40 | 0.00 | 4.20 | 0.00 | 0.68 | 0.06 | 0.13 |
| | 8.40 | 12.60 | 0.00 | 4.20 | 0.00 | 0.73 | 0.10 | 0.17 |
| | -12.60 | -8.40 | 4.20 | 8.40 | 0.00 | 0.43 | 0.00 | 0.03 |
| | -8.40 | -4.20 | 4.20 | 8.40 | 0.00 | 0.74 | 0.04 | 0.13 |
| | -4.20 | 0.00 | 4.20 | 8.40 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 0.00 | 4.20 | 4.20 | 8.40 | 0.00 | 0.55 | 0.02 | 0.08 |
| | 4.20 | 8.40 | 4.20 | 8.40 | 0.00 | 0.76 | 0.08 | 0.17 |
| | 8.40 | 12.60 | 4.20 | 8.40 | 0.00 | 0.31 | 0.01 | 0.05 |
| | -12.60 | -8.40 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 |
| | -8.40 | -4.20 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 |
| | -4.20 | 0.00 | 8.40 | 12.60 | 0.00 | 0.34 | 0.01 | 0.05 |
| | 0.00 | 4.20 | 8.40 | 12.60 | 0.00 | 0.50 | 0.03 | 0.09 |
| 4.20 | 8.40 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 8.40 | 12.60 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 | |

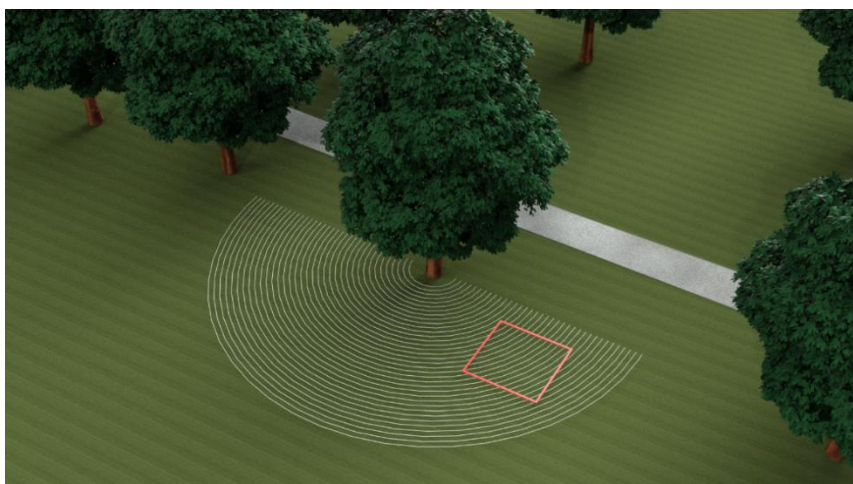
| | | | | | | | | |
|-------------|--------|-------|-------|-------|------|------|------|------|
| 0.40 - 0.50 | -12.60 | -8.40 | 0.00 | 4.20 | 0.00 | 0.35 | 0.02 | 0.07 |
| | -8.40 | -4.20 | 0.00 | 4.20 | 0.00 | 0.63 | 0.04 | 0.12 |
| | -4.20 | 0.00 | 0.00 | 4.20 | 0.00 | 1.09 | 0.10 | 0.21 |
| | 0.00 | 4.20 | 0.00 | 4.20 | 0.00 | 1.06 | 0.12 | 0.23 |
| | 4.20 | 8.40 | 0.00 | 4.20 | 0.00 | 0.67 | 0.04 | 0.12 |
| | 8.40 | 12.60 | 0.00 | 4.20 | 0.00 | 0.65 | 0.04 | 0.12 |
| | -12.60 | -8.40 | 4.20 | 8.40 | 0.00 | 0.49 | 0.01 | 0.05 |
| | -8.40 | -4.20 | 4.20 | 8.40 | 0.00 | 0.62 | 0.03 | 0.11 |
| | -4.20 | 0.00 | 4.20 | 8.40 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 0.00 | 4.20 | 4.20 | 8.40 | 0.00 | 0.31 | 0.01 | 0.06 |
| | 4.20 | 8.40 | 4.20 | 8.40 | 0.00 | 0.39 | 0.01 | 0.05 |
| | 8.40 | 12.60 | 4.20 | 8.40 | 0.00 | 0.32 | 0.00 | 0.03 |
| | -12.60 | -8.40 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 |
| | -8.40 | -4.20 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 |
| | -4.20 | 0.00 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 0.00 | 4.20 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4.20 | 8.40 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 8.40 | 12.60 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 0.50 - 0.60 | -12.60 | -8.40 | 0.00 | 4.20 | 0.00 | 1.01 | 0.12 | 0.19 |
| | -8.40 | -4.20 | 0.00 | 4.20 | 0.00 | 0.62 | 0.05 | 0.13 |
| | -4.20 | 0.00 | 0.00 | 4.20 | 0.00 | 1.11 | 0.10 | 0.22 |
| | 0.00 | 4.20 | 0.00 | 4.20 | 0.00 | 1.02 | 0.16 | 0.24 |
| | 4.20 | 8.40 | 0.00 | 4.20 | 0.00 | 1.00 | 0.10 | 0.19 |
| | 8.40 | 12.60 | 0.00 | 4.20 | 0.00 | 1.41 | 0.07 | 0.17 |
| | -12.60 | -8.40 | 4.20 | 8.40 | 0.00 | 0.45 | 0.02 | 0.08 |
| | -8.40 | -4.20 | 4.20 | 8.40 | 0.00 | 0.60 | 0.04 | 0.11 |
| | -4.20 | 0.00 | 4.20 | 8.40 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 0.00 | 4.20 | 4.20 | 8.40 | 0.00 | 0.29 | 0.00 | 0.03 |
| | 4.20 | 8.40 | 4.20 | 8.40 | 0.00 | 1.00 | 0.05 | 0.14 |
| | 8.40 | 12.60 | 4.20 | 8.40 | 0.00 | 0.64 | 0.01 | 0.07 |
| | -12.60 | -8.40 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 |
| | -8.40 | -4.20 | 8.40 | 12.60 | 0.00 | 0.81 | 0.03 | 0.12 |
| | -4.20 | 0.00 | 8.40 | 12.60 | 0.00 | 0.86 | 0.05 | 0.15 |
| | 0.00 | 4.20 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4.20 | 8.40 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 8.40 | 12.60 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 | |

| | | | | | | | | |
|-------------|--------|-------|------|-------|------|------|------|------|
| | -12.60 | -8.40 | 0.00 | 4.20 | 0.00 | 0.34 | 0.04 | 0.09 |
| | -8.40 | -4.20 | 0.00 | 4.20 | 0.00 | 0.30 | 0.00 | 0.03 |
| | -4.20 | 0.00 | 0.00 | 4.20 | 0.00 | 0.66 | 0.04 | 0.11 |
| | 0.00 | 4.20 | 0.00 | 4.20 | 0.00 | 1.24 | 0.10 | 0.18 |
| | 4.20 | 8.40 | 0.00 | 4.20 | 0.00 | 0.36 | 0.02 | 0.08 |
| | 8.40 | 12.60 | 0.00 | 4.20 | 0.00 | 0.00 | 0.00 | 0.00 |
| | -12.60 | -8.40 | 4.20 | 8.40 | 0.00 | 0.00 | 0.00 | 0.00 |
| | -8.40 | -4.20 | 4.20 | 8.40 | 0.00 | 0.35 | 0.01 | 0.04 |
| 0.60 - 0.70 | -4.20 | 0.00 | 4.20 | 8.40 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 0.00 | 4.20 | 4.20 | 8.40 | 0.00 | 0.56 | 0.02 | 0.08 |
| | 4.20 | 8.40 | 4.20 | 8.40 | 0.00 | 0.33 | 0.01 | 0.06 |
| | 8.40 | 12.60 | 4.20 | 8.40 | 0.00 | 0.00 | 0.00 | 0.00 |
| | -12.60 | -8.40 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 |
| | -8.40 | -4.20 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 |
| | -4.20 | 0.00 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 0.00 | 4.20 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 4.20 | 8.40 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 8.40 | 12.60 | 8.40 | 12.60 | 0.00 | 0.00 | 0.00 | 0.00 |

465 3.5. Results Validation through Excavation

466 A representative excavation section was identified after the application of the data processing
 467 framework, in order to limit the validation stage to a useful portion of the overall investigated area
 468 (i.e., 218.04 m²).

469 A square area of 4 m x 4 m was therefore selected on the South-West side of the investigated tree
 470 (Figure 16). The selection was made based on the root mass density distribution in the area and their
 471 expected depth. The excavation was performed by removing layers of ~0.10 m of soil up to ~0.50 m.
 472 It is worth noting that soil was significantly dry and compact in the whole excavation area. Its
 473 removal therefore presented considerable difficulties, as the excavation had to be carried out with
 474 reduced size tools, to ensure accurate operations and avoid accidental damage of the roots.



475

476

Figure 16. Rendering of the surveyed area, showing the position of the excavated site.

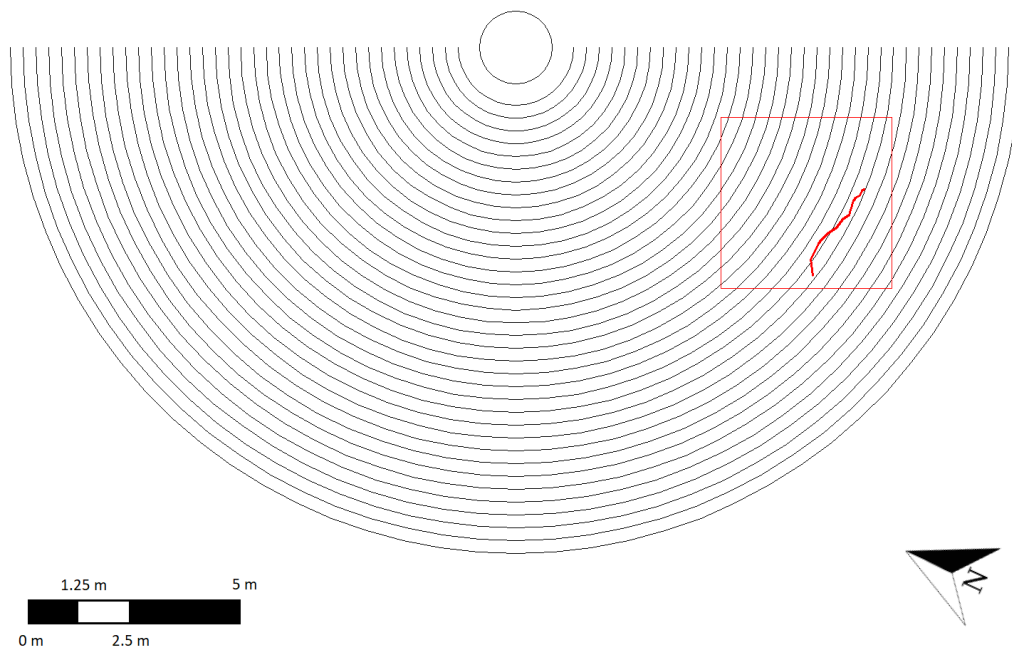
477 Several roots were found as a result of the validation survey, as shown in Figure 17. A root with
478 an average diameter of 0.06 m crosses the bottom-right part of the excavation for a length of about
479 2.53 m, at a depth varying between 0.26 m and 0.50 m. However, a local increase of density was not
480 found in the concerning density maps (i.e., depth ranges between 0.20 m and 0.30 m, between 0.30 m
481 and 0.40 m, and between 0.40 m and 0.50 m). This is due to the particular orientation of the root, that
482 crosses the investigated area along the South-East – North-West direction, transversely to an
483 imaginary radial line traced from the trunk of the tree investigated (Figure 18).



484

485

Figure 17. The excavated site.



486

487

488

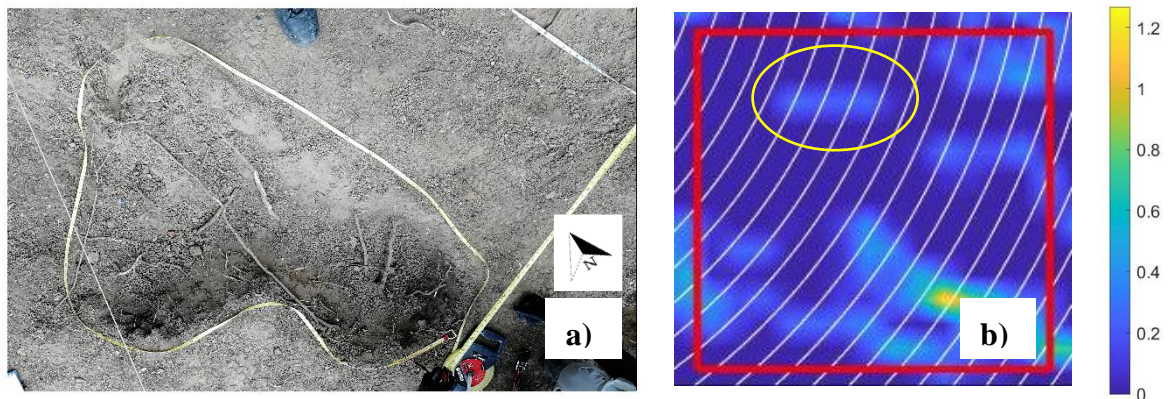
Figure 18 An outline of the survey, showing the orientation of the excavated coarse root (in red) within the test pit area.

489 Given a typical configuration of a root system, where roots expand radially from the centre of
490 the tree outwards, it is unlikely that the identified coarse root belongs to the tree under consideration.
491 On the contrary, this root likely belongs to the tree located in the vicinity of the investigated one, as
492 its direction matches with that conceivable for the nearby root system (see Figure 6). This result
493 proves the validity of the proposed methodology in automatically excluding targets not belonging to
494 the investigated tree.

495 A cluster of roots was also found at the top of the excavation area at a depth between
496 approximately 0.20 m and 0.25 m. Its position matches with the outcomes of the map in the depth
497 range 0.20÷0.30 m (Figure 19). Similarly, a root with an average diameter of 0.04 m was excavated at
498 the top-right corner, and an evidence was again found in the 0.20 m – 0.30 m density map.

499 Finally, the left-hand side of the excavation area was dug to validate the local density increase,
500 as highlighted by Figure 20(c) and Figure 21(c). Two roots with an average diameter of 0.04 m and a
501 depth varying from 0.05 m (top-left corner) to 0.20 m (bottom-left corner) were excavated.
502 Considering their position and the diameter similarity, it is reasonable to state that these sections
503 belong to the same root, that develops deeper than the performed excavation depth for a short stretch.
504 As shown in Figure 20 and Figure 21, the development of the excavated roots resembles the outputs
505 of the density maps. Lastly, roots of smaller dimensions, grouped together to form a single cluster,
506 were found at a short distance from the two aforementioned roots (Figure 21(a)).

COORDINATES: 51° 29' 45" N, 0° 17' 26" W

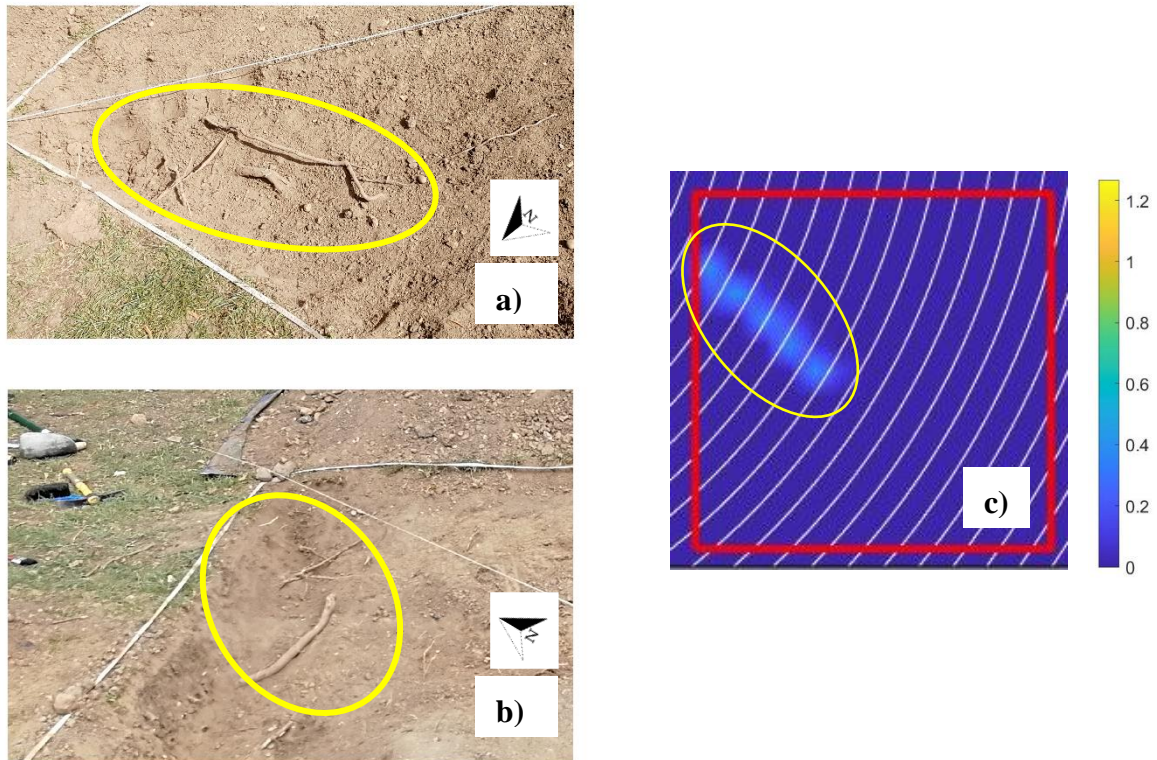


507

508
509

Figure 19. (a) The excavated root cluster, and (b) a zoom of the 0.20 m – 0.30m density map. The yellow circle highlights an area with increased density, corresponding to the cluster of roots.

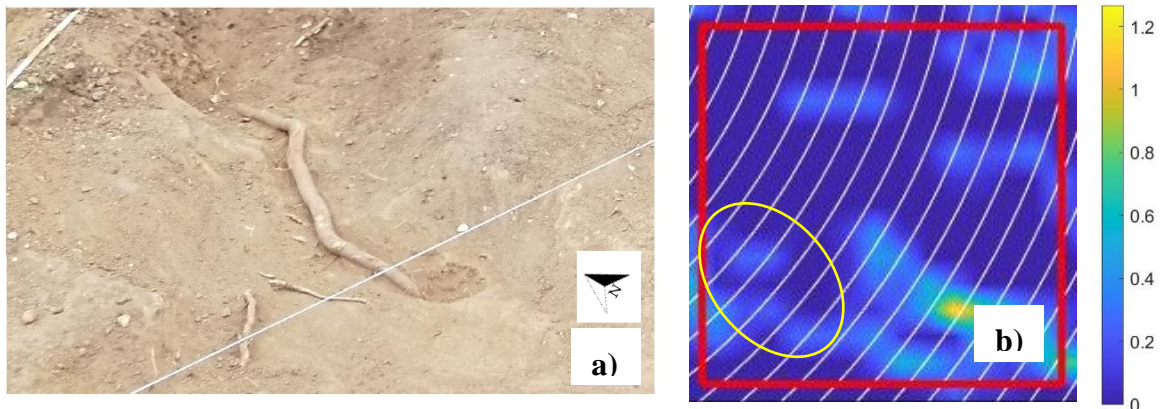
COORDINATES: 51° 29' 45" N, 0° 17' 26" W



510

511 **Figure 20.** The excavated root at the top-left corner of the excavated area, (a) detail of the excavation, (b)
 512 development of the root, and (c) a zoom of the 0.10 m – 0.20m density map. The yellow circle highlights an
 513 area with an increased density, corresponding to the excavated root.

COORDINATES: 51° 29' 45" N, 0° 17' 26" W



514

515 **Figure 21.** The excavated root at the bottom-left corner of the excavated area, (a) development of the root,
 516 and (b) a zoom of the 0.20 m – 0.30m density map. The yellow circle highlights an area with an increased
 517 density, corresponding to the excavated root.

518 In addition, the presence of numerous boulders was detected (Figure 22), the main size of which
 519 exceeded 0.15 m in some cases. Some of the boulders were found along the top edge of the excavation
 520 area, whereas other boulders were found along the left edge.

COORDINATES: 51° 29' 45" N, 0° 17' 26" W



521

522

523

Figure 22. Boulders found along the top edge of the excavation area. The boulder in the foreground has a main axial dimension of about 0.15 m.

524

525

526

However, no evidence of their presence was found in the root mass density maps. This confirms the validity of the proposed algorithm, as this is designed not to consider short segments, not correlated with root targets.

527

4. Discussion

528

529

530

531

532

The case study reported in this paper demonstrates the validity of the proposed methodology for the assessment of tree root systems. The method validation carried out through excavation and the subsequent roots exposure, confirms that GPR can detect roots as well as that the presented data processing framework is able to reconstruct their pattern and provide crucial information on their mass density.

533

534

535

536

537

538

539

540

541

542

543

544

545

546

The data processing framework explained in Section 2.5.3, requires to input a minimum amount of information related to the specific GPR survey, such as the number of scans carried out and the relative dielectric permittivity of the medium, making the data analysis relatively fast. Furthermore, the combination of the presented signal processing techniques allows for a broad applicability of the proposed methodology. A selection of standard techniques was performed to minimise the risk of data overprocessing. As for the more advanced techniques, such as the SVD filter and the F-K migration, their application has been calibrated to overcome fundamental issues, such as the presence of ringing noise and the accurate localisation of targets, without affecting the original data. The combination of the above-discussed parameters and processing steps can be regarded as a step forward for the development of a fully automated root system analysis methodology, for use of practitioners and end-users. At present, the selection of the threshold value for use in the tree root tracking algorithm is the only step requiring the operator's intervention, as explained in Section 2.5.3. Future research could task itself towards the automation of this particular step, using iterative estimations [55] or machine-learning methods, such as the back-propagation [56].

547 Regarding the survey methodology, a circular GPR acquisition method was followed, as
548 explained in Subsections 2.2 and 2.5.3. This method, chosen mainly due to the typical shape of a root
549 system (i.e. expanding radially from the trunk of the tree outwards), has the advantage of being more
550 inclusive and precise compared to a longitudinal acquisition method. In fact, circular transects allow
551 to scan the roots in a quasi-perpendicular set-up, i.e. an optimal condition in GPR data collection.
552 Furthermore, this methodology allows to collect information related to the examined tree only,
553 excluding the detection of root targets from neighbouring trees. This feature is essential for the
554 evaluation of the root system of individual trees, in case more focused analyses are required.
555 However, the circular acquisition turned up to be more time-demanding compared to traditional
556 linear acquisitions. It is in fact fair to comment that, if the purpose of the survey relates to the
557 assessment of multiple trees (e.g., a tree-lined avenue), the circular acquisition method turns up to be
558 onerous and time-consuming. A desirable future prospect of the current research is therefore to adapt
559 the discussed methodology into a linear acquisition method, to facilitate the concurrent investigation
560 of multiple nearby trees.

561 In regard to the outcomes produced by the tree root density maps, the evaluation of the mass
562 density has proven to be an effective tool in assessing the root system conditions and its interaction
563 with manmade constructions. To this extent, the provision of routine inspections could be of valuable
564 support to evaluate the health conditions of root systems, as density variations over time can be used
565 as an effective quantitative indicator of any potential diseases or fungal attacks. An early-stage
566 identification of the problem could favour immediate remedial actions, and contribute to save the
567 tree and prevent the spreading of the infection. It is also worthy to note the impact of the proposed
568 methodology in large-scale forestry applications, especially in areas with a high density of trees.
569 Implementation of routine inspections could help to identify mass-density-related issues for
570 individual trees (e.g. trees requiring special care) much more accurately, as the outcomes of the
571 methodology are independent from the root system of nearby trees.

572 **5. Conclusions**

573 The present study clearly demonstrated that the use of non-destructive testing (NDT) methods
574 for the investigation of tree root systems is the new frontier of forestry practices and the conservation
575 of the naturalistic heritage. Due to its ease of use, non-intrusiveness and the cost-effectiveness,
576 viability of the ground penetrating radar (GPR) technique was proven for root inspection purposes,
577 with a special focus on root detection and the three-dimensional mapping of the root system
578 architecture.

579 In this paper, the authors report an investigation within the context of forestry applications with
580 GPR, aiming at detecting tree roots and reconstructing the geometry of a tree root system through a
581 novel data processing methodology. A multi-stage interpretation algorithm was introduced in order
582 to reconstruct the tree root patterns based on the collected GPR data. The proposed methodology is
583 based on the provision of semi-circular scans, which expand outwards radially starting from the
584 trunk of the tree. Initially, a signal processing stage was applied, to remove noise-related information
585 and enhance the response from the real targets. Subsequently, a tracking algorithm was used in order
586 to locate and automatically track viable root paths. Lastly, the identified roots were expressed
587 through continuous functions in order to map the root mass density analytically. A case study is
588 presented, in which the proposed method was successfully applied. The tracking algorithm has
589 proven effective to identify both the shallow (i.e. within the first 25 cm of soil) and the deep (i.e. below
590 25 cm from the surface of the soil) root structures. Based on this outcome, root mass density maps at
591 different depths were estimated. To prove the validity of the proposed methodology, a validation
592 survey was carried out, in which a part of the investigated area was excavated, and tree roots were
593 exposed. The density maps were in good agreement with the actual root structure, as it was
594 demonstrated by the orientation of the bigger roots excavated as well as by the presence of clusters
595 of finer roots. In addition to this, the presence of boulders of appreciable size was not detected,

596 although these features were found at several sections and depths within the excavated area. Finally,
597 the proposed methodology has proven effective to map the root pattern and identify mass-density-
598 related issues for individual trees, independently from the root systems of nearby trees.

599 It is believed that this research has contributed and added value to the existing knowledge
600 within the context of understanding the conditions of tree roots in complex environments (e.g., urban
601 environments), supporting the premise that GPR is a powerful NDT method for large scale forestry
602 applications.

603 **Author Contributions:** Conceptualization, A.M.A., A.B. and F.T.; methodology, A.M.A., A.B., F.T. and L.L.;
604 software, L.L., I.G. and F.T.; validation, L.L., F.T., I.G., and L.Z.; formal analysis, A.M.A., F.T., L.L. and I.G.;
605 investigation, F.T., L.L. and I.G.; resources, A.M.A. and F.T.; data curation, L.L., F.T. and I.G.; writing—original
606 draft preparation, L.L.; writing—review and editing, A.M.A., A.B. and F. T.; visualization, L.L. and F.T.;
607 supervision, A.M.A., A.B. and F. T.; project administration, A.M.A.; funding acquisition, A.M.A. All authors
608 have read and agreed to the published version of the manuscript.

609 **Funding:** This research was funded by the following trusts, charities, organisations and individuals: Lord
610 Faringdon Charitable Trust, The Schroder Foundation, Cazenove Charitable Trust, Ernest Cook Trust, Sir Henry
611 Keswick, Ian Bond, P. F. Charitable Trust, Prospect Investment Management Limited, The Adrian Swire
612 Charitable Trust, The John Swire 1989 Charitable Trust, The Sackler Trust, The Tanlaw Foundation, and The
613 Wyfold Charitable Trust.

614 **Acknowledgments:** The authors would like to express their sincere thanks to Mr. Dale Mortimer (representing
615 the Ealing Council) and the Gunnersbury Park for facilitating this research.

616 **Conflicts of Interest:** The authors declare no conflict of interest. The funders had no role in the design of the
617 study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to
618 publish the results.

619 **References**

620

621

622 1. Pallardy, S.G. *Physiology of Woody Plants*, 3rd ed.; Academic Press: Cambridge, Massachusetts, 2010.

623 2. Donovan, G.H.; Butry, D.T.; Michael, Y.L.; Prestemon, J.P.; Liebhold, A.M.; Gatzliolis, D.; Mao, M.Y. The

624 Relationship between Trees and Human Health: Evidence from the Spread of the Emerald Ash Borer.

625 *American journal of preventive medicine* **2013**, *44*, 139-145. DOI: 10.1016/j.amepre.2012.09.066.

626 3. Tzoulas, K.; Korpela, K.; Venn, S.; Yli-Pelkonen, V.; Kazmierczak, A.; Niemela, J.; James, P. Promoting

627 Ecosystem and Human Health in Urban Areas using Green Infrastructure: A Literature Review. *Landscape*628 and *Urban Planning* **2007**, *81*, 167-178. DOI: 10.1016/j.landurbplan.2007.02.001.

629 4. Tallis, M.; Taylor, G.; Sinnett, D.; Freer-Smith, P. Estimating the Removal of Atmospheric Particulate

630 Pollution by the Urban Tree Canopy of London, Under Current and Future Environments. *Landscape and*631 *Urban Planning* **2011**, *103*, 129-138. DOI: 10.1016/j.landurbplan.2011.07.003.

632 5. Hwang, H.; Yook, S.; Ahn, K. Experimental Investigation of Submicron and Ultrafine Soot Particle Removal

633 by Tree Leaves. *Atmospheric Environment* **2011**, *45*, 6987-6994. DOI: 10.1016/j.atmosenv.2011.09.019.

634 6. Mullaney, J.; Lucke, T.; Trueman, S.J. A Review of Benefits and Challenges in Growing Street Trees in Paved

635 Urban Environments. *Landscape and Urban Planning* **2015**, *134*, 157-166. DOI:

636 10.1016/j.landurbplan.2014.10.013.

637 7. Hartig, T.; van den Berg, A.; Hagerhall, C.; Tomalak, M.; Bauer, N.; Hansmann, R.; Ojala, A.; Syngollitou,

638 E.; Carrus, G.; van Herzele, A. *et al.* Health Benefits of Nature Experience: Psychological, Social and639 Cultural Processes. In *Forests, Trees and Human Health.*; Nilsson, K., Sangster, M., Gallis, C., Hartig, T., de

640 Vries, S., Seeland, K. and Schipperijn, J., Eds.; Springer Netherlands: Dordrecht, 2011, pp. 127-168.

641 8. McPherson, E. G.; Nowak, D.J.; Rowntree, R.A. Chicago's Urban Forest Ecosystem: Results of the Chicago

642 Urban Forest Climate Project. Forest Service General Technical Report. U.S. Department of Agriculture,

643 Forest Service, Northeastern Forest Experiment Station **1994**, *186*.644 9. Tyrväinen, L.; Pauleit, S.; Seeland, K.; de Vries, S. Benefits and Uses of Urban Forests and Trees. In *Urban*645 *Forests and Trees.*; Nilsson, K., Schipperijn, J., Randrup, T. and Konijnendijk, C., Eds.; Springer: Berlin,

646 Heidelberg, 2005, pp. 81-114.

647 10. van Dillen, Sonja M E; de Vries, S.; Groenewegen, P.P.; Spreeuwenberg, P. Greenspace in Urban

648 Neighbourhoods and Residents' Health: Adding Quality to Quantity. *Journal of Epidemiology and*649 *Community Health* **2012**, *66*. DOI: 10.1136/jech.2009.104695.

650 11. Pandit, R.; Polyakov, M.; Sadler, R. The Importance of Tree Cover and Neighbourhood Parks in

651 Determining Urban Property Values. In 56th Australian Agricultural and Resource Economics Society

652 (AARES) Annual Conference, Fremantle, Western Australia, February 7-10, 2012. DOI:

653 10.22004/ag.econ.124357.

654 12. Coutts, M.P. Root Architecture and Tree Stability. *Plant and Soil* **1983**, *71*, 171-188. DOI:

655 10.1007/BF02182653.

656 13. Alani, A.M.; Lantini, L. Recent Advances in Tree Root Mapping and Assessment using Non-Destructive

657 Testing Methods: A Focus on Ground Penetrating Radar. *Surv. Geophys.* **2020**, *41*, 605-646. DOI:

658 10.1007/s10712-019-09548-6.

659 14. Barton, C.V.M.; Montagu, K.D. Detection of Tree Roots and Determination of Root Diameters by Ground

660 Penetrating Radar Under Optimal Conditions. *Tree physiology* **2004**, *24*, 1323-1331. DOI:

661 10.1093/treephys/24.12.1323.

662 15. Hansen, E.M.; Goheen, E.M. Phellinus Weirii and Other Native Root Pathogens as Determinants of Forest

663 Structure and Process in Western North America. *Annual review of phytopathology* **2000**, *38*, 515-539. DOI:

664 10.1146/annurev.phyto.38.1.515.

665 16. J. Rishbeth. Resistance to Fungal Pathogens of Tree Roots. *Proceedings of the Royal Society of London.*666 *Series B. Biological Sciences* **1972**, *181*, 333-351. DOI: 10.1098/rspb.1972.0054.667 17. Shaw, C.G.; Kile, G.A. *Armillaria Root Disease.*; Forest Service, US Department of Agriculture: Washington,

668 D.C, 1991.

669 18. Reubens, B.; Poesen, J.; Danjon, F.; Geudens, G.; Muys, B. The Role of Fine and Coarse Roots in Shallow

670 Slope Stability and Soil Erosion Control with a Focus on Root System Architecture: A Review. *Trees* **2007**,671 *21*, 385-402. DOI: 10.1007/s00468-007-0132-4.

672 19. Guo, L.; Chen, J.; Cui, X.; Fan, B.; Lin, H. Application of Ground Penetrating Radar for Coarse Root

673 Detection and Quantification: A Review. *Plant Soil* **2013**, *362*, 1-23. DOI: 10.1007/s11104-012-1455-5.

- 673 20. Čermák, J.; Nadezhkina, N.; Meiresonne, L.; Ceulemans, R. Scots Pine Root Distribution Derived from
674 Radial Sap Flow Patterns in Stems of Large Leaning Trees. *Plant Soil* **2008**, *305*, 61-75. DOI: 10.1007/s11104-
675 007-9433-z.
- 676 21. Gregory, P.J.; Hutchison, D.J.; Read, D.B.; Jenneson, P.M.; Gilboy, W.B.; Morton, E.J. Non-invasive imaging
677 of roots with high resolution X-ray micro-tomography. In *Roots: The Dynamic Interface between Plants and the*
678 *Earth*; Abe, J., Ed.; Springer: Dordrecht, 2003; 101, pp. 351-359.
- 679 22. Moran, C.J.; Pierret, A.; Stevenson, A.W. X-Ray Absorption and Phase Contrast Imaging to Study the
680 Interplay between Plant Roots and Soil Structure. *Plant Soil* **2000**, *223*, 101-117. DOI:
681 10.1023/A:1004835813094.
- 682 23. Paglis, C.M. Application of Electrical Resistivity Tomography for Detecting Root Biomass in Coffee Trees.
683 *International Journal of Geophysics* **2013**, *2013*, 6. DOI: 10.1155/2013/383261.
- 684 24. Amato, M.; Basso, B.; Celano, G.; Bitella, G.; Morelli, G.; Rossi, R. In Situ Detection of Tree Root Distribution
685 and Biomass by Multi-Electrode Resistivity Imaging. *Tree Physiol.* **2008**, *28*, 1441-1448. DOI:
686 10.1093/treephys/28.10.1441.
- 687 25. Benedetto, A.; Tosti, F.; Ortuani, B.; Giudici, M.; Mele, M. Soil Moisture Mapping using GPR for Pavement
688 Applications. In 2013 7th International Workshop on Advanced Ground Penetrating Radar, Nantes, July 2-
689 5, 2013; pp. 1-5. DOI: 10.1109/IWAGPR.2013.6601550.
- 690 26. Themistocleous, K.; Neocleous, K.; Pilakoutas, K.; Hadjimitsis, D.G. Damage Assessment using Advanced
691 Non-Intrusive Inspection Methods: Integration of Space, UAV, GPR, and Field Spectroscopy. In Second
692 International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2014), Cyprus,
693 April 7-10, 2014; pp. 92291O-5. DOI: 10.1117/12.2069507.
- 694 27. Hager, J.L.; Carnevale, M. GPR as a Cost-Effective Bedrock Mapping Tool for Large Areas. In Symposium
695 on the Application of Geophysics to Engineering and Environmental Problems 2001; pp. GP13-GP13.
696 DOI: 10.4133/1.2922891.
- 697 28. Daniels, D.J. Surface-Penetrating Radar. *Electronics & Communication Engineering Journal* **1996**, *8*, 165-
698 182. DOI: 10.1049/ecej:19960402.
- 699 29. Goodman, D. Ground-penetrating Radar Simulation in Engineering and Archaeology. *Geophysics* **1994**,
700 *59*, 224-232. DOI: 10.1190/1.1443584.
- 701 30. Alani, A.M.; Aboutaleb, M.; Kilic, G. Applications of Ground Penetrating Radar (GPR) in Bridge Deck
702 Monitoring and Assessment. *Journal of applied geophysics* **2013**, *97*, 45-54. DOI:
703 10.1016/j.jappgeo.2013.04.009.
- 704 31. Potin, D.; Duflos, E.; Vanheeghe, P. Landmines Ground-Penetrating Radar Signal Enhancement by Digital
705 Filtering. *TGRS* **2006**, *44*, 2393-2406. DOI: 10.1109/TGRS.2006.875356.
- 706 32. Tosti, F.; Bianchini Ciampoli, L.; D'Amico, F.; Alani, A.M.; Benedetto, A. An Experimental-Based Model for
707 the Assessment of the Mechanical Properties of Road Pavements using Ground-Penetrating Radar.
708 *Construction & building materials* **2018**, *165*, 966-974. DOI: 10.1016/j.conbuildmat.2018.01.179.
- 709 33. Brancadoro, M.G.; Ciampoli, L.B.; Ferrante, C.; Benedetto, A.; Tosti, F.; Alani, A.M. An Investigation into
710 the Railway Ballast Grading using GPR and Image Analysis. In 2017 9th International Workshop on
711 Advanced Ground Penetrating Radar (IWAGPR), Edinburgh; pp. 1-4. DOI:
712 10.1109/IWAGPR.2017.7996043.
- 713 34. Lambot, S.; Javaux, M.; Hupet, F.; Vanclooster, M. A Global Multilevel Coordinate Search Procedure for
714 Estimating the Unsaturated Soil Hydraulic Properties. *Water resources research* **2002**, *38*, 6-15. DOI:
715 10.1029/2001WR001224.
- 716 35. Huisman, J.A.; Hubbard, S.S.; Redman, J.D.; Annan, A.P. Measuring Soil Water Content with Ground
717 Penetrating Radar: A Review. *Vadose Zone Journal* **2003**, *2*, 476-491. DOI: 10.2113/2.4.476.
- 718 36. Hruska, J.; Čermák, J.; Šustek, S. Mapping Tree Root Systems with Ground-Penetrating Radar. *Tree*
719 *Physiol.* **1999**, *19*, 125-130.
- 720 37. Butnor, J.R.; Doolittle, J.A.; Johnsen, K.H.; Samuelson, L.; Stokes, T.; Kress, L. Utility of Ground-Penetrating
721 Radar as a Root Biomass Survey Tool in Forest Systems. *Soil Sci. Soc. Am. J.* **2003**, *67*, 1607-1615. DOI:
722 10.2136/sssaj2003.1607.
- 723 38. Alani, A.M.; Ciampoli, L.B.; Lantini, L.; Tosti, F.; Benedetto, A. Mapping the Root System of Matured Trees
724 using Ground Penetrating Radar. In 2018 17th International Conference on Ground Penetrating Radar
725 (GPR), Rapperswil, Switzerland, June 18-21, 2018; pp. 1-6. DOI: 10.1109/ICGPR.2018.8441535.

- 726 39. Lantini, L.; Holleworth, R.; Egyir, D.; Giannakis, I.; Tosti, F.; Alani, A.M. Use of Ground Penetrating Radar
727 for Assessing Interconnections between Root Systems of Different Matured Tree Species. In 2018 Metrology
728 for Archaeology and Cultural Heritage (MetroArchaeo), Cassino, Italy, October 22-24, 2018; pp. 22-26. DOI:
729 10.1109/MetroArchaeo43810.2018.13682.
- 730 40. Gunnersbury Park Trees. Available online: [https://gunnersburyfriends.org/gunnersbury-park-](https://gunnersburyfriends.org/gunnersbury-park-trees/)
731 [trees/](https://gunnersburyfriends.org/gunnersbury-park-trees/) (accessed on Jul 15, 2020).
- 732 41. Time and Date AS. Available
733 online: <https://www.timeanddate.com/weather/uk/london/historic?month=4&year=2019> (accessed on Jul
734 3, 2020).
- 735 42. Fayle, D.C.F. Radial Growth in Tree Roots: Distribution, Timing, Anatomy. University of Toronto, Faculty
736 of Forestry **1968**.
- 737 43. Chauvière, M.; Colin, F.; Nielsen, C.N.; Drexhage, M. Development of Structural Root Architecture and
738 Allometry of *Quercus Petraea*. Canadian Journal of Forest Research **1999**, *29*, 600-608. DOI: 10.1139/x99-
739 027.
- 740 44. Elkarmoty, M.; Tinti, F.; Kasmaeeyazdi, S.; Giannino, F.; Bonduà, S.; Bruno, R. Implementation of a Fracture
741 Modeling Strategy Based on Georadar Survey in a Large Area of Limestone Quarry Bench. Geosciences
742 (Basel) **2018**, *8*, 481. DOI: 10.3390/geosciences8120481.
- 743 45. Daniels, D.J. *Ground Penetrating Radar*, 2nd ed.; The Institution of Electrical Engineers: London, 2004.
- 744 46. Jol, H.M. *Ground Penetrating Radar Theory and Applications*, 1st ed.; Elsevier: Amsterdam, 2009.
- 745 47. Kim, J.; Cho, S.; Yi, M. Removal of Ringing Noise in GPR Data by Signal Processing. Geosci J **2007**, *11*, 75-
746 81. DOI: 10.1007/BF02910382.
- 747 48. Lantini, L.; Giannakis, I.; Tosti, F.; Mortimer, D.; Alani, A. A Reflectivity-Based GPR Signal Processing
748 Methodology for Mapping Tree Root Systems of Street Trees. In 2020 43rd International Conference on
749 Telecommunications and Signal Processing, Online event, Jul 7-9, 2020. DOI:
750 10.1109/TSP49548.2020.9163517.
- 751 49. Cui, X.H.; Chen, J.; Shen, J.; Cao, X.; Chen, X.; Zhu, X. Modeling Tree Root Diameter and Biomass by
752 Ground-Penetrating Radar. Sci. China Earth Sci **2011**, *54*, 711-719. DOI: 10.1007/s11430-010-4103-z.
- 753 50. Kreyszig, E. *Advanced Engineering Mathematics*, 9th ed.; John Wiley & Sons, 2006.
- 754 51. Hansen, P.C.; Pereyra, V.; Scherer, G. *Least Squares Data Fitting with Applications*.; Johns Hopkins University
755 Press: Baltimore, 2013.
- 756 52. Fausett, L.V. *Applied Numerical Analysis using MATLAB*, 2. ed. ed.; Pearson Prentice Hall: Upper Saddle
757 River, NJ, 2008.
- 758 53. Köstler, J.; Brückner, E.; Bibelriether, H. *Die Wurzeln Der Waldbäume*.; P. Parey: Hamburg, 1968.
- 759 54. Crow, P. The Influence of Soils and Species on Tree Root Depth. Forestry Commission **2005**.
- 760 55. Kelley, C.T. *Iterative Methods for Optimization*.; Society for Industrial and Applied Mathematics, 1999.
- 761 56. Hecht-Nielsen, R. Theory of the Backpropagation Neural Network. Neural networks **1988**, *1*, 445. DOI:
762 10.1016/0893-6080(88)90469-8.



© 2020 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).