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Comparing Interpolated Data of Sonic Tomograph and Ground Penetrating Radar to Characterize Tree Roots in Urban Environments

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Abstract. Background: Urban afforestation is widely recognized for providing numerous aesthetic and functional benefits to both the population and the environment. However, poor planning ranging from improper species selection to inadequate tree management can lead to various issues, including accidents caused by falling trees. These incidents often result from root failure, underdeveloped root systems, or advanced tree degradation. Methods: To evaluate a tree's root system, indirect methods are recommended, particularly in urban environments with sidewalks or pavements. Techniques such as sonic tomography and ground penetrating radar (GPR) each have their own advantages and disadvantages when applied to urban trees. This study aimed to assess and compare qualitatively the use of sonic tomography and GPR to characterize the root systems of 5 trees located on a sidewalk and in a square. Additionally, a new visualization approach for tomographic data is presented, using kriging interpolation of velocity and error values. Results: The results established a qualitative relationship between the high velocity zones detected by tomography, indicating root presence, and the roots mapped by GPR. The new visualization of tomography data provides better opportunities for clearer interpretation together with information of measurement errors. Conclusions: Sonic tomography and GPR both assess trees roots in urban environments, but sonic tomography is faster for mapping the extent of root coverage, whereas GPR provides a more detailed characterization of the root system's spatial distribution, depth, and diameter of coarse roots.

Keywords. GPR; Sonic Tomography; Tree Root System; Urban Trees.

INTRODUCTION

Like the trunk and leaves, roots play a fundamental role in a tree's life. They provide both structural support and absorb water and nutrients in addition to fostering ecological relationships with other organisms in both forest and urban environments. Roots, which are sensitive to water levels, oxygen, and other soil chemicals, significantly affect a tree's health and survival, particularly in urban soils that are often paved and compacted (Gregory 2006; Rahman et al. 2014). The root system is affected by competition with other plants, and the soil can be affected by climate change. This interaction between the external environment and the roots makes observing root characteristics a strong way to predict the tree's health (Urban 2008).

According to Miesbauer et al. (2025), much of the damage in trees associated with development and redevelopment occurs belowground in the root system. A significant number of large trees fall due to basal breakage or uprooting, revealing a mechanical failure at the root collar, the critical junction between the stem and the roots. While weakened anchoring roots are a key factor, in urban settings, tree stability is also threatened by root-infrastructure conflicts (Guardia 2020; Detter et al. 2023). For instance, in São Paulo, the largest city in Brazil, root system issues were responsible for 33% of tree falls (Cavalari et al. 2024). Pereira (2017) observed that buried pipes and other underground services can impede root growth, ultimately affecting a tree's structural integrity. Despite their fundamental role in urban ecosystems, tree root systems remain poorly understood, especially in tropical regions, due to their subterranean nature and complex and variable growth patterns

(Mullaney et al. 2015). As a result, many urban trees are lost due to undetected root damage, leading to decline or sudden falls. Often, these trees show no visible signs of distress in the trunk or crown, masking the underlying problems (Rizzardi and Calvo 2019).

Therefore, noninvasive technologies are essential for studying and evaluating tree roots in the subsoil for presence, distribution, size, and depth occurrence, for example, particularly in urban areas where roots often grow beneath paved surfaces (Shi et al. 2024; Grabosky et al. 2025). Compared to destructive methods like air spade or direct excavation, these tools offer significant advantages like helping maintain tree health, minimizing disruption to the urban environment, and providing reliable results quickly and cost-effectively. Two methods are commonly employed for this purpose: sonic tomography (or mechanical impulse tomography) and ground penetrating radar (GPR)(Comin et al. 2021). Sonic tomography uses mechanical waves to assess root wood density where higher velocities indicate a greater presence of roots (Arciniegas et al. 2014). Ground penetrating radar (GPR) is a high-frequency electromagnetic method that utilizes electrical property contrasts in the subsurface to generate a high-resolution image, revealing the distribution, depth, and diameter of roots (Santos and Filho 2024).

Sonic or mechanical impulse tomography is based on measuring the travel times of mechanical waves (Rinntech® 2012). Impulse velocities within wood are highly correlated with the density of the material and therefore can be used to gather information about its quality. Dense healthy wood transmits stress waves better than damaged wood which is decayed or cracked.

Each sensor is equipped with a vibration meter capable of performing direct real-time analysis of incoming pulses. By producing a vibration in the sensors, with a hammer for example, stress waves are generated that travel through the wood. The time that the stress waves travel between the sensors is recorded and converted into velocities. According to Smulski (1991), the propagation velocity of the mechanical wave is directly proportional to the square root of the elastic modulus of the wood and inversely proportional to the square root of its density. The propagation velocity of mechanical waves will be greater in wood of greater density, since the predominant factor is the elastic modulus, which is the physical property that can change with the decay of the wood (Deflorio et al. 2008).

Ground penetrating radar (GPR) is an electromagnetic (EM) method, and it uses radio waves at very high frequencies (between 10 MHz and 2600 MHz). This tool is used to identify shallow geological structures in the subsurface and to locate buried objects such as pipes or electrical cables. It is also useful for archaeology, construction, environmental studies, and forensic investigations (Santos et al. 2018).

This technology consists of transmitting EM waves (oscillation of electric and magnetic fields through a medium) repeatedly radiated into the medium by a transmitting antenna placed on the surface. The propagation of the EM signal depends on the frequency of the transmitted signal and the electrical properties of the materials, which are mainly dependent on the water content present in the soil (Daniels 2004). Changes in electrical properties in the subsurface cause part of the signal to be reflected, and the reflected and diffracted waves are received by the receiving antenna, also placed on the surface. The reflected energy is recorded as a function of the delay time (double reflection time). Both electrical conductivity (material's ability to conduct electric current) and dielectric permittivity (material's ability to store electrical energy in an electric field) are important, as they directly affect the attenuation and propagation of radar waves, respectively (Annan 1996).

Several studies have employed these techniques to improve our understanding of tree root systems. For instance, Rinn (2016) employed sonic tomography to map the root system of a maple tree, and the results were validated with site excavation. The tomography detected roots with a minimum diameter of 3 cm and no deeper than 30 cm in depth, consistent with direct measurements. Proto et al. (2020) compared sonic tomography data with a 3D root model scanned after soil removal. The coarse root distribution, as determined by sonic velocity, showed a good correlation within 30 cm of the trunk. However, this correlation diminished with distance, becoming insignificant beyond 1.20 m, and did not correlate with root diameter. Mary et al. (2015) explored the use of ultrasound to detect and map tree roots, conducting laboratory experiments to assess propagation properties and amplitude attenuation for differentiating roots from soil.

Using the GPR method, Nichols et al. (2017) conducted a study to locate and categorize tree roots beneath 3 different types of permeable urban pavements. Their results indicated that GPR could reliably determine tree root size and depth under pavements with minimal error. Fini et al. (2022) investigated the effects of pavements on urban trees through a 5-year experiment, utilizing GPR to map root growth in the subsoil. Rocha et al. (2024) proposed a GPR signal processing workflow to estimate the root diameter of 3 tropical forest tree species, achieving an accuracy of 96% in coarse root diameter estimation.

To address the limited understanding of urban tree root systems, this study compares sonic tomography and GPR, evaluating the advantages and disadvantages of each method. By superimposing results, we provide a qualitative interpretation of root distribution. In addition, we developed a kriging interpolation algorithm to enhance the visualization and interpretation of tomography data, generating a map of velocity distribution and measurement errors.

MATERIALS AND METHODS

Study Site and Data Acquisition

Two sites were selected for data acquisition with the mechanical impulse tomograph and GPR. The trees are planted along concrete pavements, the soil is typically clayey and compacted, and urban infrastructure such as inspection boxes and lighting poles are readily visible. These trees often have a small planting area with limited permeable surface or are even contained within raised beds. The first site was a sidewalk in the Escola Superior de Agricultura "Luiz de Queiroz" – USP (ESALQ/USP) Campus, Soil Science Department, Piracicaba, São Paulo, Brazil, with 2 specimens of *Cenostigma pluviosum (DC.)* Gagnon & G.P.Lewis (basionym *Caesalpinia pluviosa DC.*), a native tree with dense wood (0.978 g/cm³) widely used in urban afforestation in Brazilian cities. It can reach up to 28 m in height and a diameter at breast height (DBH) of 50 cm in adulthood. This species adapts well to soils of medium chemical fertility, is highly resistant to pests and diseases, and is fast growing (Carvalho 2003). Here, the *C. pluviosum* were labeled as 'A' (Figure 1a) and 'B' (Figure 1b), with DBHs of 47 cm and 37 cm and heights of 13 m and 11 m, respectively. Fruiting bodies of *Ganoderma* sp., a wood-decaying fungus, were present at the basal region of both trees, as highlighted in each image.

The second site chosen was Floriano Peixoto Square in the city of Mogi Mirim, São Paulo, Brazil. The square has a tree cover composed of different tree species, benches for resting, bus stops, and local commerce and is part of the Nossa Senhora do Carmo Historical Church complex. Three species were selected for data acquisition: *Ficus guaranitica* Chodat (Figure 1c), *Cariniana legalis* (Mart.) Kuntze (Figure 1d), and *Ficus religiosa* L. (Figure 1e). *Ficus guaranitica* is a native South American tree and belongs to the *Moraceae* family. It has an average height between 10 m and 20 m, a girth of 1-m DBH, and has a light and soft wood (0.40 g/cm³). It is usually found in Central Brazilian Savanna and Atlantic Rainforest ecosystems (REFLORA [date unknown]). *Cariniana legalis*, a native Brazilian species, can reach 50 m in height and a DBH of up to 7 m (Lorenzi 2002). It prefers soils with suitable physical properties (compaction, texture, structure, porosity, moisture content, good chemical fertility, well-drained) and has moderately dense wood (0.50 g/cm³ to 0.65 g/cm³). *Ficus religiosa* is an ornamental tree native from India. It can grow to over 30 m in height and has numerous adventitious roots that wrap around the stem. The species is tolerant of different climates and soils, being cultivated in many places around the world and widely used in medicine in Southeast Asia (Kumari et al. 2022).

The *F. guaranitica* specimen evaluated is a young tree with a DBH of 40 cm and an estimated height of 10 m. It is located in a small, raised flowerbed with a diameter of 1.6 m and a height of 0.45 m. The *C. legalis* has a DBH of 89 cm and a height of 28 m. It is also in a raised flowerbed, approximately 0.45 m high from the square's surface level. The *F. religiosa* has a DBH of 1.78 m and an approximate height of 29 m. The tree is located in a flowerbed at ground level in the square with an approximate diameter of 3.5 m.

For data acquisition with mechanical impulse tomography, the Arbotom® (Rinntech®, Heidelberg, Baden-Wuerttemberg, Germany) was employed with a total of 16 sensors available, plus an extra sensor within the Arboradix™ (Rinntech®, Heidelberg, Baden-Wuerttemberg, Germany) equipment. The number of sensors placed in each tree specimen varies depending on the tree's DBH. Each measurement point was spaced 1 m apart, combining data acquisition time with result resolution, covering the entire area around the tree. For the GPR method, a 900-MHz antenna and SIR® 4000 controller (Geophysical Survey Systems, Inc., Nashua, NH, USA) were used. The mapped

Figure 1. Specimens selected for the study. (a) *C. pluviosum* 'A' (sidewalk). (b) *C. pluviosum* 'B' (sidewalk). (c) *F. guaranitica* (Floriano Peixoto Square). (d) *C. legalis* (Floriano Peixoto Square). (e) *F. religiosa* (Floriano Peixoto Square).

areas also have variable dimensions, according to the operational conditions of each tree, and 2D GPR profiles were acquired in both directions according to ANDAS technology for data acquisition and processing (Santos et al. 2022).

Data Interpolation: Sonic Tomography

As previously mentioned, the Arboradix™ root tomograph provides the distribution of mechanical wave propagation velocities generated at predetermined positions. The device outputs a graph displaying lines between the sensor fixed on the tree and the wave-generating source, with each color representing a specific range of velocity values (Figure 2a). At the end of the data acquisition process, the software produces a star-like shape illustrating the velocities and their respective positions. However, when a large number of sensors and measurement positions are used, the resulting figure can appear cluttered, with superimposing lines in various colors, making interpretation challenging. To enhance visualization and facilitate comparison with GPR data, an algorithm was developed to interpolate these velocities using the kriging method. This process utilizes the numerical data file generated by the equipment, which contains measurement positions, velocities, and associated errors.

Sonic root tomography uses a mechanical wave source generated by taps to a steel rod with a hammer and receivers affixed to the basal region of the tree. The rod is kept in contact with the soil surface and measurements are collected at predetermined points. Increasing the number of acquisition points improves the resolution of the results but also increases the execution time. If a root is present at the measurement point, the mechanical wave reaches the receivers in less time. By using the transit time and distance, the propagation velocity of the wave can be determined. A higher velocity increases the likelihood of a root being present underground.

The errors are associated with the number of taps on a steel rod, and the magnitude of the error tends to decrease as the number of taps increases. In this work, a minimum of 10 taps per point was adopted to ensure the lowest measurement error. However, depending on the distance from the tree, this value remained high, indicating the absence of roots at that location or the dissipation of the wave by the medium. Therefore, the best way to interpret the data is to relate the measured velocity to the respective error, as a higher velocity with a lower error tends to indicate the presence of a root at that point.

Kriging is an interpolation method widely used in geostatistics analysis to predict spatial data. The estimate considers the autocorrelation characteristics of regionalized variables, i.e., those that have spatial dependence. If these variables have some continuity or spatial variance, this allows the data obtained by sampling specific points to be used to parameterize the estimate of points where the value of the variable is unknown (Hengl 2007). The only way to verify this continuity is through the variogram, which determines parameters that characterize this regionalized behavior, measuring the variation in the value of a variable in relation to the others from the same sample. More details about the interpolation using kriging method can be found in Kitanidis (1997).

The algorithm was developed in Python 3.11 (Python Software Foundation, Wilmington, DE, USA), using the PyKrige toolkit (Murphy et al. 2024). The input data is the coordinates of the X and Y measurement points and their respective velocities and errors. At the end of interpolation, maps are returned with the distribution of the mechanical wave propagation velocities (Figure 2b) and the error related to the measurement (Figure 2c). In the example shown in Figure 2, the eastern region of the tree showed a higher propagation velocity, as can be seen by the black, brown, and green lines. With interpolation, it is easier to identify this region (white dotted line in Figure 2b, smaller circle), which corresponds to a greater presence of roots in the subsoil, and it is possible to determine a zone of greater coverage of the root system (white dashed line, bigger circle), which in the case shown is approximately within a radius of 3 m from the tree. To improve interpretation, it is recommended to use the information from the measurement errors, which indicate whether the value found at that position is reliable. In the example, at a distance of 5 m from the tree, the measured velocities exhibit an error greater than 50%.

RESULTS AND DISCUSSION

The results obtained from the sonic tomograph and GPR for the studied specimens are presented below. In this study, to enhance visualization, the processing software was configured to limit velocities between 0 m/s and 500 m/s and use 5 distinct colors for the lines. For interpolation, the values from the data files

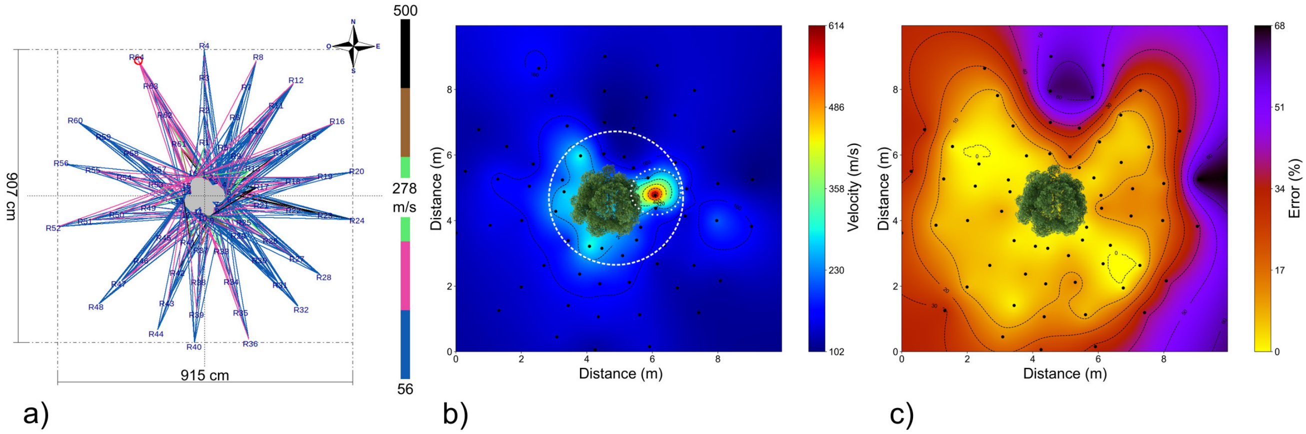

Figure 2. Example of data interpolation using kriging method. (a) Arboradix™ velocities (m/s) result. (b) Interpolated velocities (m/s) with coverage of the root system (white dashed line). (c) Interpolated error (%).

Table 1. Summary of data acquisition with sonic tomography and GPR. GRP (ground penetrating radar).

Sonic tomography			
Species	**Area dimension (m)**	**Number of points**	**Time (minutes)**
Cenostigma pluviosum 'A'	7.78 × 8.13	26	30
Cenostigma pluviosum 'B'	8.35 × 7.61	28	30
Ficus guaranitica	10.01 × 10.15	43	45
Cariniana legalis	10.55 × 10.76	47	80
Ficus religiosa	12.11 × 11.26	62	90
GPR			
Species	**Area dimension (m)**	**Number of profiles**	**Time (minutes)**
Cenostigma pluviosum 'A'	6 × 6	189	110
Cenostigma pluviosum 'B'	4 × 6	150	80
Ficus guaranitica	5 × 5	72	40
Cariniana legalis	6 × 7	119	100
Ficus religiosa	8 × 5	106	120

exported by the equipment were used. Table 1 shows a summary of the dimensions of each area, number of points and profiles acquired, and acquisition time for both methodologies.

Figure 3 shows the velocities distribution and measurement errors for *C. pluviosum* 'A' and 'B'. The data acquisition was carried out on the sidewalk and pavement. The highest velocities found by Arboradix™ (Figure 3a), corresponding to the black and brown lines, were in the western part of the tree, concentrated on the sidewalk. The maps containing the data and the measurement errors can be seen in Figure 3b and 3c, respectively. By the interpolation, the velocity varied between 1 m/s and 960 m/s, and, like the 'star' graph, the highest velocities are in the western part of the sample area. From the images generated, it is possible to obtain the root presence in the subsurface, which in the case of *C. pluviosum* 'A' is

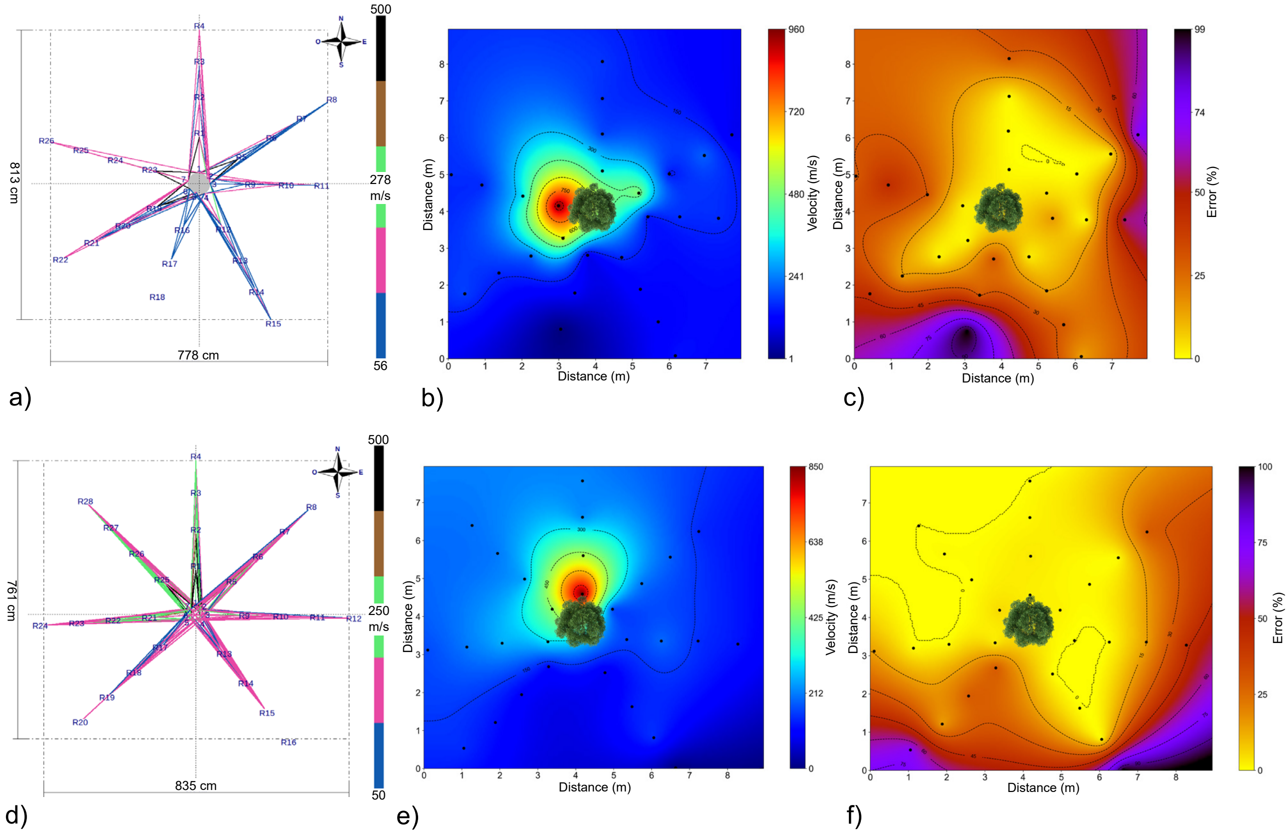

Figure 3. Sonic tomography results. (a) Arboradix™ velocities (m/s) for *C. pluviosum* 'A'. (b) Interpolated velocities (m/s) for *C. pluviosum* 'A'. (c) Interpolated error (%) for *C. pluviosum* 'A'. (d) Arboradix™ velocities (m/s) for *C. pluviosum* 'B'. (e) Interpolated velocities (m/s) for *C. pluviosum* 'B'. (f) Interpolated error (%) for *C. pluviosum* 'B'.

between 2 m and 3 m from the tree, with errors of less than 10%.

For the *C. pluviosum* 'B' the highest velocities (black/brown lines) were found on the sidewalk in the northern part of the area (Figure 3d). The interpolated velocities ranged from 0 m/s to 850 m/s (Figure 3e), with a root radius of approximately 2 m and errors of up to 5% (Figure 3f). Data acquisition took approximately 30 minutes for each specimen, since they were smaller individuals, the number of points was relatively low, and the location was easy to access.

With the GPR method, it is possible to obtain the spatial distribution, depth, and diameters of the mapped roots. The results found for *C. pluviosum* 'A' and 'B' are shown in Figure 4, the acquisition grid 'A' comprising the sidewalk and pavement areas too. Figure 4a shows the distribution of roots in relation to their depth and Figure 4b shows the same distribution but as a function of the diameter found. The specimen shows a root system just over 2 m long in relation to the tree, varying between 0.12 m and 0.40 m deep with diameters between 3 cm and 9 cm and located entirely in the sidewalk area. A pipe/wire (blue line) and an infrastructure box (white square) connected to this pipe/wire were also identified at the site. The data collection was carried out in 110 minutes.

Figure 4c and 4d show the results of the GPR application on *C. pluviosum* 'B'. The depth of the root system varied between 0.12 m and 0.30 m with diameters between 3 cm and 11 cm. Two roots near the tree were found under the pavement. In addition to the roots, a pipe/cable was also identified in the analyzed area. The acquisition lasted 80 minutes.

The superimposing results of both methodologies for specimens 'A' and 'B' are shown in Figures 5a and 5b, respectively. The highest root densities detected by GPR correspond to the regions of highest velocities obtained through tomography, west of *C. pluviosum* 'A' and north of 'B', demonstrating consistency between the methods. According to Guardia (2020), the type of surface covering the roots can influence mechanical wave propagation. Cohesive and homogeneous materials, such as concrete or asphalt, facilitate wave transmission, reducing propagation time and increasing velocity. In contrast, natural soils, especially when covered with grass or other ground cover plants, have a heterogeneous and porous structure that can dissipate part of the wave energy, reducing propagation velocity.

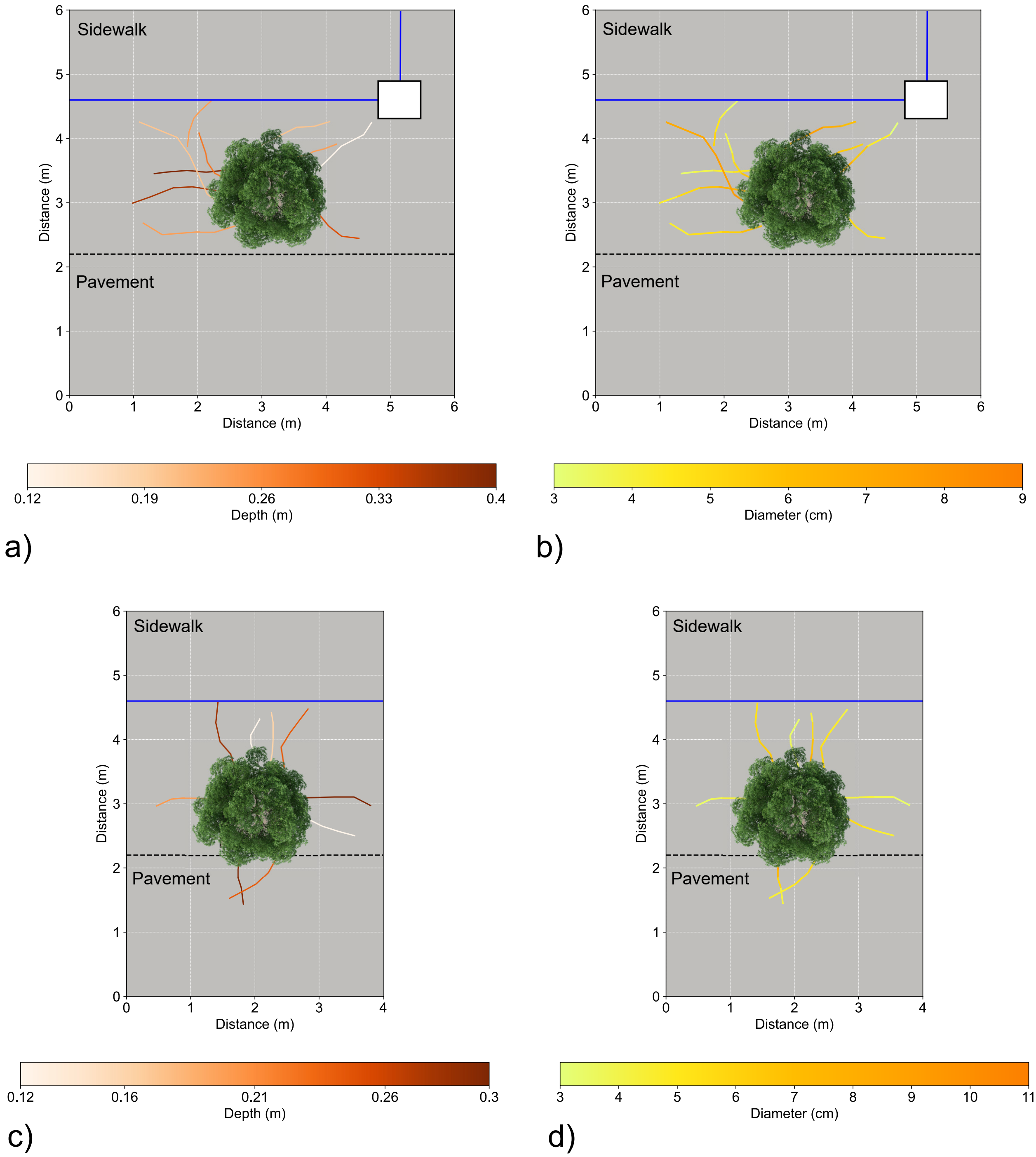

Figure 4. GPR results. (a) Depth spatial distribution for *C. pluviosum* 'A'. (b) Diameter spatial distribution for *C. pluviosum* 'A'. (c) Depth spatial distribution for *C. pluviosum* 'B'. (d) Diameter spatial distribution for *C. pluviosum* 'B'.

For specimens 'A' and 'B,' both conditions are present, as parts of the surface consist of grass/soil while others are covered with concrete/asphalt. Another important aspect of the tomograph is the investigated depth. Roots identified by GPR but exhibiting low velocities in tomography are located at depths between 0.26 m and 0.40 m, indicating a possible discrepancy between the 2 methods at these depths.

The results of the sonic tomography scans carried out in the Floriano Peixoto Square can be seen in Figure 6. In *F. guaranitica*, 43 measurement points were acquired, and most of the lines have velocities between 125 m/s and 250 m/s in pink and green colors (Figure 6a). Interpolation (Figure 6b) allows for identifying the region with the highest velocity, which is concentrated within a distance of up to 3 m from the tree, with errors ranging between 5% and 7% (Figure 6c). Data collection was completed in 45 minutes.

For the *C. legalis* specimen there is a predominance of low speeds in blue and pink colors (Figure 6d). The interpolation (Figure 6e) shows that velocity near the tree reached a maximum of approximately 300 m/s, with only one measurement point showing a value close to 420 m/s and errors of less than 15% (Figure 6f). In addition, point R36 showed the highest measured velocity (504 m/s) but with an error of more than 75%, showing no reliability in this measurement, which may be related to the distance from the tree or the composition of the surface and soil. The acquisition time was approximately 80 minutes.

As for *F. religiosa*, it is a large specimen and has 62 measurement points, also showing low values for the propagation velocity of the mechanical wave, with pink and green lines and a maximum value of approximately 400 m/s (Figure 6g). From the interpolated data (Figure 6h) it was not possible to delimit the region where the roots occur, as in the other cases, because in certain regions peaks appear with maximum and minimum values, corresponding to errors greater than 60% (Figure 6i). The data collection was carried out in 90 minutes.

The results of applying the GPR method to the 3 trees in the Floriano Peixoto Square can be seen in Figure 7. The acquisition grid for the *F. guaranitica* specimen was 5 m × 5 m, with 72 profiles acquired and an acquisition time of 40 minutes. The depth of the root system varied between 0.06 m and 0.5 m (Figure 7a), with diameters between 3 cm and 7 cm (Figure 7b). The roots had a radial distribution, developing all around the tree, despite the confinement caused by the size of the flowerbed in which it is located. For *C. legalis*, the grid is 6 m × 7 m, and a total of 119 GPR profiles were acquired. The roots are found at a depth between 0.17 m and 0.5 m (Figure

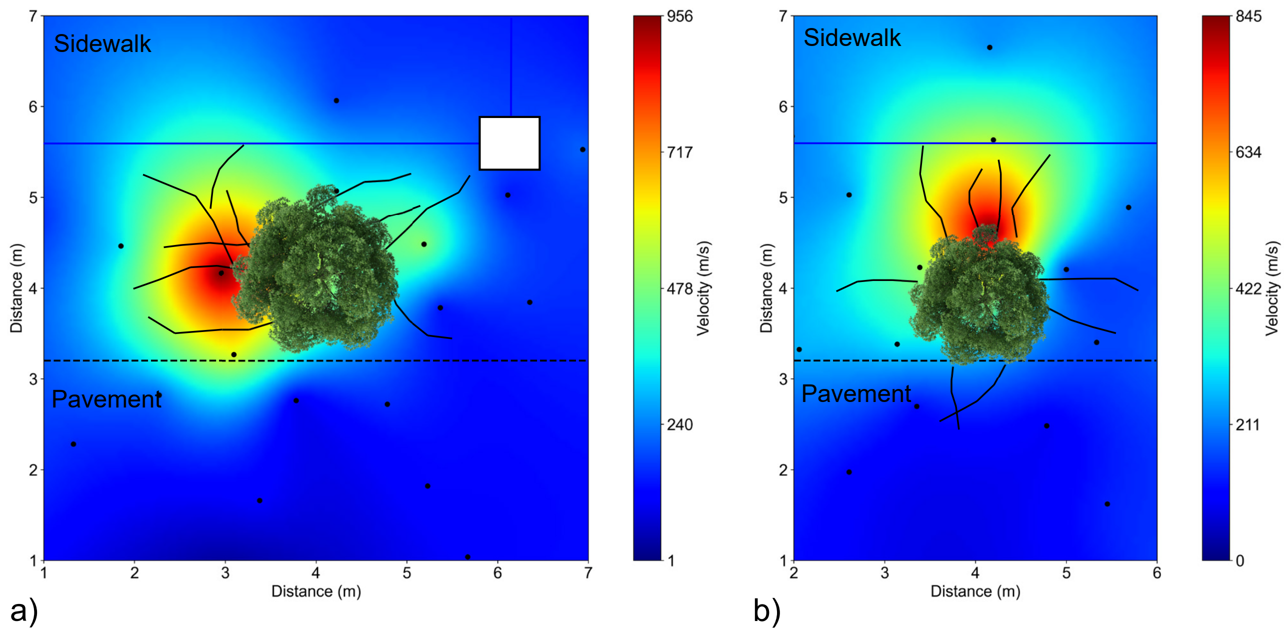

Figure 5. Superimposed images between sonic tomography and GPR methods. (a) *C. pluviosum* 'A'. (b) *C. pluviosum* 'B'.

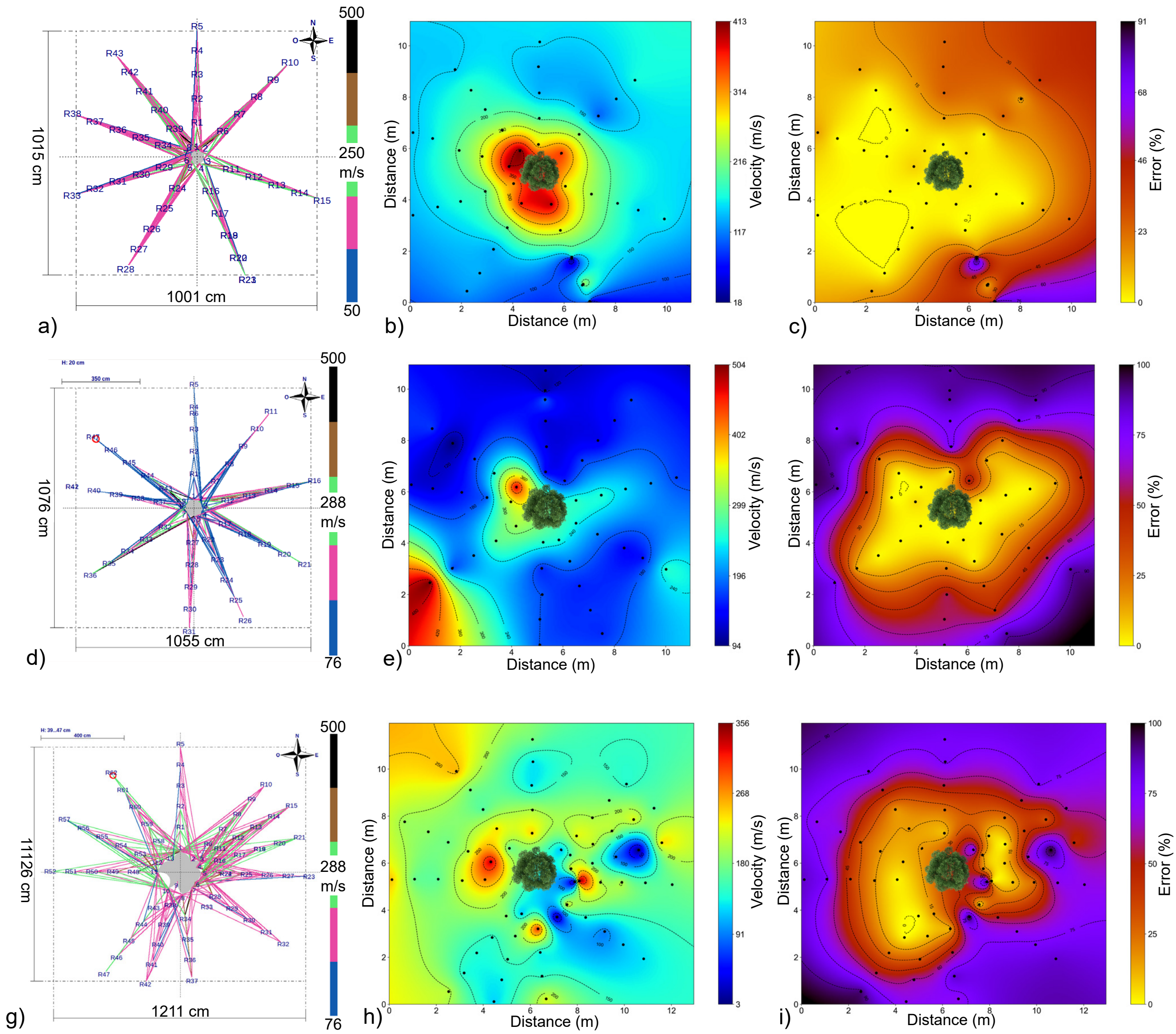

Figure 6. Floriano Peixoto Square results using sonic tomography. (a) Arboradix™ velocities (m/s) for *F. guaranitica*. (b) Interpolated velocities (m/s) for *F. guaranitica*. (c) Interpolated error (%) for *F. guaranitica*. d) Arboradix™ velocities (m/s) for *C. legalis*. (e) Interpolated velocities (m/s) for *C. legalis*. (f) Interpolated error (%) for *C. legalis*. (g) Arboradix™ velocities (m/s) for *F. religiosa*. (h) Interpolated velocities (m/s) for *F. religiosa*. (i) Interpolated error (%) for *F. religiosa*.

7c) and diameters of between 4 cm and 10 cm (Figure 7d), being more concentrated within the flowerbed where it is found. Some deeper and thicker roots expanded beyond the planting site. The total time taken to acquire data on the flowerbed and at ground level was 100 minutes. GPR data acquisition on the *F. religiosa* specimen covered an area of 8 m × 5 m, with 106 profiles in total and a data collection time of 120 minutes. The root system is well-distributed and spreads all around the tree, varying between 0.11 m and 0.6 m deep (Figure 7e) with diameters ranging from 3 cm to 9 cm (Figure 7f).

The superimposed images are shown in Figure 8. In *F. guaranitica* (Figure 8a), due to the presence of the raised flowerbed, there was no continuity of the mapped roots by GPR from the central point where the tree is located, coinciding with the region of highest velocity in the tomography. However, there is an agreement between the methodologies used, since the tomography shows this inverse behavior of

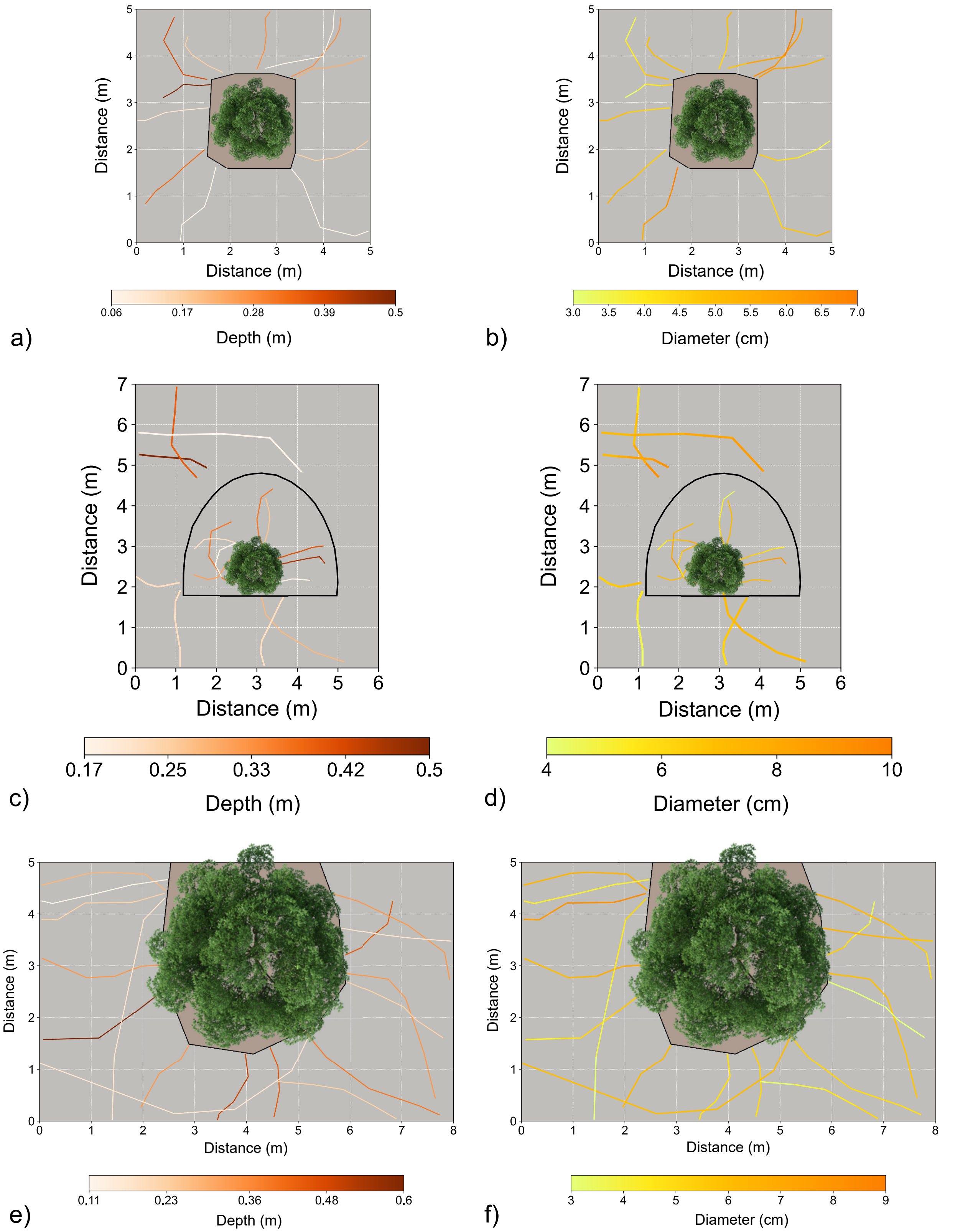

Figure 7. Floriano Peixoto Square results using GPR. (a) Depth spatial distribution for *F. guaranitica*. (b) Diameter spatial distribution for *F. guaranitica*. (c) Depth spatial distribution for *C. legalis*. (d) Diameter spatial distribution for *C. legalis*. (e) Depth spatial distribution for *F. religiosa*. (f) Diameter spatial distribution for *F. religiosa*.

decreasing velocity with increasing distance due to the fact that there are roots in the subsoil that extend beyond 2 m in relation to the tree.

Figure 8b shows the superimposed for *C. legalis*, which is also on a raised flowerbed. Within a radius of 1 m from the tree, above the flowerbed, some shallow roots were mapped between 0.17 m and 0.20 m deep, which were indicated with higher velocities by the sonic tomography, ranging from 265 m/a to 503 m/s. Some roots were also found below ground level, being further away and at a greater depth, which consequently showed velocities of less than 200 m/s.

The *F. religiosa* tree (Figure 8c) was the only specimen where sonic tomography and GPR data disagreed. While GPR mapped several roots around the tree, as well as in the flowerbed, continuity between the root system and the tree's central point was absent, similar to the *F. guaranitica*. This discontinuity was likely due to the flowerbed, where GPR data could not be collected. However, the distribution of velocities is not similar to the others, with higher velocities near the tree, and by analyzing the measurement errors it can be seen that there are points with errors of more than 75% and at a distance of 1 m (R6, R22, R24, and R33).

Table 2 presents the final comparison based on the parameters obtained during data acquisition and processing for both sonic tomography and GPR. These methodologies differ in the type of source used

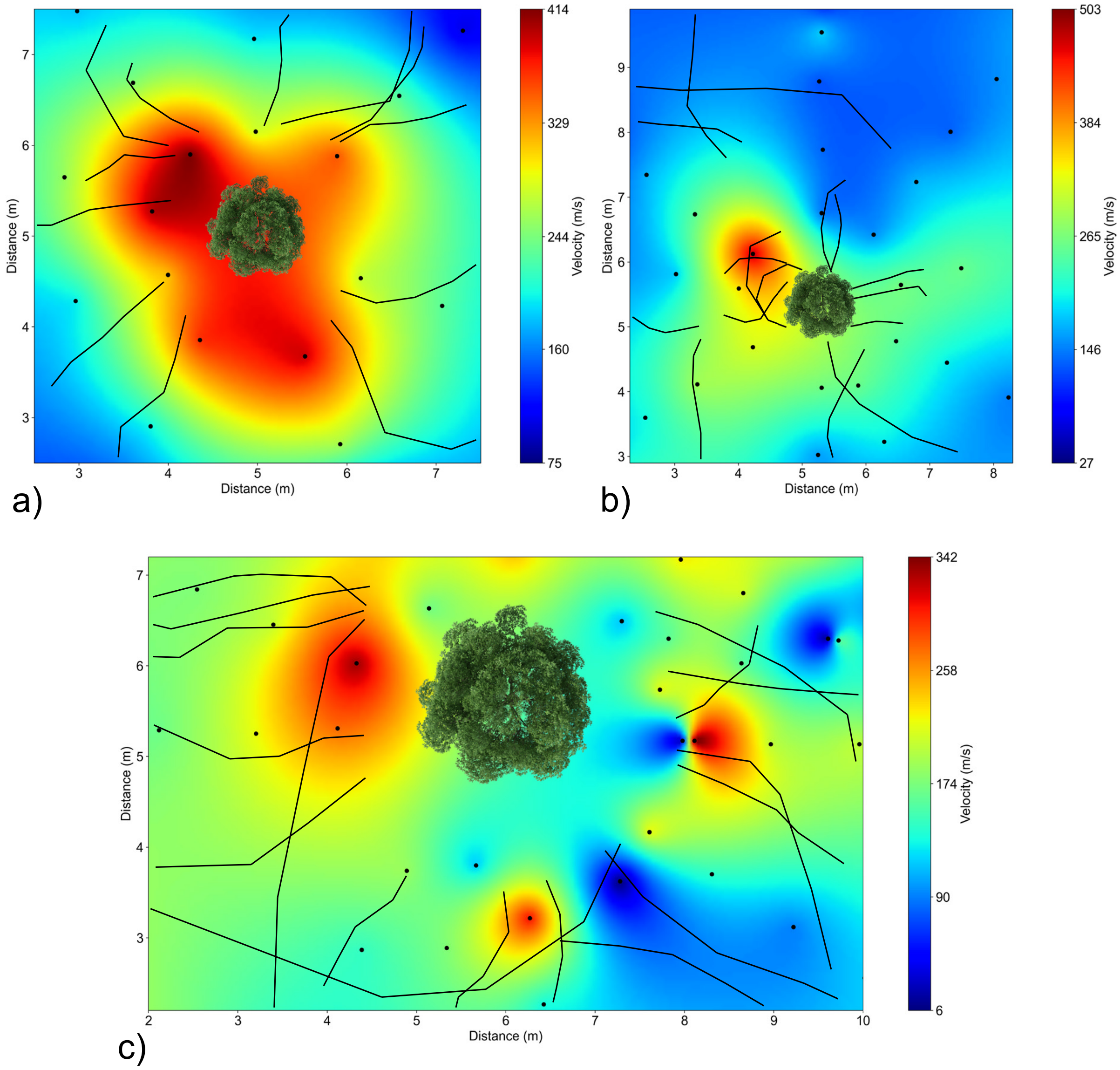

Figure 8. Superimposed images between sonic tomography and GPR methods. (a) *F. guaranitica*. (b) *C. legalis*. (c) *F. religiosa*.

Table 2. Comparison of sonic tomography and GPR methods. GPR (ground penetrating radar).

	Sonic tomography	**GPR**
Type of source	**Mechanical**	**Electromagnetic**
Root parameters	Velocity (density)	Position / depth / diameter
Acquisition time	Low	High
Data processing	No	Yes
Data resolution	Low	High
Urban applications	Yes	Yes
Type of ground	Sensitive	Not sensitive
Type of soil	Sensitive	Very sensitive
Soil moisture content	Sensitive	Very sensitive
Infrastructure mapping	No	Yes
Ambiguities	No	Yes

(mechanical in tomography and electromagnetic radiation in GPR), which affects the physical properties analyzed. Sonic tomography measures the propagation velocity of mechanical waves, allowing the identification of root system regions and the assessment of wood quality. Higher velocities indicate greater density, suggesting a better-preserved wood structure. In contrast, GPR employs 2D profiles acquired around the tree, arranged parallel to each other and in both directions, to generate a 3D representation of root distribution. This method provides information on root position, depth, and diameter but is primarily effective for detecting larger structures, typically those exceeding 2 cm to 3 cm in diameter.

As far as acquisition time is concerned, tomography usually takes less time to survey, as it is carried out using only points defined around the tree. Ground penetrating radar (GPR), on the other hand, requires profiles to be acquired by walking with the equipment coupled to the ground, which leads to a longer acquisition time. The time spent collecting data is related to the resolution of the results you want to obtain, since a greater number of points/profiles increases the resolution. But in general, tomography has a lower resolution when compared to GPR, since it is only points that define the acquisition, and the product is a region of root occurrence, unlike GPR, which can identify individual roots. However, data processing is necessary after collection through frequency filters and/or gain, for example, in order to improve the generated images.

Both methods can be applied in the urban environment, but it is necessary to be aware of the ground and soil types where the surveys will be carried out. Regarding the type of ground, tomography is more sensitive because there are distortions in the velocity caused by cohesion and homogeneity differences due to the constitution of surface such as grass/soil and concrete/asphalt (Guardia 2020; Proto et al. 2020). As for GPR, the quality of the data is not compromised by this factor, but the medium being assessed does influence the results; for example, very conductive or moist soils tend to shield the electromagnetic signal, increasing attenuation and consequently reducing the depth of investigation, compromising the results. Another very common element in the urban environment is buried infrastructure, such as pipes and cables, which can interact with tree roots and which are easily identified using the GPR method, unlike tomography, but ambiguities can occur between different types of mapped targets or even between very close roots that cause a single anomaly in the GPR.

CONCLUSION

The aim of this study was to compare sonic tomography and GPR applied to the roots of urban trees. Data were acquired from 5 specimens, 2 on a sidewalk (*C. pluviosum*) and 3 in a square (*F. guaranitica*, *C. legalis*, and *F. religiosa*). The tomography data was interpolated using the kriging method to improve the visualization of the velocity distributions and then compare with the GPR results, which provide the spatial distribution, depth, and diameter of the roots. Four of the five trees showed good agreement between both methodologies, regarding the high velocity found by the tomograph and the roots mapped by the GPR, with only *F. religiosa* not showing these patterns. Both methods can and should be applied in urban forestry to gain a better understanding of the root system of trees, but tomography can be used more comprehensively and quickly to provide information on the occurrence of roots; however, it has limitations with certain types of ground and in relation to the distance of the measurement point from the tree, and a more targeted study of this aspect would be worthwhile. Ground penetrating radar (GPR), on the other hand, can provide more information on the distribution of the root system in the soil as it is a high-resolution method, although it takes longer to acquire and is highly dependent on the soil type.

LITERATURE CITED

Annan AP. 1996. Transmission dispersion and GPR. *Journal of Environmental and Engineering Geophysics*. 1(B):125-136. https://doi.org/10.4133/JEEG1.B.125

Arciniegas A, Prieto F, Brancheriau L, Lasaygues P. 2014. Literature review of acoustic and ultrasonic tomography in standing trees. *Trees*. 28:1559-1567. https://doi.org/10.1007/s00468-014-1062-6

Carvalho PER. 2003. *Espécies arbóreas brasileiras*. Volume 1. Brasília (Brazil): Embrapa. 1044 p. https://www.embrapa.br/florestas/publicacoes/especies-arboreas-brasileiras

Cavalari AA, Velasco GDN, da Silva-Luz CL, Rosa AS, Waetge ADAN, Barbosa EDS, Biazzo FCM, Kavamura HE, da Silva Filho CA, Silva EBDFB, Locosselli GM. 2024. Predicting tree failure to define roles and guidelines in risk management, a case study in São Paulo/Brazil. *Urban Forestry & Urban Greening*. 91:128181. https://doi.org/10.1016/j.ufug.2023.128181

Comin S, Vigevani I, Fini A. 2021. Non-invasive methods for the investigation of trees' root system in the urban environment. *Italus Hortus*. 28(2):37-57. https://doi.org/10.26353/j.itahort/2021.2.3757

Daniels DJ. 2004. *Ground penetrating radar*. 2nd Ed. IET Radar, Sonar, Navigation and Avionics Series. Vol. 15. Stevenage, Hertfordshire (United Kingdom): The Institution of Engineering and Technology. 752 p. https://doi.org/10.1049/PBRA015E

Deflorio G, Fink S, Schwarze FWMR. 2008. Detection of incipient decay in tree steams with sonic tomography after wounding and fungal inoculation. *Wood Science and Technology*. 42:117-132. https://doi.org/10.1007/s00226-007-0159-0

Detter A, Rust S, Krišāns O. 2023. Experimental test of non-destructive methods to assess the anchorage of trees. *Forests*. 14(3):533. https://doi.org/10.3390/f14030533

Fini A, Frangi P, Comin S, Vigevani, I, Rettori AA, Brunetti C, Moura BB, Ferrini F. 2022. Effects of pavements on established urban trees: Growth, physiology, ecosystem services and disservices. *Landscape and Urban Planning*. 226:104501. https://doi.org/10.1016/j.landurbplan.2022.104501

Grabosky J, Pattanshetti, S, Zhang T, Blake T, Casario B, Koeser A, Miesbauer J. 2025. Testing a modified pipe model approach to predict cross-sectional area of tree roots at specific distances from the tree. *Arboriculture & Urban Forestry*. 51(1):14-28. https://doi.org/10.48044/jauf.2024.027

Gregory PJ. 2006. *Plant roots: Growth, activity and interactions with the soil*. 1st Ed. Hoboken (NJ, USA): Wiley-Blackwell. 352 p. https://doi.org/10.1002/9780470995563

Guardia I. 2020. Velocidade de onda mecânica na avaliação de raízes de ancoragem de árvores nas cidades [dissertação de mestrado]. Piracicaba, São Paulo (Brazil): Escola Superior de Agricultura Luiz de Queiroz/USP. 160 p. https://doi.org/10.11606/D.11.2020.tde-16072020-115909

Hengl T. 2007. A practical guide to geostatistical mapping of environmental variables. JRC Scientific and Technical Reports. Ispra (Italy): European Commission, Joint Research Centre, Institute for Environment and Sustainability. 143 p. https://esdac.jrc.ec.europa.eu/content/practical-guide-geostatistical-mapping-environmental-variables

Kitanidis PK. 1997. *Introduction to geostatistics: Applications in hidrogeology*. Cambridge (United Kingdom): Cambridge University Press. 272 p. https://doi.org/10.1017/CBO9780511626166

Kumari K, Jangir S, Prajaptai V, Ratan R, Rastogi S, Prajapati VM, Shrivastava S, Tater R. 2022. A review on Ficus religiosa moraceae: Distribution, traditional uses and pharmacological properties. *Journal of Biomedical and Pharmaceutical Research*. 11(5):45-54. https://doi.org/10.32553/jbpr.v11i5.925

Lorenzi H. 2002. *Árvores brasileiras: Manual de identificação e cultivo de plantas arbóreas nativas do Brasil*. 2nd Ed. Vol. 2. Nova Odessa (Brazil): Instituto Plantarum. 368 p.

Mary B, Saracco G, Peyras L, Vennetier M, Mériaux P, Baden D. 2015. Preliminary use of ultrasonic tomography measurement to map tree roots growing in earth dikes. *Physics Procedia*. 70:965-969. https://doi.org/10.1016/j.phpro.2015.08.201

Miesbauer JW, Koeser AK, Kane B. 2025. Impact of trenching on root loss and tree stability. *Arboriculture & Urban Forestry*. 51(1):94-102. https://doi.org/10.48044/jauf.2024.026

Mullaney J, Lucke, T, Trueman SJ. 2015. A review of benefits and challenges in growing street trees in paved urban environments. *Landscape and Urban Planning*. 134:157-166. https://doi.org/10.1016/j.landurbplan.2014.10.013

Murphy B, Yurchak R, Müller S. 2024. GeoStat-Framework/PyKrige: v1.7.2 [Software]. Meyrin, Geneva (Switzerland): Zenodo, CERN. https://doi.org/10.5281/zenodo.11360184

Nichols P, McCallum A, Lucke T. 2017. Using ground penetrating radar to locate and categorise tree roots under urban pavements. *Urban Forestry & Urban Greening*. 27:9-14. https://doi.org/10.1016/j.ufug.2017.06.019

Pereira B. 2017. Análise dos efeitos do entorno urbano sobre o sistema radicular de árvores viárias de São Mateus do Sul – Paraná. Curitiba, Paraná (Brazil): Universidade Tecnológica Federal do Paraná. 103 p. https://repositorio.utfpr.edu.br/jspui/bitstream/1/11011/2/DV_COENF_2017_1_04.pdf

Proto AR, Di Iorio A, Abenavoli LM, Sorgoná A. 2020. A sonic root detector for revealing tree coarse root distribution. *Scientific Reports*. 10:8075. https://doi.org/10.1038/s41598-020-65047-4

Rahman MA, Armson D, Ennos AR. 2014. Effect of urbanization and climate change in the rooting zone on the growth and physiology of *Pyrus calleryana*. *Urban Forestry & Urban Greening*. 13(2):325-335. https://doi.org/10.1016/j.ufug.2013.10.004

REFLORA. [date unknown]. REFLORA – Plantas do Brasil: Resgate histórico e herbário virtual para o conhecimento e conservação da flora Brasileira. Rio de Janeiro (Brazil): Botanical Garden Research Institute of Rio de Janeiro. [Accessed 2024 July 16]. https://reflora.jbrj.gov.br/reflora/PrincipalUC/PrincipalUC.do?lingua=pt

Rinn F. 2016. Tree root plate assessment by sounding. *Western Arborist*. Fall:26-29. https://dunster.ca/wp-content/uploads/2016/10/RINN_SonicRootInspection_WesternArborist_Fall_2016.pdf

Rinntech®. 2012. ARBOTOM® 3-D tree impulse tomograph. [User manual]. Heidelberg (Germany): Frank Rinn. 57 p.

Rizzardi S, Calvo GH. 2019. Sistema radicular de los árboles en âmbitos urbanos. *Terra Mundus*. 5(1). https://publicacionescientificas.uces.edu.ar/index.php/terramundus/article/view/552/596

Rocha AA, Borges WR, Von Huelsen MG, e Sousa FRFRDO, Maciel STR, Rocha JDA, Jacobson TKB. 2024. Imaging tree root systems using ground penetrating radar (GPR) data in Brazil. *Frontiers in Earth Science*. 12. https://doi.org/10.3389/feart.2024.1353572

Santos VRND, Almeida ER, Porsani JL, Teixeira FL, Soldovieri F. 2018. A controlled-site comparison of microwave tomography and time-reversal imaging techniques for GPR surveys. *Remote Sensing*. 10(2):214. https://doi.org/10.3390/rs10020214

Santos VRND, Caetano MF, Martinatti M, Pereira JM. 2022. Tecnologia "ANDAS" para mapeamento 3D do sistema radicular de árvores utilizando georadar e eletrorresistividade. *Revista da Sociedade Brasileira de Arborização Urbana*. 17(1):17-36. http://doi.org/10.5380/revsbau.v17i1.84535

Santos VRN, Filho DFDS. 2024. Tree roots GPR detection based on 3-D time-reversal signal processing. *IEEE Geoscience and Remote Sensing Letters*. 21:1-4. http://doi.org/10.1109/LGRS.2024.3463497

Shi F, Meng Q, Pan L, Wang J. 2024. Key factors influencing street tree root conflicts with planting pits and sidewalks in old Guangzhou, China. *Urban Forestry & Urban Greening*. 101:128538. https://doi.org/10.1016/j.ufug.2024.128538

Smulski SJ. 1991. Relationship of stress wave- and static bending-determined properties of four Northeastern hardwoods. *Wood and Fiber Science*. 23(1):44-57. https://wfs.swst.org/index.php/wfs/article/download/1290/1290/0

Urban J. 2008. *Up by roots: Healthy soils and tree in the built environment*. Champaign (IL, USA): International Society of Arboriculture. 479 p. https://www.jamesurban.net/up-by-roots

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Résumé. Contexte: Le boisement urbain est largement reconnu pour ses multiples bénéfices esthétiques et fonctionnels, tant pour la population que pour l'environnement. Cependant, une mauvaise planification, partant d'une sélection inappropriée des espèces à une gestion inadéquate de l'entretien des arbres, peut entraîner divers problèmes, notamment des incidents causés par la chute d'arbres. Ces événements résultent souvent d'une défaillance des racines, d'un système racinaire sous-développé ou d'une dégradation avancée de l'état de l'arbre. Méthodes: Pour évaluer le système racinaire d'un arbre, des méthodes indirectes sont recommandées, particulièrement dans les milieux urbains comportant des trottoirs ou des chaussées. Les techniques telles que la tomographie sonique et le radar à pénétration de sol (RPS) possèdent chacune leurs avantages et leurs inconvénients lorsqu'elles sont appliquées aux arbres urbains. Cette recherche visait à évaluer et à comparer qualitativement l'utilisation de la tomographie sonique et du RPS pour caractériser les systèmes racinaires de 5 arbres situés en trottoir et dans un square. De plus, une nouvelle approche de visualisation des données tomographiques est présentée, utilisant l'interpolation par krigeage des valeurs de vélocité et d'erreur. Résultats: Les résultats témoignent d'une relation qualitative entre les zones à haute vélocité détectées par tomographie, indiquant la présence de racines, et les racines cartographiées par RPS. La nouvelle approche de visualisation des données tomographiques offre de meilleures possibilités pour une juste interprétation ainsi que de l'information sur les erreurs de mesure. Conclusions: La tomographie sonique et le RPS permettent tous deux d'évaluer la présence des racines d'arbres en milieu urbain, mais la tomographie sonique est plus rapide pour cartographier l'étendue de la structure racinaire, tandis que le RPS fournit une caractérisation plus détaillée de la répartition spatiale du système racinaire, de la profondeur et du diamètre des grosses racines.

Zusammenfassung. Hintergrund: Die städtische Aufforstung ist weithin dafür bekannt, dass sie sowohl für die Bevölkerung als auch für die Umwelt zahlreiche ästhetische und funktionale Vorteile mit sich bringt. Eine schlechte Planung, die von einer ungeeigneten Artenauswahl bis hin zu einer unzureichenden Baumpflege reicht, kann jedoch zu verschiedenen Problemen führen, darunter Unfälle durch umstürzende Bäume. Diese Vorfälle sind häufig auf Wurzelversagen, unterentwickelte Wurzelsysteme oder fortgeschrittene Baumschäden zurückzuführen. Methoden: Zur Beurteilung des Wurzelsystems eines Baumes werden indirekte Methoden empfohlen, insbesondere in städtischen Umgebungen mit Gehwegen oder Pflasterungen. Techniken wie die Schalltomographie und das Bodenradar (GPR) haben jeweils ihre eigenen Vor- und Nachteile, wenn sie bei Stadtbäumen angewendet werden. Ziel dieser Studie war es, die Verwendung von Schalltomographie und GPR zur Charakterisierung der Wurzelsysteme von fünf Bäumen, die sich auf einem Gehweg und auf einem Platz befinden, qualitativ zu bewerten und zu vergleichen. Zusätzlich wird ein neuer Visualisierungsansatz für tomographische Daten vorgestellt, der die Kriging-Interpolation von Geschwindigkeits- und Fehlerwerten verwendet. Ergebnisse: Die Ergebnisse stellten einen qualitativen Zusammenhang zwischen den durch Tomographie erkannten Hochgeschwindigkeitszonen, die auf das Vorhandensein von Wurzeln hinweisen, und den durch GPR kartierten Wurzeln her. Die neue Visualisierung der Tomographiedaten bietet bessere Möglichkeiten für eine klarere Interpretation zusammen mit Informationen zu Messfehlern. Schlussfolgerungen: Sowohl die Schall-Tomographie als auch GPR dienen zur Beurteilung von Baumwurzeln in städtischen Umgebungen, jedoch ist die Schalltomographie schneller bei der Kartierung der Ausdehnung der Wurzelbedeckung, während GPR eine detailliertere Charakterisierung der räumlichen Verteilung, Tiefe und des Durchmessers der groben Wurzeln des Wurzelsystems liefert.

Resumen. Antecedentes: La forestación urbana es ampliamente reconocida por brindar numerosos beneficios estéticos y funcionales tanto a la población como al medio ambiente. Sin embargo, una planificación deficiente, que abarca desde la selección inadecuada de especies hasta un manejo inapropiado de los árboles, puede generar diversos problemas, incluyendo accidentes causados por la caída de árboles. Estos incidentes suelen ser resultado de fallos radiculares, sistemas radiculares subdesarrollados o degradación avanzada de los árboles. Métodos: Para evaluar el sistema radicular de un árbol, se recomiendan métodos indirectos, especialmente en entornos urbanos con aceras o pavimentos. Técnicas como la tomografía sónica y el georradar (GPR) presentan ventajas y desventajas al aplicarse al arbolado urbano. Este estudio tuvo como objetivo evaluar y comparar cualitativamente el uso de la tomografía sónica y el georradar para caracterizar los sistemas radiculares de cinco árboles ubicados en una acera y en una plaza. Además, se presenta un nuevo enfoque de visualización de datos tomográficos mediante interpolación de kriging de valores de velocidad y error. Resultados: Los resultados establecieron una relación cualitativa entre las zonas de detectadas por tomografía de alta velocidad, que indican la presencia de raíces, y las raíces mapeadas por georradar. La nueva visualización de datos tomográficos ofrece mejores oportunidades para una interpretación más clara, además de información sobre errores de medición. Conclusiones: Tanto la tomografía sónica como el georradar evalúan las raíces de los árboles en entornos urbanos, pero la tomografía sónica es más rápida para mapear la extensión de la cobertura radicular, mientras que el georradar proporciona una caracterización más detallada de la distribución espacial, la profundidad y el diámetro de las raíces gruesas del sistema radicular.