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Potential Identification of Root System Architecture Using GPR for Tree Translocation as a Sustainable Forestry Task: A Case Study of the Wild Service Tree

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Abstract: Sustainable economic development serves society but requires taking over space, often at the expense of areas occupied by single trees or even parts of forest areas. Techniques for transplanting adult trees used in various conflict situations at the interface of economy and nature work as a tool for sustainable management of urbanized and industrial areas, as well as, in certain circumstances, forest or naturally valuable areas. This study aimed to evaluate the effectiveness of ground-penetrating radar (GPR) in determining the horizontal and vertical extent of tree root systems before transplantation. Employing this non-invasive method to map root system architecture aids in the appropriate equipment selection and helps define the dimensions and depth of trenches to minimize root damage during excavation. This study specifically focused on the root systems of wild service trees (*Sorbus torminalis* (L.) Crantz) found in a limestone mine area, where some specimens were planned to be transplanted, as the species is protected under law in Poland. The root systems were scanned with a ground-penetrating radar equipped with a 750 MHz antenna. Then, the root balls were dug out, and the root parameters and other dendrometric parameters were measured. The GPR survey and manual root analyses provided rich comparative graphic material. The number of the main roots detected by the GPR was comparable to those inventoried after extracting the stump. The research was carried out in problematic soil, causing non-standard deformations of the root systems. Especially in such conditions, identifying unusually arranged roots using the GPR method is valuable because it helps in a detailed planning of the transplanting process, minimizing root breakage during the activities carried out, which increases the survival chances of the transplanted tree in a new location.

Keywords: non-destructive root detection; root ball; tree transplantation procedure; mining; forested area

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1. Introduction

In the context of ongoing climate change and anthropogenic pressures related to infrastructure development, the importance and value of trees may not be underestimated. Recent studies have shown that the global number of forest trees is approx. 3.04 trillion. This valuable resource is complemented with trees found in other types of tree plantings and cultivated trees, such as fruit trees. It is estimated that over 15 billion trees are cut down yearly. Since the beginning of human civilization, the number of trees worldwide has dropped by approx. 46% [1].

Old trees are considered the highest natural value [2]. Thus, they need to be protected and, in specific circumstances, transplanted. Transplantation of trees is typically carried out in urban areas, where space is intensively developed and constrained. In contrast, forest trees that obstruct new linear infrastructure projects or are located within open-cast mining areas are often permanently removed, especially when the transplantation process is challenging, costly, and threatened with a low probability of success. Nonetheless, in cases involving trees of high conservation value or protected species, considerable efforts are made to ensure their survival.

Trees provide a multitude of environmental, economic, and social benefits, improving the standard of living in cities and promoting human health and welfare. Nevertheless, a lack of appropriate urban planning combined with errors in road maintenance has led to conflicts between trees and urban areas. Tree transplanting may be necessary due to the expansion of urban infrastructure. Uncontrolled development of tree roots may cause extensive damage, such as cracking and buckling or lifting of pavements and curbs, seriously threatening the safety of pedestrians, cyclists, and drivers. In this context, the ground-penetrating radar (GPR) has already been successfully applied as a non-destructive testing (NDT) method in the assessment and monitoring of road pavements [3,4], as well as analyses of the impact of roots growing under the road pavements [5,6]. Easy use and cost-effectiveness combined with the reliability of results facilitate a comprehensive analysis of subsurface conditions, making it possible to plan preservation operations adequately.

Transplanting mature trees is becoming increasingly common in areas of newly constructed residential infrastructure. On the one hand, mature trees are also transplanted from construction sites to other safe places to protect individuals of high ecological or even commercial value [7,8]. Large trees are planted in newly constructed residential spaces, as smaller trees are often less adaptable; poor conditions and vandalism seriously reduce the chances that a newly planted small tree will eventually grow large enough to fulfill its intended functions, such as providing cooling shade, reducing air pollution and stormwater, and ensuring the mental well-being of residents of housing estates [9].

Small trees with typical root systems growing in deep soils are transplanted using relatively commonly employed transplanters. Most frequently, the extracted root ball is approx. 3 m in diameter [10]. When transplanting trees, it is essential to estimate the volume of the root ball together with the soil and to select an appropriate machine since the typical root ball of 1 m in diameter may weigh approx. 450 kg, while a root ball of 2 m in diameter may weigh as much as 3500 kg [9].

If a particularly large tree grows on rocky ground with a shallow soil layer, and when the root systems are extensive and overgrow the rock formation or underground infrastructure, extraction of the tree with its root ball is difficult, as it may damage structural roots. For the transplanting process to be successful, it is necessary to identify the extensive root system to expose individual structural roots before the final extraction. This inventorying of the root system facilitates the preparation of an adequately deep hole as the target location. Identification of root distribution will also ensure the selection of appropriate equipment for tree extraction and translocation. Most frequently, excavators and loaders of various sizes are used [10]. The expanse of the root system is assessed based on expert knowledge and possibly also exploratory digs. In some species, the tree crown size does not always reflect the extent of the tree's root system; therefore, it is advisable to perform exploratory linear digs. Some case studies suggest that the formation of the root ball based on the root distribution observed at the ground surface and in the exploratory trenches may facilitate the preservation of a more significant part of the root system in relation to its mass than would be the case when assuming a standard geometrical shape of the root ball [7,8]. Nevertheless, root system identification based on on-site inspection and superficial exploratory digs is highly ineffective. Roots may be damaged as a result, while the determination of their distribution may still be highly inaccurate.

Transplanted trees are exposed to considerable stress [11,12], mainly due to the disturbed balance between the aboveground organs and the reduced root ball partly damaged during extraction. Thus, tree crowns are trimmed in order to maintain this balance [13].

To a considerable extent, transplantation success is determined by the tree condition, including the root system, the size of the extracted root ball, avoiding separating soil particles from roots, soil quality in the target location, and performed tending operations [14].

The date of transplantation (the season of the year, adequate water relations) also plays an important role [13,15–17].

For the reasons mentioned, when preparing trees for transplantation, it is crucial first to predict or determine the distribution of their root systems. Apart from conventional methods, attempts have also been made to apply remote sensing methods, such as GPR, in many cases providing satisfactory results [18–20]. The georadar method is a geophysical method based on the transmission, reflection, and reception (and finally recording) of electromagnetic (radio) waves of high frequency, ranging from 10 MHz to as much as 6 GHz [21]. This method uses an antenna transmitter that emits a signal into the ground, partially reflected at the boundaries of two layers or objects with different dielectric properties (e.g., soil/tree root). The reflected wave returns to the antenna receiver on the surface, measuring the wave migration time. Then, the time, depending on the soil properties, is converted into depth units. Therefore, in GPR studies, it is possible to obtain some quantitative information, such as the depth of roots or range of their extent, as well as reliable qualitative information about the geometry of the root system. Typical scans are performed along straight lines (2D), and when they are designed and processed in a square XY grid, the 3D models are produced, where the third dimension, Z, is depth. The interpretation of roots in single 2D radargrams is difficult and subjective, but interpretation in 3D models is much more effective and the most recommended for tree root studies [22,23]. GPR studies also use circular grids oriented around the tree trunk [24,25]. The most advanced studies show the possibility of acquiring such detailed information as diameters of identified roots and estimating root biomass, preferably with the use of some additional techniques, e.g., electrical resistivity, tomography or processing the GPR data using highly advanced digital techniques, algorithms, and software [20,26–28].

The obvious benefits of GPR include the rapid analysis of roots compared to their physical extraction and the performance of cyclic analyses on the site, ensuring long-term monitoring of root system development [29]. However, the primary advantage is the lack of physical interference with the soil and no risk of root damage, otherwise caused by digging out the root system. Despite certain limitations and inaccuracy of information provided by the ground-penetrating radar (e.g., the range of root diameters detected using an antenna of specific parameters, the problem with detecting fine roots, GPR image quality, and root detectability dependent on the soil features, difficulty in detection of vertically growing roots), experiences reported by many authors for root detection by this method are nevertheless optimistic [18,30,31]. Mapping of tree root systems using ground-penetrating radars is applied, among other things, to estimate biomass, determine CO_2 storage capacity, as well as diagnose health status, e.g., fungal diseases of roots [32,33].

In tree transplantation operations, the use of non-invasive methods to identify the root system architecture allows for the determination of the size and depth of the excavation needed to avoid root damage, as well as the selection of appropriate equipment. In this project, the GPR method was tested on the root systems of wild service trees (*Sorbus torminalis* (L.) Crantz) growing on shallow soils overlying limestone, using a 750 MHz centre frequency antenna.

The premise of the presented research was the possibility of applying elements of sustainable forestry in the vicinity of a limestone mine taking over the new forest areas for exploitation. It can be assumed that the principles of sustainable forest management are included in a broader scope of sustainable development, understood as development that meets the needs of present generations without compromising the ability of future generations to meet their needs (definition from the so-called Brundtland Report [34]) Thus, the natural environment's resources should be preserved in such a way that, by the principle of justice, future generations can also benefit from them. Sustainable forestry concerns appropriate forest management, renewal, protection, preservation of biodiversity, and the simultaneous fulfilment of many services (functions) by the forest. In the specific area where the presented research was conducted, decision-makers recognized the need to expand the limestone resource exploitation, even at the expense of small forest areas. However, they pointed out that it was necessary to make an effort to protect the most valuable tree species occurring in the area designated for exploitation. These actions consisted of replanting protected, naturally essential trees. This naturally valuable species, whose individuals are subject to strict protection, was a wild service tree. It is native to Europe, Asia Minor, the Caucasus, and North Africa, with its northern range extending to eastern Denmark and the southern British Isles. It grows abundantly in Southern Europe, where it reaches altitudes up to 1200 m a.s.l., while its localities found at the highest altitudes are in Turkey, where it reaches 2200 m a.s.l. In Poland, it is relatively rare, found in scattered localities mainly in the lowlands, and has been under strict legal protection since 1946. It is a typical forest species growing in broadleaved and mixed broadleaved forests. It is a valuable species that promotes biocenosis development and is an admixture species that enhances biodiversity in forests. In some European countries, the wild service tree is grown on plantations for its valuable timber, used primarily to produce premium furniture veneers [35–38].

2. Aim and Scope of Study

This study evaluated the applicability of ground-penetrating radar (GPR) as a non-invasive method for inventorying tree root systems, particularly as a preparation for transplanting trees of ecological significance. Thus, GPR was tested as a tool for supporting activities in the sustainable management of problematic areas subjected to anthropogenic transformation and covered with valuable trees. The project for identifying root system architecture was conducted on four wild service trees. The experience gained within this study may also be used to prepare trees for translocation in the case of other species. The specific objective was to gain new knowledge concerning the spatial range of the root system in specimens of wild service trees growing in shallow, skeletal soils formed on limestone. It was hypothesized that the atypical soil conditions in the study area would promote horizontal root growth, a factor crucial in determining the appropriate size of the GPR testing plot.

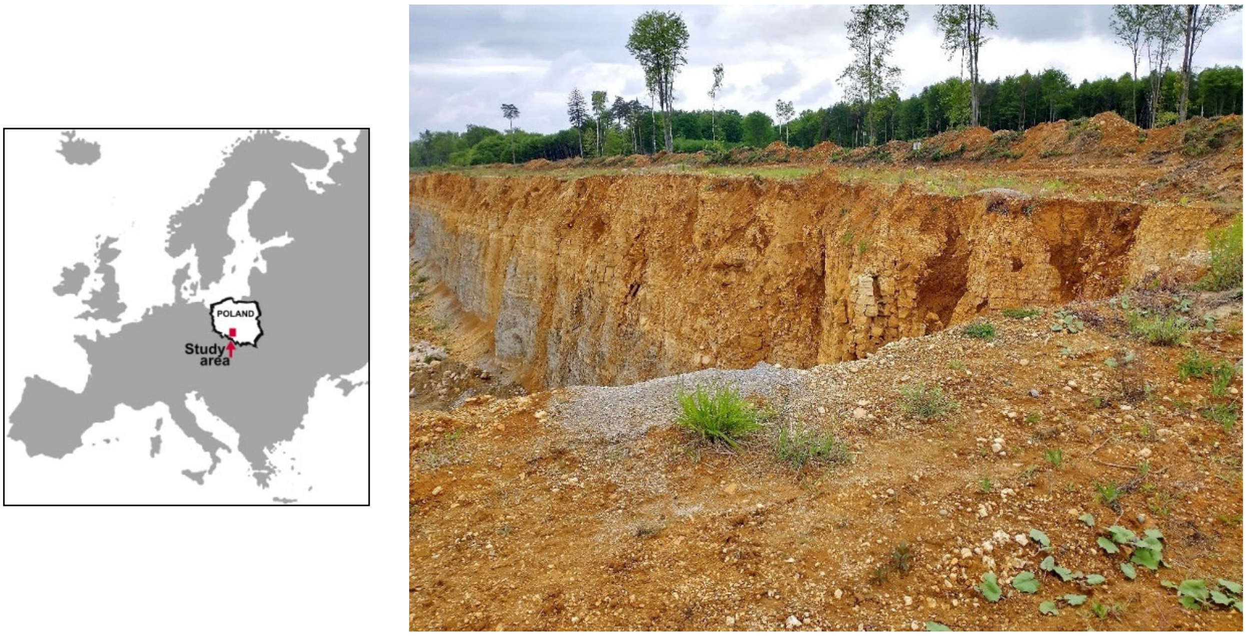
Additionally, the results of this study contribute significantly to understanding the species' biology. They are expected to further facilitate the successful extraction of large tree specimens with intact root balls as part of the research and development programme conducted by Górażdże Cement S.A., titled "In situ and ex-situ protection of the wild service tree (*Sorbus torminalis*) population in the Górażdże Quarry". The R&D programme consists of the preservation of threatened wild service trees growing in areas allocated for open-cast limestone mining by transplanting these specimens to other sites (i.e., their translocation). Trees selected for these analyses had not been qualified initially as suitable for translocation due to their poor health condition or the close vicinity of other trees preventing their translocation; as such, they were included in the experiments within this project.

It was planned first to identify the root system architectures of those trees by remote sensing using a ground-penetrating radar, and then to verify these root systems using the conventional extraction method with an excavator. As a result, the ground-penetrating radar image could be compared with the actual root system growing in the ground.

3. Study Area

The study area is located in southern Poland, in the Opole Province (Opole Silesia region) (see Figure 1a). The wild service tree is found there only in one natural locality—in the Kamień Śląski Nature Reserve and its immediate vicinity. Several dozen trees of this species are growing in the reserve, with the oldest and most monumental specimens covered by additional protection measures as monuments of nature. The Górażdże Limestone Quarry operates within the close vicinity of the Kamień Śląski Reserve. Along with limestone extraction, the company also conducts simultaneous reclamation of former mining areas and has undertaken a pioneering task involving using wild service trees for plantings in the reclaimed former mining areas and translocating selected tree specimens.

A typical root system in this species is deep with a tap root. It requires fertile and deep soils; wild service trees grow well in calcareous and clayey soils. However, the soil conditions in the study area are far from standard. Located in the Gogolin and Górażdże region, which lies within the Muschelkalk outcrop, a large quarry excavates Triassic limestone as a material for production of cement and lime products. The analyses were conducted on a land section of approximately 5 ha in the vicinity of the existing open pit prepared by the company for future excavation (see Figure 1b).



(**a**) (**b**)

Figure 1. Location of the study area (**a**); Immediate vicinity of the study area—the limestone quarry (**b**).

The region's climate, including the study area, is a transitional temperate between the oceanic climate of Western Europe and the continental climate of Eastern Europe. The climatic conditions in this region are some of the mildest in Poland and are characterised by limited temperature variations, relatively high annual temperature, and moderate precipitation. There are long, mild autumns, short winters, early springs, and warm summers. Such climatic conditions are conducive to a long vegetation season, which in the Opole Silesia region lasts for 200–225 days [39].

According to data from the Institute of Meteorology and Water Management, the mean annual temperature in the region is 8.4 °C. During the summer months (June to August), the average temperature reaches 17–18 °C, while in winter (December to February), it averages around −1 °C. Recent years have shown a rise in the mean temperature by 1–2 °C compared to the multiannual average for the 1981–2010 period. Total precipitation in 2020 was 780.1 mm, representing a notable increase compared to previous years [40].

4. Research Methods

4.1. Field Studies—Preliminary Works

The initial phase of the fieldwork involved measuring the physical characteristics of four selected wild service trees, designated as nos. 45, 52, 53, and 54 (see Figure 2). Two trees were 25 years old, and another two were about 50.

Tree no. 45 Tree no. 52 Tree no. 53 Tree no. 54

Figure 2. Investigated wild service trees (Photos by P. Stelter).

Measurements taken included tree height, crown base height, diameter at breast height (DBH), and crown projection area—assessed using the Vertical Tree Crown Projected Area method in eight cardinal directions. Observations also recorded visible signs of damage and disease, such as bracket fungi or wounds. The studied trees were located near each other (40–60 m apart), arranged in two pairs approximately 200 m apart (Figure 3). Near each pair of trees, two exploratory soil pits were excavated (Figure 3) to characterise the soil profile and collect samples for subsequent laboratory analyses.

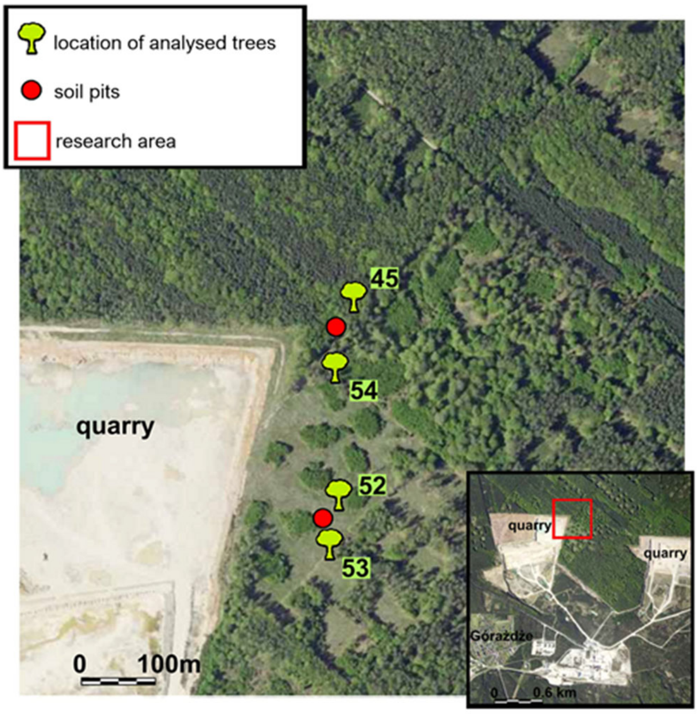


Figure 3. Location of analysed trees and exploratory soil pits (orthophotomap source: [41], changed).

4.2. Laboratory Analyses of Soil

Laboratory analyses of soil samples collected from the study area were performed to determine tree growth conditions, particularly conditions for the development of the root system, of which the architecture was then determined using the GPR and physical examination methods. Comprehensive determination of soil conditions included physical and chemical soil properties. The evaluated soil characteristics comprised grain size distribution (texture), organic carbon and humus content, nitrogen content, soil pH, calcium carbonate content, available nutrients, and the Habitat Soil Index (Polish: SIG).

4.3. Field Studies Using a Ground-Penetrating Radar

After determining physical properties, the tree root systems were examined using a ground-penetrating radar. This study performed root system mapping of the four selected trees using an antenna with a central frequency of 750 MHz (MALÅ Ground Explorer (GX) HDR).

Around each investigated tree, a testing plot was marked with the dimensions given in Table 1. An XY grid of lines oriented in N–S and E–W directions was established within the testing plots, and then the scanning was performed along these lines using the GPR system. The profiling line spacing was 25 cm in the two grid directions with an inline sampling interval of 2.5 cm. The survey depth range was 2 m (the Z-axis of the system). The trees in which root systems were analysed were found in the central point of the testing plot.

Boundaries of the investigated plot were established based on the tree crown projected area determined using the land surveying method. The established plots were also extended to include a safety zone (as detailed in Table 1) to investigate the roots eventually expanded outside the crown projection area.

Table 1. Adopted dimensions of testing plots.

Investigated Specimens	Dimensions of GPR Testing Plots	Remarks
tree no. 45	6 m × 6 m	the area of the testing plot resulting from the setting of maximum parameters in ground-penetrating radar software
tree no. 52	6 m × 6 m	
tree no. 53	6 m × 6 m	
tree no. 54	4 m × 4 m	reduction in testing plot dimensions compared to the others due to field obstacles

Data recorded during GPR profiling were processed using the MALÅ 3D Grid Project software integrated with the system (GX Controller ver.15.2.268 a1), providing 3D models based on wave amplitude and velocity. The software enables automatic processing of the collected radargrams into 3-D radar volumes and provides time-slices (isosurfaces) converted into approximate depth. Time-slices presenting arrangements of signal anomalies were used to interpret images of the root system distribution for the investigated trees. Next, the graphic interpretation results for the adopted depth intervals were compared with the actual architecture of root systems physically excavated from the soil.

4.4. Verification of Ground-Penetrating Radar Effectiveness Using the Conventional Method

The next fieldwork stage consisted of the felling of the investigated trees, measuring their length, and extracting the stumps with the root systems. For this purpose, one of the machines working in the quarry was used—a backhoe and loader with a size and loading capacity adopted to the size of the root balls. Its size made it possible to extract the stump's main part intact. Roots outside the range of the backhoe, broken from the main stump, were dug out using an excavator and transported to the site, where they were cleaned to reconstruct the entire root system.

After stumps had been cleaned from the soil with a stream of water under pressure, they were photographed, the sketches of the reconstructed root systems were drawn, and the lengths and diameters of the roots were measured successively over a length of 1 m and its multiples. The broken roots detached from the stamp were used to reconstruct the original stump root ball. Next, the root geometry interpreted from GPR data and observed in excavated and reconstructed root systems was compared to determine the accuracy of images provided by the ground-penetrating radar.

5. Results

5.1. Results of Dendrometric Measurements

Based on in situ measurements, the following dendrometric characteristics were recorded for the roots of the analysed wild service trees (as detailed in Tables 2–13):

Tree no. 45

The trunk forks at a height of several metres, with a fragment of a dead branch present at the forking site. The crown is narrow, leaning towards the north, and appears healthy, with no signs of discoloration or dead shoots. Detailed dendrometric measurements of trees and crown spread were carried out according to the methodology described in the chapter "Field Studies—Preliminary Works" and are detailed in Tables 2–4.

Table 2. Dendrometric measurements of tree no. 45.

Physical Characteristics	Measurement
DBH [mm] (measured in the N–S direction)	190
DBH [mm] (measured in the W–E direction)	185
Circumference [mm] (at breast height—1.30 m)	600
Height [m]	20.5
Crown base height [m]	11.9
Stem length [m]	20.7
Bole length (stem over 7 cm diameter outside bark) [m]	14.0

Table 3. Crown spread in tree no. 45 (distance from the stem base to extreme points of the crown).

Azimuth (from Stem Base) [°]	Distance [m]
0	4.29
45	2.82
90	3.53
135	2.81
180	1.12
225	1.12
270	1.99
315	2.26

Table 4. Measurements of root diameters in tree no. 45.

No.	Root Length [m]	ϕ per 1 m [mm]	ϕ per 2 m [mm]
1	3.7	32	25
2	3.3	27	23
3	3.2	24	20
4	1.8	19	
5	2.7	47	10
6	3.3	47	30
7	3.1	16	13
8	3.2	20	16
9	2.9	19	15
10	1.5	15	
11	1.6	15	
12	1.4	10	
13	1.2	10	
14	1.4	10	
15	3.3	30	22
16	1.2	10	
17	1.7	22	
18	1.7	11	
19	1.8	12	

Table 4. *Cont.*

No.	Root Length [m]	ɸ per 1 m [mm]	ɸ per 2 m [mm]
20	1.8	19	
21	2.0	20	
22	1.7	17	
23	1.8	10	
24	1.8	12	
25	3.0	32	20
26	1.8	21	
27	1.5	10	
28	1.2	10	
29	1.8	10	
30	1.7	12	

Tree no. 52

The trunk forks at a height of several metres, with a dead branch of several metres in length found at the forking site. A bracket fungus was found on the lower part of the trunk. The trunk leans in the easterly direction, and in the upper part of the crown are wounds visible on the trunk, covering approximately 20% of the trunk circumference. Detailed dendrometric measurements of trees and crown spread were carried out according to the methodology described in the chapter "Field Studies—Preliminary Works" and are detailed in Tables 5 and 6.

Table 5. Dendrometric measurements of tree no. 52.

Physical Characteristics	Measurement
DBH [mm] (measured in the N–S direction)	504
DBH [mm] (measured in the W–E direction)	528
Circumference [mm] (at breast height—1.30 m)	1660
Height [m]	21.6
Crown base height [m]	11.8
Stem length [m]	22.6
Bole length (stem over 7 cm diameter outside bark) [m]	19.8

Table 6. Crown spread in tree no. 52 (distance from the stem base to extreme points of the crown).

Azimuth (from Stem Base) [°]	Distance [m]
0	6.70
45	4.37
90	5.75
135	5.55
180	−0.70
225	0.50
270	0.00
315	1.15

Table 7. Measurements of root diameters in tree no. 52.

No.	Root Length [m]	ɸ per 1 m [mm]	ɸ per 2 m [mm]	ɸ per 3 m [mm]	ɸ per 4 m [mm]
1	7.8	155	127	100	41
2	5.0	148	129	124	80
3	2.8	190	160		
4	2.0	135	120		
5	1.8	50			
6	1.6	32			
7	1.3	11			
8	1.8	77			

Table 7. *Cont.*

No.	Root Length [m]	ϕ per 1 m [mm]	ϕ per 2 m [mm]	ϕ per 3 m [mm]	ϕ per 4 m [mm]
9	1.6	81			
10	1.4	50			
11	1.4	50			
12	1.5	28			
13	1.7	111			
14	1.8	20			
15	1.8	44			
16	1.6	42			
17	1.4	29			
18	1.5	72			
19	1.8	35			
20	1.7	23			
21	1.9	50			

Tree no. 53

The trunk at a height of approx. 10 m divides into three branches of comparable size. The trunk is leaning in the easterly direction, and in the lower part of the trunk auxiliary shoots are found, and no leaf discoloration is observed in the crown. Approx. 15% dead shoots are found in the crown, and the crown is healthy. Detailed dendrometric measurements of trees and crown spread were carried out according to the methodology described in the chapter "Field Studies—Preliminary Works" and are detailed in Tables 8 and 9.

Table 8. Dendrometric measurements of tree no. 53.

Physical Characteristics	Measurement
DBH [mm] (measured in the N-S direction)	421
DBH [mm] (measured in the W-E direction)	420
Circumference [mm] (at breast height—1.30 m)	1330
Height [m]	21.1
Crown base height [m]	10.5
Stem length [m]	22.2
Bole length (stem over 7 cm diameter outside bark) [m]	19.6

Table 9. Crown spread in tree no. 53 (distance from the stem base to extreme points of the crown).

Azimuth (from Stem Base) [°]	Distance [m]
0	2.20
45	5.39
90	8.81
135	5.55
180	−0.90
225	0.00
270	0.00
315	0.00

Table 10. Measurements of root diameters in tree no. 53.

No.	Root Length [m]	ϕ per 1 m [mm]	ϕ per 2 m [mm]	ϕ per 3 m [mm]	ϕ per 4 m [mm]
1	1.3	13			
2	1.8	100			
3	2.2	49			
4	1.6	41			
5	1.7	15			
6	2.4	73	42		
7	2.3	29	10		
8	1.6	42			

Table 10. *Cont.*

No.	Root Length [m]	ɸ per 1 m [mm]	ɸ per 2 m [mm]	ɸ per 3 m [mm]	ɸ per 4 m [mm]
9	1.7	30			
10	2.3	60	38		
11	1.6	40			
12	1.3	27			
13	1.9	62			
14	1.5	63			
15	1.8	47			
16	2.4	93	42		
17	2.4	33	18		
18	1.9	98			
19	1.5	33			
20	1.9	75			
21	1.5	60			
22	1.9	97			
23	3.9	112	88	73	
24	1.7	81			
25	1.9	65			
26	4.7	100	92	75	52
27	1.2	20			
28	1.1	55			
29	1.8	44			
30	1.3	55			
31	1.2	31			
32	1.3	37			
33	1.2	55			
34	1.5	44			
35	1.5	32			
36	1.2	27			
37	1.2	18			
38	1.3	30			
39	1.5	40			

Tree no. 54

The trunk forks at a height below 2 m. The crown is uniform and healthy, with no discoloration or dead shoots observed.In the lower part of the crown there is a wound on the trunk covering 20% of the circumference. Detailed dendrometric measurements of trees and crown spread were carried out according to the methodology described in the chapter "Field Studies—Preliminary Works" and are detailed in Tables 11 and 12.

Table 11. Dendrometric measurements of tree no. 54.

Physical Characteristics	Measurement
DBH [mm] (measured in the N-S direction)	174
DBH [mm] (measured in the W-E direction)	177
Circumference [mm] (at breast height—1.30 m)	550
Height [m]	11.7
Crown base height [m]	1.6
Stem length [m]	11.6
Bole length (stem over 7 cm diameter outside bark) [m]	7.7

Table 12. Crown spread in tree no. 54 (distance from the stem base to extreme points of the crown).

Azimuth (from Stem Base) [°]	Distance [m]
0	3.84
45	2.33
90	3.22
135	3.60

Table 12. *Cont.*

Azimuth (from Stem Base) [°]	Distance [m]
180	2.03
225	1.97
270	2.91
315	3.85

Table 13. Measurements of root diameters in tree no. 54.

No.	Root Length [m]	ϕ per 1 m [mm]	ϕ per 2 m [mm]
1	3.0	43	20
2	2.8	51	30
3	1.9	23	
4	1.7	19	
5	2.5	41	15
6	2.6	41	15
7	1.2	15	
8	1.5	23	
9	2.1	29	
10	3.5	91	50
11	2.0	37	
12	1.2	10	
13	2.0	50	

5.2. Results of Ground-Penetrating Radar Testing

Results provided by the ground-penetrating radar are presented in the graphic form as two types of figures: anomaly maps of time and amplitude for the waves emitted and recorded by the ground-penetrating radar (the so-called time-slices), as well as maps of root system architecture produced in the graphic programme based on time-slices—the effect of graphic interpretation. Time-slices are 2D visualisations in the horizontal plane, produced by such a plane intersecting a 3D model constructed in the digital environment of the software working with the ground-penetrating radar used in this study. When operating with the ground-penetrating radar on individual testing plots, the device collects data (as described in Section 4) and next processes these data, constructing a 3D model in the computer memory. The user has access to products of this model in the form of 2D images—the above-mentioned time-slices. The system processing wave velocity data are capable of transforming the wave migration time into depth values. In this study, depth data are given in [cm] or [m], already converted by the system; however, it needs to be remembered that these values may be burdened with a certain error. Results of processing for these values are dependent on several factors, primarily variations in the soil medium. Graphic interpretation of root system architecture was based on the analysis of horizontal time-slices generated with the interval of 0.5–1 cm. A review of time-slices in such an interval is possible on the display screen, whereas anomaly maps presented below (time-slices) were selected as examples illustrating most comprehensively the distribution of roots and soil at a given depth. An approximate depth of individual time-slices is presented in each image, in the grey field on the right and is denoted as "Depth". Interpreted maps of roots show a certain generalised image for the assumed depth intervals, which are given in individual figures.

Tree no. 45

Marked series of small anomalies, which may easily be associated with the distribution of roots in tree no. 45, are found south and south-east from the wild service tree trunk, in a shallow zone up to the depth of approx. 25 cm. In the deeper interval, the image starts to be less clear, but it seems that the lateral root zone reaches the a depth of ap-prox. 0.5 m. Strong wave reflections demonstrating clearly marked anomalies in the peripheral areas of the testing plot partly show roots of trees growing in the immediate vicinity of the plot. However, the shape and intensity of these anomalies in some depth intervals suggest also they probably differ in origin, e.g., local variations in the soil type (clay, rock), or variations in moisture content. For these reasons the lateral range of roots of the wild service tree to the south may possibly be estimated to be a maximum of approx. 2.5–3.0 m, while in other areas it may not be reliably estimated (Figure 4; Table 14).

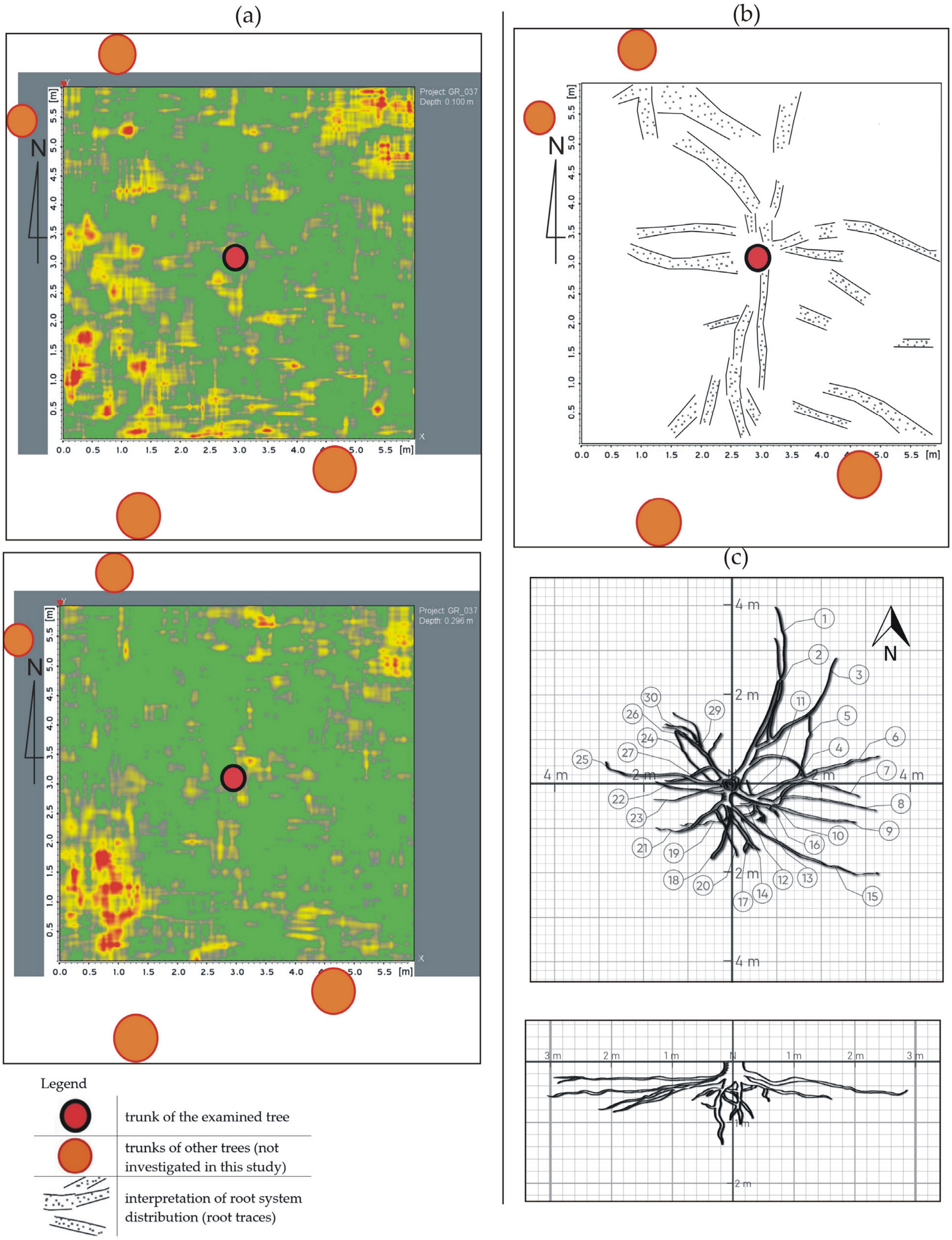


Figure 4. Tree no. 45. GPR time-slices at depths of approx. 10 and 30 cm (**a**); Interpretation of the root system distribution derived from 3D GPR model in the depth interval of 20–50 cm (**b**); Horizontal and lateral view sketches of the reconstructed stump made manually in situ. The numbers refer to the detailed in situ analysis of root diameters listed in Table 4 (**c**).

Table 14. Interpretation/comparison of root system characteristics (tree no. 45) based on GPR and in situ measurements.

Physical Characteristics	Interpretation of GPR Image	Verification Based on Excavated Stump	Conclusions
number and distribution, shape of structural roots important for the translocation process	9/10	10/11	some roots are forked, results are comparable
horizontal range	2.5–3 m	maximum 3 m	results are comparable
depth of the main root mass	0.5	0.75	GPR results underestimate the actual data

Tree no. 52

Within the shallow subsurface zone, several series of evident anomalies could be observed, which may easily be associated spatially with the trunk of wild service tree no. 52 in the centre of the testing plot. They were interpreted as roots. Below the depth of 0.4 m, the ground-penetrating radar recorded no more signals, which could be interpreted as signs of tree roots, apart from the peripheral south-eastern part of the plot, where the image may be interpreted as the end of a root at a depth of approx. 0.55 m. Generally, in the interval of approx. 0–0.4 m the root system architecture is exceptionally evident, thus a lack of anomalies below may reliably indicate that the root system simply did not grow deeper—at least this is the situation for the roots spreading sideways (Figure 5; Table 15).

Table 15. Interpretation/comparison of root system characteristics (tree no. 52) based on GPR and in situ measurements.

Physical Characteristics	Interpretation of GPR Image	Verification Based on Excavated Stump	Conclusions
number and distribution, shape of structural roots important for the translocation process	4	4	a large, compact root ball, relatively few thick structural roots
horizontal range	roots extending outside the range of the testing plot	maximum 4.5 m	roots extending outside the testing plot were of lesser importance for potential translocation; an unusual maximum diameter of 12.4 cm was found in one of the roots over a length of 3 m
depth of the main root mass	0.4	main structural roots up to 1 m, 1–2 m a bundle of roots with smaller diameters (fine roots)	roots growing directly below the trunk are the deepest, but they are not detected by the ground-penetrating radar because they are located under the trunk. The ground-penetrating radar showed only the main roots–structural roots. Bundles of fine roots, growing deeper into the soil directly below the trunk could not be detected

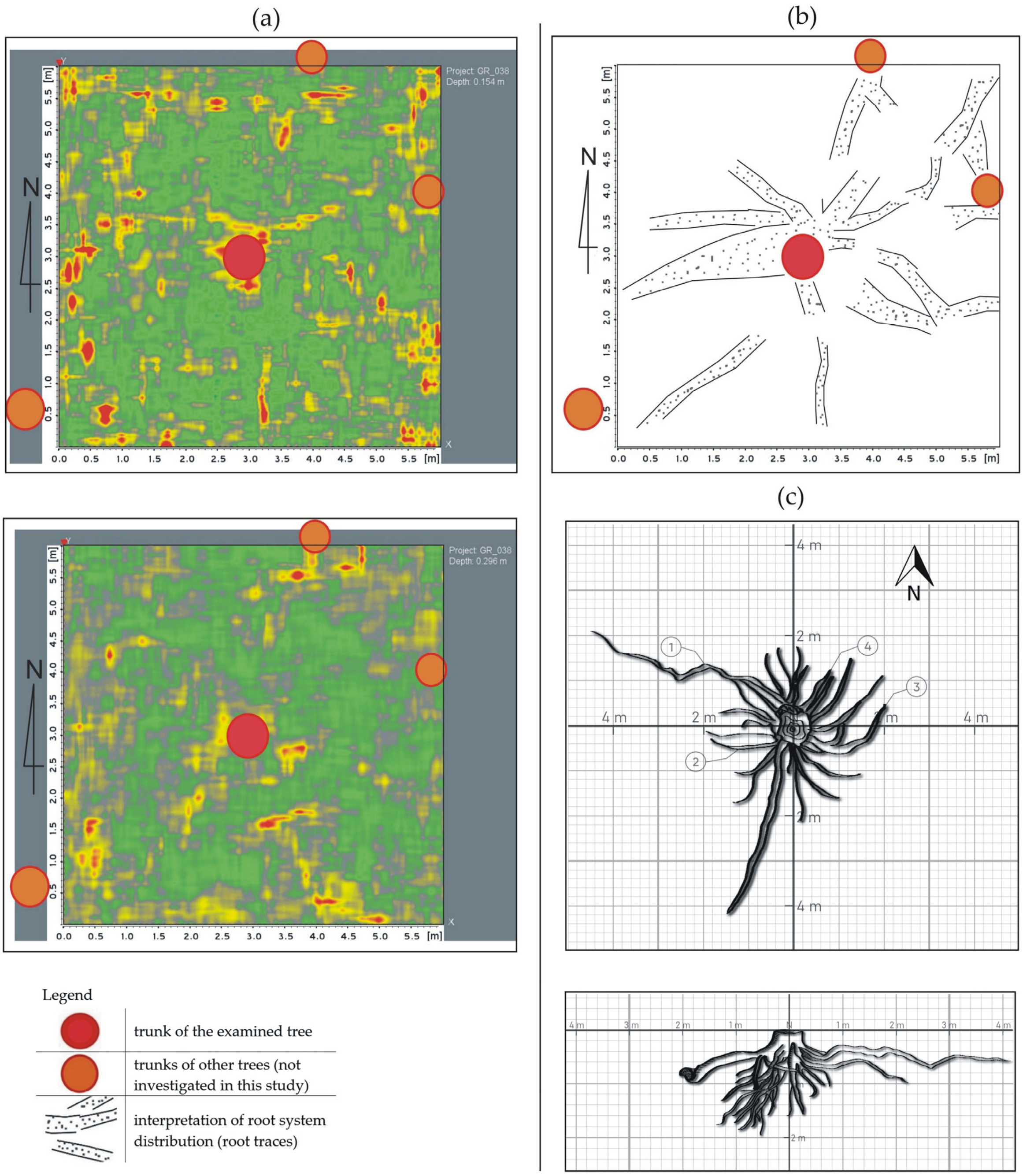


Figure 5. Tree no. 52. GPR time-slices at depths of approx. 15 and 30 cm (**a**); Interpretation of the root system distribution derived from 3D GPR model in the depth interval of 10–40 cm (**b**); Horizontal and lateral view sketches of the reconstructed stump made manually in situ. The numbers refer to the detailed in situ analysis of root diameters listed in Table 7 (**c**).

Tree no. 53

A series of anomalies showing the distribution of structural roots in tree no. 53 may be observed in the zone up to the depth of approx. 0.4 m. It is not a dense network, rather several distinct forked roots. At a depth of approx. 0.45 m, the image of anomalies, which may be associated with structural roots disappears, while at approx. 0.6 m in the boundary zones of the testing plot, again, strong wave reflections appear, resulting in the image of strong irregularly shaped anomalies. They are probably zones of geologically diverse substrate. Soil thickness, and thus also the depth of limestone, varies slightly within the testing plot. In the western part of the plot, fragments of solid rock are already abundant at the ground surface, while in other areas they are beneath a thin layer of soil. In the western and southern boundary areas of the plot, there are remnants of old trunks, but due to the shallow layer of the solid rock it is difficult to state whether the anomalies observed there are caused by disturbances within the subsoil, residue of old roots, or fragments of the wild service tree roots (Figure 6; Table 16).

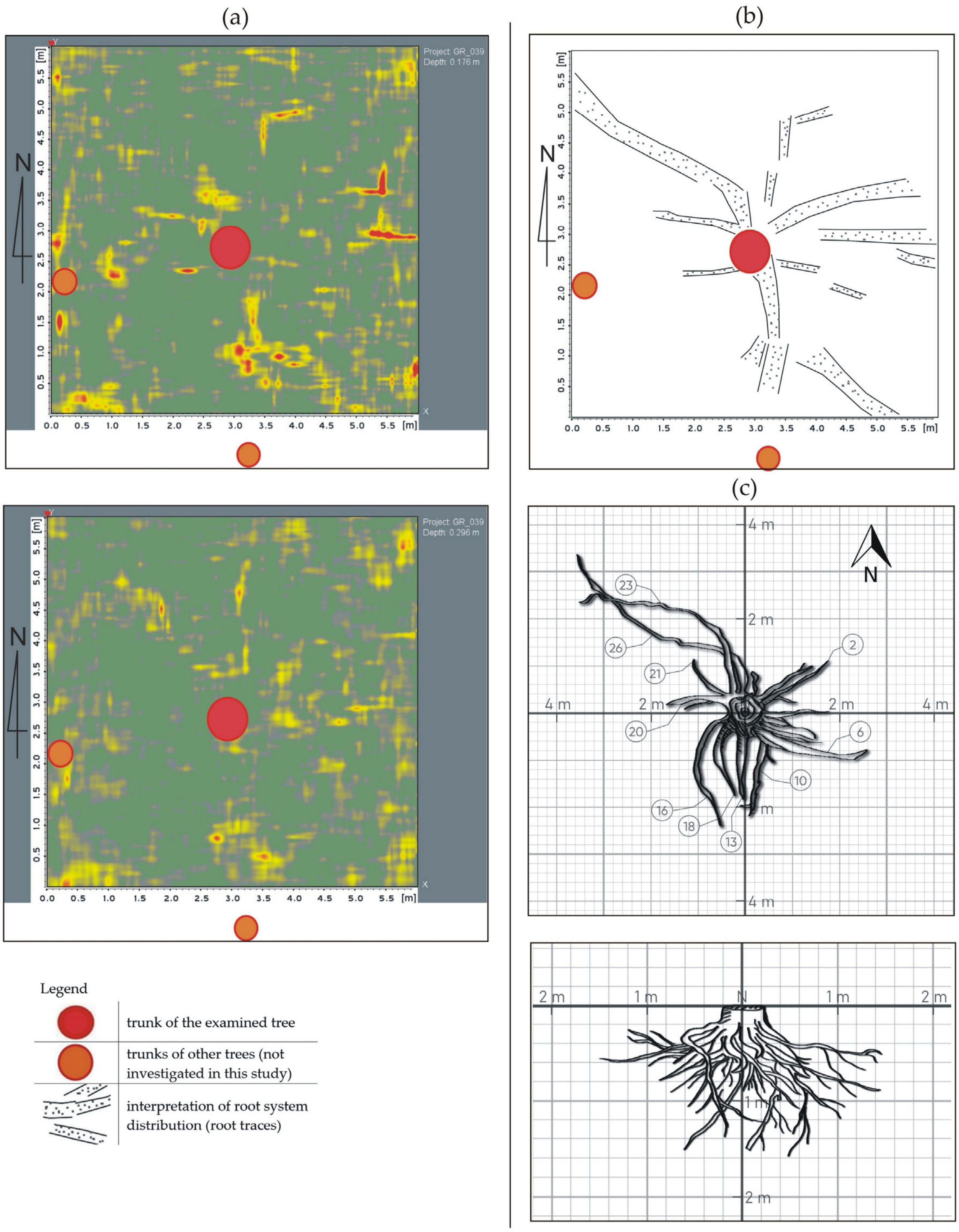


Figure 6. Tree no. 53. GPR time-slices at depths of approx. 18 and 30 cm (**a**); Interpretation of the root system distribution derived from 3D GPR model in the depth interval of 20–40 cm (**b**); Horizontal and lateral view sketches of the reconstructed stump made manually in situ. The numbers refer to the detailed in situ analysis of root diameters listed in Table 10 (**c**).

Table 16. Interpretation/comparison of root system characteristics (tree no. 53) based on GPR and in situ measurements.

Physical Characteristics	Interpretation of GPR Image	Verification Based on Excavated Stump	Conclusions
number and distribution, shape of structural roots important for the translocation process	8	10	the root distribution provided by the ground-penetrating radar is close to the actual one. Differences result from problems in the interpretation of many additional fine roots—less significant for tree stability (smaller root diameter)
horizontal range	maximum 3 m	4 m (roots 23 and 26)	the GPR value is slightly underestimated as a result of the reduced testing plot. The GPR result is close to the actual one
depth of the main root mass	0.45 m	0.75 m	The GPR value is underestimated—the tree translocation still requires deeper penetration of the backhoe below 1 m. Roots growing directly below the trunk are deepest, and they are not detected by the ground-penetrating radar

Tree no. 54

The root system of tree no. 54, to a considerable degree, was overgrown by the root system of a neighbouring, much larger tree. Thus, they may not be separated in the GPR image. It may only be assumed with considerable probability that lateral roots growing in the northerly direction belong to the wild service tree. In the time-slices generated for the depth interval of approx. 5–30 cm, anomalies of time and amplitude elongated in shape may be seen, generated by wave reflection from roots. Below this zone the image is gradually blurred and starts to disappear. Up to a depth of approx. 0.6 m, signs of roots of the neighbouring tree may still be seen, while below the depth of 0.6 m there are no zones of anomalies, which could be associated with tree roots. Roots belonging probably to the wild service tree are visible at a length of approx. 1.2 m in the GPR image; it might be assumed that they reach the northern boundary of the testing plot (Figure 7; Table 17).

Table 17. Interpretation/comparison of root system characteristics (tree no. 54) based on GPR and in situ measurements.

Physical Characteristics	Interpretation of GPR Image	Verification Based on Excavated Stump	Conclusions
number and distribution, shape of structural roots important for the translocation process	highly hindered due to roots being intertwined with those of a neighbouring tree (pine)	roots of both trees with mutually overgrown tissues	in the case of such a close vicinity of trees, it is impossible to identify roots as belonging to a specific tree. During translocation, it is necessary to extract the root balls of both trees
horizontal range	2 m (the range of the testing plot)	3 m	the difference of 1 m results from the adopted dimensions of the testing plot. If possible, it is recommended (when there are no neighbouring trees) to increase the range of the testing plot (correlated with the age of species of a given tree)
depth of the main root mass	0.6 m	0.8 m	depth interpreted from GPR measurements is underestimated

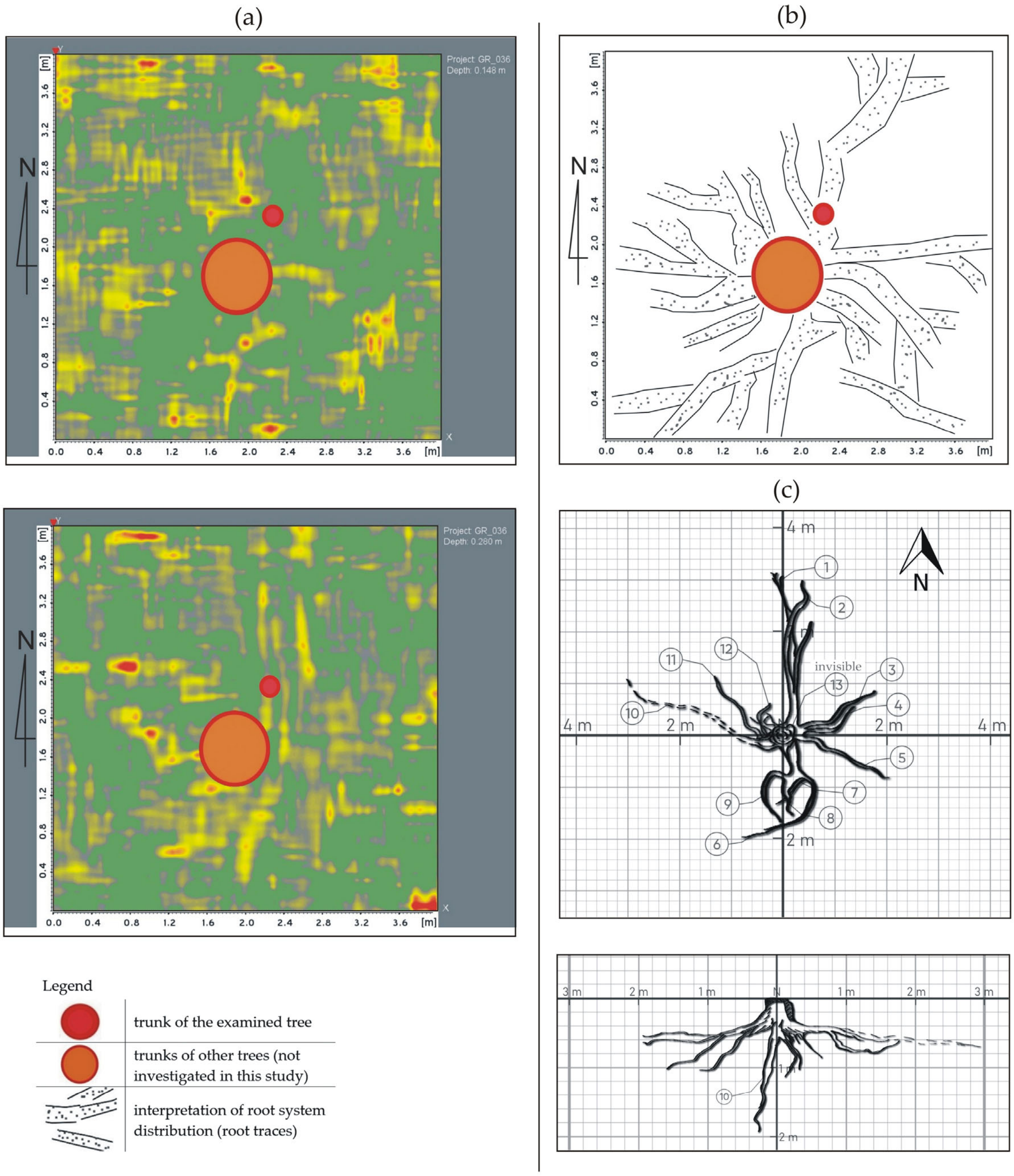


Figure 7. Tree no. 54. GPR time-slices at depths of approx. 15 and 30 cm (**a**); Interpretation of the root system distribution derived from 3D GPR model in the depth interval of 20–40 cm (**b**); Horizontal and lateral view sketches of the reconstructed stump made manually insitu.The numbers refer to the detailed in situ analysis of root diameters listed in Table 13 (**c**).

5.3. Results of Soil Property Tests

A characteristic feature of soil in the study area, evident in the soil profile (see Figure 8), is connected with the very shallow location of the parent rock. Weathered clay, together with dense limestone debris, was observed already at a depth of 20–30 cm both in exploratory pits excavated specially for the soil profile, and in other places, e.g., in holes dug to remove stumps of wild service trees. In places, the roof of the limestone layer was found at a slightly greater depth (approx. 50 cm), which resulted from the fact that it is a surface exposed to erosion and it is strongly weathered. In the examined outcrops, the humus horizon (A) reached a depth of as little as several centimetres to approx. 20 cm. The eluvial horizon

(Eet), as well as the illuvial horizon (Bt), were also identified, but they were of a markedly reduced thickness of only several cm. In the investigated soils in the A horizons, the grain size distributions of clayey sands and sandy clays were also identified. The Eet horizon was composed primarily of clayey sands, the Bt horizon was composed of loams, while the parent rock horizons (C) were characterised by the dominant limestone rock fragments (fractions of stones and pebbles) surrounded by sandy clay loams, which in combination formed a deposit with a very high share of stone fragments—being clayey-stone.

(1) (2)

Figure 8. Soil profiles nos. 1 and 2. (Photos by P. Stelter).

According to the results of laboratory analyses, the tested soils were classified as typical lessive soils. They are characterised by an average soil carbon content typical of forest soils, ranging from the highest values in the humus horizons (1.87%, 2.34%) to the lowest value in the parent rock (0.14%).

Laboratory analyses showed the carbon to nitrogen ratio (C/N) of 16.71 and 17.00 (in the two soil profiles). These are values indicating high microbial activity, which leads to rapid mineralisation of the organic matter. The pH H_2O value in the soil ranged from 5.19 to 8.25. According to the environmental indicators [42], the soil acidity index specifies the most typical pH in H_2O for the wild service tree to be above 7. In contrast, according to Pacyniak [43], soil reaction (at a depth of 10 cm) in localities of wild service tree ranges from pH 4.25 to as much as 7.65. In the chemical composition of some tested soil samples, a high carbonate content ($CaCO_3$) was recorded, with a maximum up to as much as 9.66%, which is obviously related to the type of rock found in the substrate. In the analysed sample, the content of phosphorus (P_2O_5) was relatively low, ranging from 0.20 to 1.20 mg P_2O_5/100 g soil. Whereas, in the Eet and Bt horizons of the first exploratory dig, this component was not found. The content of potassium (K_2O) was low (from 3.34 mg/100 g soil to 20.04 mg/100 g soil). Only in one examined horizon the level of this nutrient reached a value considered optimal for growth of young seedlings ($\geq$14 mg K_2O/100 g). The content of magnesium (MgO) in the tested samples varied and fell within the range of 1.08–18.35 mg MgO/100 g soil. In the case of the Ca:Mg ratio, the level of 2.5–7.1:1 is considered optimal for growth of tree seedlings. Only at such a ratio is the uptake of calcium and magnesium adequate and plant growth normal. In the analysed samples, this ratio was not found within the optimal range, which resulted from a low content of magnesium and a high content of calcium. In the tested material, the Ca:Mg ratio ranged from 15.28 to 70.72.

6. Discussion

The analysis of root systems in the wild service trees using a ground-penetrating radar showed that preliminary identification of the horizontal and vertical range of the root systems in the investigated trees is feasible, although the quantitative results of such analyses may be burdened with a specific error. Such a conclusion drawn in the study on the wild service tree is consistent with the experiments by other researchers, who previously stated the applicability of this tool in analyses of root systems [23] and recommended their GPR identification prior to any possible performance of destructive measures [22], thus clearly indicating the usefulness of this device in tree transplantation operations [18].

Depending on ground conditions and the habitat on the ground surface, in many cases, it is possible to determine the distribution and range of roots spreading laterally with high probability and to identify the depth zone where the roots are found. The best results may be obtained in a dry, relatively homogenous soil or geological environment, where trees are loosely scattered. Unfortunately, results are uncertain when it is impossible to distinguish roots from stones or other anomalous objects found in the diverse soil medium [18]. The quality of data provided by the ground-penetrating radar also deteriorates with an increase in soil moisture content or the presence of organic matter [44]. In the present study area, the soil environment was disadvantageous in terms of its structure and the content of a large fraction of limestone stones and the share of the fine loam and silt fractions, forming a clay mixture. For this reason, the images of anomalies obtained from time-slices were difficult to interpret, as, at times, the anomalies provided no image continuity, which could be identified with the extending root. In other situations, image anomalies may have reflected the diverse soil structure.

The more compact a given stand is, the more difficult it is to distinguish an individual root system of the examined tree in the GPR image. A taproot is difficult to detect (most often impossible to distinguish) if it grows into the soil vertically, directly below the trunk; this problem was also indicated by Hugenschmidt and Kay [31]. In our study, this issue was manifested when we compared the range of depths for the presence of roots read from GPR data with those measured on the actual stump. The vertical taproots of the excavated stumps typically grew the deepest into the soil; hence, in the final physical measurements, we recorded greater depths than those provided by the ground-penetrating radar. In turn, in the case of taproot deformation, its intense twisting and lateral growth, such a deformation may be detected in the GPR image. However, it is impossible to distinguish the taproot from an ordinary lateral root in such a case.

The GPR method, while facilitating, with some limitations, the identification of root system architecture, makes it also possible to diagnose some deformation characteristics and the degree of transformations. As mentioned, this refers to an altered direction of growth in the case of lateral roots or even taproots in specific situations, as well as severe flattening of the entire root system. The information on the depth interval for the root system's presence may indicate deformation.

Applying the 3D model construction technique from a series of grid profiling is a pretty standard procedure [45,46], although a definite interpretation of root thickness based solely on the analysis of time-slices obtained from the 3D model is complex. Following recommendations given by many authors, it is advisable to be supported by other methods and advanced algorithms for processing data [24,25] or work on single echograms and interpret each root individually. However, this is laborious and time-consuming, and it does not provide rapid results in the form of a specific expert opinion in a given situation when planning tree translocation operations.

Dimensions of testing plots for GPR analyses of roots need to facilitate scanning possibly the entire root system. These dimensions should be established considering the dendrometric parameters of analysed trees since these parameters may suggest the predicted range of root system spread. On the other hand, the size of the examined plot around a tree may also be determined by the presence of other trees growing in its vicinity. Confirming intertwined and fused roots belonging to a specific tree may not be possible.

In such cases, already at the interpretation stage of the resulting material, the potential joining of different root systems needs to be considered. However, most typically, trees to be transplanted are solitary or grow in rows, so this problem may be considered marginal.

An element affecting the quality of the 3D model provided by radar analyses is also connected with the density of the GPR profile lines grid. In our study on wild service trees conducted in difficult soil conditions, we applied a 25 cm interval between grid lines, which was probably not optimal. Some authors suggested a higher grid density, e.g., as little as 5 cm [47,48].

7. Conclusions and Recommendations

The article presents circumstances in which, as a result of industrial activity development, an interference in the forest environment was planned due to the lack of alternative possibilities. However, an action was taken to reduce the negative effects, preserving the most valuable trees by transplanting them to another favourable place in the forest area. Such an activity is consistent with the concept of sustainable development and sustainable forest management, as one of the conditions of sustainable forestry has been met—preserving valuable natural trees for future generations. The tests of the effectiveness of GPR in tree roots detection enrich the pool of experience providing a basis for developing methodological details for the practical implementation of such operations not only in forests or other natural areas, but also in the urban environment, when it becomes necessary to relocate valuable dendroflora. Our GPR tests provide specific detailed conclusions regarding the use of GPR in such situations.

In view of the soil conditions observed in the study area, the potential translocation of trees is very difficult. Chemical properties of soil do not determine the manner of root growth and spread, since the availability of nutrients and water is similar in individual soil horizons. In turn, the high content of rock fragments of varying sizes in soil practically starting from the ground surface considerably hinders the excavation of the stump with roots in a manner preventing its damage. Moreover, such soil forms a specific barrier for root growth, so those trees do not develop a typical taproot system. It may be assumed that the greater the share of rock fragments in the soil and the shallower the mineral horizon of the soil, the more challenging the conditions for potential tree translocation are. Earlier identification of soil conditions may facilitate the estimation of the feasibility of tree translocation along with the required labour consumption and necessary equipment.

It is commonly accepted that the main root ball is found in the vertical projection area of the tree crown. The analysed horizontal spread of the root systems in the examined trees did not confirm the hypothesis that the main root system is found directly under the crown. In the investigated case, in very shallow soil, the roots were growing strongly in the horizontal plane, while the taproot was deformed or underdeveloped. The analysed root balls were not typical of this tree species. This resulted from their growth in shallow soil. The root systems spread unnaturally in the horizontal plane, while the taproot was atrophied or deformed. In the case of such atypical root balls, common transplanters would be ineffective, as too many roots would be broken. In such cases, it is necessary to perform exploratory digs or use non-invasive methods, such as GPR.

The conducted GPR tests confirmed the applicability of this method to identify root system architecture. Most of the primary structural roots were detected. The number of the main roots detected by the GPR was comparable to those inventoried after extracting the stump. Based on in situ and laboratory studies, the shape and spread of root systems in the analysed trees were correlated with the size of the tree, vicinity of other trees, soil type, and thickness. The effectiveness of the GPR method is determined by the homogeneity of the soil medium. In the presented studies, the structural properties of the soil—significant differentiation of fractions and the high content of limestone fragments of various sizes—made interpreting the material obtained from the GPR partly uncertain. Nevertheless, the results were satisfactory.

When preparing the research project involving the ground-penetrating radar, it is also important to appropriately select the testing plot's dimensions. The testing grid established by the surveying method only in the crown projection area will sometimes prevent inventorying all roots.

When analysing trees of natural value that are to be transplanted, it is recommended to:

- conduct dendrometric analyses of each tree,
- determine each tree's health condition,
- perform an exploratory dig or borehole under the crown of the analysed tree in order to determine soil characteristics and calibrate the depth parameters for the GPR,
- preliminarily estimate the horizontal and vertical spread of the root system using the GPR,
- prepare visualisation of the root ball,
- in ambiguous situations, expose the surface of the root ball to determine the potential spread of structural roots.

These operations will facilitate the selection of an optimal technique and machinery to extract the tree with an entire root ball. They thus will considerably increase the chances of a successful tree translocation.

To summarise, the non-invasive GPR method provides sufficiently reliable information about the tree's root ball. Thus, it is recommended to use for the preliminary assessment of the potential for translocation of trees of natural value and the determination of the optimal transplantation technique.

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