Exploring spatial distribution characteristics of *Populus simonii* Carr coarse roots using ground penetrating radar

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Nghiên cứu đặc điểm phân bố rễ thô của loài cây dương lá nhỏ (*Populus simonii* Carr) dựa trên công nghệ truyền sóng radar xuyên đất

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ABSTRACT

A comprehensive root database holds paramount importance for agro-forestry endeavours, providing valuable insights into the ecological characteristics and stability of plant species. However, the creation of such databases presents a formidable challenge. This study is devoted to shedding light on the spatial distribution characteristics of coarse roots (diameter ≥1 cm) in Populus simonii trees, which naturally flourish in Tongde County, Thanh Hai province, China. Ground-penetrating radar (GPR) technology was employed to investigate the distribution of these coarse roots, while tree root diameters were estimated through controlled experiments involving buried objects. A total of 40 P. simonii trees were meticulously selected for data collection, and the coarse roots of these trees were categorized into three diameter classes: 1-2 cm, 2-3 cm, and ≥3 cm. The study findings have unveiled a robust correlation between the density of coarse roots and the diameter at breast height (dbh) of the trees. Moreover, the total coarse root density moderately correlates with canopy width and tree height within a horizontal plane extending 3-5 m from the tree base and a vertical plane at a soil depth of 20-40 cm. This study underscores the effectiveness of GPR in elucidating the spatial distribution of tree roots and accurately estimating root diameters. This underscores the potential of GPR to significantly enhance investigations related to root ecology and below-ground biomass estimation.

Từ khóa:

Chiều cao vút ngọn, công cụ kiểm tra không phá hủy, độ sâu tầng đất, mặt cắt dọc, mật độ rễ cây.

TÓM TẮT

Cơ sở dữ liệu về hệ thống rễ của thực vật hữu ích cho các hoạt động sản xuất nông lâm nghiệp, cung cấp thông tin về đặc điểm sinh thái của loài và tính ổn định của cây. Tuy nhiên, để xây dựng được cơ sở dữ liệu này là thách thức không nhỏ. Nghiên cứu này được thực hiện nhằm làm sáng tỏ đặc điểm phân bố không gian của rễ thô (đường kính ≥ 1 cm) của loài cây Dương lá nhỏ phân bố tự nhiên ở huyện Đồng Đức, tỉnh Thanh Hải, Trung Quốc. Công nghệ radar xuyên đất được sử dụng để khám phá sự phân bố của các rễ thô, trong khi đường kính rễ cây được ước tính dựa trên thí nghiệm chôn vật thể có kiểm soát. Tổng cộng 40 cây Dương lá nhỏ đã được lựa chọn để thu thập dữ liệu. Rễ thô của những cây này được chia thành ba loại đường kính: 1-2, 2-3 và ≥ 3 cm. Kết quả nghiên cứu cho thấy mật độ của rễ thô có mối tương quan chặt với đường kính ngang ngực của cây. Tổng mật độ rễ thô thể hiện mối tương quan trung bình với chiều rộng tán và chiều cao của cây trong mặt phẳng ngang có bán kính 3-5 m đo từ vị trí của thân cây và trong mặt phẳng theo chiều thẳng đứng 20-40 cm dựa trên độ sâu của tầng đất. Nghiên cứu này nhấn mạnh tính hiệu quả của GPR trong việc khám phá sự phân bố không gian của rễ cây và ước tính đường kính rễ, nêu bật tiềm năng của nó trong việc thúc đẩy các nghiên cứu về sinh thái rễ cây và ước tính sinh khối dưới mặt đất.

1. INTRODUCTION

Plant roots are fundamental not only for plant growth and development but also for carrying out various essential functions. These functions include carbon storage, nutrient cycling, and energy exchange within forest ecosystems, as well as providing stability and anchorage for the plant [1]. However, studying plant roots poses significant challenges for ecologists due to their predominantly subterranean nature [2]. To gain insights into the coexistence mechanisms of different plant species, numerous researchers have advocated for investigating the spatial distributions of plant roots [3]. They have suggested that incorporating tree species with varying root lengths and densities can significantly enhance their efficiency in utilizing resources. The study of plant root systems holds theoretical and practical significance, particularly in forestry production. However, a faction of the scientific community argues that pursuing this research direction, especially in diverse tropical forests, may present unique challenges. Traditional methodologies such as drilling, soil excavation, or rhizotron tube technology can be cost-prohibitive, labour-intensive, and time-consuming, requiring several decades to compile a comprehensive database of the root systems of tropical plant species [4]. Therefore, there is a pressing need to embrace modern methods and state-of-the-art technology to advance the study of plant roots.

Ground-penetrating radar (GPR) represents a contemporary technology for studying plant root systems [5]. It allows researchers to explore subterranean environments without disturbing the soil or jeopardizing the integrity of plant root systems, rendering it an eco-friendly and non-invasive alternative. The functioning of GPR revolves around the emission of high-frequency electromagnetic waves into the subsoil, followed by the recording of reflections originating from various subterranean objects, including roots, geological formations, and soil strata. These reflections are processed to generate images, which can be scrutinized to ascertain the precise location, dimensions, and distribution of plant roots. Applying GPR technology in plant root studies bestows several advantages compared to conventional techniques [6]. It is characterized by swiftness, heightened accuracy, and diminished labour requirements. Consequently, GPR is an efficient modality for subterranean data acquisition. Furthermore, GPR's ability to survey extensive areas and generate three-dimensional representations empowers researchers to examine the entirety of a plant's root system non-invasively. This attribute is precious in ecologically diverse tropical forests housing complex plant root systems.

In recent years, some Chinese scientists have harnessed GPR to investigate the root systems of many plant species. For instance, Zhou et al. leveraged GPR to explore the spatial distribution of *Populus alba* roots in various habitats within the Loess Plateau of northwestern China [7]. Cai et al. utilized GPR to scrutinize the root systems of ten prevalent woody plant species in Shanghai's parklands [8]. Gan et al. applied GPR technology to identify structural anomalies in the trunk and root system of *Platycladus orientalis* species in the Yellow Emperor's tomb in Shaanxi Province [9]. These researchers collectively underscored the effectiveness of GPR in the examination of root systems in perennial plant species.

Populus simonii Carr, commonly called Simon's poplar or Chinese cottonwood, is a member of the Salicaceae family within the *Populus* genus [10]. It is naturally found in northern China, predominantly in the middle and lower regions of the Yellow River, encompassing Henan, Shaanxi, and Gansu provinces [11]. *P. simonii* is a large woody plant capable of reaching heights of up to 30 m and diameter at breast height (dbh) that can exceed 100 cm. The wood derived from this species is characterized by its lightweight and soft composition, featuring a straight grain, rendering it highly suitable for use in papermaking and furniture construction. Additionally, the bark of this tree possesses medicinal properties that allow for the extraction of anti-inflammatory and analgesic compounds [12].

Notably, *P. simonii* exhibits remarkable resilience to adverse environmental conditions, including drought, cold temperatures, and waterlogging. As a result, it is recognized as a crucial element in the fight against desertification and in efforts to improve China's ecological landscape [13]. Numerous prior research endeavours have focused on the intricate root system of *P. simonii*. For example, in a study by Liu, the root distribution of *P. simonii* in artificially planted forests within the Mu Us Sandland was investigated using the ground drilling method [14]. The analysis classified root diameters into two categories: those measuring 3 mm or less and those greater than 3 mm. Liu's findings revealed that the highest root density of *P. simonii* was concentrated within a soil depth of 0-40 cm. In a study by Shi et al., the researchers employed the root plant excavation method to explore the distribution characteristics of *P. simonii* roots in China's Gonghe Basin, located in Qinghai Province [13]. Their research uncovered decreased root biomass and density with increasing soil depth. In another comprehensive study by Cheng et al., the authors adopted a profiling method to investigate the distribution of *P. simonii* roots [15]. Their findings indicated a high density of fine roots in shallow soil layers, with root density gradually decreasing with increasing soil depth.

The investigation of *P. simonii*'s root system has historically relied predominantly on conventional methodologies, primarily focusing on the fine roots. In these prior studies, the substantial role played by the coarser roots in the tree's overall vitality and growth should be mentioned more. Consequently, the primary objective of the present study is to explore the spatial distribution of *P. simonii*'s coarse roots (defined as having a root diameter of 1 cm or greater) utilizing the GPR technology. The selection of GPR technology for this investigation is predicated on its non-invasive characteristics, rendering it an optimal instrument for this purpose. Its non-destructive nature allows us to obtain precise and reliable data without causing any harm to the root systems of *P. simonii* trees. By scrutinizing the spatial layout of these coarse roots, we aspire to attain a comprehensive comprehension of the coarse root system inherent to this species. The outcomes derived from this study are poised to offer valuable insights into the management and cultivation of *P. simonii* trees. This research aims to enhance the growth and minimize the potential risks associated with root system disturbance of *P. simonii* trees, ultimately contributing to the overall health and sustainability of these trees.

2. RESEARCH METHODS

2.1. Study area

The study area is situated within the alluvial plain of the Huanghe River, located in Tongde County, Qinghai Province, China. It is geographically defined by coordinates spanning from 35º31'35.13'' to 35º32'33.23'' north latitude and 100º09'1.53'' to 100º10'1.33'' east longitude. The elevation of this study area ranges from 2664 to 2668 m a.s.l. The topography of this region is characterized by dunes deposited by the river, which have given rise to a valley and an alluvial plain landform [16].

Tongde County experiences a high-altitude continental climate featuring prolonged, cold winters and brief summers. The annual precipitation within this locale measures 371.5

mm, while the relative humidity oscillates between 50 to 61%. This region falls within the classification of semi-arid and arid areas, with evaporation rates ranging from 1260.1 to 1643.6 mm. The vegetation in the study area is predominantly composed of *P. simonii* trees, which thrive in sandy alluvial soil. The tree density is notably low, with approximately 25 trees ha^{-1} [16].

2.2. Data collection

In December 2022, we established ten study plots, each measuring 30 m × 30 m, on the floodplain of the Yellow River in Tongde County, Qinghai province, China. A total of 40 *P. simonii* individuals were meticulously selected, ensuring their root systems did not overlap. These trees were positioned at a uniform distance of 5 m from each other and were intentionally isolated from other trees. Subsequently, we conducted comprehensive measurements for each *P. simonii* individual, including their dbh, canopy width, and tree total height. The smallest recorded dbh among the *P. simonii* individuals was 45 cm, while the largest reached 104.5 cm. To categorize these 40 *P. simonii* individuals effectively, they were sorted into six distinct diameter classes described in Table 1.

Table 1. Basic characteristics of *P. simonii* in the study plots

No.	dbh classes (cm)	N (trees)	dbh (cm)	Canopy width (m)	Height (m)
1	45-54.9	9	49.83 ± 2.48	8.2 ± 1.52	10.59 ± 2.5
2	55-64.9	8	59.83 ± 3.49	10.75 ± 1.27	14.58 ± 3.11
3	65-74.9	6	70 ± 2.53	11.18 ± 1.92	14.88 ± 2.82
4	75-84.9	7	79.5 ± 2.66	10.78 ± 1	14.83 ± 2.69
5	85-94.9	5	88.83 ± 2.64	12.08 ± 1.49	16.17 ± 1.89
6	95-104.9	5	99.67 ± 4.12	12.54 ± 1.18	17.77 ± 3.59

2.3. Research equipment

The research equipment employed in this study consists of the TerraSIRch™ Ground-Penetrating Radar (GPR) system manufactured by GSSI, USA [17]. This system comprises a computer-controlled SIR-3000 unit with a 900 MHz Model 3101D antenna. The 900 MHz antenna offers a root mean square resolution of a minimum of 1cm and can achieve a maximum detection depth of 1m. The scanning procedure involves a concentric circle method with the tree trunk as its central point. Scanning is carried out at five distinct distances from the trunk: 1, 2, 3, 4, and 5 m. The scanning process initiates from the northern direction and proceeds clockwise until a full circle is completed.

2.4. Data analysis

In this investigation, we employed the root inversion method, a technique widely utilized in the GPR technology for the detection and analysis of plant roots. This method is founded on the fundamental principle that electromagnetic waves emitted by a radar antenna, upon encountering a plant root, undergo reflection towards the antenna. Analyzing these reflected waves yields valuable information concerning the root's dimensions, configuration, and spatial coordinates. Within the framework of the root inversion method, GPR data is systematically gathered through the scanning of the target area, generating a two-dimensional subsurface image. This image effectively portrays the root's position as a hyperbolic curve, and crucial insights into the root's size can be deduced based on the width and positioning of this curve. To ensure precision in the measurements, a calibration procedure is a prerequisite. This entails the insertion of known objects with diverse sizes and shapes into the soil, followed by the subsequent measurement and evaluation of their reflective properties.

In this study, we implemented the buried-root method, initially proposed by Barton and

Montagu [18]. We selected *P. simonii* roots within the study area, each measuring 1 m long. To enhance the accuracy of root detection by the GPR system and to prevent water loss, we coated the root ends with melted wax. To conduct the experiments, we excavated a flat and open sandy pit measuring 6×1.2×1.2 m. Within this pit, we buried eight roots with varying diameters, ranging from 1 to 4 cm, at a depth of 30 cm. These roots were placed in a parallel orientation with a horizontal spacing of 70 cm, and sand was used as the backfill medium. We established five measurement lines perpendicular to the longitudinal axis of the roots, each line being spaced 20 cm apart. Subsequently, the radar antenna was systematically moved along each line for scanning. The determination of buried root size was accomplished by analyzing GPR parameters, and a fitting equation was derived by converting radar wave parameters into root diameter. The equation for estimating root diameter, derived from these calculations and control measurements, is as follows:

$$y = 0.576x + 1.206 \quad (R^2 = 0.874) \qquad (eq.\ 1)$$

In equation 1, x denotes the time (in seconds) required for the electromagnetic wave from the GPR to traverse the root system. At the same time, y represents the root diameter (in cm). For each scanning route, offset processing was performed using the Reflexw 9.5 radar wave analysis software to capture the time (in seconds) taken for the radar wave to penetrate the root system. Subsequently, the corresponding root diameter values were computed based on this time measurement. The coarse roots of *P. simonii* were then categorized into three distinct diameter classes, dependent on their root diameter sizes: 1-2 cm, 2-3 cm, and ≥ 3 cm.

The assessment of coarse root density was performed using TreeWin software. For vertical distribution analysis, statistical examinations were carried out at four specific depths: 0-20 cm (topsoil layer), 20-40 cm (B horizon), 40-60 cm (C horizon), and 60-80 cm (regolith layer). Regarding horizontal distribution, statistical analysis was conducted at five radii: 1, 2, 3, 4, and 5 m. Each root scanning file underwent meticulous analysis, and the TreeWin software calculated the root density value for each transect after manually identifying coarse roots in the radar images. Since the GPR-generated image represents a vertical cross-section, the calculation of root density was based on the count of roots reflected at various depths along the vertical section of each transect. It is important to note that the methodology employed for assessing coarse root density in this study deviates from traditional approaches. Root density is defined as the number of root points per meter of transect length (roots m^{-1}), and the calculation formula is as follows:

$$RD = N_R/L \qquad (eq.\ 2)$$

where, N_R represents the count of root points observed at various depths in the vertical cross-section; L represents the transect length in m. RD signifies the root density within the designated depth range (roots m^{-1}).

The total coarse root density is computed by dividing the cumulative count of root points in the five circular regions around each tree by the total length of the transect. The formula for this calculation is expressed as follows:

$$TRD = (N_1+N_2+N_3+N_4+N_5)/(L_1+L_2+L_3+L_4+L_5) \qquad (eq.\ 3)$$

where,

N_1-N_5 represents the count of root points within circular regions of the transect;

L_1-L_5 signifies the length of these circular regions in meters;

and TRD represents the overall root

density (roots m^{-1}).

The data analysis was conducted using R software, version 4.3.1. This analysis encompassed comparisons of coarse root density at various horizontal distances and soil depths, as well as the exploration of correlations between coarse root density and tree characteristics, including dbh, tree total height, and crown width.

3. RESULTS

3.1. Vertical distribution of coarse roots

The investigation focused on the vertical distribution of coarse root density within a sample of 40 *P. simonii* trees. Our findings unveiled a discernible pattern, indicating that coarse root density exhibited an increasing trend followed by a subsequent decrease as soil depth increased (Fig. 1a). Specifically, the coarse root density at different soil layers were as follows: 4.26 roots m^{-1} for the topsoil layer, 8.17 roots m^{-1} for the B horizon, 4.73 roots m^{-1} for the C horizon, and 2.61 roots m^{-1} for the Regolith layer. Notably, the coarse root density at the B horizon and Regolith layer displayed significant disparities compared to other soil layers, with p-values < 0.05. This result showed that the B horizon consistently exhibited the highest coarse root density across all three root diameter classes. At the same time, the lowest values were consistently observed in the Regolith layer.

Figure 1b depicts the distribution of coarse roots in *P. simonii* trees concerning variations in soil depth and root diameter sizes. The results illuminated that the highest coarse root density was observed within the 1-2 cm root diameter class, closely followed by the 2-3 cm class. In contrast, the lowest density was recorded for roots ≥ 3 cm in diameter. With increasing soil depth, the density of coarse roots within the 1-2 cm root diameter class gradually declined, diminishing from 70.3% in the topsoil layer to 42.5% in the regolith layer. Conversely, the density of coarse roots within the 2-3 cm root diameter class exhibited an ascending trend, increasing from 23.7% at the topsoil layer to 47.2% in the regolith layer. Notably, the density of coarse roots greater than or equal to 3 cm in diameter initially showed an upward trend with depth, reaching its peak at the C horizon before declining.

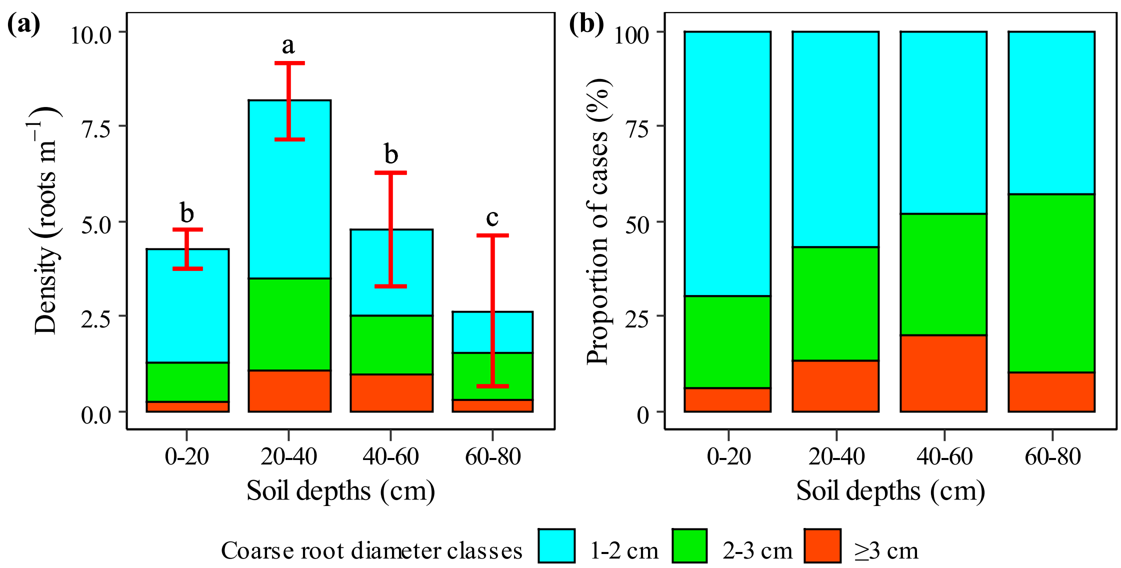

Figure 1. Density distribution of coarse roots (a) and proportion of coarse roots of different diameter classes of *P. simonii* in different soil depths (b)

Density distinctions in coarse root among diverse root diameter classes are symbolized by the letters a, b, and c, signifying a p-value below 0.05, as determined through analysis of variance.

3.2. Horizontal distribution of coarse roots

We analyzed the mean coarse root density within a 5-m radius surrounding the base of each trunk in the horizontal plane for a sample of 40 *P. simonii* trees. The study results revealed a clear trend of decreasing coarse root density with increasing radius (Fig. 2a). Notably, the highest density of coarse roots was observed at a 1-m radius, and this density progressively decreased as the radius expanded, culminating in the lowest density at a 5-m radius. Statistical analyses also unveiled noteworthy differences in coarse root density across the various radii. Furthermore, the study investigated variations in root density concerning different root diameter classes. Specifically, the density of 1-2 cm coarse roots initially decreased, then exhibited an increase as the radius expanded. The lowest density, at a mere 1.99 roots m^{-1}, was recorded at a 3-m radius. Similarly, the density of 2-3 cm coarse roots gradually declined as the radius increased, reaching its nadir at a 5-m radius with only 0.66 roots m^{-1}. In contrast, for the root diameter class greater than or equal to 3 cm, their initial density demonstrated an increase followed by a decrease. The peak density of 0.73 roots m^{-1} was observed at a 2-m radius.

Figure 2b illustrates the distribution of coarse roots across various diameter classes within a 1-5 m radius in the horizontal plane. The findings disclosed that coarse roots within the 1-2 cm diameter class exhibit the highest proportion, followed by those with a 2-3 cm diameter. In contrast, the proportion of coarse roots greater than or equal to 3 cm in diameter is the lowest. As the radius expands, the proportion of roots in the 1-2 cm diameter class initially decreases, then increases. Notably, the lowest proportion of coarse roots with a 1-2 cm diameter, constituting 49% of the total coarse root density, was observed at a 2 m radius from the trunk.

In contrast, the proportion of roots with a 2-3 cm diameter and those greater than or equal to 3 cm increased and then decreased with increasing radius. Coarse roots within the 2-3 cm diameter class accounted for 34% of the total coarse root density at a 2-meter radius from the trunk, while those with a diameter greater than or equal to 3 cm reached a maximum of 17%. Overall, within the 1-3 m radius surrounding the trunk, coarse roots with a diameter of 2-3 cm and greater than or equal to 3 cm predominate, while coarse roots with a 1-2 cm diameter are primarily concentrated at radii greater than or equal to 3 m.

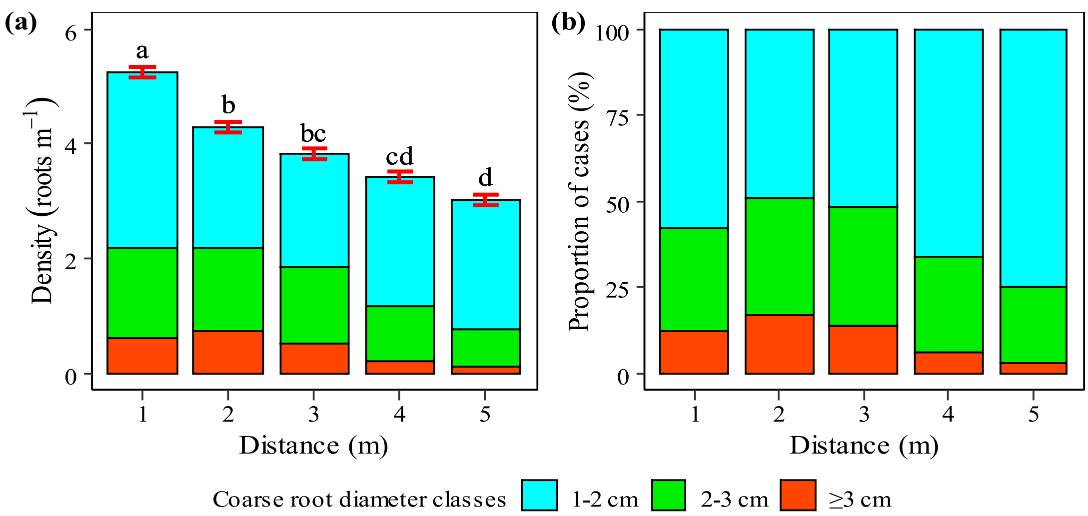

Figure 2. Density distribution of coarse roots (a) and proportion of coarse roots of different diameter classes of *P. simonii* at different distances from the trunk (b)

Density distinctions in coarse root among diverse root diameter classes are symbolized by the letters a, b, and c, signifying a p-value below 0.05, as determined through analysis of variance.

3.3. Correlation between coarse root density with dbh, total height, and crown width of trees

The investigation examined the relationship between coarse root density and the dbh of 40 *P. simonii* trees. The findings unveiled a positive correlation between dbh and coarse root density (Table 2). Within the various analyzed coarse root diameter classes, the 1-2 cm class displayed the highest density, with values ranging from 7.91 to 18.67 roots m^{-1}. In contrast, the 2-3 cm and ≥ 3 cm diameter classes exhibited lower densities, ranging from 4.78 to 7.03 roots m^{-1} and 1.76 to 2.464 roots m^{-1}, respectively. Furthermore, the outcomes of the variance analysis underscored the presence of significant differences in coarse root density across six dbh classes.

Table 2. Coarse root density of *P. simonii* trees according to different dbh classes

dbh classes (cm)	Coarse root density in different root diameter classes			
	1-2 cm	2-3 cm	≥3 cm	Total root density
45-54.9	8.29 ± 0.96 c	5.3 ± 0.89 c	1.76 ± 0.43 a	15.34 ± 1.45 c
55-64.9	7.91 ± 1.66 c	4.78 ± 1.2 c	1.78 ± 0.35 a	14.47 ± 2.84 c
65-74.9	9.72 ± 2.2 c	5.14 ± 1.56 c	1.81 ± 0.39 a	16.67 ± 3.59 c
75-84.9	12.72 ± 2.07 b	5.82 ± 0.96 ab	1.91 ± 0.29 a	20.45 ± 2.72 b
85-94.9	14.19 ± 1.43 b	5.97 ± 1.98 ab	2.41 ± 0.84 a	22.57 ± 2.24 b
95-104.9	18.67 ± 2.68 a	7.03 ± 1.04 a	2.46 ± 0.7 a	28.16 ± 3.78 a

Density distinctions in coarse root among diverse root diameter classes are symbolized by the letters a, b, and c, signifying a p-value below 0.05, as determined through analysis of variance.

We conducted a comprehensive correlation analysis to assess the relationship between coarse root density and growth characteristics in 40 *P. Simonii* trees. Our investigation unveiled statistically significant positive correlations among coarse root density, dbh, tree total height, and crown width, as outlined in Table 3. More specifically, we observed that dbh exhibited the strongest positive correlation with coarse root density (r=0.827, p=0.000), followed by tree crown width (r=0.392, p=0.018) and tree height (r=0.384, p=0.021). These findings emphasize the pivotal role of growth characteristics in influencing coarse root density within the *P. Simonii* species.

Furthermore, we employed regression analysis to investigate the influence of dbh, tree height, and crown width on coarse root density. The analysis yielded a regression model highlighting tree dbh and crown width as the most effective predictors of coarse root density in *P. Simonii*. The model can be expressed as follows: Total coarse root density (TRD) = 5.917 + 0.312 dbh - 0.865 crown width (R^2=0.736, p=0.000). These results underscore the significant impact of dbh and crown width on coarse root density within the *P. Simonii* species.

Table 3. Correlation between coarse root density and tree dbh, height, and crown width

TRD	dbh	height	crown width
R^2	0.827	0.384	0.392
p-value	0.000	0.021	0.018

An additional layer of analysis was undertaken to explore the distribution of coarse root density in *P. Simonii* trees, encompassing horizontal and vertical dimensions, considering soil depths and distances from the tree trunk (Table 4). Our findings revealed that within a 5-m radius from the trunk, coarse root density exhibited a significant positive correlation with dbh (p<0.01). Furthermore, within the 3-5 m radius, coarse root density also significantly positively correlated with tree height and canopy width. The vertical distribution analysis unveiled significant positive correlations between coarse root density and tree dbh within the various soil layers. Additionally, the coarse root density within the B horizon exhibited significant positive correlations with tree height and canopy width. In sum, the results suggest that the most reliable predictors for coarse root density within the 3-5 m radius in the horizontal plane and the B horizon in the vertical plane are tree dbh, total height, and canopy width.

Table 4. Correlation between coarse root density and tree dbh, height, and crown width according to root spatial distribution

Coarse root spatial distribution		dbh	Total height	Crown width
Horizontal plane	1 m radius	0.704**	0.264	0.382*
	2 m radius	0.758**	0.312	0.316
	3 m radius	0.827**	0.365*	0.411*
	4 m radius	0.837**	0.443**	0.415*
	5 m radius	0.803**	0.444**	0.339*
Vertical plane	Topsoil (0-20 cm)	0.366*	0.395*	0.191
	B horizon (20-40 cm)	0.763**	0.380*	0.495**
	C horizon (40-60 cm)	0.740**	0.274	0.354*
	Regolith (60-80 cm)	0.670**	0.281	0.299

*(Significance level: * p < 0.05; ** p < 0.01)*

4. DISCUSSION

4.1. Coarse root distribution characteristics

The spatial distribution of tree roots within the soil plays a pivotal role in a plant's ability to access essential resources. In the context of *P. simonii*, this investigation has unveiled that the highest concentration of coarse roots is localized within the soil depth of 20-40 cm. In contrast, the research conducted by Liu yielded divergent results, as they reported the peak density of *P. simonii* roots within the 0-20 cm soil depth [14]. This disparity may stem from variations in the influence of river dynamics on the vertical distribution of the same species in distinct environmental conditions [19]. The spatial arrangement of tree roots is intricately linked with the physical and chemical properties of the soil [20]. Wang and colleagues have established that the topsoil within the root zone of Populus euphratica exhibits elevated levels of organic matter, total nitrogen, and electrical conductivity compared to other soil layers. This uppermost soil layer also corresponds to the primary zone of root concentration for the tree, underscoring its suitability for robust root growth [21].

Furthermore, our research has uncovered that the density of coarse roots with large diameters tends to increase with greater soil depth. Cai's study similarly documented an increase in the density of coarse roots in Salix gordejevii as soil depth increased. In contrast, Zhang's investigation demonstrated the predominance of fine roots in the surface layer. In our study, the density of coarse roots exhibited a "high-low-high" pattern, highlighting the vertical expansion characteristics of coarse roots and their enhanced conductive capacity in deeper soil layers [22, 23]. While deep soil hosts a limited number of roots, their presence remains critical for the water absorption capabilities of trees. In the horizontal dimension, the highest density of coarse roots in *P. simonii* is observed at a distance of 1 meter from the tree trunk, aligning with the findings in Cheng's study [15]. As the distance from the tree increases, a distinct pattern emerges in the proportions of coarse roots with different diameters. Specifically, the proportion of coarse roots with a diameter of 1-2 cm initially decreases and subsequently increases, while the proportions of coarse roots with diameters of 2-3 cm and ≥3 cm exhibit an opposite trend, increasing initially and gradually diminishing afterwards. This observation implies that the increase in the density of coarse roots with a diameter of 1-2 cm around the tree may be attributed to adventitious roots originating from coarse roots with diameters of 2-3 cm and ≥3 cm [7]. It is crucial to acknowledge that the distribution of coarse roots with varying diameters is influenced by the specific soil conditions prevalent in river floodplain areas.

4.2. Response of coarse root density to dbh, tree height, and crown width

The density of coarse roots is intricately linked to the growth characteristics of trees. As the dbh increases in *P. simonii*, there is a gradual augmentation in the overall coarse root density. However, substantial disparities in the density profiles are observed across different diameter classes within this species, with the primary contributing factor being the coarse root density within the 1-2 cm diameter range. In a study investigating the spatial distribution patterns of roots in jujube orchards of varying ages, Ma et al. also reported an increase in the number of roots across different diameter categories with tree age. Notably, the growth rate of coarse roots lags behind that of fine roots, suggesting a shift towards a more absorption-focused root development with increasing tree age [24]. Among various plant growth indicators such as dbh, total height, and crown width, the total coarse root density in *P. simonii* is more significantly influenced by dbh and crown width than tree height. This relationship is primarily attributed to the close association between dbh and tree age. Throughout the developmental stages of trees, the positive impact of dbh on crown width gradually intensifies [25]. Furthermore, Li et al. found that as the dbh of *Camellia aliens* increases, there is a tendency for root density to decrease, underscoring the intricate interplay between tree characteristics and root system development [26].

The analysis of the correlation between the distribution of horizontal and vertical coarse root density and the dbh, total height, and crown width of *P. simonii* revealed significant patterns. Coarse root density within a 5-m radius in the horizontal direction and at depths ranging from 0 to 80 cm below the soil surface exhibited a positive correlation with dbh. This observation suggests that larger dbh values in *P. simonii* are associated with a higher density of coarse roots within a 5-m radius in the horizontal plane and the top 80 cm of the soil profile. A similar trend was observed in a study by Lu, where the distribution of *Larix gmelinii* roots in the horizontal direction indicated an increase in root numbers with the tree's age [27]. Furthermore, in our research, we found that coarse root density at distances ranging from 3 to 5 m in the horizontal direction and at depths of 20 to 40 cm below the soil surface in *P. simonii* also exhibited positive correlations with dbh, total height, and crown width. Interestingly, the response of coarse root density at a distance of 1-2 m from the trunk and a deeper layer of 40-80 cm to dbh, total height, and crown width was comparatively less sensitive than that observed at distances of 3-5 m from the trunk and a shallower soil depth of 20-40 cm. These findings underscore the intricate relationship between tree characteristics and coarse root density, with specific distances from the trunk and soil depths playing crucial roles in shaping these correlations.

In contrast to conventional excavation techniques, ground-penetrating radar offers several distinct advantages, including convenience, enhanced visual capabilities, and a systematic approach. This research leveraged ground-penetrating radar technology to conduct non-destructive assessments of the root system of *P. simonii* and to estimate root diameter sizes. These findings hold the potential as a valuable reference for non-destructive assessments of root systems in various other tree species.

It is worth noting that the utilization of ground-penetrating radar for plant studies remains limited in Vietnam, and its application in field root detection is a relatively recent development. As radar systems evolve and analysis software becomes more advanced, ground-penetrating radar is poised to assume an increasingly significant role in plant detection, underground biomass estimation, and urban greenery planning.

5. CONCLUSION

This study utilized GPR technology to conduct non-destructive detection of coarse roots in *P. simonii* trees growing on the Huanghe River floodplain in Qinghai, China. Our findings unveiled significant variations in the density and distribution of coarse roots within these trees, which were influenced by both vertical and horizontal distances from the trunk, as well as varying tree dbh. Notably, we observed a higher density of coarse roots in *P. simonii* trees with greater dbh, implying that the increase in tree height and crown width positively impacts root growth. This insight highlights the potential for improving the management practices of *P. simonii* trees by considering the distribution of coarse roots within different dbh categories.

These results contribute to a deeper comprehension of the growth dynamics of *P. simonii* trees and provide valuable guidance for optimizing strategies aimed at promoting their growth and development. As fellow researchers continue to explore non-destructive detection methods, such as GPR, the management of forest tree species can draw upon the knowledge acquired through this study.

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