SPECIES-SPECIFIC CONTRIBUTIONS OF ROOT LENGTH AND WEIGHT DENSITY TO SOIL COHESION AND STABILITY IN FOREST ECOSYSTEMS

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Abstract. Root systems play a critical role in soil stabilization, particularly in hillsides prone to erosion and mechanical stress. This study investigates the species-specific effects of root length and weight density on soil cohesion and internal friction angle across different soil depths for *Amorpha fruticosa* Linn., *Lespedeza bicolor* Turcz., and *Swida alba* Opiz. in forest ecosystems of northeastern China. Using the shear strength test and root density test, we analyzed the response of root-soil complex at different soil depths. The results revealed that the *Amorpha fruticosa* Linn. exhibited the highest soil cohesion at both soil layers, with significantly greater root density compared to the *Lespedeza bicolor* Turcz. and *Swida alba* Opiz. The deeper root penetration and denser root network enhanced root-soil complex stability by improving soil cohesion, but not by improving internal friction angle. Our findings provide quantitative evidence of how species-specific root density parameters, enhance soil cohesion at varying depths. The root morphology of *Amorpha fruticosa* Linn. was shown to be most effective in hillside stability. These insights facilitate our understanding of the mechanisms of root-soil interactions and provide a more comprehensive perspective into soil conservation and ecological restoration efforts in forest areas.
Keywords: *root morphological traits, root-soil complex, hillside erosion, shear strength*

Introduction

In forest ecosystems, soil stability is equally a critical factor in maintaining ecosystem integrity, particularly in regions prone to erosion, landslides, or mechanical stress due to natural phenomena (Johnson et al., 2020). Vegetation in forests, especially through plant root systems, enhances soil mechanical properties by improving cohesion and shear strength, providing long-term stability for the overall ecosystem (Miller et al., 2020a).

For shallow soils, the primary characteristic of the unstable state of plant root-soil complex was the shear failure of root-containing soil (Ji et al., 2020). In contrast to trees, shrubs in forest ecosystems tend to have shallower but more widespread root systems, which play a crucial role in providing resistance to shear, particularly in the upper soil layers where erosion is most pronounced (Zhou et al., 2023). Shrub roots form dense networks that effectively bind soil particles, thereby preventing surface erosion and contributing to soil stability in areas susceptible to mechanical stress (Anderson et al., 2022a). Despite their shallower depth compared to tree roots, shrub root systems are highly effective in stabilizing surface soils and protecting against the loss of topsoil, making them essential components of erosion control in forest ecosystems (Li et al.,

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2018). However, the mechanisms of soil stabilization in forest ecosystems are complex, particularly due to variations in root depth, density, and structure across different tree species.

While prior studies have established the importance of vegetation, particularly shrub roots, in enhancing soil cohesion and stability (Chen et al., 2019), the extent to which root biomass and density at various soil depths influence soil shear strength and internal friction angle remains unclear. There remains a gap in understanding the species-specific contributions of root density and length to soil mechanical properties. Previous studies have provided a general understanding of the role of roots in soil reinforcement (Zhou et al., 2021), but few have focused on the distinct contributions of different shrub species in both shallow and deeper layers of soil. The findings of this research are expected to fill this knowledge gap and provide a more detailed understanding of how root systems contribute to soil cohesion and stability under varying mechanical stresses (Sun et al., 2023; Anderson et al., 2023).

The primary objective of this research is to investigate the species-specific contributions of root length density and root weight density to soil cohesion and internal friction angle at different soil depths. In this study, we hypothesize that shrubs with higher root length density and root weight density will demonstrate greater soil cohesion and internal friction angle, particularly in the shallow soil layers where the root-soil interaction is the strongest. We selected *Amorpha fruticosa* Linn., *Lespedeza bicolor* Turcz., and *Swida alba* Opiz. for this study because these shrub species are dominant in the study region, frequently utilized in local ecological restoration projects, and exhibit contrasting root architectures and biomass distributions. Their prevalence and ecological importance make them suitable candidates for examining species-specific contributions to soil reinforcement. Additionally, we anticipate that root systems will have a more pronounced effect on soil cohesion than on internal friction angle, reflecting the primary role of roots in binding soil particles rather than altering friction properties.

The study focuses on two critical questions: (1) How do root length density and root weight density influence soil mechanical properties such as cohesion and internal friction? (2) Which species contribute most significantly to soil stability across different soil depths? By addressing these questions, this study is novel in its comprehensive analysis of the species-specific effects of root density parameters on soil mechanical properties across different soil depths. By investigating the contributions of shrubs root systems to soil stability in forest ecosystems, this research not only broadens the comparison with forest ecosystems but also provides a more comprehensive perspective for soil conservation and ecological restoration efforts in forested areas.

Materials and methods

Study area introduction

The study area is located in the Wuying national nature reserve of Yichun City, Heilongjiang Province, northeastern China (48°02’–48°12’N, 128°58’–129°15’E), on a hillside with a slope angle of approximately 25°. A map illustrating the study area and sampling points is provided in *Figure 1*. It is situated in the upper reaches of the Tangwang River, in the heart of the southern foothills of the Lesser Khingan Mountains. Most of the area consists of mountainous terrain, with only a small amount of alluvial plains along the Tangwang River. The study site is located in a temperate continental monsoon climate zone. The forest community in the study area is a natural mixed coniferous and broad-leaved

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forest. The dominant tree species include *Pinus koraiensis* and *Picea asperata*, while the primary shrub species are *Amorpha fruticosa* Linn. (AFL), *Swida alba* Opiz (SAO), and *Lespedeza bicolor* Turcz. (LBT). The study plots were characterized by the following shrub attributes, as outlined in *Table 1*. The basic physical properties of the soil in the experiment site were determined, as outlined in *Table 2*.

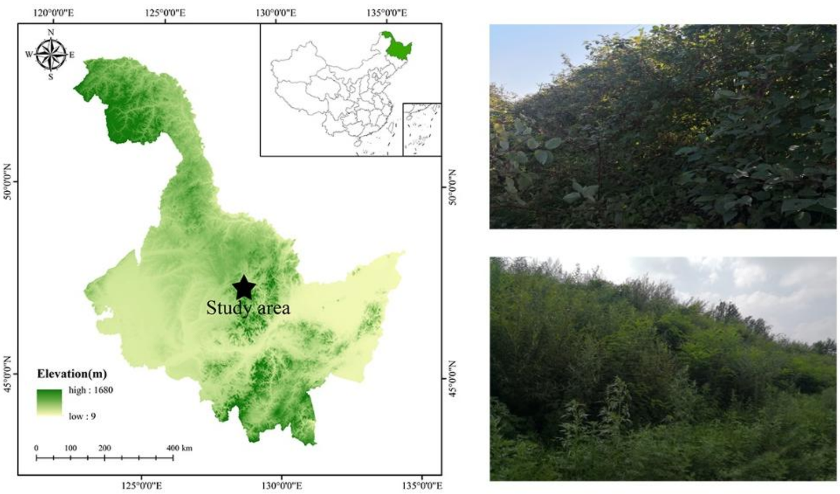

Figure 1. *Sample plot and diagram of the experimental design in Wuying national nature reserve, Yichun city, Heilongjiang province, northeastern China*

Table 1. *Characteristics of important shrub species in the study area*

Species	Mean height (cm)	Mean coverage (%)	Canopy (cm)	Basal diameter (cm)
AFL	178.28 ± 3.76	96.5 ± 1.02	135.67 ± 9.66	1.87 ± 0.12
LBT	221.15 ± 5.66	92.4 ± 0.99	153.66 ± 11.23	2.25 ± 0.07
SAO	211.45 ± 2.66	92.7 ± 1.42	166.29 ± 10.57	1.92 ± 0.09

Table 2. *Physical properties of the soil*

Soil type	Soil content (%)	Wet density (g/cm^3)	Liquid limit (%)	Plastic limit (%)	Plasticity index
Clay	13	1.9	32.5	18.7	13.8

'Soil Content (%)' indicates the percentage of clay particles in the soil, determined by standard particle size distribution analysis. The 'liquid limit (%)' represents the moisture content at which soil behaves as a liquid, an important geotechnical property indicating soil plasticity and its consistency limits

Direct shear test on root-soil complex

Test preparation and sample preparation

Sampling was conducted in July 2023 at three replicate plots per species. Each plot was located at a similar slope angle (25°) and at the similar height on the hillside. For each species, we collected 5 replicate samples per soil layer (0–10 cm and 10–20 cm) resulting in a total of 15 samples per species. A total of 45 samples were collected (15 per species). The sampling took place under stable weather conditions (no recent heavy

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rainfall events) to ensure consistent moisture levels. The sampling process was as follows: The vegetation protruding from the surface was trimmed first. To facilitate the collection of the required samples, the vegetation above the surface was cut off. Samples were collected starting from the surface and proceeding vertically downward. The vertical depth was divided into two groups: 0–10 cm for the first group and 10–20 cm for the second group. A ring knife was used during collection. The ring knife was pressed into the soil until the soil completely filled it. Excess soil and roots protruding from the top and bottom of the ring knife were trimmed. Each ring knife sample had a diameter of 61.8 mm and a height of 20 mm, yielding a soil volume of approximately 60 cm^3 per sample. On average, each soil sample weighed approximately 100 g (±5 g). After trimming, the sample was wrapped in plastic film and sealed with transparent tape to prevent moisture loss. Additionally, the plastic film was labeled with a number. For the control group, root-free soil samples were prepared using the same method at a bare slope position. All collected samples were placed in a thermal insulation box at 4°C, with dry ice inside, and transported back to the laboratory for testing.

After transporting the shear samples to the laboratory, shear force was measured using the SJ-1 type equal-stress direct shear apparatus, with a calibration coefficient of 1.835 KPa/0.01 mm. The laboratory direct shear test was performed using a strain-controlled direct shear apparatus, with a shear displacement of 4 mm and a shear rate of 2.4 mm/min. The applied pressures were 50 KPa, 100 KPa, 200 KPa, and 300 KPa. The Coulomb formula was applied to determine shear resistance indicators, specifically internal friction angle (φ) and cohesion (c). Mohr–Coulomb equation (*Eq. 1*):

$$\tau = \sigma \tan \varphi + c \quad \text{(Eq.1)}$$

where τ is the shear strength (kPa); σ is the normal stress (kPa); c is the cohesion (kPa); and φ is the internal friction angle (◦).

Experimental procedures

The quick shear test was conducted using the SJ-1 type electric equal-stress direct shear apparatus. Place a clean permeable plate in the bottom box and insert a filter paper. Take the ring knife sample with the cutting edge facing up. Place another piece of filter paper and a clean permeable plate on top of the ring knife sample. Align the shear apparatus and vertically insert the sample from the ring knife into the shear box. Test Preparation: Move the instrument’s transmission component to ensure the steel ball in the upper box is aligned with the force gauge. Then, sequentially add the pressure transmission components. For each test, prepare four samples. Conduct the tests under four different pressure conditions: 50 KPa, 100 KPa, 200 KPa, and 300 KPa. Set the dial gauge on the testing instrument to zero. Sample Shearing: Remove the fixing pin, start the stopwatch, and begin recording the test. Maintain a constant loading speed of 0.8 mm/min (4 r/min), applying horizontal shear force to the sample. Record readings at every two rotations of the handwheel. Note both the force gauge and displacement readings. Stop recording when the force gauge reading reaches its peak. If the needle stops moving forward or significantly reverses, it indicates that the sample has failed. According to the test requirements, stop the shear test when the sample deformation reaches approximately 4 mm. If the needle reading continues to increase, stop the test when the sample deformation reaches about 6 mm.

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Test for determining the density parameters of root systems

After completing the shear test of the root-soil complex, each sample and the soil near the plant roots were carefully cleaned. The roots and soil were separated manually. Roots were separated by manually teasing the soil samples collected directly beneath the target shrubs. We identified shrub roots based on their point of origin from the sampled shrub stem base and distinct morphological characteristics (color, thickness, branching pattern). After initial manual separation, samples were passed through a 5 mm sieve twice to ensure that only roots from the target shrub species were retained. Any non-target roots were minimized by careful field identification and marking of the sampled shrubs prior to extraction. The soil was then placed in a 5 mm sieve twice consecutively to extract the remaining roots. Subsequently, the morphological characteristics and root density parameters of the shrub roots were measured. The measurements included root length density (RLD, cm/cm^3) and root weight density (RWD, g/cm^3). Root length density (RLD, cm/cm^3) was calculated by dividing the root length by the soil volume, and root weight density (RWD, g/cm^3) was calculated by dividing the root weight by the soil volume. The measurement method for the samples was based on the testing method introduced by Ristova and Barbez (2020). All roots found in each sample were weighed and scanned using an Epson Perfection V850 Pro scanner at a resolution of 600 dpi. We used WinRhizo software (Regent Instrument Inc., Instruments, Québec, Canada) to measure the root length.

RLD refers to the total length of the roots contained in the soil relative to the soil volume. It is calculated as (*Eq. 2*):

$$RLD = L / V_S = (L_1 + L_2 + L_3 + \ldots + L_n) / a \times b \times h \quad \text{(Eq.2)}$$

where L is the total length of the roots contained in the soil (cm); Vs is the volume of the soil (cm^3); Vs = As× h = a× b × h, where a, b, h are the width (cm), length (cm) and height (cm) of the soil sample. The unit for RLD is cm/cm^3.)

RWD, which is the root weight density, refers to the mass of roots per unit volume of soil. It is calculated as follows (*Eq. 3*):

$$RWD = W / V_S = (W_1 + W_2 + W_3 + \ldots + W_n) / a \times b \times h \quad \text{(Eq.3)}$$

where w is the mass of the roots in the soil (mg); Vs is the soil volume (cm^3); Vs = a×b×h, where a, b, and h are the width (cm), length (cm), and height (cm) of the soil sample, respectively. The unit for RWD is mg/cm^3.

Statistical analysis

In the study, normality and homogeneity of variance for all data were tested using the tests of Kolmogorov-Smirnov and Levene, respectively. This chapter employed regression analysis to investigate the relationship between shear strength parameters and root properties under different soil depths with shrub root participation. All statistical analyses were performed using R version 4.1.2 (R Core Team, 2021) and the ggplot2 package (Wickham, 2016) for plotting. The Tukey-Kramer-HSD one-way analysis of variance (ANOVA) method was used to explore the characteristics and differences in shear strength parameters and root density parameters among different depths, and shrub species, and to analyze their significance. Multi-factor ANOVA was utilized to systematically evaluate the effects of

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different shrub species, soil depths, and their interactions on the relevant parameters. These ANOVA analyses were performed using SPSS software (version 22.0, IBM, USA) and SigmaPlot software (version 12.5, Systat, California, USA).

Results

Shear strength of root-soil complex

The shear strength of the root-soil complex showed distinct differences across species and soil depths (*Fig. 2a* and *b*). In the 0-10 cm soil layer, all root-reinforced soils exhibited higher shear strength compared to bare soil, with the AFL and LBT roots providing the most substantial reinforcement. This suggests that in shallow soils, the root networks of these species are particularly effective in enhancing soil cohesion, potentially due to denser root distribution near the surface. At a greater depth of 10-20 cm, the trend continued, but the differences between species became more pronounced. The AFL maintained the highest level of shear strength, followed by the LBT and SAO, emphasizing the increased contribution of deeper roots to soil stability. The improvement in shear strength with depth highlights the critical role of root penetration in strengthening the soil matrix, with the AFL showing the most significant enhancement across both depths. These findings indicate that root systems primarily strengthen soil through increased cohesion, with deeper layers benefiting more from the structural reinforcement provided by larger, more penetrating root systems. The results underscore the crucial function of root presence in stabilizing soil under mechanical stress, particularly in soils subjected to varying normal loads.

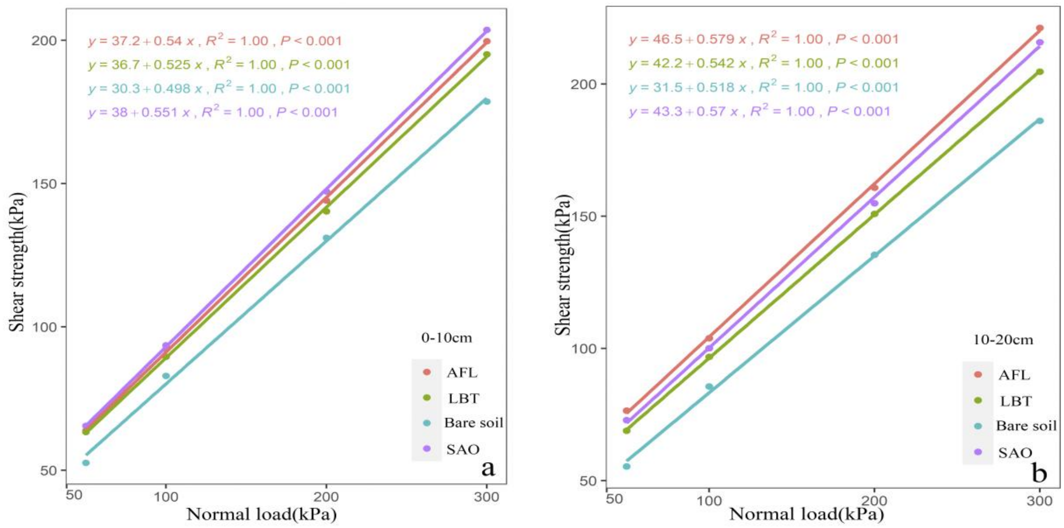

Figure 2. *Relationship between normal load and shear strength at the soil layer depths of 0-10 cm (a) and 10-20 cm (b). AFL represents Amorpha fruticosa Linn., LBT represents Lespedeza bicolor Turcz., and SAO represents Swida alba Opiz*

Soil cohesion and internal friction angles of root-soil complex

The root-soil complex exhibited significant variations in both soil cohesion and internal friction angle across different soil depths and species (*Fig. 3*a and *b*). In the 0-10 cm soil layer, root-reinforced soils, particularly those associated with the AFL, showed markedly

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higher cohesion than bare soil. This enhancement was even more pronounced in the deeper 10-20 cm layer, where the root systems further increased soil cohesion, with the AFL continuing to provide the most substantial reinforcement. The improvement in soil cohesion with increasing depth underscores the greater interaction between deeper roots and soil, suggesting a critical role of root penetration in stabilizing the soil matrix.

For internal friction angle, while differences between root-reinforced soils and bare soil were less marked, the AFL and LBT showed slightly reduced internal friction angles compared to bare soil in both soil layers. The minimal variation across species and depths suggests that roots primarily enhance soil strength through cohesion rather than friction modification. The results from both soil layers reveal a stronger influence of root systems on soil cohesion, particularly in the deeper layer, emphasizing the importance of root presence in maintaining soil structural integrity under mechanical loads. These findings indicate that, although roots contribute primarily to increasing soil cohesion, their influence on internal friction is relatively minimal compared to bare soil.

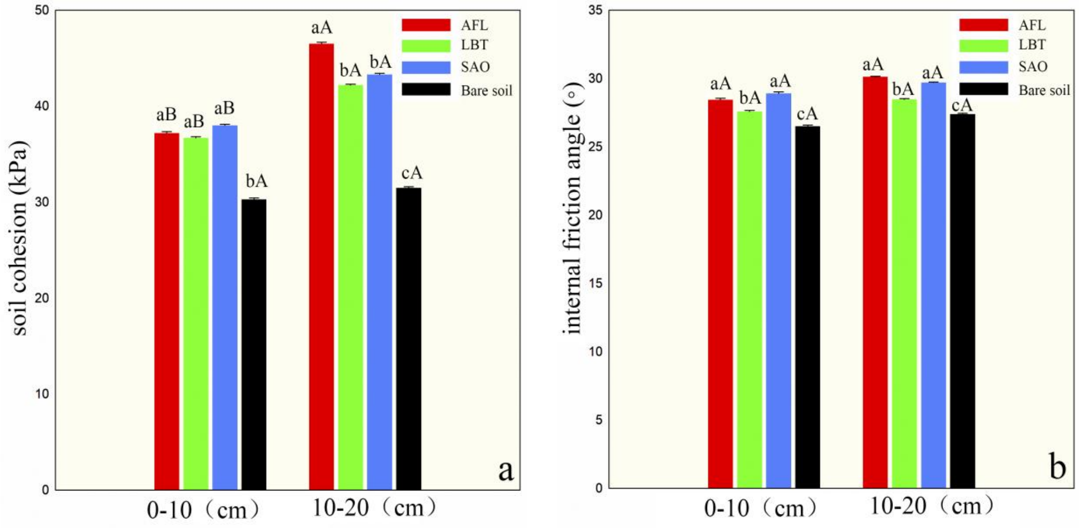

Figure 3. *Soil cohesion (a) and internal friction angles (b) at different soil layer depths. Notes: AFL represents Amorpha fruticosa Linn., LBT represents Lespedeza bicolor Turcz., and SAO represents Swida alba Opiz. Error bars represent standard errors. The capital letters represent the Student's t-test results at p < 0.05 across species for each of the depth of the two soil layers; in case of significance, 'A' represents the larger value, while 'B' represents the smaller value. The lower-case letters represent differences between plant species; in case of significance, 'a' represents the larger value, while 'b' represents the smaller value*

Root length density and root weight density

The root length density and root weight density exhibited significant variation across soil depths (*Fig. 4a* and *b*). In the 0-10 cm soil layer, root length density was notably higher in the AFL, followed by the LBT and SAO, indicating that the AFL develops a denser root network in the upper soil layer. This denser root structure suggests a more effective capacity for soil reinforcement and nutrient uptake near the surface. The 10-20 cm soil layer, however, showed a more pronounced increase in root length density for all three species, with the AFL again leading, followed by a similar density observed for the LBT and SAO. These trends highlight the critical role of root systems, particularly the AFL, in contributing to soil stability at greater depths through increased root proliferation.

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Root weight density followed similar trends (*Fig. 4b*), with the AFL consistently showing the highest values across both soil layers, particularly in the 10-20 cm layer. This deeper soil layer revealed more significant differences in root biomass among the species, with AFL demonstrating a considerably higher weight density than the LBT and SAO. The higher root biomass in deeper layers suggests that the AFL contributes more substantially to soil mechanical properties, as greater root weight is often associated with enhanced soil cohesion and stability. The LBT and SAO showed comparable root weight densities, though their influence on soil reinforcement appeared less pronounced than that of the AFL. These results underscore the critical role of root density—both in length and weight—in influencing soil stability, with species-specific differences, particularly for the AFL, becoming more evident at greater soil depths.

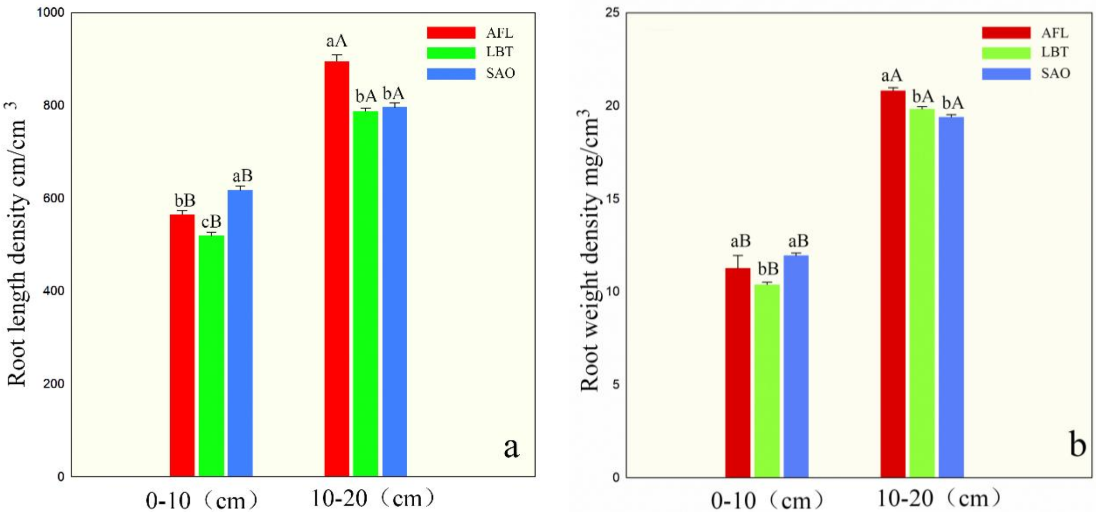

Figure 4. *Root length density (a) and Root weight density (b) at different soil layer depths. Notes: The same as in Figure 2*

Relationship between shear strength indicators and root density parameters

The relationship between root length density and soil cohesion, as well as internal friction angle, demonstrates a clear positive correlation across different shrub species (AFL, LBT, SAO) and soil layers (*Figs. 5* and *6*). In the 0-10 cm soil layer, soil cohesion increased proportionally with root length density, with the AFL roots exhibiting the most significant enhancement in cohesion (*Fig. 5a*). The LBT and SAO followed a similar trend, albeit with slightly lower contributions. The denser root systems of the AFL, particularly near the surface, appear to play a crucial role in binding soil particles more effectively, thereby improving soil cohesion and resisting external mechanical forces. Internal friction angle also showed a positive correlation with root length density in the 0-10 cm layer, though to a lesser extent compared to cohesion (*Fig. 6*a). In the 10-20 cm soil layer, the positive correlation persisted but with a more pronounced effect, especially for the AFL (*Figs. 5b* and *6b*). This suggests that deeper root systems exert a stronger influence on soil mechanical properties, contributing more to soil stability as root penetration increases. The substantial increase in cohesion in this layer indicates that deeper roots not only improve the structural integrity of the soil but also enhance its ability to withstand varying loads. Similarly, internal friction angle increased with root length density, though the effect was less substantial than for cohesion (*Figs. 5a* and *6b*). The

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consistent increase across species implies that roots contribute primarily to soil strength by enhancing cohesion rather than modifying the internal friction angle.

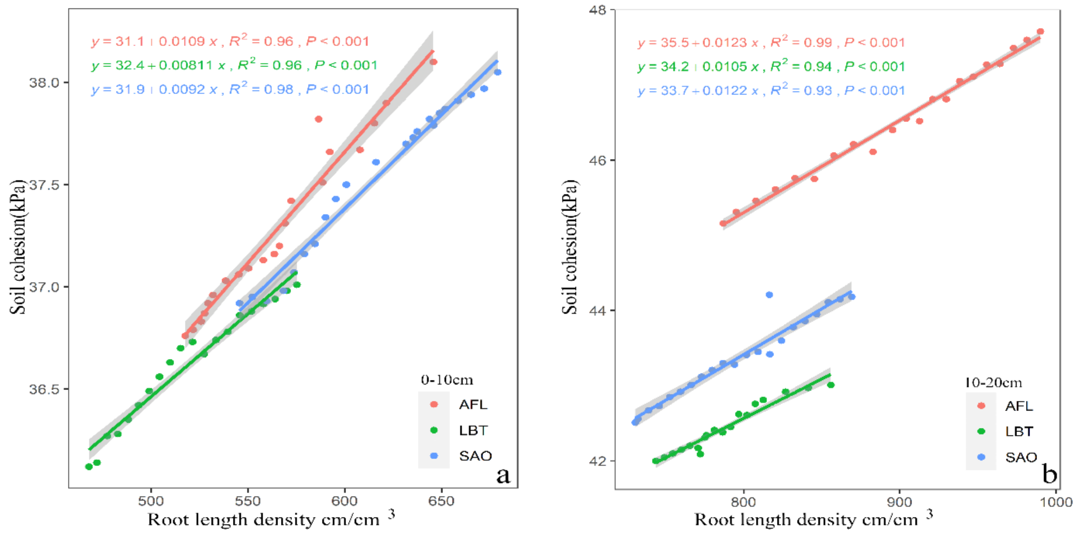

Figure 5. *Relationship between soil cohesion and root length density at the soil layer depths of 0-10 cm (a) and 10-20 cm (b). Notes: AFL represents Amorpha fruticosa Linn., LBT represents Lespedeza bicolor Turcz., and SAO represents Swida alba Opiz*

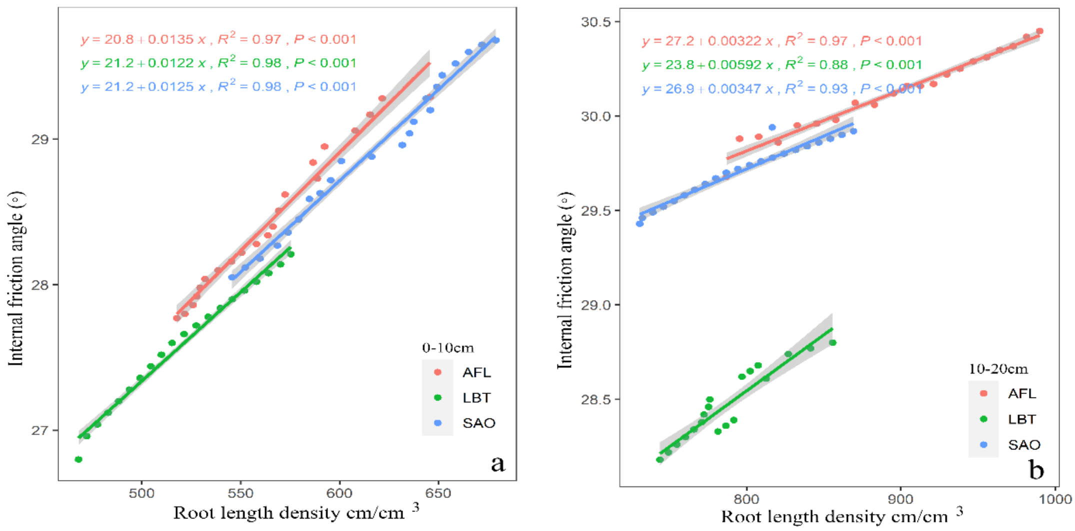

Figure 6. *Relationship between internal friction angle and root length density at the soil layer depths of 0-10 cm (a) and 10-20 cm (b). Notes: AFL represents Amorpha fruticosa Linn., LBT represents Lespedeza bicolor Turcz., and SAO represents Swida alba Opiz*

Regarding root weight density, the results echoed the patterns observed for root length density. Both cohesion and internal friction angle increased with higher root weight density, with the AFL showing the most significant effects (*Fig. 7a* and *b* for cohesion; *Fig. 8a* and *b* for internal friction angle). The greater root biomass of AFL, particularly at deeper soil layers, likely facilitates improved root-soil interaction. This contribution of roots to soil strength, especially in deeper layers, underscores their role in stabilizing soils

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under varying mechanical stresses and highlights their importance in preventing soil erosion.

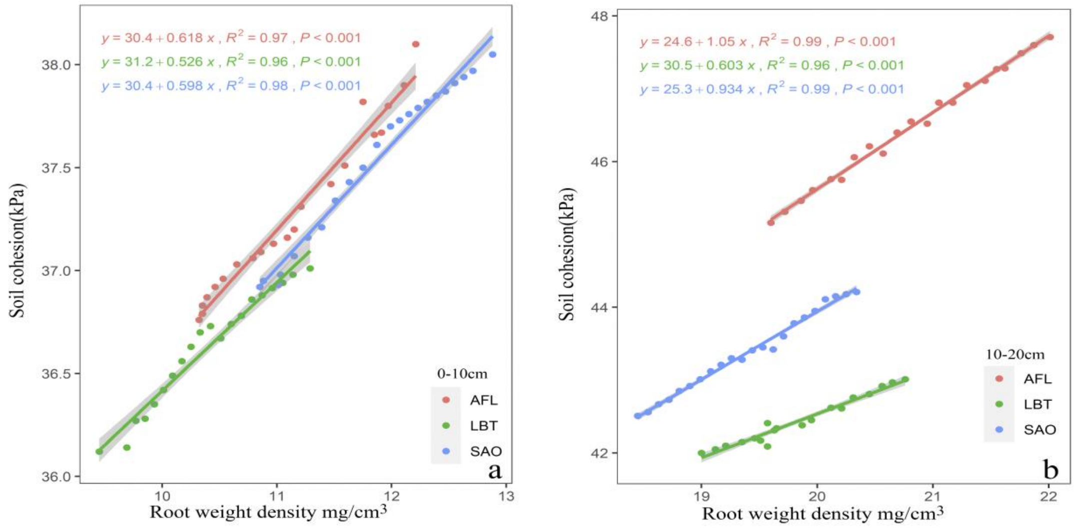

Figure 7. *Relationship between soil cohesion and root weight density at the soil layer depths of 0-10 cm (a) and 10-20 cm (b). Notes: AFL represents Amorpha fruticosa Linn., LBT represents Lespedeza bicolor Turcz., and SAO represents Swida alba Opiz*

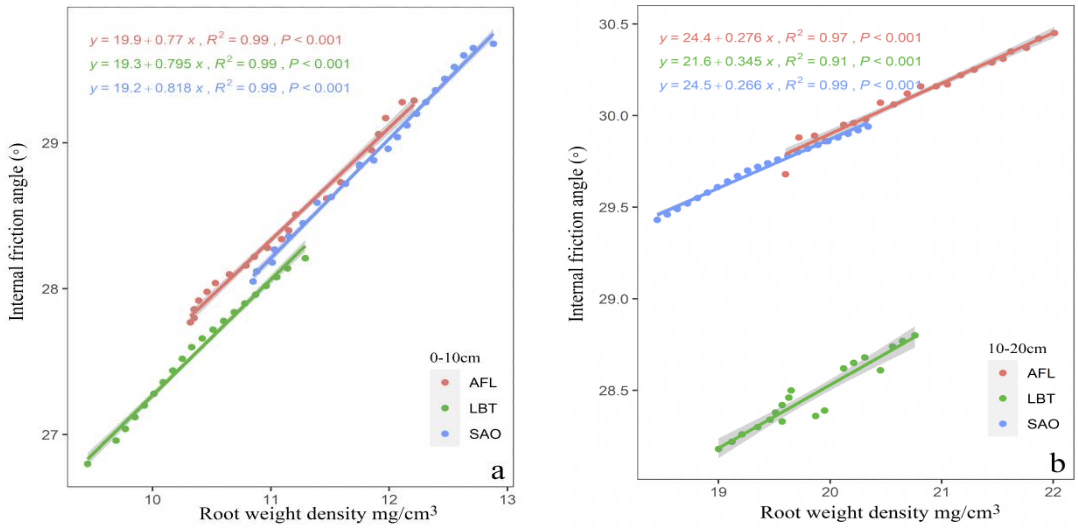

Figure 8. *Relationship between internal friction angle and root weight density at the soil layer depths of 0-10 cm (a) and 10-20 cm (b). Notes: AFL represents Amorpha fruticosa Linn., LBT represents Lespedeza bicolor Turcz., and SAO represents Swida alba Opiz*

Discussion

Comparing the shear strength of root-soil complex at different soil layer depths

The results reveal clear species-specific differences in the shear strength of the root-soil complex across different soil depths, with the AFL and LBT roots providing the greatest reinforcement in the 0-10 cm soil layer, and the AFL continuing to exhibit the

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highest performance at 10-20 cm. This reinforces the notion that root density and penetration depth are key factors in soil stabilization (Zhang et al., 2019). The notable enhancement of shear strength in the AFL can be attributed to its dense surface root systems, which are more effective at binding soil particles and enhancing cohesion near the soil surface, thereby offering increased resistance to mechanical stress (Thompson et al., 2020). Such root-soil interactions are critical for slope stability and erosion prevention, particularly in soils subject to varying mechanical loads.

The observed increase in shear strength with soil depth underscores the critical role of deeper root systems in strengthening the soil matrix. The continued dominance of AFL in the 10-20 cm layer suggests that its root architecture is particularly adept at penetrating deeper into the soil, creating greater mechanical interlocking between roots and soil particles. This deep root penetration likely enhances soil cohesion by increasing the contact area and binding force, facilitating more effective resistance to external shear forces (Jones et al., 2021). The greater root-soil interface also allows the AFL to better distribute mechanical loads across the soil profile, a mechanism that has been demonstrated in similar studies (Li et al., 2020). In contrast, the LBT and SAO exhibit lower performance, likely due to their less extensive root systems, which, while effective in surface layers, lack the depth and density required for substantial reinforcement at greater depths (Chen et al., 2018).

The variation in species performance can also be explained by differences in root morphology and biomass. The denser and more penetrating roots of AFL provide a greater surface area for mechanical bonding with the soil, leading to improved cohesion and shear resistance (Zhou et al., 2021). The moderate performance of LBT, while still effective in stabilizing surface soils, suggests that its root architecture is less suited for deeper soil stabilization, where more extensive root systems are required to maintain soil integrity under mechanical stress (Smith et al., 2021). The contribution of root biomass, particularly in the AFL, further supports these findings, as larger root systems have been shown to distribute mechanical forces more effectively, thereby reducing localized soil displacement and erosion (Anderson et al., 2021).

In conclusion, the results highlight the importance of root system architecture in soil stabilization. The superior performance of AFL across both soil layers emphasizes its potential application in ecological engineering, especially in environments where deep soil reinforcement is critical for slope stability and erosion control. These findings align with previous studies and provide further evidence that root systems, especially those with deep penetration, are essential for enhancing soil mechanical properties under stress (Roberts et al., 2020; Johnson et al., 2022).

Comparing the soil cohesion and internal friction angles of root-soil complex

The results revealed significant variations in both soil cohesion and internal friction angle across different species and soil depths, with the AFL exhibiting the highest enhancement in soil cohesion in both the 0-10 cm and 10-20 cm layers. This finding suggests that root systems, particularly those of the AFL, are crucial for improving soil structural integrity through increased cohesion. The greater enhancement of soil cohesion in the deeper soil layer (10-20 cm) further emphasizes the importance of root penetration depth in stabilizing soil matrices, as previously observed in the work of Li et al., 2018, where deeper root systems enhanced soil strength significantly.

The minimal changes in internal friction angle between root-reinforced soils and bare soil, particularly in the deeper layer, suggest that root systems contribute primarily to soil

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cohesion rather than modifying internal friction (Xu et al., 2023). This phenomenon can be explained by the fact that roots, especially those of the AFL, tend to increase mechanical interlocking within the soil matrix, thereby enhancing soil cohesion while exerting a lesser influence on the frictional properties of the soil (Yang et al., 2022). In contrast, internal friction is largely influenced by particle size and texture, factors that roots are less likely to modify directly (Zhang et al., 2021). Thus, the primary mechanism by which root systems improve soil strength is through cohesion, which increases with root depth and density, allowing roots to better bind soil particles and prevent displacement under mechanical stress (Robinson et al., 2023).

The continued dominance of AFL in enhancing soil cohesion across both soil layers is likely due to its root morphology, which features deeper and denser roots capable of greater interaction with the surrounding soil. This deeper penetration creates a more extensive root-soil contact area, facilitating increased cohesion, as demonstrated in the studies by Luo et al., 2022. The minor influence of roots on internal friction aligns with findings of Wang et al., which showed that root systems play a more dominant role in soil cohesion enhancement, contributing less to frictional resistance (Wang et al., 2023).

These findings underscore the critical role of root systems, particularly those of the AFL, in maintaining soil integrity under varying mechanical loads. By enhancing cohesion, especially in deeper layers, roots contribute to the long-term stabilization of soils, a crucial aspect in preventing soil erosion and maintaining hillside stability in ecological engineering contexts (Tang et al., 2021).

Comparing the root length density and root weight density

The results reveal significant variation in both root length density and root weight density across soil depths, with the AFL consistently exhibiting the highest values, particularly in the 10-20 cm soil layer. These findings underscore the critical role of root system architecture, particularly the ability of the AFL to develop a denser and deeper root network, which is instrumental in enhancing soil stability. The increased root length density in the upper soil layer suggests a more effective capacity for soil reinforcement and nutrient uptake near the surface, while the greater root proliferation at deeper layers, especially in the AFL, implies a critical contribution to soil cohesion at these depths. This aligns with previous research, which has shown that root density is a key factor in soil reinforcement, directly contributing to the mechanical properties of soils (Jackson et al., 2019).

The substantial differences observed in root weight density, particularly in the deeper soil layer, further highlight the superiority of AFL in contributing to soil stability. Root biomass, especially in deeper layers, is known to correlate strongly with soil cohesion and mechanical resistance (Miller et al., 2020b). The AFL is a deep-rooted shrub, the higher root biomass of AFL in the 10-20 cm layer suggests that it plays a more prominent role in enhancing soil mechanical properties compared to the LBT and SAO. This can be attributed to the deeper root penetration of AFL, which increases root-soil contact and facilitates greater mechanical interlocking, thereby improving soil cohesion and stability (Thompson et al., 2021a).

The mechanisms driving these results are primarily related to root morphology and biomass distribution. The ability of AFL to establish a more extensive root system in deeper soil layers enhances its interaction with the soil matrix, providing increased anchorage and resistance to external mechanical forces (Anderson et al., 2022b). This deeper root proliferation not only increases cohesion but also redistributes mechanical

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loads across the soil profile, minimizing soil displacement and erosion (Meyer et al., 2022). The relatively lower performance of the LBT and SAO in both root length and weight density likely stems from their less extensive root systems, which, while effective in surface layers, lack the depth required for substantial reinforcement in deeper soils (Peters et al., 2021).

In conclusion, the results highlight the significant influence of both root length and root weight density on soil stability, with the AFL demonstrating a more substantial impact due to its superior root architecture. These findings underscore the critical role of root system traits in maintaining forest ecosystem stability, particularly in the context of slope stabilization and erosion control. Root systems not only enhance soil cohesion but also contribute to the resilience of forest landscapes by preventing soil degradation and maintaining structural integrity under varying environmental conditions. In forest ecosystems, the ability of roots to stabilize slopes is vital for preserving biodiversity and protecting the forest floor from erosion (Henderson et al., 2023). Understanding these mechanisms is essential for developing effective ecological engineering practices that support the long-term sustainability of forests.

Correlation between shear strength indicators and root density parameters

The findings of this study demonstrate a clear positive correlation between root length density and soil cohesion across the different shrub species and soil layers, with the AFL showing the most pronounced effects. Specifically, the AFL exhibited the highest increase in soil cohesion in both the 0-10 cm and 10-20 cm layers, suggesting that denser root systems near the surface, combined with deeper root penetration, significantly enhance soil structural integrity. The increase in internal friction angle, though less pronounced than cohesion, also showed a positive trend with root length density, indicating that while roots primarily enhance soil strength through cohesion, they contribute modestly to internal friction modification as well (Morris et al., 2019).

These results are consistent with those reported by Wang et al. (2020) who found that root systems play a vital role in improving soil cohesion, particularly in deeper layers. The stronger impact of roots on cohesion, compared to internal friction, can be attributed to the physical interactions between root systems and soil particles. The dense root structure of AFL likely increases soil-root contact, allowing for greater mechanical interlocking and resistance to external forces, which is a key mechanism in enhancing cohesion (Anderson et al., 2018). Deeper roots also anchor the soil more effectively, which not only stabilizes the soil matrix but also enhances its ability to resist varying mechanical stresses (Thompson et al., 2021b).

The greater root weight density observed in the AFL further supports its role in improving soil mechanical properties, particularly at deeper soil layers. Increased biomass at greater depths amplifies root-soil interactions, leading to enhanced soil cohesion and reduced displacement under stress (Miller et al., 2022). The relatively lower contribution of the LBT and SAO suggests that their root systems, while beneficial for surface layer stabilization, are less capable of providing reinforcement at greater depths due to limited root penetration and biomass (Garcia et al., 2019). This variation highlights the importance of root morphology and biomass distribution in determining the effectiveness of soil reinforcement.

In summary, the findings suggest that root systems, especially those of the AFL, contribute primarily to soil stability through enhanced cohesion, with deeper root proliferation playing a critical role. These results align with the broader body of research

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on root-soil interactions, reinforcing the idea that root density, depth, and biomass are crucial determinants of soil mechanical properties (Robinson et al., 2020; Smith et al., 2023). These insights have important implications for ecological engineering practices, particularly in the boundary zones of forest ecosystems prone to erosion or mechanical stress.

Conclusion

This study provides essential insights into the species-specific contributions of shrub root systems to soil cohesion and stability in forest ecosystems, particularly in relation to root length density and root weight density. Among the studied species, *Amorpha fruticosa* Linn. demonstrated the most significant impact on soil cohesion, especially at deeper soil layers (10-20 cm), where its denser and more extensive root network effectively enhanced soil mechanical properties. *Lespedeza bicolor* Turcz. and *Swida alba* Opiz. also contributed to soil stability, though their influence was more limited, particularly in deeper soils. Our findings reveal that root systems primarily improve soil strength through increased cohesion rather than through modifications to the internal friction angle, highlighting the importance of root density and penetration depth in maintaining soil structural integrity under mechanical stress.

The significance of this research lies in its comprehensive analysis of root-soil interactions, which advances our understanding of how shrub root morphology and density contribute to slope stabilization and erosion control. These insights are critical for developing effective soil conservation strategies and ecological restoration efforts, particularly in forested landscapes vulnerable to erosion. Future research should focus on the long-term dynamics of root development and its influence on soil reinforcement under varying environmental conditions, such as drought, extreme weather events, and human interventions. Such studies will further clarify the role of root systems in mitigating soil degradation, ultimately contributing to more sustainable landscape management practices.

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