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Root System Traits and Mechanical Properties of Three Shrub Species: Implications for the Structural Stability of the Ecological Slope

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ABSTRACT

The purpose of this paper is to find the shrub species more suitable to enhance the structural stability of the ecological slope in the study area. Through the investigation, we found three common shrubs, there are Amorpha fruticosa Linn. (AFL), Syringa oblata Lindl. (SOL) and Forsythio mandshurica Uyeki. (FMU). In this study, the root system traits and mechanical properties were characterized and described using reliable experimental approaches. The results shown that the root withdrawal force was proportional to diameter (from 0.6-6 mm). The mean specific root length, individual length, surface area, and mean diameter of fine roots in different slopes were higher for AFL and SOL than for FMU, especially for high root orders. Although previous studies have focused on the relevant content, the reinforcement ability of different shrubs is rarely quantitatively compared under the same road conditions. Moreover, the morphology traits of the fine root were considered in this study. These results suggested that the root system traits and mechanical properties of AFL would enable more effective consolidated slopes structure than SOL and FMU, revealing that planting AFL might be a better way for enhancing ecological slope structure stability.

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1. INTRODUCTION

Expressway landslides caused by rainfall are a major engineering problem worldwide [1]. So far, it has affected extensive areas in different parts of the world for a longtime [2]. Factors leading to slope damage include natural rainfall, soil erosion, and soil characteristics [3]. They are usually caused by reduced soil suction and shear strength after rainfall on slope terrain [4]. Normally, the compacted soil layers during the construction stage and service life is unsaturated [5]. After natural rainfall, the soil becomes saturated. Weak soil composed of saturated clay is prone to fail and causes stability problems [6]. The continuous occurrence of soil erosion will not only reduce the soil quality, but also cause a series of problems such as the deterioration of the water environment [7].

Planting plants on the ecological slope to improve the shear strength and hydrological response of the soil is an effective measure to slow down the landslide of the ecological slope [8]. The positive effect of planting plant on road ecological slope structure stability and erosion resistance is mainly related to the mechanical strengthening effect of plant roots and the soil hydrological effect [9]. Previous studies have found that plant mechanical reinforcement can directly enhance the shear strength of the soil in a variety of ways [10]. Plant fine roots (<1mm) can form a membrane structure, increase the apparent cohesion of the soil, and is conducive to ecological slope structure stability [11]. Through some field hydrologic effect studies, we have some understanding of the hydrological effect of roots on ecological slope structure stability [12-13].

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In this study, after field investigation, three typical types of shrubs in the northeast range were selected. The three shrub species are Amorpha fruticosa Linn. (AFL); Syringa oblata Lindl. (SOL); Forsythio mandshurica Uyeki. (FMU). In the process of selection, we choose the shrubs with the same life type, age, living environment to ensure better comparison. Due to differences in different species traits, we assumed the mechanical reinforcement of root traits, such as scour resistance and hydrological effects, in different response directions to different shrubs. The research results are expected to provide data support for the selection and cultivation of shrubs on ecological shrubs slope roads in northeast China to determine the plant species needed for the stability of ecological slope in specific places, and produce positive ecological and economic benefits to the construction of roads in cold regions.

2. MATERIALS AND METHODS

2. 1. Study Sites Expressway Heha Expressway starts in Harbin and ends in Hegang City, the traffic mileage is 303 km. The Heha Expressway natural zoning is II_2 (heavy-freeze zone of mountain-front plain in the central of northeast china). The site test was conducted on the slope of the Heha Expressway form Suihua to Tieli, which is in the northeastern China. The study area has longer winter, shorter summer, cold winter and warm summer. It is typical of a temperate continental monsoon climate. In the study area, the shrub species planted in the ecological slopes of the Expressway mainly include AFL, SOL and FMU. The map of the study area is presented in Figure 1.

2. 2. Experimental Design and Sampling The selection and setting of the experimental research area were completed in July 2020. Due to different shrub planting areas along the test region, six 20m × 20m plots are randomly established between each two plots and a buffer zone greater than 10 m wide between each one. Three of these were on the slopes of 30° and three are on the slopes of 60°. A total of eighteen plots were established.

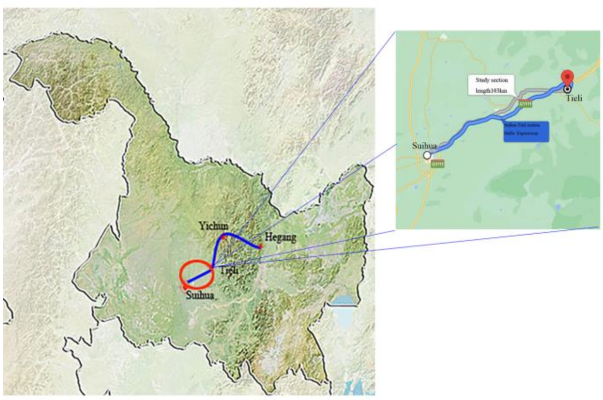


Figure 1. The map of the study area, which is in the Heha Expressway form Suihua to Tieli

In each site, three plants of each study shrub species were randomly selected, and then root samples of 0-20 cm soil depth within the 1 m range for each study shrub main stem were excavated and manually collected in July 2020. Then, we mixed all root samples taken from the same plot. The sub-sample was treated for root morphological traits experiments. Using stainless steel spirals of 5cm in diameter, six cores were randomly collected from each site at a depth of 0-20cm. Combine all soil samples of each lot and then remove visible foreign material (e. g., roots, stone, etc.) by hand. This one was used to measured basic soil properties. Based on the experimental data and statistical analyses, the final conclusion can be reached. The flowchart of the methodology is presented in the Figure 2.

2. 2. 1. Soil Properties The sub-sample was retrieved from the sample to the laboratory and the soil sub-samples were weighed in the laboratory. Natural soil density (g/cm^3) was measured by wet soil weight and core volume. The sample was then placed in the drying box and the temperature adjusted to 75 ℃ to dry the sample. When the drying was complete, the samples already dried were weighed and the dry density (g/cm^3) of the soil was measured.

We used a pH meter (Sartorius PB-10, Gottingen, Germany) to measure the pH, and used the oil bath-$K_2Cr_2O_7$ titration method to measure the soil organic

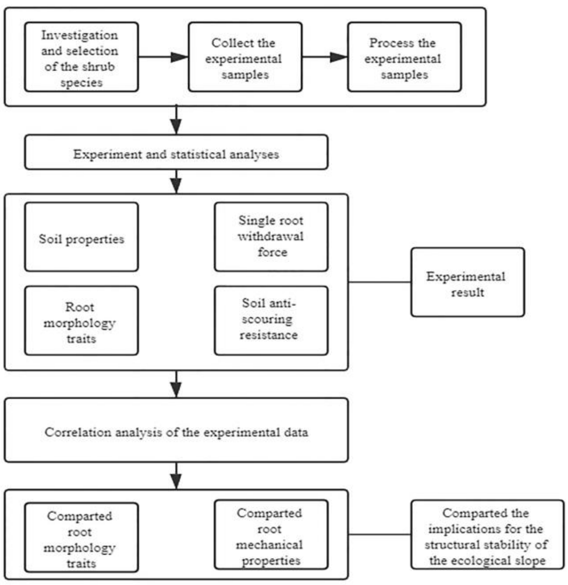


Figure 2. The flowchart of the methodology

matter. We used the shear-testing device (Nanjing Soil Machine DZJ-1, Nanjing, China) to measure the mechanical properties of the disturbed soil, and used the shear-testing device (Nanjing Soil Machine DZJ-1) to measure the elasticity modulus (EM) [14]. We placed undisturbed soil samples in a shear-testing device. A series of shear tests were conducted with three replications for each species under each normal load, and then the value of Elasticity Modulus (EM) was recorded. Soil cohesion (Sc) was calculated from the intercept of the failure envelope with the point of zero shear strength, and the friction angle was determined from the angle between the failure envelope and the normal stress axis (horizontal).

2. 2. 2. Root Withdrawal Force Tests The test was measured by a hand-held tension meter. At the beginning of the survey, the portion of wild plant growth was manually removed and the plant roots were excavated to the soil at a depth of 0.4m. After the root system was exposed, the main root was all removed with a saw bar. The root was pulled in a parallel and opposite direction to the root growth. After the root system was removed, record the maximum tension, the exposed root diameter and the root diameter at the fracture [15]. Methods were as follows: The root length between the branch nodes was measured by the natural growth length of the root system, with the longest root length along the direction of the root growth growing from the main root stem [16]. The roots growing from each branch node were divided into primary, secondary and below secondary side roots according to the number of branch nodes.

2. 2. 3. Root Morphological Traits In the laboratory, the residual soil particles from the roots were carefully cleaned with tweezers in deionized water. Identified the different root orders, a different roots were separated one by one [17]. The sample root was scanned using a scanner which was the Expression scanner (Expression 11000XL, Epson, NSW , Australia) with a scan resolution of 600 dpi. Measured the root number, mean diameter, single and total root length, single root surface area and root volume using root analysis software (WinRHIZO TronMF 2012, Regent Instrument Inc., Quebec, Canada). The root samples were dried at 75°C oven and the weight was recorded. Then, the specific root length (SRL) and branch ratio were calculated. The specific root length was defined as the total root length divided by the corresponding dry mass. The branch ratio (%) is calculated as the number of root roots divided by the number of root roots above it.

2. 2. 4. Soil Anti-scouring Resistance Index The device of experiment in this study was modified based on the original soil wash tank (Figure 3). Not to damage the original soil structures, made a sampler for the 20 cm × 18 cm × 10 cm, the ram-resistant tank was set to two slopes of 30° and 60°. According to the natural rainfall situation of the study area, our experimental design was divided into two kinds, which were large rainfall (2 L/min) and small rainfall (0.5 L/min), with the experimental scouring time length of 10 min [18]. Cut off the ground part of the plant before washing, cut the pot, divided the two layers of the plant soil, marked, and followed Lu lixia's methods for specific operations. We did 3 repeats for each sample. This paper used the water quantity Q required to wash away 1 g of soil with a certain water flow rate to indicate the soil anti-scouring resistance.

3. STATISTICAL ANALYSES

The normal distribution and variances homogeneity of all the data were tested by the Kolmogorov-Smirnov test and Levene's test, respectively. The difference of soil properties, root architectural and morphological traits among different shrub species were determined with one-way analysis of variance (ANOVA) with Tukey Kramer HSD. The interaction effects of species and diameter or slopes on different parameters were evaluated using a multi-factor analysis of variance. All data analysis was performed using the SPSS software version22.0 (SPSS, IBM, USA). All figures were conducted using SigmaPlot 12.5 (Systat Software Inc., San Jose, CA, USA).

4. RESULTS

4. 1. Soil Properties Based on the results obtained, the soil moisture and density did not significantly differ among different species and slopes (Table 1). Meanwhile, the difference in soil density and soil moisture of the three shrubs remained insignificant after considering the slope (30° and 60°) (Table 1). EM

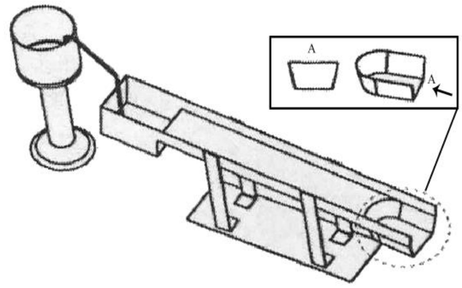


Figure 3. The experiment device based on the original soil wash tank

and Sc were relatively highest for AFL, followed by SOL and lowest for FMU at the same slope (Table 2). EM and Sc were generally higher at 30° slopes than at 60° slopes among all species (Table 2).

TABLE 1. The main physical traits of study site soils in different soil slopes at soil depth 0-20cm (n=3, Mean±SE).

	Slope	Soil Moisture (%)	Natural soil density (g/cm^3)
AFL	30°	17.01±0.73aA	1.58±0.03aA
	60°	16.55±0.16aA	1.59±0.01aA
SOL	30°	16.12±0.21aA	1.56±0.02aA
	60°	15.53±0.41aA	1.57±0.01aA
FMU	30°	16.07±0.19aA	1.55±0.02aA
	60°	15.37±0.25aA	1.53±0.02aA

	Slope	Dry density of soil (g/cm^3)	Sand (%)	Clay (%)
AFL	30°	1.34±0.01aA	40.12±1.36aA	21.07±2.01aA
	60°	1.36±0.01aA	41.12±1.71aA	22.53±1.33aA
SOL	30°	1.33±0.02aA	38.37±1.92aA	19.25±1.92aA
	60°	1.35±0.01aA	41.01±1.65aA	20.69±2.33aA
FMU	30°	1.33±0.01aA	37.93±1.77aA	19.04±2.36aA
	60°	1.34±0.01aA	38.04±2.08aA	19.65±1.09aA

Note: Each value is the Mean (SE) of three replications. Different lowercase letters represent statistical significances in different soil slopes for the same plant types; different capital letters represent statistical significances in same soil slopes for the different plant types. AFL, Amorpha fruticosa Linn; SOL, Syringa oblata Lindl; FMU, Forsythio mandshurica Uyeki.

TABLE 2. Mechanical properties and chemical characteristics of study site soils in different soil slopes. Elasticity modulus (EM); Soil cohesion (Sc), (n=3, Mean±SE).

	Slope	Organic matter (%)	pH
AFL	30°	1.77±0.18aA	5.98±0.39aA
	60°	1.49±0.21bA	6.01±0.25aA
SOL	30°	1.74±0.31aA	5.87±0.21aA
	60°	1.47±0.21bA	5.93±0.25aA
FMU	30°	1.73±0.12aA	5.89±0.22aA
	60°	1.45±0.16bA	5.95±0.19aA

	Slope	EM(kPa)	Sc(kPa)
AFL	30°	7.69±0.21aA	42.12±2.38aA
	60°	7.24±0.22bA	35.79±2.08bA
SOL	30°	7.45±0.11aB	40.59±1.78aB
	60°	7.05±0.21bB	33.57±1.45bB
FMU	30°	7.35±0.12aB	40.17±1.87aB
	60°	6.99±0.19bB	33.27±1.79bB

Note: Different lowercase letters represent statistical significances in different soil slopes for the same plant types; different capital letters represent statistical significances in same soil slopes for the different plant types.

4. 2. Single Root Withdrawal Force With the root diameter increased, the root withdrawal force of AFL, SOL and FMU increased at both of 30° and 60° slopes (Figure 4). The maximum pull force appeared in AFL and the maximum value reaches 517.9N. Minimal appeared in samples of smaller root diameters of different plants, and in samples of smaller root lengths (Figure 4). At the slope of 60°, with the same root diameter, the AFL had the highest root withdrawal force, the second FMU and the lowest SOL. On the other hand, at the slope of 30°, with the same root diameter, the FMU had the highest root withdrawal force, the second AFL and the lowest SOL (Figure 4). At 30° slope, the AFL root withdrawal force was the highest, except at 2-3mm diameter; At 60° slope, the AFL root withdrawal force was the highest at all of diameter, the FMU was significantly above SOL, except at less than 2mm diameter (Figure 5). The main factors affecting the root withdrawal force were the root diameter, root length, branching nodes, and plant species (Table 3).

4. 3. Root Morphology Traits The specific root length was significantly higher in AFL than that in

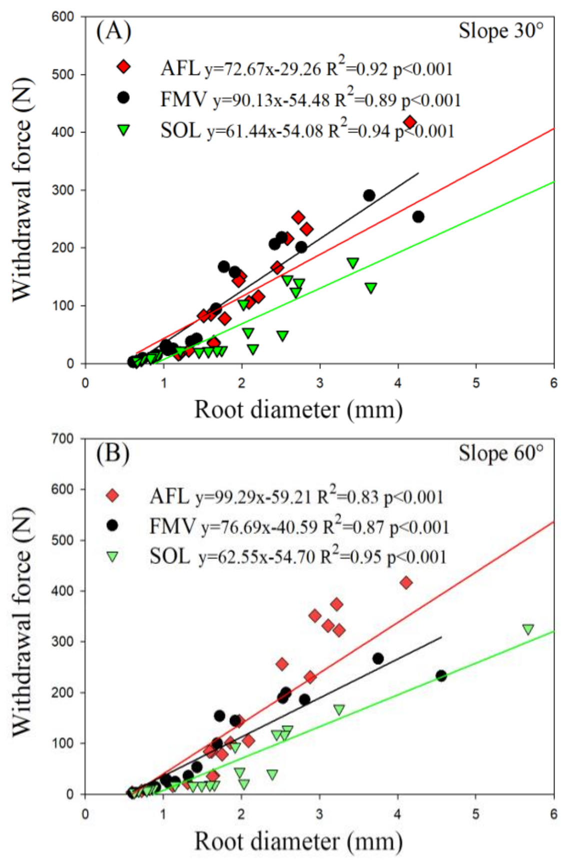


Figure 4. Relationship between root withdrawal forces of three shrub species at different slopes with root diameter (from 0.6 to 6 mm)

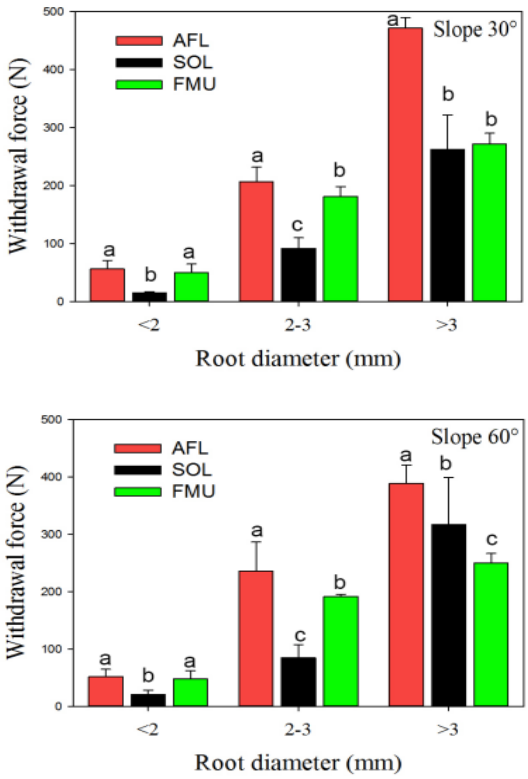


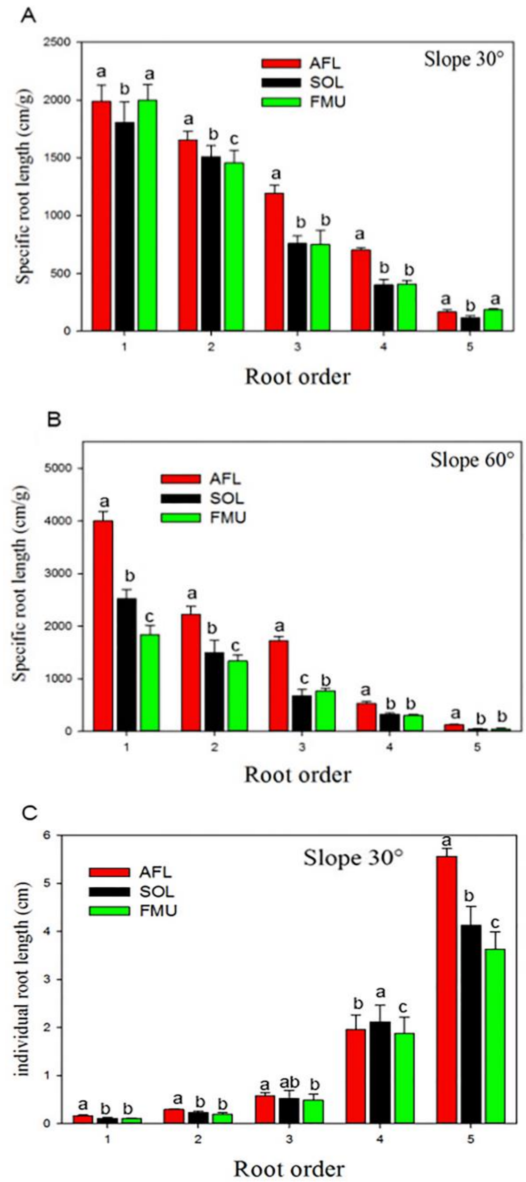
Figure 5. Withdrawal force of the fine roots in different diameter levels among different plant types (Mean±SE). Different lowercase letters represent statistical significances among different plant types. AFL, Amorpha fruticosa Linn; SOL, Syringa oblata Lindl; FMU, Forsythio mandshurica Uyeki

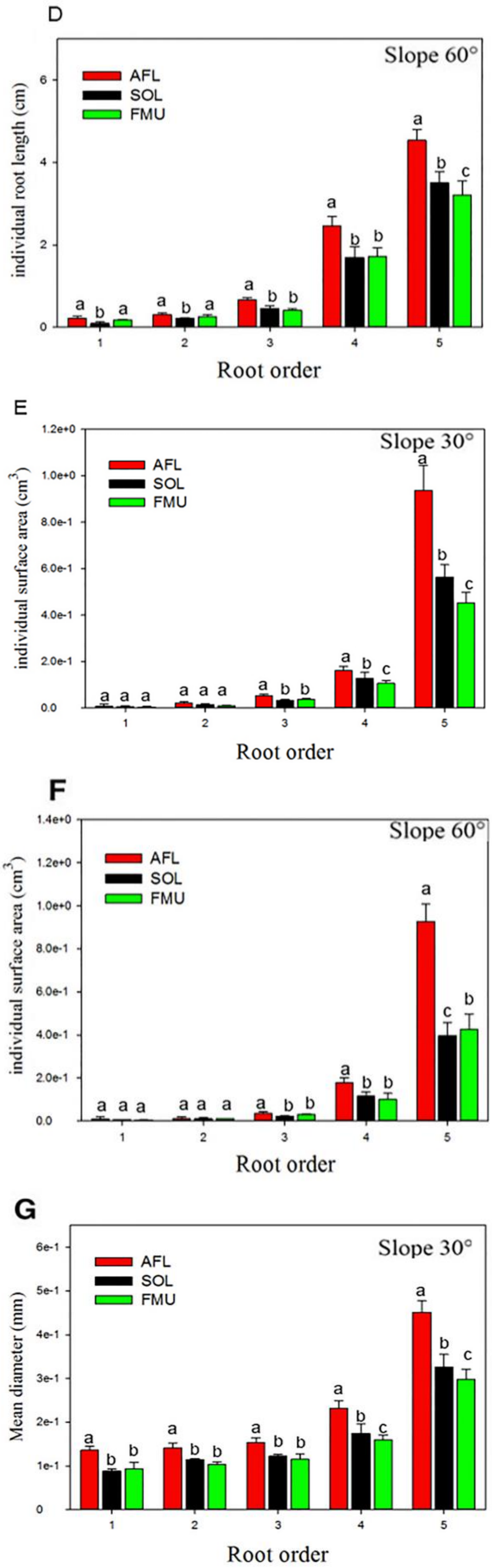
TABLE 3. Correlation between root diameter, maximum root length, total root length number of branch nodes and withdrawal force

Species	Slope	Diameter	MRL	TRL	NBN
AFL	30°	0.96***	0.92***	0.97***	0.97***
	60°	0.91***	0.86***	0.93***	0.95***
FMV	30°	0.94***	0.88***	0.86***	0.89***
	60°	0.93***	0.92***	0.89***	0.97***
SOL	30°	0.97***	0.70***	0.81***	0.86***
	60°	0.98***	0.83***	0.84***	0.95***

Note: MRL, Maximum root length (cm); TRL, Total root length (cm); NBN, Number of branch nodes; ***, p<0.001.

SOL and FMU in the second to fourth root orders at 30° slope (Figure 6A), and the specific root length was significantly higher in AFL than that in SOL and FMU in all root orders at 60° slope (Figure 6B). The individual root length, which was significantly higher in AFL than that in SOL and FMU in the fifth root orders at 30° slope (Figure 6C). The individual root length was significantly higher in AFL than that in SOL and FMU in the third to fifth root orders at 60° slope (Figure 6D). The individual root length was significantly higher in SOL than that in AFL and FMU in the fourth root orders at 30° slope (Figure 6C). The individual surface area, which was significantly higher in AFL than that in SOL and FMU in the third to fifth root orders at both of 30° and 60° slopes (Figure 6EF). The mean diameter, which was significantly higher in AFL than that in SOL and FMU in the all-root orders at all slopes (Figure 6GH). Furthermore, plant types, root order, slope, and their interaction had a significantly effect on all root anatomical, architectural and morphological traits at all slopes (Table 4).





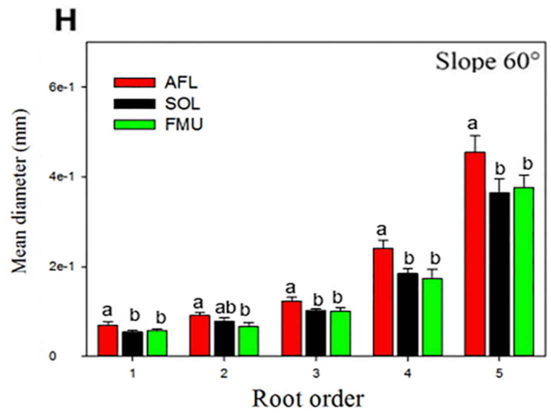


Figure 6. Specific root length, individual root length, individual root surface area, and mean diameter of fine roots at different slope among five roots orders of three plant types (Mean±SE). Different lowercase letters represent statistical significances among different plant types. AFL, Amorpha fruticosa Linn; SOL, Syringa oblata Lindl; FMU, Forsythio mandshurica Uyeki

TABLE 4. A general linear regression model (GLM) was used to examine the effect of plant type, root order, and their interaction on specific root length, individual length and surface area, and mean diameter, and the significances (p-value) were presented on the graphs. Results of general linear regression model (GLM) on the influence of root order (1-5), slope (30° slope and 60° slope) and species (AFL, Amorpha fruticosa Linn; SOL, Syringa oblata Lindl; FMU, Forsythio mandshurica Uyeki.) including all the interaction terms on four root morphology

	df	P value			
		SRL	IRL	IRS	MRD
Species	2	<0.001	<0.001	<0.001	<0.001
Order	4	<0.001	<0.001	<0.001	<0.001
Slope	1	<0.001	<0.001	<0.001	<0.001
Species*Order	8	<0.001	<0.001	<0.001	<0.001
Species*Slope	3	<0.001	<0.001	<0.001	<0.001
Order*Slope	4	<0.001	<0.001	<0.001	<0.001
Species*Order *Slope	8	<0.001	<0.001	<0.001	<0.001

Note: Shown are degrees of freedom (df) and the P value of the respective variables and the model itself. SRL represents the specific root length; IRL represents the individual root length; IRS represents the individual root surface area; MRD represents the mean root diameter.

4. 4. Soil Anti-scouring Resistance The impulse resistance index under heavy rain scouring is significantly lower than that under light rain scouring. Under the light rain, AFL has stronger soil anti-scouring resistance than SOL and FMU at both of slopes 30° and 60° (Figure 7). Under the heavy rain, AFL has stronger

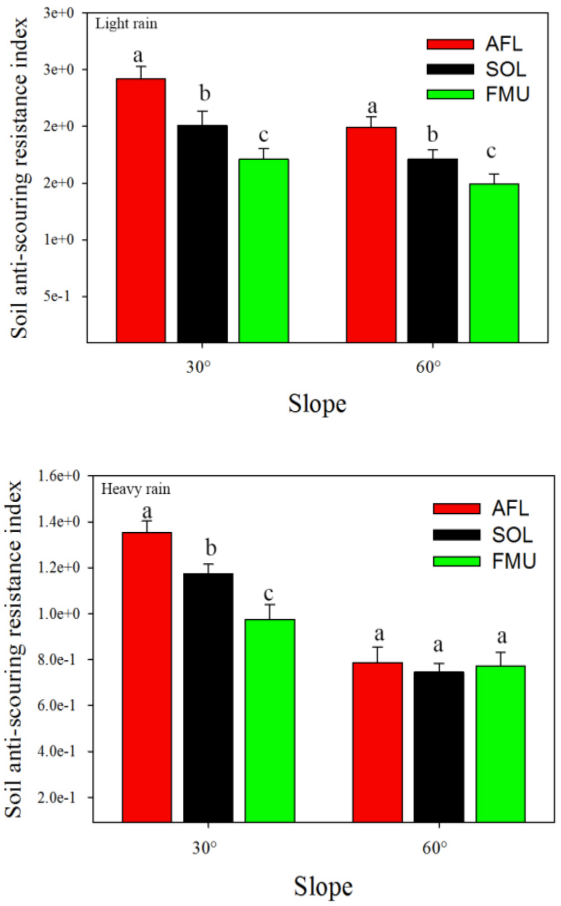


Figure 7. Soil anti-scouring resistance index in different rain intensity among different plant types (Mean±SE). Different lowercase letters represent statistical significances among different plant types. AFL, Amorpha fruticosa Linn; SOL, Syringa oblata Lindl; FMU, Forsythio mandshurica Uyeki

soil anti-scouring resistance than SOL and FMU at the slope of 30° (Figure 7). However, under the heavy rain, the soil anti-scouring resistance of AFL was almost equal to SOL and FMU at the slope of 60° (Figure 7).

5. DISCUSSION

The ability of root reinforcement provided by different shrubs can represent the role of ecological slope in improving the stability of road slope structure [19]. Under the same geological, geomorphological, and hydrological conditions, if a shrub has a better ability to enhance the stability of the slope structure, the smaller the probability of the slope structure being destroyed [20]. In this study, by comparing the root strengthening traits of AFL, SOL and FMU, under the same vertical conditions, the shrubs that are more suitable for enhancing the structure stability of the target slope can be obtained. In the context of carbon neutrality, we use the method of planting plants to improve the shallow slope structural stability, which can achieve the goal of enhancing the structural stability of road slope, but also improving the win-win ecological benefits [21].

5. 1. Comparted Root Morphology Traits

In previous studies, many studies have focused on the length of the root. Usually, associate the length of the plant root with the biomass of the plant root, yielding a specific parameter: specific root length (SRL), one of the most studied features in the root system [22]. Higher SRL, may be associated with a faster relative growth rate (RGR) and metabolic activity [23]. High SRL is more beneficial to slopes against sliding and erosion [22]. Therefore, according to previous studies found that the higher the proportion of fine roots (i. e. higher SRL), the higher the ability to prevent ecological slope landslides and erosion is an ideal feature of plant roots [24]. This conclusion is consistent with our results measuring the root morphology traits of all shrub species with different slopes. The study of the root system of the subject found that the SRL of the 3 shrubs showed great differences at both slopes of 30° and 60°. The SRL of AFL is highest at both slopes of 30° and 60°. These results show that AFL can not only meet the structure stability of gentle slope, but also adapt to the challenging environment on steep slope.

5. 2. Comparted Root Withdrawal Force

The withdrawal force of root system is an important index of soil slope consolidation and is related to soil withdrawal strength [25]. The shrub root system mainly uses reinforcement and anchor to prevent and control shallow landslide [23]. The wool beard root mainly plays the reinforcement role, and the coarse root with large root diameter mainly plays the anchorage role [26]. Previous studies have found that the withdrawal force was the root system buried in the soil against the withdrawal force, which reflected the combination of the root soil [287]. Also in previous studies have found that the main factors affecting the withdrawal force were the root diameter, root length, branching node and plant species, and the extraction force was proportional to the root diameter, root length and branching node [28]. This conclusion was consistent with our results measuring the root withdrawal force of all shrub species with different slopes. Under the same conditions, the root withdrawal force of the subject (AFL, SOL, FMU) is significantly differed; the root withdrawal force is stronger AFL than SOL and FMU. These results show that AFL can enhance the stability of the slope structure better than SOL and FMU.

5. 3. Comparted Root Anti-scouring Properties

Few previous studies involved the connection between root structures and ecological slope anti-scouring traits [29]. Therefore, we should comprehensively consider the mechanical properties and hydrologic process of the root system, and their interaction, so as to study the ecological slope structure stability more scientifically [30]. Studies have shown, as the rainfall increases, the value of the soil anti-scouring resistance gradually decreased. Rainfall intensity is inversely proportional to the soil anti-scouring resistance [31]. The results of previous studies have shown that with the increase of the slope the anti-scouring traits decrease [32]. Our results are in good agreement with the above research results. That is, the enhancement effect of the same tree species on the soil impulse resistance decreases with the increasing slope [33]. These changes fully illustrate the important role of the root system in improving the soil impulse resistance [34]. The study found that the anti-scouring traits of the 3 shrubs showed great differences at the slope of 30°. The soil anti-scouring resistance of AFL is highest at both slopes of 30° and 60°, especially in light rain. These results show that the soil anti-scouring resistance of AFL was better than SOL and FMU. AFL was more conducive to improving the slope structural stability.

6. CONCLUSIONS

In this study, we selected three shrubs with similar living types and cross-compare under the two slopes to reveal the effect of different plants on ecological slope structural stability in the respect of root system traits and mechanical properties. The following conclusions are observed from the study.

a. The SRL of AFL is highest at all slopes. These results show that AFL is more conducive to enhance the structure stability in gentle slope and steep slope.

b. The root withdrawal force is stronger AFL than SOL and FMU at all slopes. These results show that AFL can enhance the stability of the slope structure better than SOL and FMU.

c. In light rain, the soil anti-scouring resistance of AFL is highest at all slopes. These results show that AFL is more conducive to improve the slope structural stability.

In conclusion, AFL has more ideal traits than SOL and FMU in improving ecological slope stability. Therefore, AFL may be a shrub species more suitable for ecological slope structural reinforcement than SOL and FMU in our study area. This research will have a positive application significance for expressway construction and ecological environment improvement of the study region.

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Persian Abstract

چکیده

هدف این مقاله یافتن گونه‌های درختچه‌ای مناسب تر برای افزایش پایداری ساختاری شیب اکولوژیکی در منطقه مورد مطالعه است. از طریق بررسی، ما سه درختچه معمولی یافتیم، Amorpha fruticosa Linn. (AFL)، سیرینگا اوبلاتا لیندل. (SOL) و Forsythio mandshurica Uyeki. (FMU). در این مطالعه، ویژگی‌های سیستم ریشه و خواص مکانیکی با استفاده از روش‌های تجربی قابل اعتماد توصیف و توصیف شد. نتایج نشان داد که نیروی خروج ریشه متناسب با قطر (از ۰/۶ تا ۶ میلی متر) است. میانگین طول ریشه ویژه، طول فردی، سطح و قطر متوسط ریشه های ریز در شیب های مختلف برای AFL و SOL بیشتر از FMU بود، به خصوص برای ردیف های ریشه بالا. اگرچه مطالعات قبلی بر محتوای مربوطه متمرکز شده‌اند، توانایی تقویت درختچه‌های مختلف به ندرت تحت شرایط جاده‌ای یکسان از نظر کمی مقایسه می‌شود. همچنین صفات مورفولوژیکی ریشه ریز در این مطالعه مورد توجه قرار گرفت. این نتایج نشان داد که ویژگی‌های سیستم ریشه و خواص مکانیکی AFL ساختار شیب‌های تلفیقی مؤثرتری را نسبت به SOL و FMU ممکن می‌سازد، و نشان می‌دهد که کاشت AFL ممکن است راه بهتری برای افزایش پایداری ساختار شیب‌های اکولوژیکی باشد.