INTERSPECIFIC VARIATION AND THRESHOLD DYNAMICS OF SOIL SEPARATION CAPACITY IN SHRUB ROOT-SOIL COMPLEXES UNDER SEQUENTIAL FREEZE–THAW CYCLES AND CONTROLLED HYDRODYNAMIC CONDITIONS

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Abstract. In regions characterized by seasonal freeze-thaw cycles and intense hydrodynamic conditions, shrub root-soil complexes play a pivotal role in mitigating soil erosion. However, the interspecific differences in soil separation capacity and their relationship with freeze-thaw frequency and water flow velocity remain poorly understood. This study aimed to elucidate these complex interactions and identify thresholds governing soil stabilization. Soil samples were collected from a 25° hillside in the Wuying National Nature Reserve, northeastern China, which experiences a temperate continental monsoon climate. Controlled laboratory experiments were then conducted to simulate the effects of freeze-thaw cycles and hydrodynamic forces on soil separation capacity. We selected three shrub species, *Amorpha fruticosa, Swida alba*, and *Lespedeza bicolor*, and subjected their root-soil complexes to 0–20 freeze-thaw cycles and varied flow rates (2, 6, and 10 L/min) in controlled laboratory simulations. *Amorpha fruticosa* consistently exhibited the highest soil separation capacity, surpassing *Lespedeza bicolor* and *Swida alba.* Soil separation capacity increased with both water flow velocity and freeze-thaw cycles, stabilizing at lower cycle counts under higher flow conditions. Critical thresholds emerged after 10 cycles at 2 L/min and 5 cycles at 6 and 10 L/min. These findings underscore the importance of species-specific root traits and the synergistic influence of freeze-thaw processes and hydrodynamic forces in shaping soil stability. The identified thresholds offer insights for managing erosion-prone landscapes under shifting environmental regimes.
Keywords: *root reinforcement, soil detachment dynamics, hydrodynamic stress, freeze-thaw-induced erosion, plant-soil interaction*

Introduction

Soil erosion poses a critical challenge to global environmental sustainability, particularly in regions prone to extreme climatic events and anthropogenic disturbances (Borrelli et al., 2020). Among the natural mechanisms mitigating soil erosion, vegetation plays a vital role in stabilizing soil through root-soil interactions, reducing surface runoff, and promoting soil aggregation (Gong et al., 2024). Shrub species play a crucial role in soil stabilization, particularly in erosion-prone environments where their root systems act as primary soil-binding structures. Unlike dominant tree species, which typically develop deeper root systems that anchor the soil over longer timescales, shrubs possess dense, fibrous, and horizontally spreading roots that directly interact with the topsoil layer. Given that freeze-thaw cycles and hydrodynamic forces predominantly affect the upper

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soil profile, examining shrub root systems provides a more direct assessment of soil separation dynamics under these conditions (Reubens et al., 2007). Thus, this study focuses exclusively on shrub species rather than dominant trees to isolate the most influential belowground mechanisms driving soil stability in the studied system. However, the specific contributions of shrub species to soil separation capacity remain underexplored, particularly in ecosystems characterized by seasonal freeze-thaw cycles.

Freeze-thaw processes, common in temperate and cold regions, significantly alter soil physical properties by creating microcracks, reducing aggregate stability, and weakening soil cohesion (Liu et al., 2022). These structural changes, combined with hydrodynamic forces such as water flow, amplify the detachment of soil particles from root-soil complexes (Ma et al., 2023). Previous studies have identified key factors influencing soil separation capacity, including root biomass, root architecture, and root biochemical properties (Pierret et al., 2007). However, there is a limiting understanding of how these factors interact with freeze-thaw cycles and water flow velocity to shape soil separation capacity, particularly at the interspecific level.

The three shrub species selected for this study, *Amorpha fruticose (A. fruticose), Swida alba (S. alba)*, and *Lespedeza bicolor (L. bicolor)*, represent distinct morphological and functional root traits, making them ideal candidates for examining interspecific differences in soil separation capacity. *A. fruticosa* is characterized by its fibrous and extensive root system, which has been associated with improved soil stabilization (Yang et al., 2022). *L. bicolor*, with its moderate root density and flexibility, provides a contrasting intermediate case (Krishnamurthy et al., 2011). *S. alba*, known for its coarse roots and lower root biomass, represents a species with relatively weaker soil-binding capacity (Bodner et al., 2021). The inclusion of these three species allows for a comprehensive assessment of how root traits influence soil separation across varying environmental conditions.

Despite advancements in understanding root-soil dynamics, critical knowledge gaps persist. First, the relative performance of different shrub species in enhancing soil separation capacity under varying environmental conditions is poorly understood. Second, while freeze-thaw cycles are known to disrupt soil structure, their combined effects with hydrodynamic forces remain underexplored, particularly concerning stabilization thresholds under different flow rates. Third, little is known about how root traits mediate soil separation capacity in ecosystems experiencing dynamic environmental stresses, such as fluctuating flow velocities and repeated freeze-thaw cycles.

To address these gaps, this study hypothesizes the following: (1) *A. fruticosa* exhibits the highest soil separation capacity among the three studied shrub species (Bi et al., 2025); (2) soil separation capacity is positively correlated with water flow velocity, with freeze-thaw treatment consistently resulting in higher separation capacity than non-freeze-thaw treatment (Liu et al., 2024); and (3) soil separation capacity increases with freeze-thaw cycles, stabilizing at a lower threshold under higher flow rates (Ghazavi et al., 2013). These hypotheses provide a foundation for investigating the complex interplay between root traits, freeze-thaw processes, and hydrodynamic forces in shaping soil separation capacity.

The primary objectives of this study are to evaluate the soil separation capacity of three shrub root-soil complexes under varying freeze-thaw and hydrodynamic conditions and to identify the mechanisms driving differences in their performance. By integrating root trait analysis with environmental dynamics, this research offers novel insights into the

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factors influencing soil stabilization in erosion-prone ecosystems. This study's findings have significant implications for soil management strategies, particularly in regions where freeze-thaw processes and high water flow velocities exacerbate soil erosion risks.

Materials and methods

Sampling area introduction

A total of 90 soil samples were collected from a 25° hillside in the Wuying National Nature Reserve (48°02'–48°12'N, 128°58'–129°15'E), northeastern China. The samples consisted of undisturbed soil blocks (20 cm × 20 cm × 15 cm) extracted at a depth of 0-15 cm to preserve the natural structure of the root-soil complex. Sampling was conducted for three shrub species (*Amorpha fruticosa, Swida alba*, and *Lespedeza bicolor*), with each species represented by 30 replicates. To ensure consistency, three separate sites were selected within the reserve, and 10 samples per species were collected from each site. The collected samples were then air-dried and prepared for controlled laboratory experiments on freeze-thaw cycling and soil separation capacity. A map illustrating the 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 soil is classified as sandy loam, with an average sand, silt, and clay composition of 62%, 25%, and 13%, respectively. The mean soil organic matter content is 4.2%, with a bulk density of 1.35 g/cm^3 and a pH of 5.8. These properties were determined using standard soil analysis methods (USDA texture classification, Walkley-Black method for organic matter, and pH measurement in a 1:2.5 soil-to-water suspension). The forest community in the area is a natural mixed coniferous and broad-leaved forest. The dominant tree species include *Pinus koraiensis* and *Picea asperata*, while the primary shrub species are *Amorpha fruticosa* (*A. fruticosa*), *Swida alba* (*S. alba*), and *Lespedeza bicolor* (*L. bicolor*).

Experimental equipment and scheme design

Experimental equipment

The freeze-thaw cycles were simulated using a hydraulic low-temperature circulating box (DWS410-S, Chongqing Haoyuan Environmental Testing Equipment Co., Ltd.), with a temperature range of -40 to 60°C. The required flow rate for the scouring tests was controlled and adjusted using a peristaltic pump (Shencheng YZ35, Baoding Shencheng Pump Co., Ltd.), capable of delivering a maximum flow rate of 10 L/min. The scouring apparatus consisted of a water tank, a steady flow device, a scouring tank, and a collection system. A perforated acrylic barrier separated the water tank from the steady flow device, ensuring smooth water flow into the scouring tank. The rectangular scouring tank measured 4.8 m (L) × 0.15 m (W) × 0.10 m (H), with a sediment chamber positioned 30 cm from the outlet for soil sample placement. The slope of the tank could be adjusted between 0% and 42%, using varying mesh types at the bottom to mimic natural surface roughness. Sediments and runoff were collected during the scouring tests.

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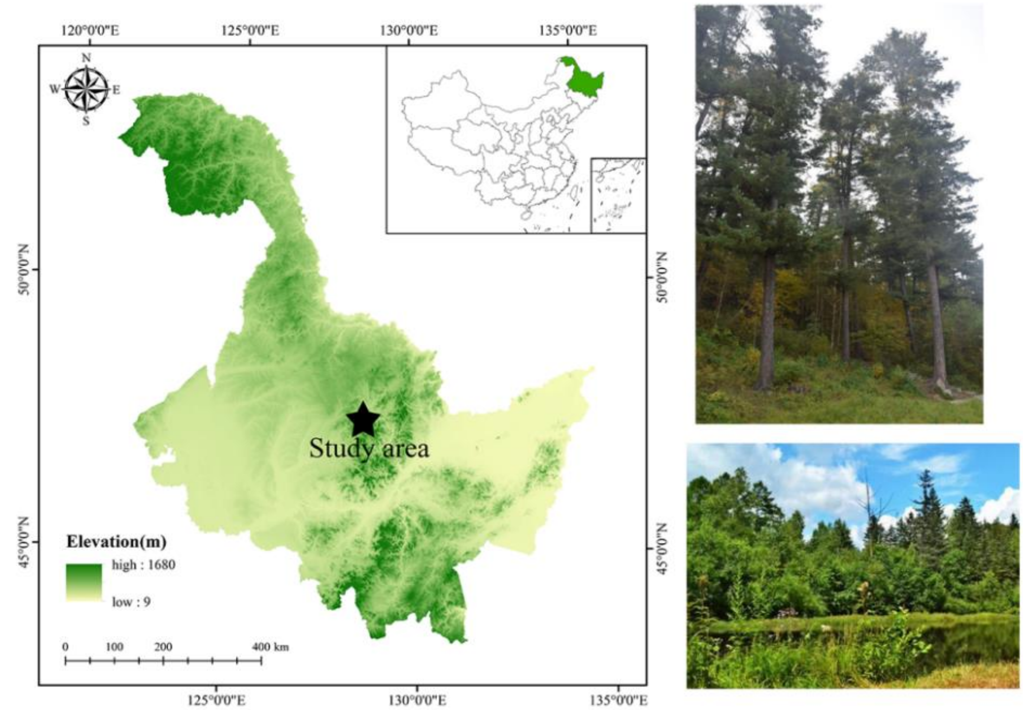

Figure 1. *Sample plot and diagram of the experimental design in Wuying national nature reserve, Yichun city, Heilongjiang province, northeastern China*

Experimental design

The selection of shrub species in this study was based on their dominant role in stabilizing the upper soil layer, which is most susceptible to freeze-thaw disturbance and hydrodynamic forces. Each experimental treatment (combination of freeze-thaw cycles and flow rates) was conducted with three replicates to ensure statistical validity. Unlike deep-rooted tree species that primarily contribute to long-term slope stabilization, shrubs exhibit fine and fibrous roots that interact directly with the soil surface, making them more relevant for studying short-term soil separation capacity. Therefore, the study specifically targeted shrub species (*Amorpha fruticosa*, *Swida alba*, and *Lespedeza bicolor*), whose root architectures provide meaningful insights into the mechanisms of soil detachment under dynamic environmental conditions.

The selection of shrub species for this study was based on their diverse rooting characteristics and ecological significance in soil stabilization. *Amorpha fruticosa* was chosen for its fine, fibrous root system that enhances soil aggregation. *Lespedeza bicolor* represents an intermediate rooting strategy with moderate depth and branching. *Swida alba*, characterized by its coarser root structure and lower root density, was selected to examine the role of reduced root complexity in soil separation capacity. Through field investigations and by referencing relevant literature, the chosen species for investigation include *A. fruticosa*, *S. alba*, and *L. bicolor*. Form the root-soil complex of these three species. Based on field observations and meteorological data, the freeze-thaw cycles were set to 0, 1, 5, 10, and 20, with a controlled temperature difference of approximately 25 °C (freezing and thawing temperatures at -15 °C to 0 °C and 0 °C to 10 °C, respectively). The 0-cycle condition served as the control group. The flow rates for the indoor scouring tests were set to 2, 6, and 10 L/min based on comprehensive regional rainfall data,

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corresponding to precipitation intensities of 10, 25, and 50 mm/h, respectively. These values represent typical small, moderate, and heavy rainfall events in the study region. The experiments were conducted at a slope of 10°. While the natural slope at the sampling site was approximately 25°, a 10° slope was used in the laboratory to maintain hydraulic stability, prevent excessive runoff, and facilitate controlled soil separation measurements under freeze-thaw conditions.

Freeze-thaw cycling

Soil samples were oven-dried at 105 °C to ensure a moisture content of 0%. After cooling, a predetermined mass of soil was placed in a polystyrene foam box (50 cm × 30 cm × 20 cm) and moistened to the designed water content using a mist sprayer. The samples were sealed to minimize evaporation and allowed to equilibrate at room temperature for 24 hours. Following this, the soil was packed into cylindrical containers (10 cm diameter, 5 cm height) at the desired bulk density and compacted using a multifunctional electric tamper. Each treatment condition (freeze-thaw cycle count and flow rate) was replicated three times, ensuring statistical rigor. Excess soil was removed to ensure a flush surface, after which the samples were weighed and sealed with plastic wrap before undergoing freeze-thaw cycles in a freeze-thaw machine, with drainage holes provided for aeration.

Indoor scouring simulation

Flow rates measurement

Flow rates were controlled by the peristaltic pump, with three measurements taken to ensure stability within a 5% margin. For each combination of freeze-thaw cycles and flow rates, three experimental replicates were performed to ensure statistical consistency in soil separation capacity measurements. Surface flow velocities were determined using potassium permanganate tracing at three points (left, center, right) along the tank, 2 m upstream from the outlet. The average flow velocity was calculated from the time taken for the tracer to travel this distance.

Soil separation capacity measurement

Soil samples were placed in the sediment chamber, aligning their surfaces with the tank bed. Prior to testing, the slope and flow rate were adjusted to meet the experimental conditions. The duration of scouring was controlled to limit the depth to a maximum of 2 cm, thereby minimizing edge effects. Eroded sediments were collected in a runoff bucket, which was allowed to settle for 12 hours before the supernatant was removed. The remaining sediment was dried at 105 °C, with the soil separation capacity calculated as the weight of the dried sediment divided by the cross-sectional area of the soil sample and the duration of scouring. The calculation formula *(Eq. 1)* is as follows:

$$Sc = \frac{W}{At} \quad \text{(Eq.1)}$$

where: Sc is the soil separation capacity, kg $m^{-2}s^{-1}$; A is the projection area of the bottom of the soil box, m^2; t is the time when the soil sample is washed by water flow, s; W is the drying mass of sediment stripping during the scouring process, kg.

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Statistical analysis

Data normality and variance homogeneity were assessed using the Kolmogorov-Smirnov and Levene's tests, respectively. To investigate the effects of freeze-thaw cycles and flow velocity on separation capacity across different shrub species (*S. alba*, *L. bicolor*, and *A. fruticosa*), a two-way ANOVA was performed, examining the interaction between freeze-thaw cycles and flow velocity on separation capacity. Post-hoc comparisons were conducted using the Tukey-Kramer HSD test to identify significant differences between species under various conditions. Additionally, regression analysis was employed to explore the relationship between flow velocity (u) and separation capacity (Dc) under both freeze-thaw and non-freeze-thaw conditions, utilizing the ggplot2 package in R (version 4.2.1, R Core Team, 2018). All statistical analyses were performed using SPSS version 22.0 (IBM, Armonk, NY, USA), while SigmaPlot 12.5 (Systat Software Inc., San Jose, CA, USA) was utilized for bar chart and regression line generation.

Results

The soil separation capacity between different shrub root-soil complex

The soil separation capacity showed significant differences among the three shrub root-soil complexes (*Figure 2*). Specifically, *A. fruticosa* exhibited the highest soil separation capacity, which was significantly higher than that of *L. bicolor* and *S. alba*. *L. bicolor* showed an intermediate soil separation capacity, which was significantly higher than that of *S. alba*. *S. alba* displayed the lowest soil separation capacity (*Figure 2*).

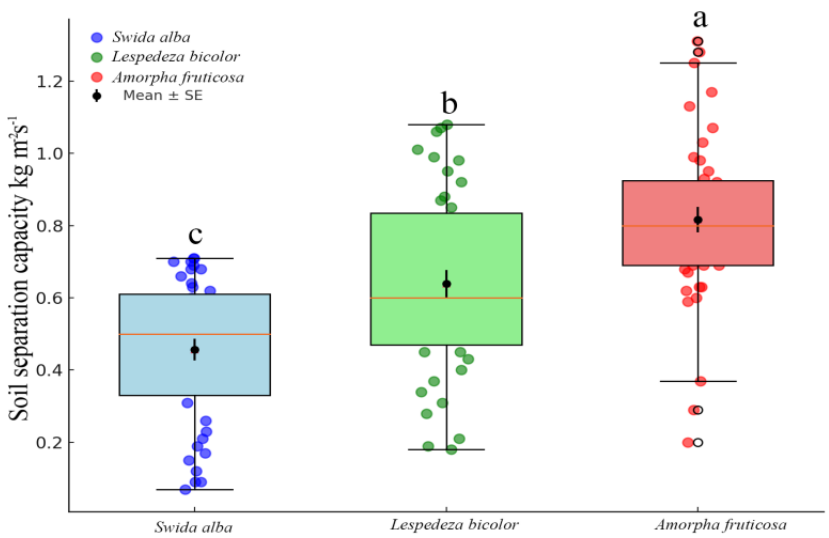

Figure 2. *the separation capacity between different shrub root-soil complex. Notes: The lower case letters represent differences between plant species; Error bars represent standard errors. The lowercase letters (a, b, c) above the boxplots indicate significant differences between plant species based on statistical analysis. 'a' represents the group with the largest soil separation capacity. 'b' indicates an intermediate value. 'c' corresponds to the group with the smallest soil separation capacity. The data are presented as boxplots, where the black dots inside each box represent the mean ± standard error (SE)*

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Relationship between water flow velocity and soil separation capacity

There was a significant positive correlation between soil separation capacity and water flow velocity, with significant differences observed between freeze-thaw and non-freeze-thaw treatments (*Figure 3*). The soil separation capacity showed a significant positive correlation with water flow velocity, increasing as flow velocity increased. Across all plant species, the freeze-thaw treatment consistently resulted in significantly higher soil separation capacity compared to the non-freeze-thaw treatment. The magnitude of the differences between the freeze-thaw and non-freeze-thaw treatments became more pronounced with increasing water flow velocity, indicating that the effects of freeze-thaw cycles were amplified under higher flow conditions. Among the three plant species, *A. fruticosa* exhibited the highest soil separation capacity, followed by *L. bicolor*, with *S. alba* displaying the lowest values (*Figure 3*).

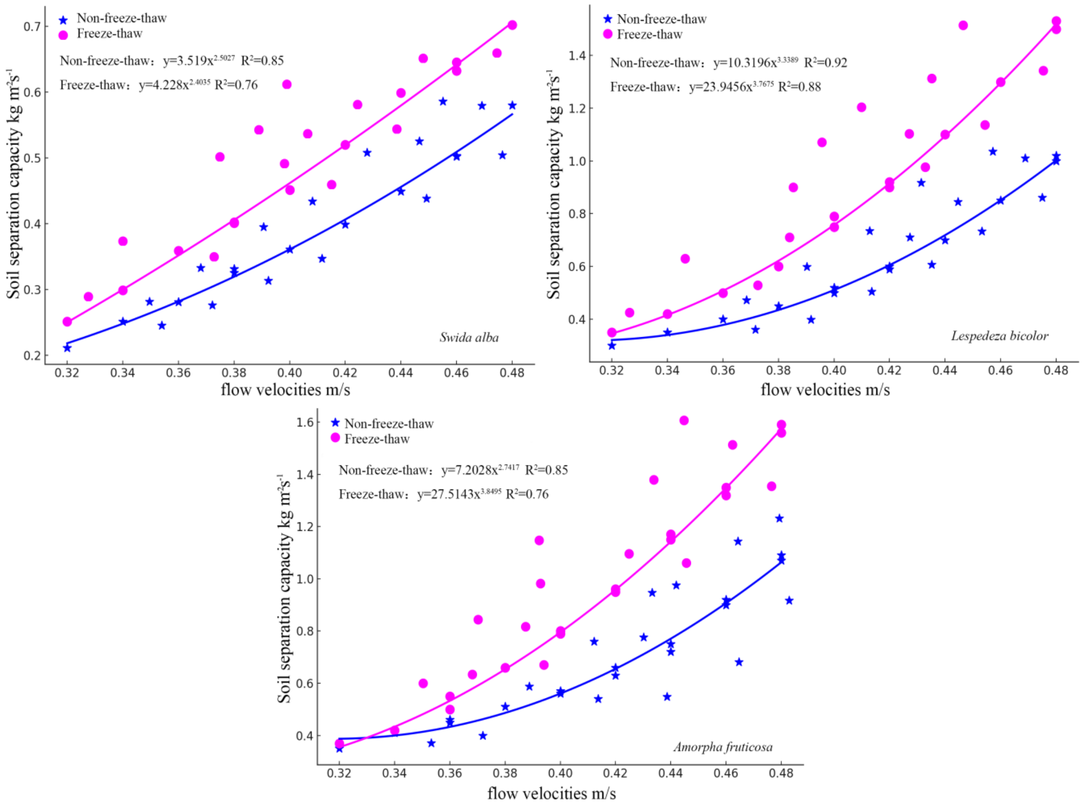

Figure 3. *Relationship between water flow velocity and soil separation capacity*

Relationship between the number of freeze-thaw cycles and soil separation capacity of root-soil complex

Under different freeze-thaw cycle times (0, 1, 5, 10, and 20) and flow rate conditions (2 L/min, 6 L/min, and 10 L/min), the soil separation capacity exhibited significant differences among plant species (*Figure 4*). Soil separation capacity increased significantly with an increasing number of freeze-thaw cycles and higher flow rates. However, statistical analysis (ANOVA, Tukey’s HSD test) revealed that beyond 10 freeze-thaw cycles at 2 L/min and 5 cycles at 6 and 10 L/min, soil separation capacity did not exhibit significant increases ($P > 0.05$). This stabilization indicates that a threshold

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value has been reached, beyond which additional freeze-thaw cycles have minimal impact on soil separation capacity (*Figure 4*). The differences among plant species became more pronounced under higher flow rates and freeze-thaw cycles.

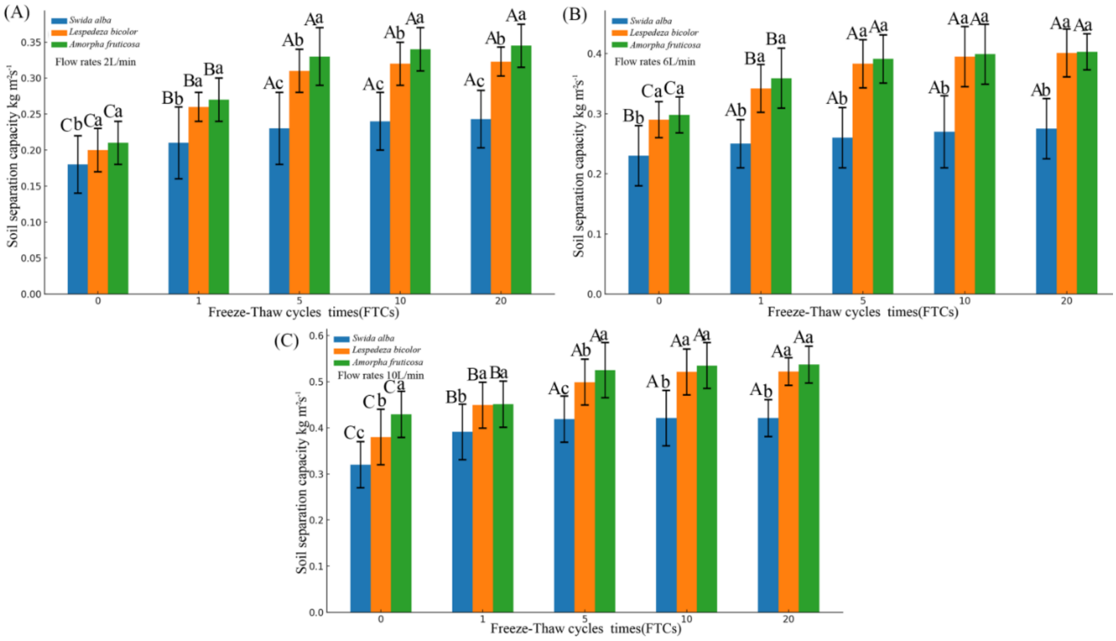

Figure 4. *The relationship between the freeze-thaw cycles times and the soil separation capacity when the flow rate is 2 L/min (A), the relationship between the freeze-thaw cycles times and the soil separation capacity when the flow rate is 6 L/min (B), the relationship between the freeze-thaw cycles times and the soil separation capacity when the flow rate is 10 L/min (C). Notes: Different lowercase letters indicate significant differences among different plant species, while different uppercase letters indicate statistically significant differences in the same plant species under different numbers of freeze - thaw cycles*

The following patterns can be observed across different flow rate conditions as the number of freeze-thaw cycles increases: the soil separation capacity gradually increased with an increasing number of freeze-thaw cycles. However, after 10 freeze-thaw cycles, the rate of increase slowed, and the values began to stabilize, reaching their critical point. This phenomenon was observed under all three flow rate conditions (2 L/min, 6 L/min, and 10 L/min), but the critical value and stabilization trend varied with flow rate (*Figure 4*).

At a flow rate of 2 L/min, the soil separation capacity stabilized after 10 freeze-thaw cycles. At flow rates of 6 L/min and 10 L/min, the soil separation capacity stabilized after 5 freeze-thaw cycles, with the rate of increase diminishing. Under higher flow rate conditions, the soil separation capacity was greater, and the critical value number of freeze-thaw cycles required to reach stabilization was lower (*Figure 4*).

ANOVA results indicated that species, freeze-thaw cycles, and flow rate significantly affected soil separation capacity ($p < 0.001$), with significant interactions between species and freeze-thaw cycles ($p < 0.01$), species and flow rates ($p < 0.01$), and freeze-thaw cycles and flow rates ($p < 0.05$) (*Table 1*).

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Table 1. *Analysis of variance (ANOVA) results for effects of species, freeze-thaw cycles times, flow rates and interactions on soil separation capacity*

Source of variation	df	soil separation capacity
species	2	***
freeze-thaw cycles times	4	***
flow rates	2	***
species×freeze-thaw cycles times	8	**
species×flow rates	4	**
freeze-thaw cycles times×flow rates	8	*
species×freeze-thaw cycles times×flow rates	16	*

* $p < 0.05$; ** $p < 0.01$, ***$p < 0.001$, NS represents no significant. Shown are degrees of freedom (df) and the P value of the respective variables and the model itself

Discussion

Comparing the differences in soil separation capacity of root-soil complex

The results demonstrated that the soil separation capacity varied significantly among the three shrub root-soil complexes (*Figure 2*). Specifically, *A. fruticosa* exhibited the highest soil separation capacity, which was significantly higher than that of *L. bicolor* and *S. alba*. The intermediate soil separation capacity was observed in *L. bicolor*, while *S. alba* displayed the lowest value.

The results clearly indicate that *A. fruticosa* possesses a superior soil separation capacity compared to *L. bicolor* and *S. alba*, supporting the hypothesis that *A. fruticosa* performs better in enhancing soil separation. This suggests that the root structure and traits of *A. fruticosa* play a dominant role in its ability to improve soil separation.

The observed differences in soil separation capacity among the shrub species are consistent with findings from previous studies (Parhizkar et al., 2024). For example, larger root biomass and more extensive root-soil interactions have been reported to improve soil stability and separation capacity (Hallett et al., 2022). The higher soil separation capacity of *A. fruticosa* may be attributed to its well-developed root architecture, which enhances root-soil cohesion and effectively reduces soil particle detachment (Zhu et al., 2018). In addition, previous research demonstrated that species with finer roots and larger specific root length contribute significantly to soil aggregation and stability (Le et al., 2018). Conversely, *S. alba*, which exhibited the lowest soil separation capacity, might possess coarser roots and a lower root density, limiting its ability to enhance soil cohesion (Yang et al., 2024). Differences in root exudates, microbial activity, and glomalin-related soil proteins (GRSPs) associated with the root-soil interface may further explain the variation in soil separation capacity (Delian et al., 2011).

The findings align well with the initial hypothesis that *A. fruticosa* has the highest soil separation capacity (Zhou et al., 2025). The superior performance of *A. fruticosa* can be attributed to several factors. First, *A. fruticosa* likely possesses a deeper and more extensive root system, enabling it to bind soil particles more effectively (Bi et al., 2025). Previous studies have emphasized that plants with denser and more fibrous root systems exhibit enhanced soil separation and stabilization properties (Hao et al., 2020). Second, root traits such as root length density and surface area may facilitate stronger root-soil interactions, as observed in high-performing species like *A. fruticosa* (Dunbabin et al.,

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2013). Third, the biochemical properties of roots, including root exudates and GRSP production, are critical in improving soil cohesion and separation (Addesso et al., 2023). In contrast, the lower soil separation capacity of *S. alba* could be due to a less developed root structure and reduced production of root-associated biochemicals (McCormack et al., 2015).

Furthermore, the discrepancy between *A. fruticosa* and *L. bicolor* may be explained by differences in root mechanical properties and physiological adaptation (Li et al., 2021). Plants with more elastic and flexible roots can withstand greater external forces, promoting soil particle cohesion and separation under varying conditions (Schwarz et al., 2010). This mechanistic explanation suggests that the performance of *A. fruticosa* in soil separation is driven not only by its root morphology but also by its physiological resilience and adaptability to soil environments.

Overall, the results provide strong evidence supporting the hypothesis and highlight the role of root traits in determining soil separation capacity. The superior soil separation capacity of *A. fruticosa* underscores its potential in soil stabilization applications, particularly in erosion-prone ecosystems. Future research should focus on exploring the interactions between root architecture, biochemical processes, and microbial communities to further elucidate the mechanisms underlying soil separation capacity.

Comparing the number of freeze-thaw cycles and the soil separation capacity of root-soil complex

The results revealed a significant positive correlation between soil separation capacity and water flow velocity, with freeze-thaw treatment consistently resulting in significantly higher soil separation capacity than non-freeze-thaw treatment (*Figure 3*). Moreover, the differences between freeze-thaw and non-freeze-thaw treatments became more pronounced as water flow velocity increased, indicating that the effects of freeze-thaw cycles were amplified under higher flow conditions.

These findings suggest that soil separation capacity is strongly influenced by hydrodynamic forces and freeze-thaw processes. The significant positive correlation with water flow velocity demonstrates that higher flow velocities enhance soil separation by generating greater shear stress, which detaches soil particles from aggregates. Additionally, the freeze-thaw treatment disrupted soil cohesion, making soil more vulnerable to separation, especially at higher flow velocities.

The observed relationship between soil separation capacity and water flow velocity aligns with previous studies. Higher flow velocities are known to impose stronger hydrodynamic forces on soil particles, promoting their detachment from the soil matrix (Zi et al., 2023). Freeze-thaw cycles exacerbate this effect by increasing soil porosity, creating micro-cracks, and weakening the mechanical integrity of soil aggregates (Zhou et al., 2024). As reported by Mikha et al. (2024), repeated freeze-thaw processes reduce soil cohesion and disrupt aggregate stability, particularly under dynamic water flow conditions. In contrast, under non-freeze-thaw conditions, the soil structure remains relatively intact, resulting in lower separation capacity even at higher flow velocities (Jia et al., 2024).

The amplification of freeze-thaw effects under higher flow velocities can be attributed to the combined impact of mechanical and hydrodynamic processes (Wu et al., 2024). Freeze-thaw cycles loosen the soil structure, while increasing flow velocity generates greater shear forces that exploit these structural weaknesses (Liu et al., 2021). This synergistic effect explains the larger differences observed between freeze-thaw and non-

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freeze-thaw treatments as flow velocity increases (Gao et al., 2020). The diminished soil cohesion under freeze-thaw treatment highlights its role in reducing the soil's resistance to hydrodynamic forces (Sun et al., 2018).

The findings are consistent with the initial hypothesis that soil separation capacity is positively correlated with water flow velocity and that freeze-thaw treatment enhances soil separation (Zuo et al., 2022). The mechanisms driving these results can be attributed to two primary factors. First, the hydrodynamic forces associated with higher flow velocities increase the rate of soil particle detachment, as shown in studies on erosion dynamics (An et al., 2012). Second, freeze-thaw cycles induce structural changes in soil, including the formation of micro-cracks and increased porosity, which weaken soil cohesion and facilitate separation (Zhou et al., 2024). The synergy between these two processes amplifies soil separation capacity under combined freeze-thaw and high-flow conditions (Couper et al., 2003).

In conclusion, this study highlights the critical role of hydrodynamic forces and freeze-thaw processes in determining soil separation capacity. The results underscore the importance of understanding the interaction between environmental factors and soil mechanical properties, particularly in regions subject to seasonal freeze-thaw cycles and high water flow velocities. Future research should focus on quantifying the micro-scale effects of freeze-thaw cycles on soil structure and exploring the thresholds of hydrodynamic forces required to overcome soil cohesion under different environmental conditions.

Correlation between water flow velocity and soil separation capacity

The results demonstrated that soil separation capacity significantly increased with the number of freeze-thaw cycles and flow rates (*Figure 4*). Across all flow rate conditions (2 L/min, 6 L/min, and 10 L/min), the soil separation capacity exhibited an initial increase with freeze-thaw cycles. However, after 10 freeze-thaw cycles at a flow rate of 2 L/min and 5 freeze-thaw cycles at flow rates of 6 L/min and 10 L/min, the capacity stabilized, indicating a diminishing rate of increase and an approach to a critical value (*Figure 4*). Notably, higher flow rates resulted in greater soil separation capacity and required fewer freeze-thaw cycles to reach stabilization. The results of the ANOVA analysis further confirm the significant effects of species, freeze-thaw cycles, and flow rate on soil separation capacity, with notable interactions between species and freeze-thaw cycles, species and flow rates, and freeze-thaw cycles and flow rates (*Table 1*). These interactions highlight the complex interplay between biotic and abiotic factors in determining soil separation capacity.

The findings suggest that both freeze-thaw cycles and flow rate significantly influence soil separation capacity. Higher flow rates enhance the hydrodynamic forces acting on soil particles, while freeze-thaw cycles disrupt soil structure, facilitating particle detachment. The stabilization of soil separation capacity after a certain number of freeze-thaw cycles reflects the soil's structural reorganization, reaching a state where further freeze-thaw cycles have a negligible impact (Lu et al., 2019).

The observed increase in soil separation capacity with freeze-thaw cycles is consistent with prior studies that highlight the role of freeze-thaw processes in weakening soil aggregates and increasing porosity (Rooney et al., 2022). This structural disruption, characterized by micro-cracks and reduced cohesion, renders soil more susceptible to hydrodynamic forces (Peth et al., 2010). Additionally, higher flow rates amplify the shear stress exerted on soil particles, further enhancing soil separation (Ghezzehei et al., 2000).

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The results also align with findings by Voigtländer et al. (2024), who demonstrated that the interplay between hydrodynamic and mechanical forces during freeze-thaw processes significantly impacts soil stability.

However, the stabilization of soil separation capacity at different freeze-thaw cycle thresholds under varying flow rates has been less extensively documented (Yuan et al., 2021). The observed phenomenon may stem from the saturation of structural changes in the soil matrix (Alaoui et al., 2021). Once soil aggregates are fully disrupted and internal cohesion is significantly reduced, additional freeze-thaw cycles contribute minimally to further separation (Tang et al., 2021). This critical point varies with flow rate due to the differential shear stress imposed at higher velocities, which accelerates structural changes (Katritsis et al., 2007).

The results strongly support the hypothesis that soil separation capacity increases with freeze-thaw cycles and that higher flow rates result in greater separation capacity with fewer cycles required for stabilization (Ma et al., 2022). The underlying mechanisms can be explained by the synergy between freeze-thaw-induced structural changes and hydrodynamic forces (Cai et al., 2017). Freeze-thaw cycles weaken soil aggregates by creating fractures and increasing porosity, reducing the resistance to shear forces (Zhang et al., 2025). Simultaneously, higher flow rates impose greater hydrodynamic forces, accelerating particle detachment and reducing the critical number of freeze-thaw cycles required for stabilization (Anderson et al., 2010).

The diminishing impact of additional freeze-thaw cycles beyond the stabilization threshold highlights the interplay between physical and mechanical soil properties. Once the structural integrity of the soil is sufficiently weakened, additional cycles do not significantly enhance separation capacity. The higher critical value of soil separation capacity observed under increased flow rates underscores the importance of hydrodynamic conditions in shaping soil behavior during freeze-thaw cycles. This finding provides new insights into the combined effects of environmental processes and flow dynamics on soil stability.

In conclusion, the results emphasize the critical roles of freeze-thaw cycles and flow rate in determining soil separation capacity. The identified stabilization thresholds and their dependence on flow rate provide a framework for understanding soil behavior under dynamic environmental conditions. Future research should focus on quantifying the micro-scale effects of these processes and exploring their implications for soil management in freeze-thaw-affected regions.

Conclusion

This study provides clear evidence that *A. fruticosa* consistently exhibited the highest soil separation capacity among the three shrub root-soil complexes, significantly outperforming *L. bicolor* and *S. alba.* This finding underscores the critical role of root structure and traits in enhancing soil separation, particularly in erosion-prone ecosystems where soil stabilization is vital.

The results further demonstrated a significant positive correlation between soil separation capacity and water flow velocity. Soil separation capacity was consistently higher under freeze-thaw treatment compared to non-freeze-thaw treatment, with the differences becoming more pronounced as water flow velocity increased. These findings highlight the synergistic effects of freeze-thaw processes and hydrodynamic forces in weakening soil cohesion and facilitating particle detachment.

Additionally, soil separation capacity increased progressively with the number of freeze-thaw cycles, eventually stabilizing as it approached a critical value. Notably, the stabilization thresholds varied with flow rate: under a flow rate of 2 L/min, stabilization occurred after 10 freeze-thaw cycles, while at 6 L/min and 10 L/min, stabilization was achieved after just 5 cycles. Higher flow rates not only amplified soil separation capacity but also reduced the number of freeze-thaw cycles required to reach stabilization, indicating that hydrodynamic forces accelerate structural changes in soil aggregates.

These findings emphasize the intricate interplay between root traits, freeze-thaw processes, and hydrodynamic forces in shaping soil separation capacity. The identification of critical thresholds and their dependence on environmental conditions provides valuable insights for soil management strategies in regions affected by seasonal freeze-thaw cycles and high water flow velocities. Future research should integrate micro-scale analysis of soil structural changes and investigate the implications of these findings for improving soil stability and reducing erosion risk in diverse ecosystems.

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