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Influence of topographic factors on the distribution of herbaceous vegetation and mechanical root properties of the Xijitan giant landslide in the upper reaches of the Yellow River, northwestern China

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Abstract

Background The upper reaches of the Yellow River, located on the northeastern Qinghai-Tibet Plateau, host numerous giant landslides characterised by sparse vegetation cover and a fragile ecological environment. Along the Longyangxia-Jishixia river corridor, critical infrastructure such as the Longyangxia, Laxiwa, Lijiaxia and Gongboxia hydropower stations depends on the ecological and geological integrity of these slopes, which also support the livelihoods of local communities. However, the ecosystem characteristics of giant landslide areas in the upper Yellow River remain poorly understood, particularly regarding how locally dominant herbaceous species and their root mechanical properties influence the shallow stability of these landslides.

Methods Focusing on the Xijitan giant landslide in the upper reaches of the Yellow River, we combined field vegetation surveys with laboratory single-root tensile tests. We analysed how topographic factors structure plant community distribution patterns, with particular emphasis on the effects of slope aspect on root morphological traits and biomechanical properties of dominant herbaceous species.

Results Fresh biomass and ground cover decreased with increasing solar exposure, following the sequence shady slope > semi-shady slope > semi-sunny slope > sunny slope under otherwise comparable conditions. Principal component analysis identified slope aspect as the primary topographic factor controlling herbaceous community composition, and its associated axis 1 explained 67.74% of the community variance. Slope aspect influenced plant root mechanical properties by altering habitat conditions, which not only affected the aboveground community structure but also affected the structural morphology of the root system. The results of single-root tensile tests further showed that there were significant differences in the mechanical properties of roots between sunny and shady slopes. Specifically, the tensile strength of *Poa araratica* roots in sunny slope habitats was 25.77 MPa, significantly

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higher than that in shady slopes (24.38 MPa). *Stipa aliena* exhibited the same trend, with a higher tensile strength on sunny slopes (30.52 MPa) compared to shady slopes (28.75 MPa). These results reflect that the habitat differences caused by slope aspect drove the changes in the root mechanical behavior of herbaceous plants.

Conclusion This study demonstrates a clear link between slope aspect, herbaceous community distribution and the mechanical properties of plant roots on a giant landslide. The findings provide essential theoretical support for ecological restoration in landslide-prone regions and offer a scientific basis for using vegetation to control slope soil erosion and mitigate shallow landslide risk in the upper reaches of the Yellow River basin.

Keywords Upper reaches of the Yellow River, Xijitan giant landslide, Vegetation distribution, Topographic factors, Root mechanical properties

Introduction

Giant landslides typically occur in areas with steep terrain, active tectonics or extreme climatic conditions, and are characterised by their large spatial extent, long run-out distances, strong destructive potential and complex formation processes (Highland et al. 2008; Hungr et al. 2014). The upper reaches of the Yellow River is located at the tectonic boundary between the northeastern Qinghai-Tibet Plateau and the western Loess Plateau and is one of the most landslide-prone sections of the Yellow River Basin (Lan et al. 2022). For example, 508 landslides of various types, including 24 giant and 92 extra-large landslides, have been identified in the Sigouxia-Laganxia reach (Yin et al. 2021), some of which have blocked the main river, triggered secondary landslides and debris flows, and caused serious damage (Ji et al. 2025; Wei et al. 2017; Zhang et al. 2017). At the same time, more than a dozen hydropower stations, such as Longyangxia, Laxiwa, Lijiaxia and Gongboxia, are distributed along this corridor (Wang et al. 2025). Maintaining the stability of the geo-environment in giant landslide zones is therefore critical for the long-term safe operation of hydropower projects and for protecting the lives and livelihoods of residents along the river.

Giant landslides in the upper reaches of the Yellow River are characterised by extremely rugged topography (high mountains, deep gorges, fault basins), average elevations above 3,000 m, sparse vegetation cover, thin and discontinuous soils and intensive human activity (Peng et al. 2020). These features create highly heterogeneous microhabitats across different slope aspects and positions, and amplify both geological and ecological vulnerability. Under such conditions, vegetation is not only a key component of the fragile ecosystem but also an important measure for ecological slope protection. Aboveground stems and leaves help reduce raindrop impact and surface runoff (Wang et al. 2013), while roots increase soil shear strength and the safety factor of the slope (Liu et al. 2018). The combined effect of these aboveground and belowground processes can effectively reduce soil erosion and mitigate shallow landslide risk.

For these reasons, it is necessary and practically significant to study how topographic factors control vegetation distribution patterns and root mechanical properties specifically on giant landslides, rather than extrapolating from smaller or more stable slopes. Our study aims to link slope-aspect-driven differences in herbaceous communities and root strength to shallow soil stability on a representative giant landslide (Xijitan), thereby providing a scientific basis for designing vegetation-based slope protection strategies tailored to the unique geomorphic and ecological conditions of giant landslides in the upper reaches of the Yellow River.

Vegetation is an important element of the ecological barrier and functions to reduce the risk of massive landslides. An important step in guiding ecological conservation and sustainable development in this area is to understand how the vegetation is distributed. The distributions of vegetation types at regional and global scales are largely determined by dominant factors, such as local hydrothermal conditions, as revealed by relevant studies. On small scales of watersheds or communities, topographic factors can change local climatic conditions, leading to changes in vegetation types and thus in determining their distribution patterns (Wang et al. 2011). In reality, the terrain and some related factors are among the most important driving factors for different ecological processes and phenomena (Fang et al. 2004; Campos et al. 2026). Plant distributions are influenced by topographic factors such as altitude, slope direction, position, and steepness, which in turn affect light, temperature, moisture, and soil nutrients (Huang et al. 2016; Wu et al. 2019; Erfanzadeh et al. 2025). Numerous studies have examined how vegetation patterns are shaped by topographic gradients. Among these factors, elevation exerts a direct influence on community structure and species diversity, and the most commonly reported elevational trends are either a monotonic decline or a hump-shaped pattern (Zhang 2019; Di Musciano et al. 2024). Slope aspect plays a fundamental role by modifying local habitat conditions, such as sunlight, temperature, soil water and nutrient availability, and thus strongly constrains where different plant communities can occur (Zhang et al. 2019; Liang et al. 2024). In particular, aspect-driven

differences in solar radiation affect the spatial distribution of soil moisture and nutrients, making slope aspect a key determinant of plant distribution patterns (Li et al. 2019). In addition, slope position, latitude and longitude have also been shown to exert varying degrees of influence on vegetation composition and structure (Li et al. 2019; Guo et al. 2022).

Plant roots are known to enhance soil shear strength and thereby improve the stability of shallow slopes (Hao et al. 2023; Noorasyikin et al. 2023). At the same time, root morphology is strongly regulated by topographic factors, and these morphological traits in turn influence root mechanical indices to varying degrees. For example, Fu et al. (2022) examined the root mechanical properties of *Elymus nutans* on slopes with different aspects and found that plants growing on sunny slopes developed thicker and more robust roots, which effectively increased root tensile strength. Li et al. (2016) performed tensile tests on eight species, including *Artemisia argyi*, *Lolium perenne* and *Festuca elata*, and reported that for *A. argyi* and *F. elata* both root diameter and tensile strength were higher on sunny than on shady slopes. They also showed that tensile strength tended to be greater at mid-slope and slope-battom positions than at the slope top. Qi et al. (2025) investigated *Lespedeza bicolor* along an altitudinal gradient and observed that, with increasing elevation, plants developed shorter and thicker roots in response to low-temperature stress, which was accompanied by enhanced root tensile strength. In addition, Li et al. (2020) found that on slopes with gradients between 40° and 60°, increasing slope angle led to larger main-root diameters but smaller lateral-root diameters, resulting in a significant increase in overall root pull-out resistance.

However, little research has focused on how vegetation is distributed or how the mechanical strength of plant roots plays a role in the giant landslides in the upper reaches of the Yellow River region. To fill this gap, we choose the Xijitan giant landslide in this region as a case study. The goal of this research was to explore the vegetation distribution, the topographic factors that shape plant patterns, and the mechanical strength of the roots of two key herbaceous plants, *Poa araratica* and *Stipa aliena*. Specifically, we aim to: (i) to describe vegetation distribution patterns and the response of aboveground biomass to slope aspect on the Xijitan landslide; (ii) to identify the key topographic factors controlling vegetation distribution and to quantify their relative contributions using principal component analysis (PCA); (iii) to characterise the relationships between root mechanical resistance indices and root diameter for two dominant herbaceous species; and (iv) to elucidate the mechanism by which key topographic factors regulate the mechanical properties of herbaceous roots via their effects on root morphology. The findings of this study provide guidance for selecting and deploying dominant plant species that combine high mechanical strength with regional adaptability, thereby establishing an important theoretical basis for ecological restoration in giant landslide areas of the upper reaches of the Yellow River. Moreover, the implementation of vegetation-based ecological protection measures can effectively reduce sediment input from slopes into the river and help prevent secondary disasters such as collapses and landslides. These outcomes are of significant practical importance for ensuring the safe operation of critical infrastructure, including hydropower stations, in the region.

Materials and methods

Study area

The Xijitan giant landslide is located on the northern bank of the Yellow River in the Guide Basin, northeast of the Qinghai-Tibet Plateau in China (Fig. 1). Its geographical coordinates are approximately 101°24′-101°29′E, 36°2′-36°7′N. This area has a typical plateau continental climate with strong solar radiation and a large diurnal temperature range. The average temperature is 9.03 °C, and the yearly average precipitation is 254.8 mm (Gui 2021). Rainfall occurs most often in the form of occasional heavy downpours, although these occur mainly in the summer months, in the stretch between June and September (Wang et al. 2022).

The total volume of the Xijitan giant landslide is close to 8.4×10^8 m^3 (approximately 65 m thickness × 3,500 m width × 7,200 m length) (Zhao 2016a). It has a maximum altitude of approximately 3150 m, and its front edge extends to the bank of the Yellow River at an altitude of approximately 2220 m (Fig. 1). The rear edge of the landslide scarp is steeply inclined, whereas its middle section at an altitude of approximately 2460–2640 m maintains relatively gentle topography. The sliding body of the landslide measures 5,900 m from the shear outlet to the front edge, suggesting that it is a high-speed, long-distance landslide, as shown in Fig. 2 (Zhao 2015).

Field investigations

In late July 2022, our research group carried out field investigations and collected samples in the area of the Xijitan giant landslide on the basis of altitude, slope, aspect, and slope position. The Xijitan landslide features steep topography with extensive deep tensile cracks and large gullies. In total, 20 sampling locations were laid out along the landslide profile from the rear edge to the front by considering the topographic features (e.g., every section was represented). At each sampling location, 3–6 experimental plots measuring 0.5×0.5 m^2 in size were established via random and equidistant sampling methods. In total, 21 sampling plots were set up at five collection points in front of the landslide, 48 samples were

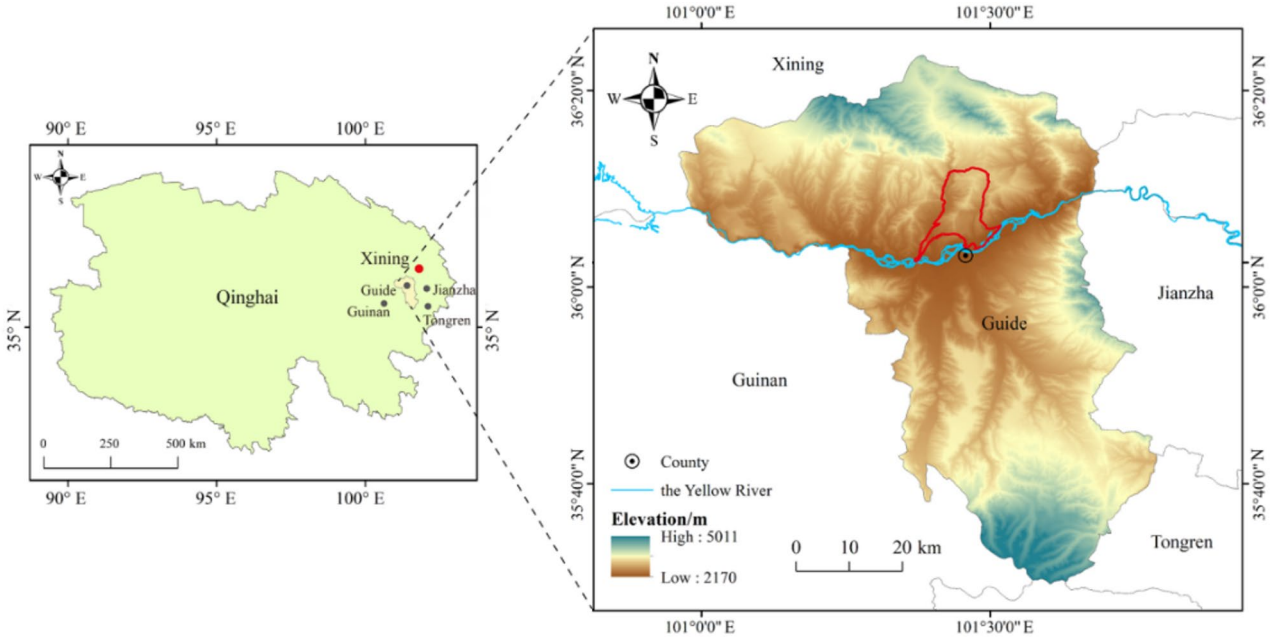


Fig. 1 Location of the study area in Qinghai Province and the terrain in the vicinity of the study area (red polygon) next to the Yellow River

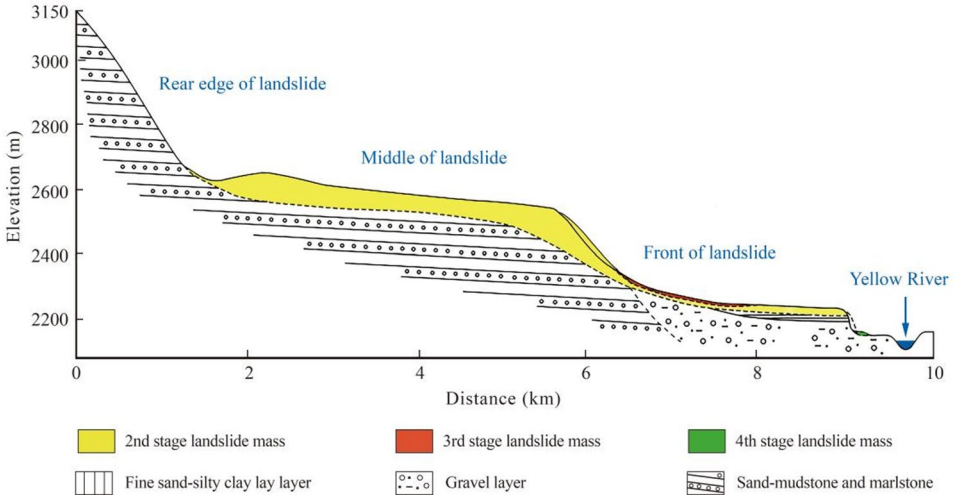


Fig. 2 Profile of the Xijitan giant landslide body

set up at 8 collection points in the middle of the landslide, and 27 samples were set up at 5 collection points at the rear edge of the landslide, resulting in a total of 96 samples collected from the 18 collection points. The layout and location of each collection point in the area are shown in Fig. 3.

Within each sampling plot, several vegetation parameters, such as the coverage in each quadrat of the plot, height, coverage, number of plants, and names, were recorded. Then, different kinds of plants in the quadrat were removed and weighed to determine their fresh biomass. Next, the plant roots were collected by excavating the soil around the plants using the section wall method, and complete roots were placed into a test basin, numbered at the same time, and immediately transported to the laboratory for single-root tensile testing. Finally, the location of each sampling plot was determined using a GPS receiver. Other collected geographic data included altitude, longitude and latitude, slope, and aspect.

Spatial vegetation patterns

The spatial distribution patterns of vegetation within the Xijitan landslide area were analyzed using two ecological indices: the Morisita index, the *F* test and the mean crowding formula (Zhang 1995).

The Morisita index was calculated by using the following formula:

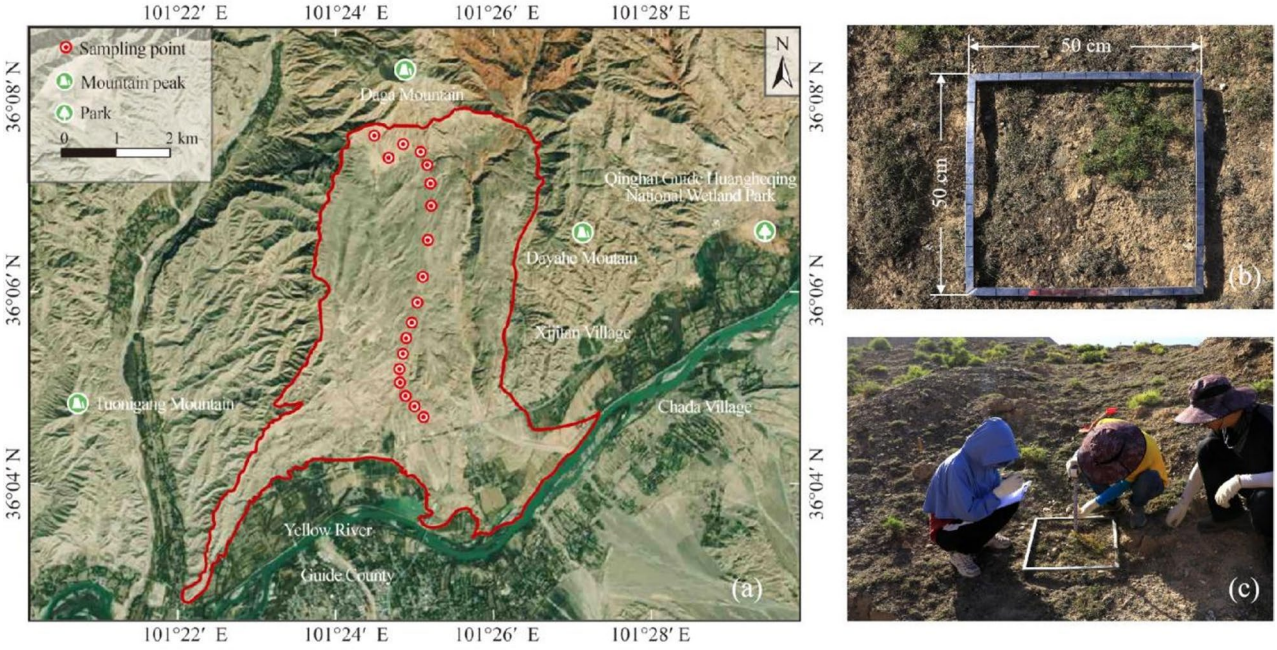


Fig. 3 Distribution of sampling points, sampling quadrats, and their layout in the field. Circle color: section of the landslide body (Zhao et al. 2024)

$$I_\delta = n \times \frac{\sum_{i=1}^{n} X_i(X_i - 1)}{N(N-1)} \tag{1}$$

The *F* test was calculated by using the following formula:

$$F = \frac{I_\delta(N-1) + n - N}{n-1} \tag{2}$$

The mean crowding was calculated by using the following formula:

$$m = \frac{\sum_{i=1}^{n} X_i(X_i - 1)}{\sum_{i=1}^{n} X_i} \tag{3}$$

where N is the total number of plants observed and n is the number of quadrats (in this study, the front of the landslide contains 21 quadrats, the middle of the landslide contains 48, and the rear edge of the landslide contains 27). The number of individual plants present in the i-th quadrat is X_i. When $I_\delta = 1$, the plant population is randomly distributed; when $I_\delta > 1$, the population is cluster distributed; and when $I_\delta < 1$, the plant population is uniformly distributed.

Derivation of topographical factors

On the basis of field survey information on the plant communities of the Xijitan giant landslide, the sample plots were classified according to altitude, landslide location, slope, aspect, and slope position(Li et al. 2019; Zhang et al. 2023; Tian et al. 2021)., as shown in Table 1

Table 1 Standards for dividing the topographical factors in the study area

Topographical factor	Classification	Criteria for the classification
Location of landslide	Front of landslide	2220 ~ 2490 m
	Middle of landslide	2490 ~ 2640 m
	Rear edge of landslide	2620 ~ 3150 m
Slope (°)	Flat slope	0 ~ 5°
	Gentle slope	6 ~ 15°
	Slope	16 ~ 25°
	Steep slope	26 ~ 35°
	Sharp slope	36 ~ 45°
	Risky slope	> 46°
Aspect (°)	Shady aspect	316 ~ 45°
	Semishady aspect	46 ~ 135°
	Sunny aspect	136 ~ 225°
	Semisunny aspect	226 ~ 135°
Slope position	Top of slope	
	Middle of slope	
	Bottom of slope	

Root tensile strength test

For this study, we selected two dominant herb species, *P. araratica* and *S. aliena*, which grow on different slope aspects (sunny and shady slopes) in the middle of the Xijitan giant landslide. Both are grasses with fibrous root systems. To test their root strengths, we carefully washed the soil from the roots of these plants and selected intact

roots that were between 8 and 13 cm long for the tensile strength tests.

We measured the root diameters using a Vernier caliper (with an accuracy of 0.01 mm) by took three measurements per root and averaging them to obtain the final result. The tensile tests were conducted using an HY-0580 electronic universal testing machine (Shanghai Hengyi Precision Instrument Co., China). The testing setup was as follows: a standard distance of 20 mm between fixtures, with a testing speed of 20 mm per minute. During the tests, we recorded the point at the center between the two fixtures where the root broke, and the data from 60 roots were collected for each group (Fig. 4).

The tensile strength of a single root T in MPa was determined by using the following formula (Zhu et al. 2008):

$$T = \frac{4F}{\pi D^2} \tag{4}$$

where F is the tensile resistance of a single root (N) and D is the average diameter of the root (mm).

The ultimate elongation rate of a single root was determined by using the following formula (Zhu et al. 2008):

The following formula helps us determine how much the root is supposed to stretch before it breaks (the ultimate elongation rate) (Zhu et al. 2008):

$$\varepsilon_{\max} = \frac{\Delta L_{\max}}{20} \tag{5}$$

where $\varepsilon_{\max}$ is the elongation limit of a single root (%) and where $\triangle L_{\max}$ denotes the increase in root length in the limit state.

Statistical analysis

Through tensile root testing, we quantitatively compared the mechanical properties of two herbaceous plans using one-way analysis of variance, examining aspect-dependent variations in the mean single-root tensile resistance, tensile strength, and ultimate elongation rate. We used unconstrained principal component analysis (PCA) to identify the key topographic factors that influence vegetation communities. Several quadrats were located in relatively low-lying, moist microsites where vegetation cover and aboveground biomass were much higher than in the rest of the landslide area. Because these special habitats could bias the multivariate analysis and are not representative of the typical slope conditions, 21 such quadrats were excluded from the PCA. Consequently, 75 representative quadrats were retained for the ordination analysis. In these quadrats, the response variables included the number of species, fresh biomass weight, average plant height, coverage, and number of plants, while the supplementary variables consisted of landslide position, altitude, slope, aspect, and slope position. These were used to construct a 75 × 5 topographic factor matrix and a 75 × 5 quadrat species matrix for the PCA ordination analysis.

Topographic factors such as landslide location, slope direction, and slope position were converted into numerical values for PCA via methods from previous studies (Li et al. 2019; Zhang et al. 2023; Feng et al. 2008). Specifically, landslide location along the longitudinal profile from the rear edge to the front was assigned integer values from 1 to 3 (rear edge = 1, middle = 2, front = 3). Similarly, Slope position along the vertical profile was coded from top to bottom (top of slope = 1, mid-slope = 2, bottom of slope = 3). Slope aspect was grouped into four categories based on relative solar radiation, with higher values indicating greater sunlight exposure (1 = shady, 2 = semi-shady, 3 = semi-sunny, 4 = sunny). In contrast, slope steepness and elevation were treated as continuous variables using field-measured values.

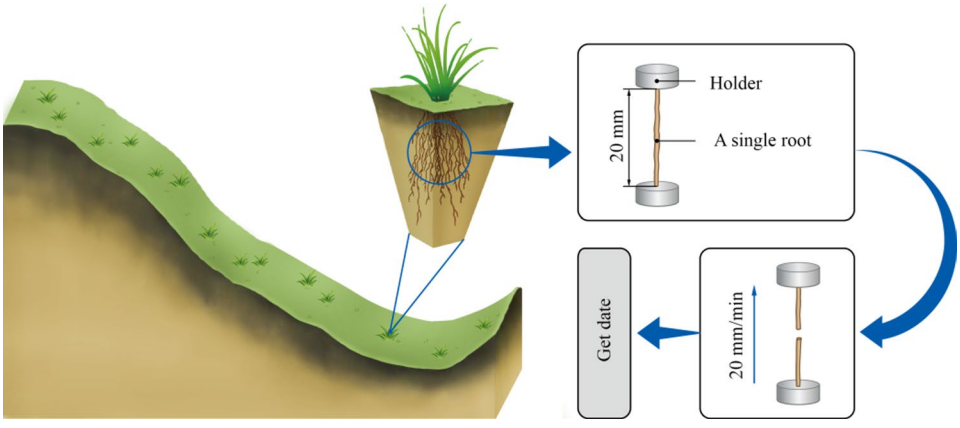


Fig. 4 Schematic diagram illustrating a tensile test of a single-root between the holders

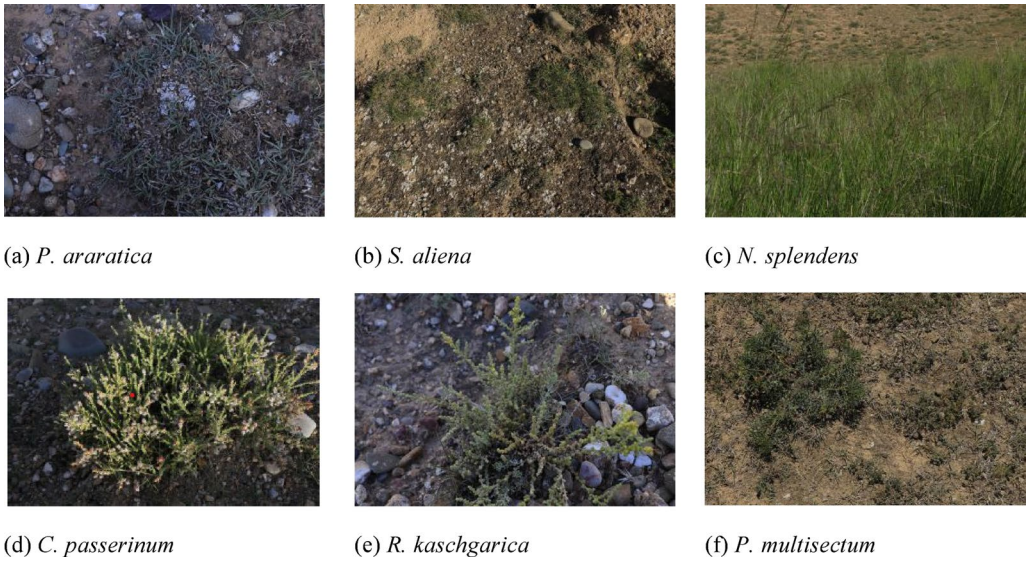
Results and analysis

Based on the research objectives, this section first analyzed the distribution patterns of plant communities and the response of aboveground biomass to slope aspect in Xijitan. It then employed principal component analysis (PCA) to identify the key topographic factors influencing vegetation distribution. Finally, a quantitative analysis was conducted to examine the effects of slope aspect on root diameter and mechanical indices of the root systems of two dominant herbaceous species.

Distribution characteristics of plant communities

Field investigations revealed that the overall vegetation coverage in the study area was relatively low and was composed mainly of herbaceous plants and shrubs, with shrubs and few trees scattered amid the herbaceous plants. In total, we identified 53 plant species from 41 genera and 16 families. The Gramineae family was the most common, accounting for 24.53% of the total plant population, followed by the Asteraceae family, which accounted for 20.75%. The main herbaceous plant types are *Achnatherum inebrians*, *S. aliena*, *P. araratica*, *Neotrinia splendens*, *Potentilla multifida*, *Sibbaldianthe bifurca*, and *Aster altaicus*. The shrubs mainly consisted of *Caragana roborovskyi*, *Caroxylon passerinum*, *Reaumuria kaschgarica*, *Lespedeza davurica*, and *Ajania fruticulosa*. Figure 5 shows the state and appearance of some herbaceous plants in the study area.

The steep surface at the rear edge of the Xijitan landslide is not conducive to the colonization of plants, so its vegetation coverage is rather low, ranging from only 8 to 30%. The main constructive species of the plant community include *P. araratica* and *S. aliena*, with accompanying herbs such as *Peganum multisectum*, *Convolvulus ammannii*, *A. altaicus*, *Neopallasia pectinata* and *N. splendens*, as well as shrubs, such as *C. roborovskyi*, *C. passerinum*, and *A. fruticulosa*. In the landslide depression, the terrain surface is flat with dry cracks, and the vegetation coverage is between 12 to 45%, 12 to but is not spatially uniform. The main constructive species are *P. multisectum*, *N. splendens*, and *Leymus secalinus*, accompanied by *A. inebrians, Carex myosuroides*, and other plants. The slope section in the middle of the landslide area is relatively flat, and the vegetation coverage is between 10 and 35%. The main constructive species are *P. araratica*, *S. aliena*, *A. inebrians and Stipa breviflora*. The companion species are *S. bifurca*, *A. altaicus*, *Oxytropis ochrocephala*, *P. multisectum*, and others. The low-lying area in the middle of the landslide has high vegetation coverage ranging from 60 to 96%, with the main constructive species being *N. splendens*, *A. inebrians*, and *C. myosuroides*, accompanied by *Ixeridium gramineum*, *P. multifida*, *Oxybasis glauca*, *N. pectinata*, and *P. multisectum*. The front of the landslide is crisscrossed with gullies, and the vegetation coverage ranges from 5 to 24%. The main constructive species are *P. araratica*, followed by *N. splendens*, *S. aliena*, *P. multisectum*, and *A. altaicus*. The vegetation types and distributions in the study area are shown in Fig. 6 and Table 2. The distribution pattern of the number of plant species followed the trend slope section in the middle of the landslide > low-lying area in the middle of the landslide > front of the landslide > rear edge of the landslide > landslide depression. The vegetation coverage is highest in the low-lying area of the middle landslide section, followed by the landslide depression, middle slope section, rear edge, and lowest at the front of the landslide.



(a) *P. araratica* (b) *S. aliena* (c) *N. splendens*

(d) *C. passerinum* (e) *R. kaschgarica* (f) *P. multisectum*

Fig. 5 State and appearance of some herbaceous plants in the study area

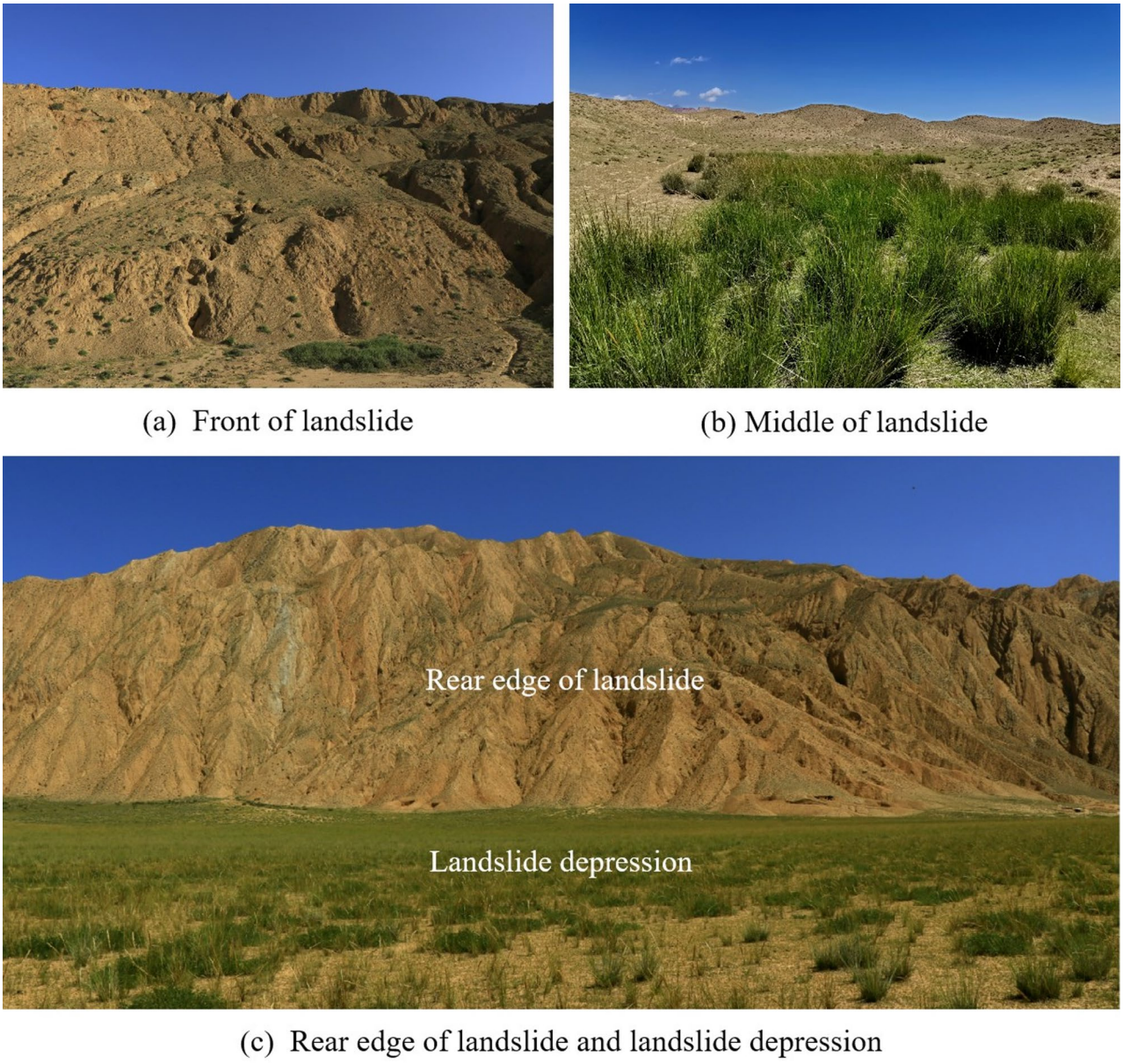


Fig. 6 Vegetation growth and distributions in different sections of the landslide

Table 2 The distributions of plants in various locations in the study area

Location of landslide	vegetation coverage (%)	Dominant species
Rear edge of landslide	8 ~ 25	*P. araratica*, *S. aliena*
Depression of landslide	15 ~ 65	*P. multisectum*, *N. splendens*, *L. secalinus*
Slope section in the middle of landslide	10 ~ 55	*P. araratica*, *S. aliena*, *A. inebrians and S. breviflora*
Low-lying area in the middle of landslide	60 ~ 96	*N. splendens*, *A. inebrians*, and *C. myosuroides*
Front of landslide	5 ~ 45	*P. araratica*

Table 3 Vegetation distribution patterns and aggregation intensities of the Xijitan giant landslide

Location of landslide	Morisita index			Mean crowding
	I_δ	*F*	Pattern	
Rear edge of landslide	1.463	41.828	C	124.168
Middle of landslide	1.970	112.097	C	220.970
Front of landslide	1.516	33.937	C	92.178

C is the cluster distribution

The Morisita index at different locations of the Xijitan giant landslide is $I_\delta > 1$ (Table 3), indicating that the spatial distribution pattern of the vegetation is generally clustered. The values of the Morisita index are ranked as follows: middle of the landslide > front of the

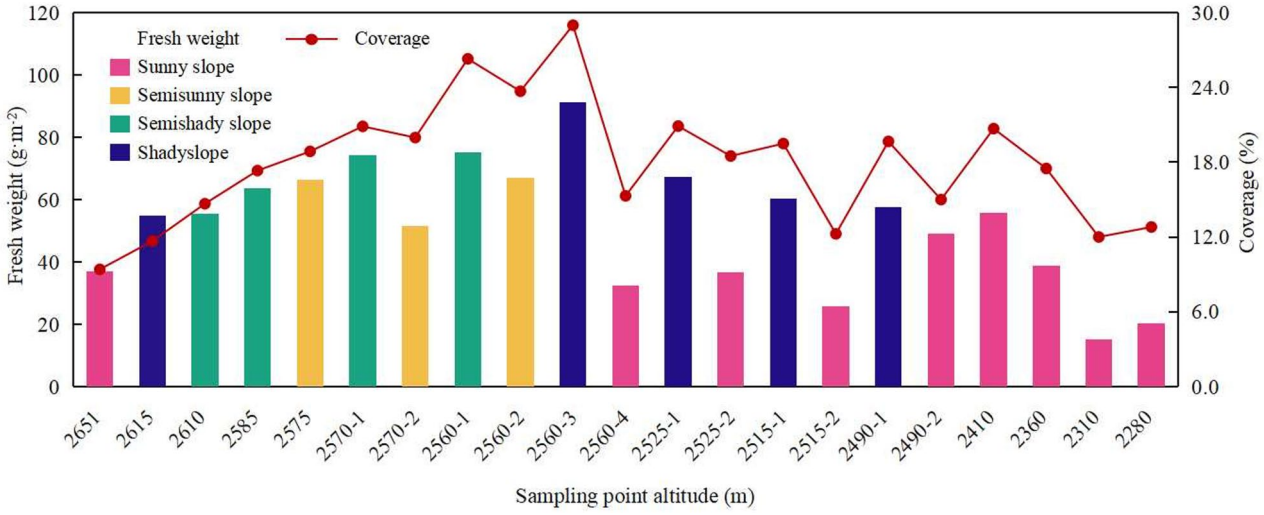


Fig. 7 Aboveground biomass amounts at different points in the study area

Table 4 PCA ordination results of the plant community and topographic factors associated with the Xijitan giant landslide

Statistic	Axis 1	Axis 2
Eigenvalues	0.68	0.13
Plant community distribution and topographic factors cumulative explained fitted variation (%)	67.74	80.66
Plant community distribution and topographic factors correlation	0.53	0.54
All eigenvalue	1	

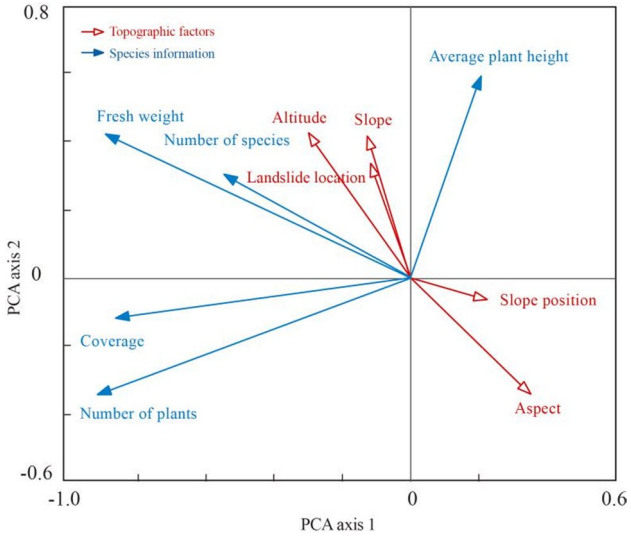


Fig. 8 Principal component analysis results of the plant distributions in relation to topographic factors

landslide > rear edge of the landslide, average degree of crowding is the middle of the landslide > rear edge of the landslide > front of the landslide. The degree of clustering and average degree of crowding in the middle of the landslide are the highest, whereas those in the front of the landslide are the lowest, and the degree of soil erosion is relatively high.

The herbaceous aboveground biomass on the Xijitan giant landslide shows a regular spatial distribution, as shown in Fig. 7. It decreases from an altitude of 2560 m toward both sides or gradually decreases from the middle of the landslide toward its back and front edges. At the same landslide location, the higher the aspect's exposure to sunlight is, the lower the fresh biomass weight and plant coverage. For the four different slope aspects, the fresh biomass weight and coverage of herbaceous plants occur in descending order as follows: shady slope 2560–3 (91.364 $g{\cdot}m^{-2}$, 29.0%) > semishady slope 2560–1 (75.12 $g{\cdot}m^{-2}$, 26.3%) > semisunny slope 2560–2 (66.96 $g{\cdot}m^{-2}$, 23.7%) > sunny slope 2560–4 (32.52 $g{\cdot}m^{-2}$, 15.3%).

Correlations between the plant community and topographic factors

The PCA ordination results of the plant community and topographic factors indicate that the first ordination axis cumulatively explains 67.74% of the variations among the samples, whereas the second axis cumulatively explains 80.66% (Table 4). There is a significant correlation between the first and second ordination axes and the topographic factors, with eigenvalues of 0.68 and 0.13, respectively. The first and second ordination axes can better reflect the relationships between the plant community in the landslide area and topographic factors and have biological statistical significance.

As shown in Fig. 8, the slope position and aspect have positive correlations with the first ordination axis, with the aspect showing a greater correlation. The second ordination axis shows the strongest correlation with altitude. The first ordination axis mainly explains the variations in plant community distribution patterns along the

Table 5 Results of single-root tensile tests for two herbaceous plants from different slope aspects in the study area

Plant growth position	Herbal name	Average root diameter (mm)	Average tensile resistance of single root (N)	Average tensile strength of single root (MPa)	Ultimate elongation rate of single root (%)	Samples number (No.)
Sunny slope	*P. araratica*	0.48 ± 0.08 a	4.52 ± 1.01 b	25.77 ± 5.04 c	17.62 ± 6343 c	60
Shady slope	*P. araratica*	0.47 ± 0.08 a	4.10 ± 0.87 c	24.38 ± 5.42 d	21.18 ± 4.32 b	60
Sunny slope	*S. aliena*	0.47 ± 0.09 a	5.03 ± 1.17 a	30.52 ± 7.17 a	17.39 ± 5.93 c	60
Shady slope	*S. aliena*	0.46 ± 0.09 a	4.60 ± 1.16 b	28.72 ± 7.68 b	24.59 ± 7.99 a	60

Table 6 Fitting relationships between the single-root tensile resistances, tensile strengths and root diameters of two herbaceous plants on different slope aspects

Plant growth position	Plant name	Fitted equation of single root tensile resistance and root diameter	Goodness of fit (R^2)	Significance level	Fitted equation of single root tensile strength and root diameter	Goodness of fit (R^2)	Significance level
Sunny slope	*P. araratica*	$y = 1.5069e^{2.2539x}$	0.7223	0.859**	$y = 12.871x^{-0.894}$	0.6073	-0.766**
Shady slope	*P. araratica*	$y = 1.4543e^{2.1619x}$	0.6365	0.798**	$y = 11.07x^{-0.996}$	0.6306	-0.763**
Sunny slope	*S. aliena*	$y = 2.0907e^{1.8267x}$	0.6044	0.794**	$y = 12.762x^{-1.081}$	0.6782	-0.767**
Shady slope	*S. aliena*	$y = 1.6458e^{2.1599x}$	0.6315	0.785**	$y = 12.32x^{-1.025}$	0.6562	-0.791**

**: $P < 0.01$

aspect gradient, whereas the second ordination axis predominantly accounts for the altitudinal distribution patterns of the vegetation community.

Aspect is the main factor that affects the distribution of the plant community and is negatively correlated with the fresh biomass weight, number of species, and vegetation coverage. That is, the more sunlight an aspect receives, the lower its fresh biomass weight, species diversity, and vegetation coverage are, and vice versa. Altitude and slope exert significant influences on plant distribution patterns, whereas landslide location and slope position have relatively weaker effects on the composition of the vegetation community.

Root mechanical properties of two herbaceous plants on different slope aspects

As shown in Table 5, under the same growth conditions, the average single-root tensile resistance, tensile strength, and ultimate tensile strain rate of *S. aliena* were 4.60 N, 28.72 MPa, and 24.92%, respectively. These values were greater than the corresponding values for *P. araratica*, which were 4.10 N, 24.38 MPa, and 21.18%, respectively.

Slope aspect influences habitat conditions (e.g. moisture and nutrient distribution), which in turn affects root traits. In our study area, both species showed slightly larger mean root diameters on sunny slopes than on shady slopes (for *P. araratica*: 0.48 mm vs. 0.47 mm; for *S. aliena*: 0.47 mm vs. 0.46 mm). Although these differences are small in absolute terms, they are consistent with the expectation that drier, sunnier slopes select for thicker roots in response to altered water and nutrient availability (Gangurde et al. 2025).

In single-root mechanical properties exhibit a consistent response pattern to slope aspect. For both species, single-root tensile resistance and ultimate elongation rate vary significantly between sunny and shady slopes, whereas tensile strength does not differ significantly. For *P. araratica*, tensile resistance on sunny slopes is 1.10 times that on shady slopes, while the ultimate elongation rate is reduced to 80.03% of the shady-slope value. For *S. aliena*, the corresponding ratios are 1.06 for tensile resistance and 70.47% for ultimate elongation. The absence of significant differences in tensile strength suggests that these species may adjust root mechanical behaviour not primarily by altering the intrinsic strength, but through subtle changes in root diameter and internal microstructure. We now explicitly interpret this as evidence that slope aspect indirectly modulates root mechanics by altering habitat conditions and thereby root morphology.

The relationship between single-root tensile resistance (y) and root diameter (x) fits an exponential model ($y = ae^{bx}$) with $R^2 > 0.6$ and $p < 0.01$ for both species (Table 6), indicating a strong, size-dependent increase in resistance. *P. araratica* on sunny slopes shows the highest exponential coefficient ($b = 2.2539$), implying that even modest increases in root diameter under high-light, relatively water-limited conditions can markedly enhance tensile resistance, consistent with the trend shown in Fig. 9. In contrast, the exponential coefficients for *S. aliena* differ less between aspects (sunny: $b = 1.8267$; shady: $b = 2.1599$), pointing to a more stable mechanical response across contrasting habitats. (Fig. 10).

The relationship between tensile strength (y) and root diameter (x) fits a power-law model ($y = cx^d$, $R^2 > 0.6$, $p < 0.01$). The negative exponents (d ranging from − 1.081

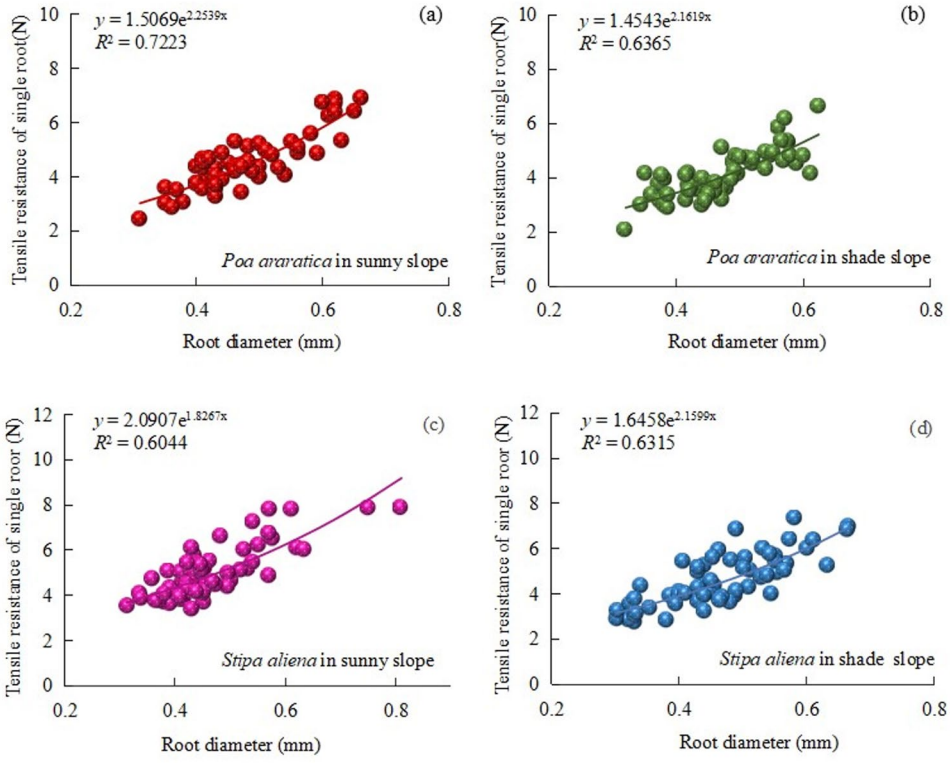


Fig. 9 Relationships between single-root tensile resistance values and root diameters of two herbaceous plants on different slope aspects

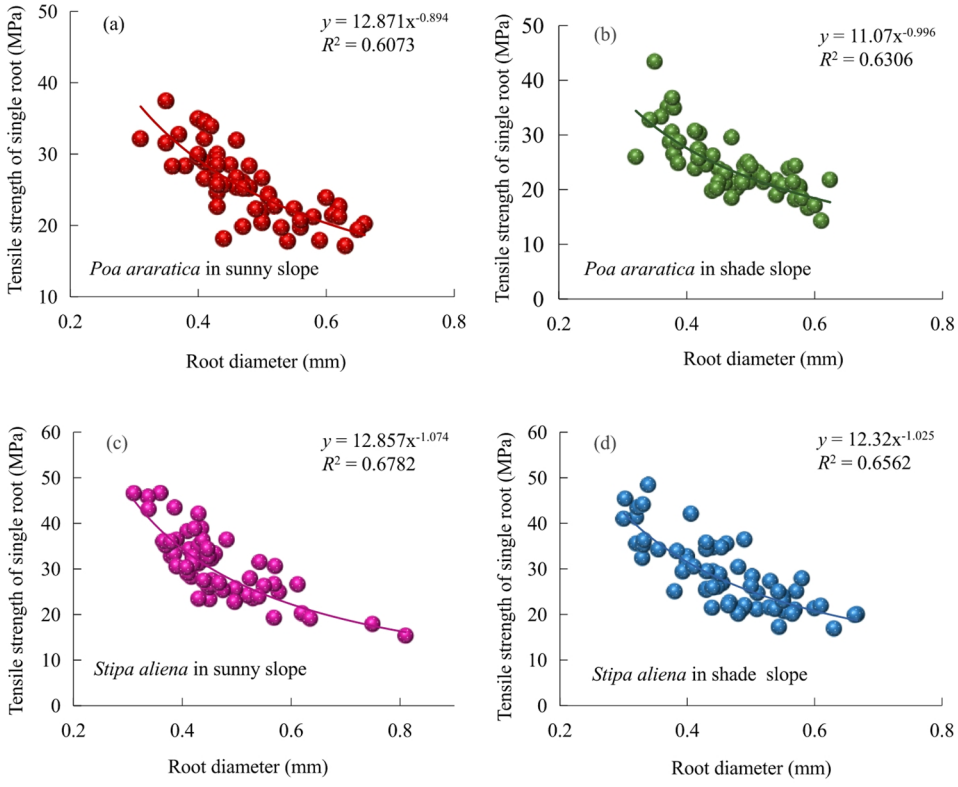


Fig. 10 Relationship between single-root tensile strengths and root diameters of two herbaceous plants on different slope aspects

to – 0.894) indicate a clear inverse relationship, i.e. tensile strength decreases as root diameter increases. This pattern is consistent with a trade-off between root thickening and stress-bearing capacity per unit cross-sectional area. From the goodness-of-fit perspective, the model for *P. araratica* on sunny slopes ($R^2 = 0.7223$) shows the best fit, reflecting a particularly tight coupling between root morphology and mechanical resistance under drought-like conditions. In comparison, *S. aliena* displays similar R^2 values on sunny (0.6044) and shady (0.6315) slopes, further supporting the idea that its root system exhibits relatively stable mechanical behaviour across different slope aspects.

Discussion

This study investigates the Xijitan giant landslide in the upper reaches of the Yellow River, combining field vegetation surveys and with laboratory single-root tensile tests on two dominant herbaceous species (*Poa araratica* and *Stipa aliena*), it explored the influence of topographic factors—particularly slope aspect—on the distribution of herbaceous vegetation and the mechanical properties of root systems. The following content will analyze and discuss the influence of slope aspect on herbaceous vegetation distribution, root morphology and mechanical properties, as well as its implications for enhancing shallow slope stability, based on existing theories and findings from this study.

Effects of topographic factors on plant distribution patterns

This study identified, using principal component analysis (PCA), that aspect is the main topographic factor driving community variations in the Xijitan giant landslide. In the case of the same altitude, slope position, and no significant difference in slope, the higher the amount of sun the slope received, the lower the aboveground biomass was; that is, the fresh weight and coverage of the ground were as follows: shady slope > semishady slope > semisunny slope > sunny slope, and the aboveground biomass was significantly greater on shady slopes than on sunny slopes, This is consistent with the results of Zhang et al. (Zhang et al.2025).Owing to the relatively large numbers of sunshine hours on sunny slopes, their surface temperatures are high, the evaporation is strong, and the soil moisture evaporates, causing the vegetation coverage to be relatively low. In contrast, the sunshine durations on shady slopes are relatively short, soil moisture is lost at a slower rate, and the vegetation coverage is relatively high.

This study revealed that slope and altitude are the two topographic factors that significantly impact the distribution of herbaceous plants (Li et al. 2019; Peng et al. 2010; Li al. 2022). With increasing altitude, the slope gradient gradually increases, leading to changes in the soil temperature and moisture content. Species selection, resource competition, and habitat changes caused by water and heat differences due to topographical spatial heterogeneity are important factors that affect the structure of the plant community (Zhang et al. 2023).

Effects of topographic factors on root morphology and mechanical properties of the plant roots

Topographic factors affect root morphology by changing plant habitat conditions. Slope aspect is a key topographic factor shaping microclimatic and edaphic conditions on mountain slopes, particularly temperature, soil moisture and nutrient availability, and thereby influences how plant communities are assembled and where they can persist (Xu et al. 2016; Hou et al. 2014). On sunny slopes, prolonged exposure to solar radiation elevates air and soil temperatures, enhances evaporation and transpiration, and often subjects plants to chronic water deficit. By contrast, shady slopes tend to retain more soil moisture but receive less direct radiation. Under water-limited conditions on sunny slopes, stomatal closure reduces gas exchange and suppresses photosynthesis and tissue growth, ultimately leading to lower total biomass production.These habitat contrasts are reflected in plant morpho-physiological responses (Fig. 11).

Our results are in line with this general picture. For both *P. araratica* and *S. aliena*, mean root diameter was slightly but consistently larger on sunny than on shady slopes. Plants tend to reduce root length and fine-root density but increase the proportion of coarse roots to improve access to deep or patchy water sources (Zhao et al. 2023). This pattern agrees with previous findings that root diameters are typically larger on sunny slopes than on shady slopes (Hultine et al. 2020; Wang et al. 2021). In the herbaceous plants, root diameter exhibited an exponential relationship with tensile resistance, whereas it showed a power-law relationship with tensile strength. Consequently, herbaceous roots on sunny slopes not only exhibit larger diameters but also higher single-root tensile strength than those on shady slopes, indicating that slope aspect modifies root morphology via habitat filtering and, in turn, affects root mechanical properties and the capacity of vegetation to mechanically stabilise shallow soils (Gangurde et al. 2025).

Effects of plant roots on the stability of shallow soil mass on the Xijitan giant landslide

Vegetation can not only affect the ecological environment but also play a significant role in slope protection. This role mainly occurs in two ways: plant stems and leaves influence water movement (the hydrological effect) and through the physical support and anchoring provided by the roots (the mechanical effect) (Feng et al. 2020).

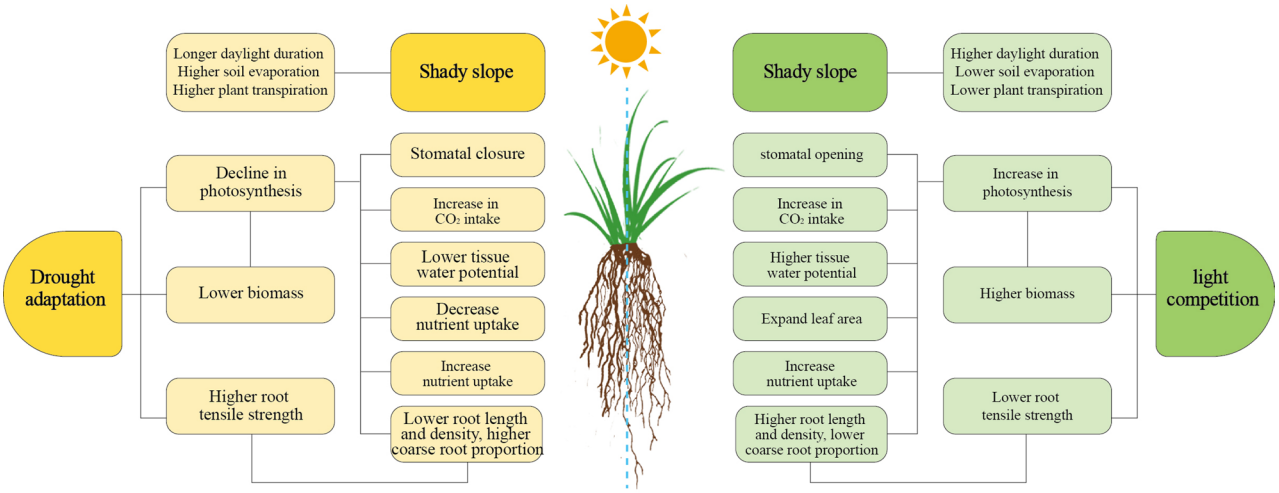


Fig. 11 Effects of slope aspect on morpho-physiological responses in plants (adapted from Song et al. 2026)

Under rainfall, rainwater is first intercepted by vegetation, and the rainwater not intercepted infiltrates the soil and forms surface runoff. The vegetation cover on slopes significantly reduces the soil water content and pore water pressure through multiple mechanisms, including precipitation interception by plant canopies, water absorption through root systems, and transpiration processes. It can also weaken raindrop impact erosion and intercept suspended solids such as sediment, thus effectively slowing the formation of slope surface runoff (Wang et al. 2013). Correspondingly, under conditions with no rainfall, a hydraulic redistribution process occurs. That is, when the water level in the soil is greater than the water within the roots, it flows from the soil to the roots. Conversely, water moves from the roots to the soil (Nadezhdina et al. 2010). The underground root systems of plants enhance the structural stability of slope soil through three fundamental mechanical effects: anchoring, tensioning, and reinforcement (Xu et al.,2021 ; Wu et al. 2014) (Fig. 12). Thus, plant roots not only significantly increase the strength of shallow soil on slopes but also effectively prevent and control soil and water loss, grassland degradation, and shallow landslides. The synergistic action of these mechanisms effectively mitigates surface runoff and soil erosion in landslide-prone areas, thereby providing sustained soil and water conservation and enhancing shallow slope stability.

Herbaceous root systems play an important role in reinforcing shallow slope soil by enhancing its shear strength and thereby improving the stability of the superficial layer. In the Xijitan landslide, roots of *P. araratica* and *S. aliena* form an interwoven network within the upper soil, and during shear deformation this network mobilises tensile resistance that counteracts soil displacement, effectively increasing the shear strength of the root-soil composite (Zhang et al. 2025a, b; Wang et al. 2024).

The additional shear strength provided by roots has often been evaluated using the classical Wu-Waldron Model (WWM), which offers an analytical framework for quantifying the contribution of roots to soil reinforcement (Thomas et al. 2010).

$$\Delta S_r = (\cos\theta \tan\varphi + \sin\theta) \sum_{i=1}^{n} t_{ri} \left(\frac{A_r}{A}\right) \quad (6)$$

In Eq. (7), ΔS_r denotes the root-induced increase in soil shear strength (MPa), θ represents the shear deformation angle of the root system, ϕ is the internal friction angle of the composite, t_{ri} refers to the tensile strength (MPa), is the ratio of root cross-sectional area to soil cross-sectional area on the cross section of root-soil composite, and n is the number of roots intersecting the shear plane (roots).

As described by the Wu-Waldron Model (WWM), a positive correlation exists between root tensile strength and the enhancement of soil shear strength, indicating that greater tensile strength corresponds to a higher soil-reinforcement capacity. This relationship is consistent with the findings of Zhao et al. (2016b) and Shen et al. (2021). Under tensile loading, roots mobilise friction along the root-soil interface and generate reinforcement and traction effects that jointly resist soil deformation (Zhang et al. 2025).

As shown in Table 5, the average single-root tensile strength of *P. araratica* and *S. aliena* on the sunny slope was 25.77 MPa and 30.52 MPa, respectively, compared with 24.38 MPa and 28.72 MPa on the shady slope. These values suggest that, all else being equal, roots on sunny slopes have a somewhat greater potential to contribute

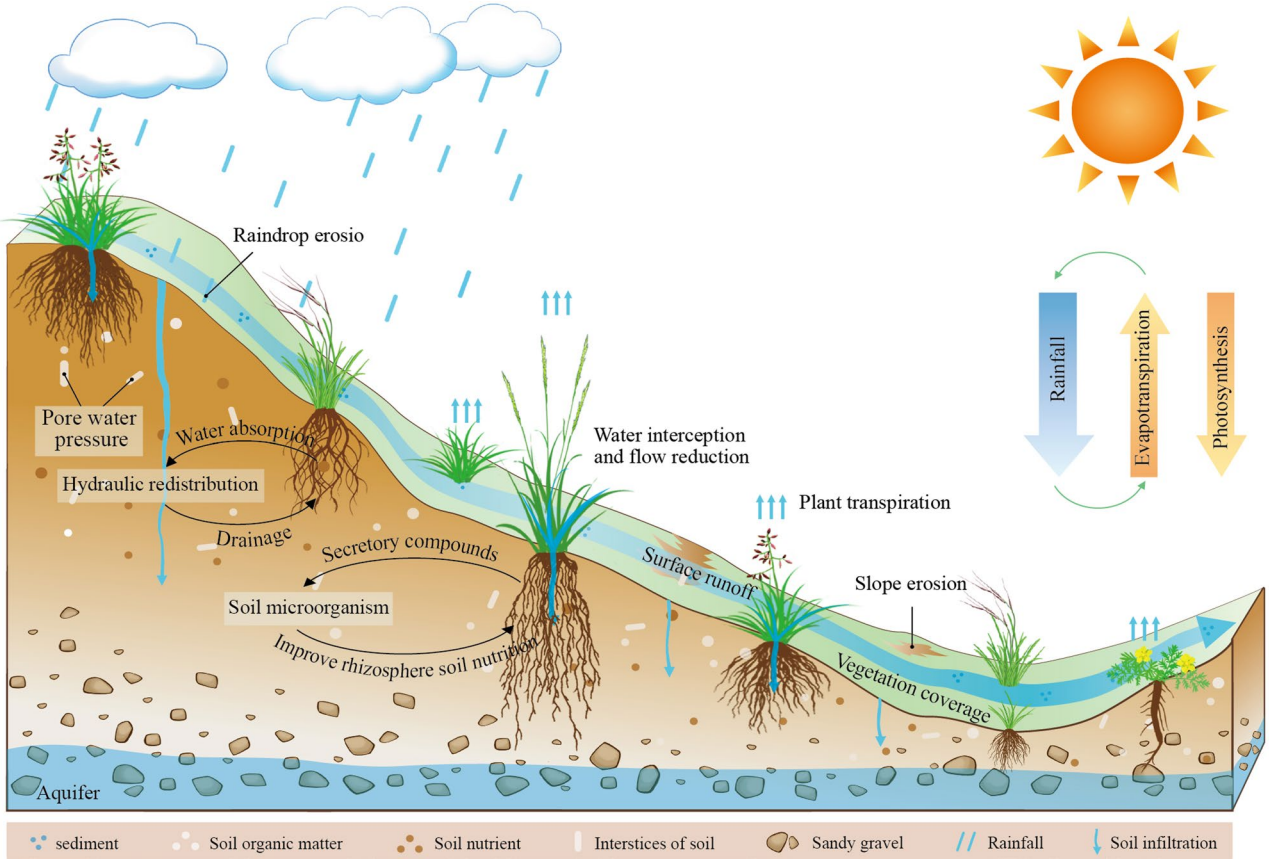


Fig. 12 Coupling process of slope, vegetation, and roots on the surface of the Xijitan giant landslide

to shear strength in the shallow soil layer than those on shady slopes.

Although the explicit quantification of ΔSr using the WWM is beyond the scope of the present study, our measurements provide the key mechanical parameters required by the model and thus lay the groundwork for future analyses of herbaceous root reinforcement on the Xijitan landslide. In subsequent work, we plan to combine root mechanical data, root distribution information and the Wu-Waldron Model framework to estimate the additional shear strength contributed by *P. araratica* and *S. aliena* on sunny and shady slopes, and to more comprehensively assess their role in enhancing shallow soil stability in this area.

Slope aspect-driven root mechanical response mechanisms and their significance for ecological slope protection

In the study area of the Xijitan landslide, vegetation cover is notably sparse and soil erosion is pronounced. For ecological vegetation restoration and slope reinforcement in this area, it is necessary to comprehensively consider the impact of site conditions on the long-term survival and growth of plant roots. Soil moisture is the primary factor governing plant distribution and growth in the study area (Zhao et al. 2024). Additionally, variations in hydrothermal conditions and soil nutrients across slope aspects create distinct microhabitats. These differentiated microhabitats thereby lead to divergent plant community compositions between sunny and shady slopes. Consequently, root mechanical properties also vary significantly among species adapted to these contrasting environments. For example, the root diameter of *P. araratica* growing on sunny slopes was 0.48 mm, and that of *S. aliena* was 0.47 mm; under the corresponding conditions, the single-root tensile strength of Stipa aliena (30.52 MPa) was higher than that of *P. araratica* (25.77 MPa). In addition, the root morphology and mechanical properties of the same species exhibited marked differences under the contrasting microhabitat conditions of different slope aspects. For example, the root diameter of *S. aliena* was 0.47 mm on sunny slopes and 0.46 mm on shady slopes. Correspondingly, its single-root tensile strength on sunny slopes (30.52 MPa) was higher than that on shady slopes (28.72 MPa). Root mechanical properties differentiate among herbaceous species within a given slope aspect and show mechanical adaptation in response to varying slope-aspect microhabitats. The interwoven root systems of different herbaceous species create a pervasive network in the soil. This root-soil composite structure strengthens the

slope primarily through root reinforcement, leading to improved soil shear resistance.

Slope aspect shapes the mechanical properties of herbaceous plant roots by modifying microhabitat conditions. This mechanistic serves as a practical guide for designing vegetation-based slope protection at the Xijitan landslide. In the ecological restoration of slope vegetation, reasonable species screening and configuration should be carried out according to the micro-habitat characteristics of different slope directions, combined with the mechanical properties and ecological adaptability of plant roots, so as to give full play to the role of plant roots in strengthening slope soil, so as to improve the shallow stability of slope.

Conclusion

(1) The Xijitan giant landslide is dominated by herbaceous plants, with sporadic shrubs and very few trees. The spatial vegetation distribution shows an aggregated distribution. The degree of clustering and average degree of crowding in the middle of the landslide are the highest, whereas those in the front of the landslide are the lowest, and the degree of soil erosion is relatively high.

(2) Slope aspect is the main topographic factor driving the variations in the plant community in the study area. The above-ground biomass of herbaceous plants indicates that the more sunny the slope is, the lower the fresh weight and coverage. To some extent, slope aspect affects the tensile strength index of individual herbaceous plant roots, with different slope aspects showing significant zonal differences in single-root tensile resistance and the ultimate elongation rate of single roots. On sunny slopes, the tensile resistance of single roots of *P. araratica* and *S. aliena* was greater than on shady slopes, and the ultimate elongation rate of single roots was the opposite.

(3) Increased vegetation coverage on the Xijitan giant landslide can be achieved by planting dominant herbaceous plants on slopes, such as sunny slopes with lower vegetation coverage, especially the areas with the most severe soil erosion at the front of the landslide. On the one hand, these changes can prevent and control soil erosion and contribute to ecological restoration. On the other hand, the occurrence of geological disasters such as debris flows and shallow landslides can be scientifically prevented and controlled through the mechanical effects of plant roots.

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Author contributions
JZ: Writing—original draft, investigation, data curation and Formal analysis. GX, HL and JF: Data curation. CL: Formal analysis, Review. XH: Project administration, funding acquisition. XL and YZ: Resources, Identifying plants.

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Data availability
Data will be made available on request.

Declarations

Competing interests
The authors declare no competing interests.

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