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The influence of plant root system architectural properties upon the stability of loess hillslopes, Northeast Qinghai, China

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Abstract: To investigate the influence of root system architectural properties of three indigenous (cold-adapted) shrubs on the hillslope stability of loess deposits in the Xining Basin, northeast part of Qinghai-Tibet Plateau (QTP), indoor direct shear tests have been conducted on the remolded rooted soil of three shrubs. Test results show that root system architectural indices (root area ratio (RAR), root length density (RLD) and root density (RD)) of the shrubs decline with depth and the relationship between RAR, RD and depth is exponential, while a power relationship describes the relationship between RLD and depth. The cohesion force of remolded rooted soil for the shrubs initially increases with depth, but it then demonstrates a slightly decreasing trend, which can be described with a power relationship. Power relationships also describe relationships between cohesion force and RAR, RLD and RD for the shrubs. As the growth period increases from 10 to 17 months, the incremental increase in RAR is 48.32% ~ 210.25% for *Caragana korshinskii* Kom and 0.56% ~ 166.85% for *Zygophyllum xanthoxylon* (Bunge) Maxim. This proportional increase is notably larger than that for RLD and RD. The increment in RAR is marginally greater for *C. korshinskii* than it is for *Z. xanthoxylon*. Correspondingly, the cohesion force incremental rates of remolded rooted soil for *C. korshinskii* and *Z. xanthoxylon* are 12.41% ~ 25.22% and 3.45% ~ 17.33% respectively. Meanwhile, as root content increases, the contribution by roots to cohesion force increases

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markedly until a threshold condition is reached.

Keywords: Cold region; Semiarid region; Soil reinforcement; Hillslope stability; Root system architectural indices; Plateau

Introduction

Vegetation removal and revegetation programmes have a significant influence upon soil erosion and sediment flux. These influences are especially prominent in semiarid environments such as the highly dissected loess landscapes of northwestern China. Loess deposits in China extend over an area of 6.3×10^5 km^2 (Xu et al. 2007; Zhang 1993). Vegetation removal over the past centuries has triggered extensive gully system development, in many instances cutting through deposits that are several hundred meters thick (Zhu 1956; Wu and Liu 2000; Zheng 2006). Recurrent hillslope failures via shallow landslide activity have accompanied channel network expansion. As a result, soil erosion and shallow landslides are significant geological hazards in this region.

Loess deposits in the Xining region of northeastern Qinghai, at the western margin of the Loess Plateau, typically extend 100 ~ 300 m thick (Wang and Teng 1983; Li and Nie 1999; Li et al. 1999). Due to rapid population growth, urbanization and infrastructure development (especially expansion of the road and rail network), geological hazards like water and soil loss, shallow landslides and so on occur frequently, and the accompanied damages become more and more serious. Relevant studies (Wu 1976; Waldron 1977; Hu et al. 2013) show the slope protection by vegetation is an effective way to increase shear strength of slope soil and slope stability, thus reducing these geological hazards.

Hillslope protection by plants is achieved by two primary mechanisms: mechanical and hydrological effects. Mechanical effects include reinforcement of fibrous roots, the traction effect of horizontal roots and the anchorage effect of taproots. Various studies have shown how structure-related root factors such as root area ratio (RAR), root length density (RLD), root density (RD), number of roots, maximum root depth and branching pattern exert a greater impact upon hillslope stability than factors such as root tensile strength (e.g. Waldron and Dakessian 1981; Reubens et al. 2007; Baets et al. 2008a, b; Pollen-Bankhead and Simon 2005). The influence of roots varies with plant growth over time, with the shear strength of rooted soil increasing with root diameter, while roots perpendicular to the shear surface can significantly enhance the strength of rooted soil (e.g. Liu et al. 2007; Normaniza et al. 2008). Hu et al. (2013) showed that root reinforcement in the Xining region is most effectively achieved using *Atriplex canescens* (Pursh) Nutt. and *Caragana korshinskii* Kom. In general terms, shallow roots have a notable effect upon soil reinforcement, while deep and vertical shrub roots impact upon the anchorage effect. Building on these studies mentioned above, two shortages need to be further resolved: (1) many studies assess factors relevant to root system architecture (root area ratio (RAR), root length density (RLD), root density (RD) and so on) and its influence on stability of hillslope, but investigations on variation of these factors in different depths and its influence on the stability of hillslope are relatively scarce; (2) there should be more further relevant studies concerning cohesion force of rooted soil and its variation in different depths of the slope, the influence on cohesion force of rooted soil in different growth stages and the relationships between the cohesion force and root area ratio (RAR), root length density (RLD), and root density (RD).

For these reasons, this study further investigates the influence of roots on cohesion force in loess regions in the cold and arid environment of the Xining Basin. In this area, relatively reduced vegetation coverage has induced serious water and soil loss and fragile ecosystems. Three indigenous shrubs which are adapted to the cold and arid conditions have been selected as test species to study variations of RAR, RLD, RD and the cohesion force of rooted soil at different depths. The relationship between RAR, RLD, RD and their corresponding cohesion force of rooted soil is tested. Also, the influence of different root contents on cohesion force is assessed. Plants that are 10 and 17 months old are analyzed for three shrubs: *Caragana korshinskii* Kom, *Zygophyllum* *xanthoxylon* (Bunge) Maxim, and *Nitraria tangutorum* Bobr. In addition, properties of two herbs are assessed for potential inclusion in management programmes: *Elymus nutans* Griseb and *Agropyron trachycaulum* cv. Slender. Questions addressed in this study are as follows:

(1) How do RAR, RLD and RD vary with depth for the three selected shrubs?

(2) How do the root networks of the three shrubs and two herbs affect the shear strength of soil?

(3) How does the influence of roots vary with plant growth over time?

(4) How can the selected herbs and shrubs assist in the management of soil erosion and hillslope stability in the Xining region?

1 Materials and Methods

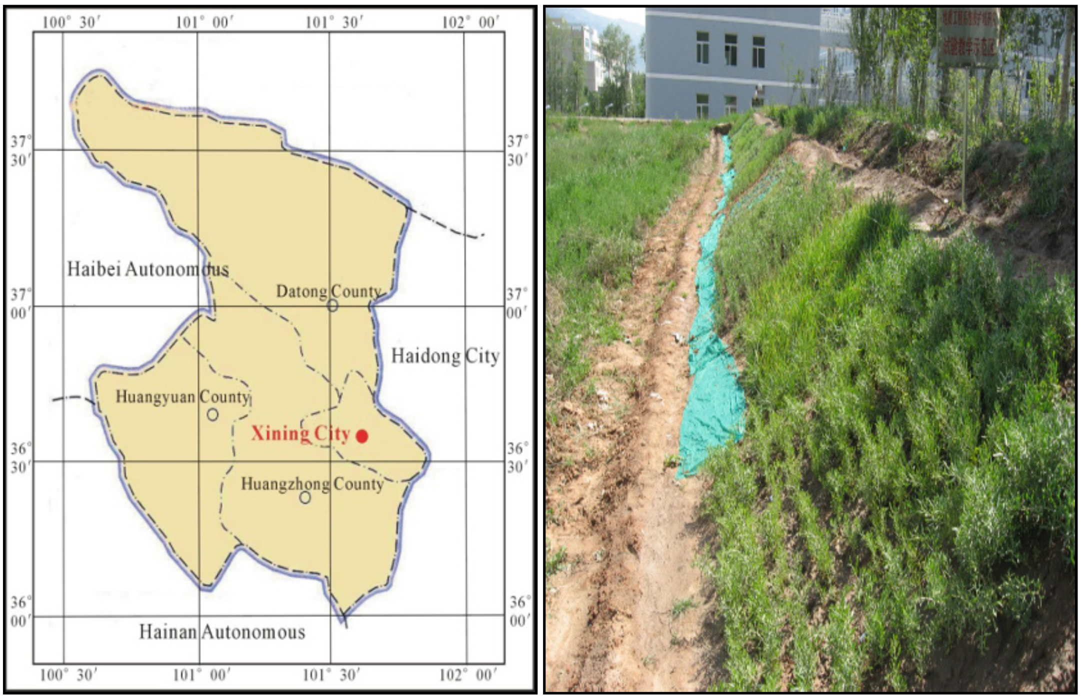
1.1 Study area

The Xining Basin lies at the northeast margin of the Qinghai-Tibet Plateau and the western margin of the Loess Plateau (Figure 1). The central valley of the Huangshui River is surrounded by dissected and deeply eroded plateau mountains and hills composed of loess and red mudstone (Riyue Mountains to the west, Daban Mountains to the north, and Laji Mountains to the south). Relief decreases from west to east. The valley floor has an elevation of 2250 m.

The area lies at the margin between continental and monsoonal climatic influences. Conditions are cold and dry; indeed, this is one of the driest areas in China. The region has long hours of radiation and sunshine, with large temperature differences between a long cold winter and a short cool summer. The mean annual temperature is 6.0°C, with maximum temperature of 33.9°C in summer and minimum temperature in winter of -26.3°C (Mei et al. 2013). A notable precipitation gradient increases from the northwest to the southeast (from 330 to 600 mm/year; Chen 2011). Average annual precipitation is 350 mm, with annual average evaporation of 1400~2000 mm (Yang and Liu 2012). Rainfall is accentuated in summer, with 65% of the annual precipitation occurring from July ~ September.

1.2 Shrub and herb selection

Three shrubs (*C. korshinskii, Z. xanthoxylon* and *N. tangutorum*) and two herbs (*E. nutans* and *A. trachycaulum*) were selected for study. These



(a) Location of the Xining Basin (b) The growth condition of the plants

Figure 1 Loess distribution and the location of the test area.

Table 1 Soil physical property indices in the test area

Soil samples	ω	ρ	n	ω_L	ω_p	Particle size (%)		
						d<0.5	d<0.25	d<0.075
Plot Ⅰ	17.6	1.50	52.8	25.7	17.2	98.30%	80.80%	3.40%
Plot Ⅱ	18.7	1.53	52.3	28.6	17.0			
Plot Ⅲ	16.1	1.41	55.0	23.0	14.6			

Notes: ω = Soil moisture content (%); ρ = Soil density (g/cm^3); n = Porosity (%); ω_L = Fluid limit (%); ω_p = Plastic limit (%).

are compatible (co-located) species. Criteria for plant selection were as follows:

- Adapted to the cold-dry climatic conditions.
- Tolerant to poor, saline-alkali soils.
- Relatively fast growing perennial plants that quickly generate significant cover within a short period (< 17 months).
- Relatively short above-ground biomass, with well-developed fast-growing strong roots (in terms of tension and shear) and long taproots that extend to permeability depths of 3~5 m when fully grown (rather than horizontal or sinker roots).
- Resistant to plant disease and insect pests, and competitive against less desirable plants.
- Easily adapted to extensive management, with ready capacity for seed production at reasonable cost.

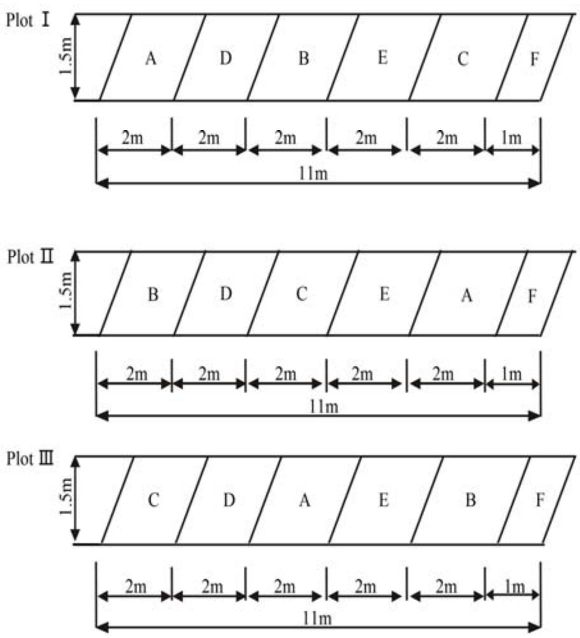


Figure 2 Schematic diagram showing species plantation. Letters refer to the species planted in a given plot (A = *C. korshinskii*; B = *Z. xanthoxylon*; C = *N. tangutorum*; D = *E. nutans*; E = *A. trachycaulum*; F is a bare plot = the control group).

1.3 Description of the self-established plots

The artificial slope of the test area at Qinghai University has a dimension of 33 m × 1.5 m, a gradient of 32° and a silty soil texture. Physical soil properties are summarized in Table 1. Herbaceous seeds were planted by line seeding with a row spacing of 5 cm. Shrub seeds were planted by hole seeding with a drilling depth of 1 cm, a distance between plants of 5 cm and row spacing separation of 5 cm. The above-ground and subsurface biomass of the studied species was measured at different growth periods/stages.

The three selected shrubs and two selected herbs were planted in three 1.5 × 11 m^2 plots (Figure 2). Each plot was divided into six small plots, five of which are planted with herbs or shrubs (1.5 × 2.0 m^2; A-E on Figure 2), with the last plot left bare as a control (1.5 × 1.0 m^2; F on Figure 2).

1.4 Derivation of root system architectural indices

RAR refers to the fraction of soil cross-sectional area occupied by roots (Gray and Andrew 1982). It is calculated as:

$$RAR = \frac{A_r}{A_S} = \frac{\sum_{i=1}^{n} \frac{\pi d_i^2}{4}}{a \times b} \times 100\% \quad (1)$$

where A_r is the total cross-sectional area of the root in the excavated quadrat (mm^2); A_s is the size of the excavated quadrat (mm^2); a is the length of the excavated quadrat (mm); b is the width of the excavated quadrat (mm); d_i is the "i^{th}" root diameter in the excavated quadrat (mm); n is the total number of the roots in the excavated quadrat. The unit for RAR is %.

RLD refers to the total length of the roots contained in the soil relative to the soil volume

(Bland and Dugas 1988; Adhikari et al. 2013). It is calculated as:

$$RLD = \frac{L}{V_S} = \frac{L_1 + L_2 + L_3 + \cdots + L_n}{a \times b \times h} \quad (2)$$

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

RD refers to the total number of fresh roots contained in the soil (Li et al. 1991). It is calculated as:

$$RD = \frac{N}{V_S} = \frac{N_1 + N_2 + N_3 + \cdots + N_n}{a \times b \times h} \quad (3)$$

where N is the total number of the root contained in the soil sample. The unit for RD is roots/cm^3.

1.5 Root system excavation and statistical methods

In our study, the step-by-step excavation method was accompanied by step-by-step measurement of the root system architectural indices (RAR, RLD and RD) for the three shrubs. The selected species were seeded simultaneously, with a spacing of 5 cm. As the same species germinated at the same time, plant height, basal stem diameter and other attributes were approximately identical. Three quadrats, separately planted with *C. korshinskii, N. tangutorum* and *Z. xanthoxylon*, were selected randomly as the candidates to be excavated. As the maximum lateral root length for *C. korshinskii* and *N. tangutorum* at 17 month growth stage was 20 ~ 25 cm, the site for excavation was 30 cm × 30 cm. Horizontal and vertical excavation was carried out in 5 steps:

(1) Horizontal excavation in both north-south and east-west directions. The excavated area was gradually increased from an initial area of 5 × 5 cm^2, with successive 5 cm increments in both directions until a total area of 30 × 30 cm^2 was reached. Hence, there were six excavation sub-areas of 5 × 5, 10 × 10, 15 × 15, 20 × 20, 25 × 25 and 30 × 30 cm^2 (see Figure 3a). For vertical excavation, 5 cm increments were extracted from the slope surface until the maximum growth depth for the shrubs was reached. In this process, a series of iron wire frames with a size of 5 × 5, 10 × 10, 15 × 15, 20 × 20, 25 × 25 and 30 × 30 cm^2 were placed on the ground successively in the lower right corner of the quadrats to be excavated to determine the excavation boundary (see Figure 3a). Then the soil mass beyond the excavation boundary (30 × 30 cm^2) was dug out to make a trench, conserving only the soil mass to be excavated. Hence, a soil mass with a three dimension size of 30 × 30 × 60 cm^3 was excavated in a step-by-step excavation process.

(2) Growth characteristics of the plants were determined, with the above-ground part cut using scissors.

(3) The soil was excavated for the determined size using the incremental step-by-step (layer-by-layer) method, with each layer being 5 cm thick. To reduce disturbance and damage to the soil and roots, two flanks in the left and upside of the soil mass were excavated (see Figure 3b). The excavation origin commenced from the top left

(a) (b)

Figure 3 Measuring procedures of the architectural property indices for the three selected shrubs. (a) The wire excavation frame used to control excavation size; (b) Excavation step-by-step following the prescribed area.

corner with an area of 30 × 30 cm^2, and then gradually decreased to 5 × 5 cm^2, so the successive sub-excavation areas were 30 × 30, 25 × 25, 20 × 20, 15 × 15, 10 × 10 and 5 × 5 cm^2 (see Figure 3b). The root growth indices such as root number, root length, root diameter in each excavated area were determined following each layer of excavation, and the corresponding RAR, RLD, RD in different excavation sub-areas were calculated using formulas 1, 2, and 3.

(4) After the excavation of the topsoil layer at a depth of 5 cm, the next excavation was carried out 5 cm deeper in the vertical direction with excavation in the horizontal direction unchanged, as described in step 3. This process continued until the maximum root growth depth was reached. Hence the successive excavation volumes in the vertical direction are 30 × 30 × (0~5), 30 × 30 × (5~10), 30 × 30 × (10~15), 30 × 30 × (15~20), 30 × 30 × (20~25), 30 × 30 × (25~30), 30 × 30 × (30~35), 30 × 30 × (35~40), 30 × 30 × (40~45), 30 × 30 × (45~50), 30 × 30 × (50~55) and 30 × 30 × (55~60) cm^3 (figures in brackets refer to excavation depth).

(5) Soil samples were collected at each 5 cm increment to determine vertical soil moisture content to support direct shear tests. Only the roots within the determined quadrat (30 × 30 cm^2 area) were investigated.

1.6 Direct shear test on rooted soil

Shear strength was assessed using a standard direct shear test (see Hu et al. 2013). Internal friction angle and cohesion force of the rooted soil for the three shrubs were measured separately. Soil shear strength was determined for each 5 cm depth increment.

Investigations into the influence of root arrangement and how root inclination to the shear plane impacts upon soil shear strength and hillslope stability are beyond the scope of this paper. As noted by Gray and Ohashi (1983), the perpendicular model provides a reliable estimate of all possible root orientations, as demonstrated in experiment tests and theoretical analysis by Gray and Andre (1982). On this basis, the fresh roots were arranged vertically and weighed (0.001 g precision). Similar methods of root arrangement in remolded rooted soil were applied by Hu et al. (2013) and Li et al. (2015). The soil moisture content and wet density followed field conditions (16.1 % and 1.41 g/cm^3, respectively).

Soil samples were sieved at 0.5 mm to be remodeled in the laboratory. The three shrub root samples with a growth period of 10 months were collected to the maximum growth depth. Plants with soil matrix were dug out and transferred into experiment pots. Strict procedures were applied in the remodeling process. Root length was unified at 20 mm. The root diameter for 10 month growth periods were 1.2 ~ 1.8 mm for *C. korshinskii*, 1.5 ~ 2.5 mm for *Z. xanthoxylon*, and 1.4 ~2.4 mm for *N. tangutorum*. The root number followed measured root area ratios derived from the field experiments.

Four duplicate specimens were subjected to direct shear test under different normal stresses (50, 100, 200 and 300 kPa). Disturbed soil samples were carefully prepared as follows:

- The disturbed soil was dried in an oven at 105°C ~ 110°C for eight hours.
- The staved soil block was pulverized into small particles on a rubber pad with a wood roller, minimizing damage to the structure of soil particles.
- The pulverized soil was sieved using a 0.5 mm sieve.
- The sieved soil (m_s) was placed on a stainless steel plate and sprayed with water to achieve the moisture content from the field site soil (16.1%), and stirred thoroughly.
- In order to avoid moisture loss, the soil was covered overnight with plastic wrap to ensure good water penetration through the sample.

Preparation procedures for direct shear samples of disturbed soil were as follows:

- According to the soil density in the test area, the soil mass weight (m_s) of each sample was calculated.
- The weighed soil was put into a 3-plate mould and the soil layers were compacted.
- After compaction the 3-plate mould was removed, giving a soil sample with height and diameter of 125 and 61.8 mm, respectively.
- Four soil samples were cut out as duplicates for direct shear tests.

When the soil samples with four duplicates for direct shear test were finished, the following steps were applied to guarantee the uniform distribution of roots within the rooted soil (see Figure 4):

- An iron wire with the same diameter as the arranged root diameter was used to punch holes in the soil confined in the cutting ring, with equal distance between roots.

- The hole number was equivalent to the number of the roots arranged in the soil confined in the cutting rings.
- The 20 mm long pre-prepared roots were inserted into the holes, and the surface of the rooted soil was smoothed using a trowel to guarantee good contact between soil matrix and inserted roots. Care was taken to avoid any damage to the soil and root samples.

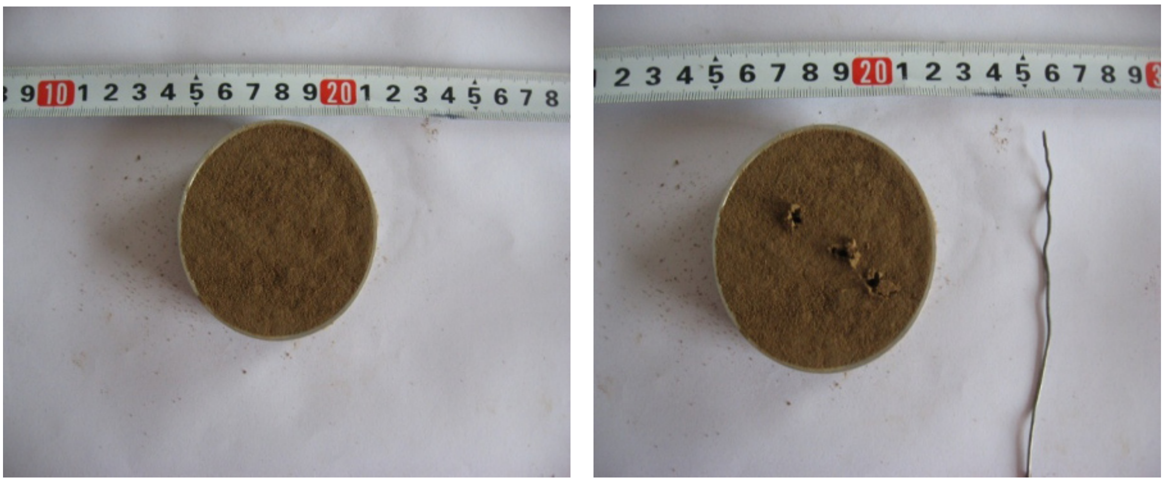
Following procedures outlined in Hu et al. (2013), direct shear tests were performed using a ZJ strain type direct shear apparatus (Nanjing Soil Instrument Factory Co., Ltd). The relationship curve of shear stress with shear displacement was plotted for applied vertical step loads of 50, 100, 200, and 300 kPa. Triple replicate tests were performed for each set of the four samples.

Although this is an in-depth investigation of particular root and soil strength properties, incorporating detailed analysis of their variability with depth and over time for differing species, the small number of replicate samples limits opportunities for comprehensive statistical analyses.

2 Results

2.1 Plant growth conditions and plant characteristics

Growth stage data for the three shrubs and two herbs are summarized in Table 2. At 10 months, mean plant height of studied shrubs ranged from 13.14 to 24.12 cm, mean basal diameter ranged from 1.96 to 3.14 mm, and the mean branch number ranged from 4 to 5. After 17 months, mean plant height ranged from 25.92 to 47.64 cm, mean basal diameter ranged from 3.08 to 5.49 mm, and the mean branch number ranged from 4 to 7. The



(a) Non-rooted soil before test (b) Rooted soil preparation

Figure 4 Non-rooted soil and rooted soil before test.

Table 2 Growth parameters for the three selected shrubs with growth periods of 10 and 17 months

Plant name	Growth period of 10 months					Growth period of 17 months				
	MPH	MBD[a]	B No.[b]	CS	S. No.	MPH	MBD[a]	B No.[b]	CS	S. No.
C. korshinskii	24.12	2.86	4	26×22	20	47.64	4.24	5	45×52	20
Z. xanthoxylon.	17.62	3.14	5	18×16	20	38.58	5.49	7	30×27	20
N. tangutorum	13.14	1.96	4	14×10	20	25.92	3.08	4	18×32	20
E. nutans	10.36	1.43	10	12×10	20	18.67	1.67	11	15×16	20
A. trachycaulum	12.43	1.54	12	15×18	20	20.06	1.84	16	20×26	20

Notes: MPH = Mean plant height (cm); MBD = Mean basal (rhizome) diameter (mm); B No. = Branch (Tillering) number; CS = Canopy size (cm^2); S. No. =Number of samples. [a] Mean basal diameter is for shrubs, and Mean rhizome diameter is for herbs; [b] Branch numbers is for shrubs, and Tillering numbers is for herbs.

mean height for *C. korshinskii* is larger than that of *Z. xanthoxylon*, followed by *N. tangutorum*. Also, the mean basal diameter and branch number of *Z. xanthoxylon* are larger than that of *C. korshinskii* and *N. tangutorum*.

Following the branch pattern classification system for root structures proposed by Yen (1987), the five species studied in this paper can be classified into four classes. The root system for *C. korshinskii* is VH-type, with relatively large taproots and well-developed lateral roots. As such, it is beneficial for slope stabilization and wind resistance. The root system for *Z. xanthoxylon* is R-type, with relatively longer lateral roots and relatively shorter taproots. The root system for *N. tangutorum* is H-type, with relatively well-developed lateral roots and shallow taproots. As such, it is beneficial for soil reinforcement. The root systems of the two herbs are M-type, and benefit soil reinforcement.

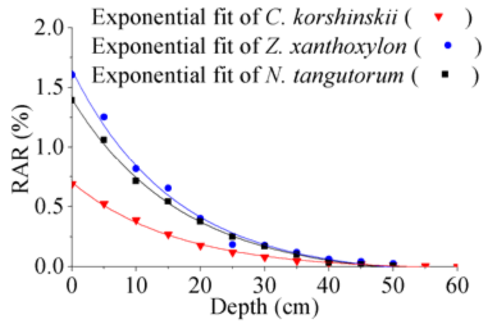
The maximum permeation depths of the three shrub taproots after 17 months were 70 cm. Skeleton roots with diameter >5 mm were concentrated from 0 to 40 cm. Fine fibrous roots with diameter <1 mm made up 65% ~ 85% of the total roots, typically extended from 50 ~ 70 cm beneath the slope surface. The maximum lateral root length for the three shrubs was 20 ~ 120 cm for 17 month growth. At full growth, 3 ~ 5 years after plantation, taproots of *C. korshinskii* and *N. tangutorum* extend to 3 ~ 5 m depth (Niu 1998; Niu et al. 2003; Zhou et al. 2006). Due to the shorter growth period (from 10 to 17 months), the roots for the 3 shrubs do not extend to such depth. After 17 months' development, the taproot for *C. korshinskii* typically extend to 50 ~ 100 cm depth, with a root diameter of 3.0 ~ 6.5 mm. Branch and fibrous roots equalize growth of both taproots and lateral roots. Most branch and fibrous roots are distributed from 30 to 50 cm beneath the ground surface with root extension from 0 to 25 cm. *Z. xanthoxylon* is a relatively shallow root shrub with a developed fleshy taproot that extends to 40 ~ 80 cm and a thick root diameter of 4.0 ~ 8.0 mm. Branch roots distributed from 60 to 120 cm are several times longer than the taproots. Most branch roots range from 10 to 35 cm beneath the ground surface, with 75% perpendicular to the taproot (i.e. lateral roots). Root extension ranges from 60 to 120 cm. Developed roots of *N. tangutorum* have a taproot diameter that ranges from 2 to 6 mm and length from 30 to 60 cm, root extension from 0 to 20 cm, and developed lateral roots, with most of the branch roots distributed from 10 to 40 cm beneath the ground surface. These results accord well with those reported by Li et al. (2005).

Given their shallow roots, herbs are only able to reinforce shallow soils and topsoils. Growth stage data for the two herbs are summarized in Table 2. Mean plant height of studied herbs range from 10.36 to 12.43 cm, mean rhizome diameters range from 1.43 to 1.54 mm after 10 months, and the mean tillering number range from 10 to 12. After 17 months, mean plant height range from 18.67 to 20.06 cm, mean rhizome diameters range from 1.67 to 1.84 mm, and the mean tillering number range from 11 to 16. Given its thickly developed fibrous roots, *E. nutans* is resistant to cold, alkaline and sand-blown conditions. At a 17 month growth period it attains a mean height of 10 ~ 20 cm. In the seedling stage, *E. nutans* slowly transitioned to the tillering stage. The plants developed quickly when the third true leaf emerged. Given its high tillering ability and fibrous roots, this herb has adapted to many soil environments including upland meadow, meadow steppe and alluvial flat meadow conditions. *A. trachycaulum* has thick fibrous roots and many leaves. Roots extend approximately 30 cm beneath the ground surface. Height at 17 months is around 10 ~ 30 cm. It is well adapted to cold, semiarid climatic conditions and can develop well in alkaline soil environments. Overall, the basic growth indices (mean height, mean rhizome diameter, mean tillering and canopy size) for *E. nutans* are relatively smaller than those of *A. trachycaulum*.

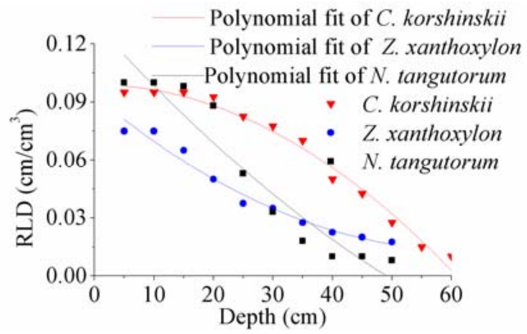
2.2 Root system architectural indices for the plants

Variable relationships between RAR, RLD, RD and depth are shown for the three study shrubs for the 20 × 20 ×60 cm^3 plots for 10 months growth in Figure 5. Changes from 10 to 17 month growth periods are summarized in Table 3. RAR decreased rapidly within 20 cm of the ground surface (Figure 5a). It decreased systematically with depth, as roots become sparser and more slender. For samples from 0 to 40 cm, RAR is the largest for *Z.*

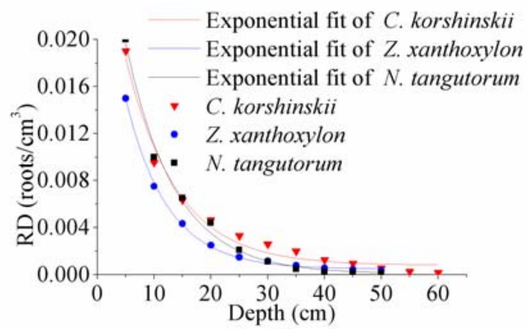
xanthoxylon, followed by *N. tangutorum* and *C. korshinskii*. Beyond 45 cm, *Z. xanthoxylon* has the largest value in RAR, followed by *C. korshinskii*



(a) RAR for the three shrubs



(b) RLD for the three shrubs



(c) RD for the three shrubs

Figure 5 Relationships between architectural property indices and depth for the three shrubs in the test area. Data are shown for the 20 × 20 × 60 cm^3 plots at 10 month growth. The fitting equation between RAR and depth for *C. korshinskii*, *N. tangutorum* and *Z. xanthoxylon* are y=1.177$e^{-0.10x}$, R^2=0.9427, y=1.947$e^{-0.08x}$, R^2=0.9886, and y=2.256$e^{-0.10x}$, R^2=0.9466; the fitting equation between RLD and depth for *C. korshinskii*, *N. tangutorum* and *Z. xanthoxylon* are y=-3E-05x^2-1E-05x+0.099, R^2=0.9841, y=2E-05x^2-0.002x+0.093, R^2=0.9736, and y=1E-05x^2-0.0034x+0.1309, R^2=0.9196; the fitting equation between RD and depth for *C. korshinskii*, *N. tangutorum* and *Z. xanthoxylon* are y=0.024$e^{-0.07x}$, R^2=0.9828, y=0.015$e^{-0.08x}$, R^2=0.9711, and y=0.034$e^{-0.11x}$, R^2=0.9878.

and *N. tangutorum*. Only *C. korshinskii* has a root length that extends to 60 cm (the maximum growth or permeability depth), while *N. tangutorum* and *Z. xanthoxylon* extend to more than 50 cm.

Equivalent plots of RLD show a power function relationship with depth for the three shrubs (Figure 5b). RLD for *C. korshinskii* remains constant from 5 to 15 cm beneath the ground, then decreases slowly from 20 to 35 cm. Beyond 35 cm, RLD decreases rapidly. Most roots are concentrated from 0 to 35 cm beneath the ground surface. RLD for *Z. xanthoxylon* is relatively smaller and slightly varied beneath the ground surface to 15 cm depth (＜13.3%). It decreases sharply from 20 to 50 cm beneath the ground surface. RLD for *N. tangutorum* varies relatively slowly from 0 to 20 cm beneath the ground surface, indicating that most roots are concentrated at this depth. From 25 to 45 cm, RLD decreases rapidly with depth. RD for the three shrubs also decreases exponentially with depth, decreasing more rapidly from 5 to 20 cm (Figure 5c).

2.3 Relationship between root number and sample shear strength

The cohesion force varies with the number of roots (Table 3). For example, for rooted soil with one root of *C. korshinskii* the cohesion force increased by 0.8 kPa (i.e 11.3%). For eight roots, the cohesion force of the rooted soil is more than twice that of soil without roots (cohesion force increment is 7.5 kPa; an increase rate of 105.6%). The cohesion force for the rooted soil of *Z. xanthoxylon* increased progressively when the number of roots increased from 1 through 2, 3, 4, 5 and 8, but dropped for 11 and 15 roots. This indicates that there is an optimal root content in the rooted soil when the rooted soil is sheared.

2.4 Shear strength of rooted soil with depth

The cohesion force of the three rooted soils is notably larger than that of the non-rooted soil, increasing with growth period from 10 to 17 months (Table 4). Figure 6 shows that the cohesion force increases initially and then decreases gradually with depth. Peak cohesion force values were recorded at 5 cm depth for *C. korshinskii*

Table 3 Variation in RAR, cohesion force and cohesion force increment rate of rooted soil for the three shrubs with growth periods of 10 and 17 months

Growth period	Depth (cm)	NS	*C. korshinskii*				*Z. xanthoxylon*				*N. tangutorum*			
		CF	M. RAR	R. No.	CF	CFIR[a]	M. RAR	R. No.	CF	CFIR[a]	M. RAR	R. No.	CF	CFIR[a]
10 months	0	7.1	0.687	11	13.9	95.77	1.606	15	14.3	101.41	1.391	14	14.8	108.45
	5		0.525	8	14.6	105.63	1.253	11	15.0	111.27	1.059	11	15.4	116.90
	10		0.388	6	14.5	104.23	0.817	8	15.6	119.72	0.714	8	15.6	119.72
	15		0.270	4	13.0	83.10	0.655	5	15.1	112.68	0.542	5	15.2	114.08
	20		0.174	3	11.1	56.34	0.400	4	14.2	100.00	0.377	4	14.1	98.59
	25		0.118	2	9.3	30.99	0.184	3	12.3	73.24	0.248	3	11.6	63.38
	30		0.078	1	7.9	11.27	0.177	2	10.8	52.11	0.168	2	9.9	39.44
	35		0.048	*	*	*	0.117	1	8.7	22.54	0.099	1	8.8	23.94
17 months	0	7.1	1.019	10	16.8	136.62	1.757	10	16.5	132.39	1.410	-	-	-
	5		0.925	9	17.6	147.89	1.260	7	17.6	147.89	1.095			
	10		0.821	8	16.3	129.58	0.987	6	16.6	133.80	0.766			
	15		0.670	6	15.5	118.31	0.777	5	16.0	125.35	0.598			
	20		0.506	5	13.9	95.77	0.597	4	15.3	115.49	0.399			
	25		0.366	3	11.2	57.75	0.491	3	13.6	91.55	0.272			
	30		0.242	2	9.7	36.62	0.401	2	11.3	59.15	0.173			
	35		0.148	1	8.0	12.68	0.299	1	9.0	26.76	0.100			

Notes: NS = Non-rooted soil; CF = Cohesion force (kPa); M. RAR = Measured root area ratio (%); R. No. = root number in rooted soil; CFIR = Cohesion force increment rate (%). [a]"Cohesion force increment rate" is calculated as follows:$[(C_{i+1}-C_i)/C_i]\times100\%$, where: C_{i+1} means the soil cohesion force of the $(i+1)^{th}$ layer beneath the slope; C_i means the soil cohesion force of the i^{th} layer beneath the slope; "i" means the i^{th} layer soil of the slope. "*"means the number of the roots in the prepared rooted soil sample is less than 1. This value is selected because the RAR of the rooted soil with 1 root is considered too large. "-"means no data.

(105.63% increase) and at 10 cm depth for *Z. xanthoxylon* and *N. tangutorum* (119.72% increase). Beyond these depths, the cohesion force increment decreases with depth as the number of roots decreases.

2.5 Influence of RAR, RLD and RD upon shear strength

The influence of RAR, RLD and RD on the cohesion force initially increases and then decreases beyond a peak value, indicating that there is an optimal root content with which to reinforce soils (Figure 7). The fitting equation between cohesion force and RAR for *C. korshinskii*, *N. tangutorum* and *Z. xanthoxylon* are y = -37.554x^2 +37.983x +5.3676, R^2=0.9934, y=-10.273x^2 +19.325x +7.3347, R^2 = 0.9526, and y = -7.0049x^2 +14.507x +8.6069, R^2 = 0.8658; the fitting equation between cohesion force and RLD for *C. korshinskii*, *N. tangutorum* and *Z. xanthoxylon* are y = -200.57x^2 +86.841x+5.5767, R^2 = 0.9874, y = -145.3x^2 +73.942x +6.9748, R^2 = 0.9351, and y =-125.79x^2 +65.233x +7.7943, R^2 = 0.9104; the fitting equation between cohesion force and RD for *C. korshinskii*, *N. tangutorum* and *Z. xanthoxylon* are y =-2E+06x^2 +8887x +5.4352, R^2 = 0.9936, y =-2E +06x^2 +7598.7x +6.8433, R^2 = 0.94, and y =-1E +06x^2 +6567.6x +7.7566, R^2 = 0.9026.

Initially, cohesion force of the rooted soil increases markedly as RAR, RLD and RD increase. However, when the root system architectural indices (RAR, RLD and RD) increase to and beyond particular values (0.525%, 0.2135 cm/cm^3, 0.0021 roots/cm^3 for *C. korshinskii*; 0.817%, 0.2135 cm/cm^3 and 0.0021 roots/cm^3 for *Z. xanthoxylon*; 0.714%, 0.2135 cm/cm^3 and 0.0021 roots/cm^3 for *N. tangutorum*), their corresponding cohesion force gradually declines by a certain extent.

2.6 Temporal variability in plant root system architectural indices

Proportional changes to root system architectural indices with depth, and their impact upon cohesion forces, are shown for 10 and 17 month samples of *C. korshinskii* and *Z. xanthoxylon* in Table 5. Although notable temporal variability is evident for RAR, negligible changes were determined for RLD and RD. A marked increase in RAR increment rate with depth is noted for *C. korshinskii*, especially beyond 20 cm depth.

Table 4 Direct shear results for rooted and non-rooted soil for the three shrubs (A= *C. korshinskii;* B = *Z. xanthoxylon;* C = *N. tangutorum*) with growth periods of 10 and 17 months

Plant	Depth (cm)	Growth period					
		10 months			17 months		
		FD	CF	IFA	FD	CF	IFA
A	0	0.999	13.9	25.1	1.000	16.8	27.1
	5	0.998	14.6	25.2	1.000	17.6	29.0
	10	0.998	14.5	25.0	0.999	16.3	24.5
	15	0.998	13.0	25.2	0.999	15.5	25.4
	20	0.998	11.1	25.2	0.998	13.9	29.2
	25	0.999	9.3	25.1	0.997	11.2	28.0
	30	0.999	7.9	25.1	1.000	9.7	27.2
	35	-	-	-	1.000	8.0	28.6
B	0	1.000	14.3	25.3	0.999	16.5	28.3
	5	1.000	15.0	25.4	0.999	17.6	24.4
	10	0.999	15.6	25.3	1.000	16.6	25.8
	15	0.999	15.1	25.3	0.994	16.0	27.1
	20	0.999	14.2	25.3	1.000	15.3	26.7
	25	0.999	12.3	25.1	1.000	13.6	26.8
	30	0.999	10.8	25.1	0.997	11.3	26.2
	35	0.999	8.7	25.0	0.997	9.0	26.9
C	0	0.999	14.8	25.2	-	-	-
	5	0.999	15.4	25.3			
	10	0.999	15.6	25.2			
	15	0.999	15.2	25.2			
	20	0.999	14.1	25.2			
	25	0.999	11.6	25.3			
	30	0.998	9.9	25.3			
	35	0.999	8.8	25.2			
NS	*	0.999	7.1	25.1	0.999	7.1	25.1

Notes: FD= Fitting degree; CF = Cohesion force (kPa); IFA = Internal friction angle (°); NS = Non-rooted soil. "*"means cohesion force and the internal friction angle of the non-rooted soil from 0 to 35 cm beneath the slope surface."-"means no data.

Table 5 Increment rate of measured root area ratio (RAR) and corresponding cohesion forces at different depths for rooted soil of two shrubs with growth periods of 10 and 17 months

Depth (cm)	*C. korshinskii*		*Z. xanthoxylon*	
	RAR IR**	CFIR	RAR IR**	CFIR
0	48.32	20.86	9.4	15.38
5	76.19	20.54	0.56	17.33
10	111.60	12.41	20.81	6.41
15	148.14	19.23	18.63	5.96
20	190.80	25.22	49.25	7.75
25	210.17	20.43	166.85	10.57
30	210.25	22.78	126.55	4.63
35	*	*	155.56	3.45

Notes: RAR IR = RAR increment rate (%); CFIR = Cohesion force increment rate (%). "*"means the number of the roots in the prepared rooted soil sample is less than 1. This value is selected because the RAR of the rooted soil with 1 root is considered too large. **"RAR increment rate" is obtained as: $[(RAR_{i+1}-RAR_i)/RAR_i]\times100\%$, where: RAR_{i+1} means the RAR of the $(i+1)^{th}$ layer beneath the slope; RAR_i means the RAR of the i^{th} layer beneath the slope; "i" means the i^{th} layer soil of the slope.

However, this does not correspond to an equivalent increase in cohesion force, which demonstrates a non-linear trend with depth.

2.7 The influence of shrubs and herbs upon hillslope stability

Cohesion force increases to a varying extent as growth period increases from 10 to 17 months. For example, the cohesion force for *C. korshinskii* and *Z. xanthoxylon* at 10 cm depth increases from 14.5 and 15.6 kPa, to 16.3 and 16.6 kPa from 10 to 17

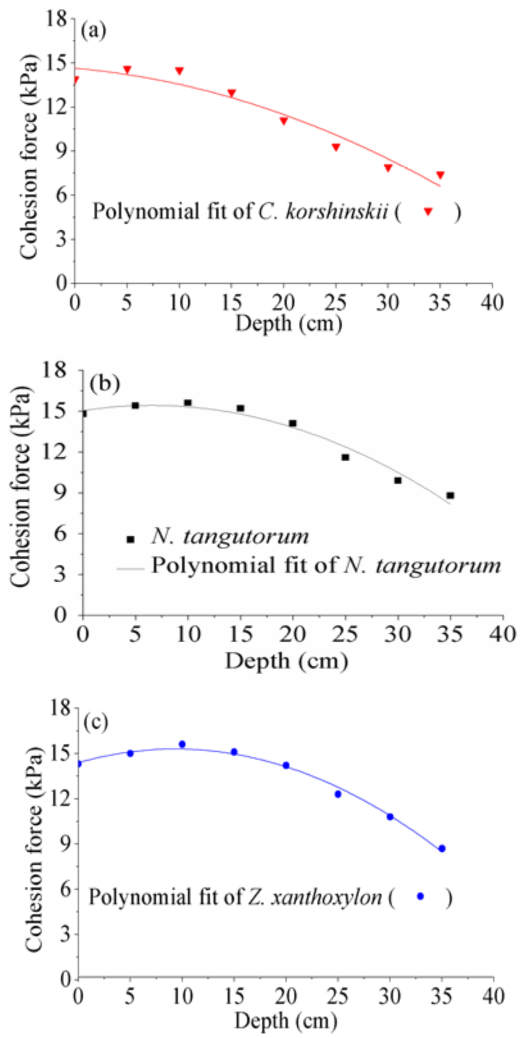
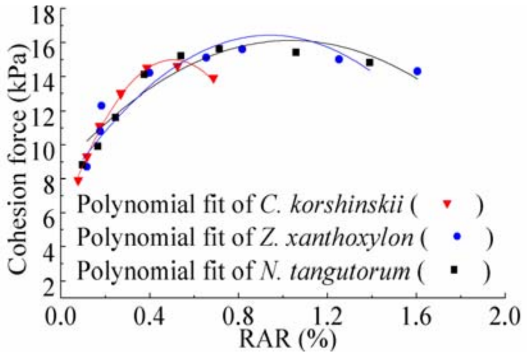
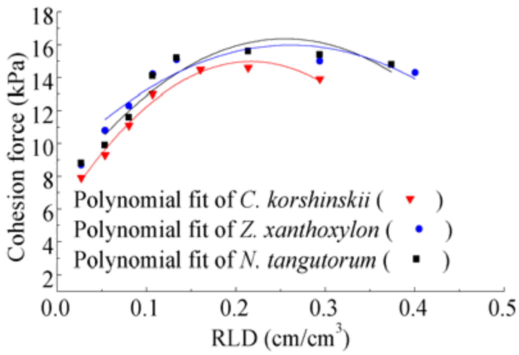


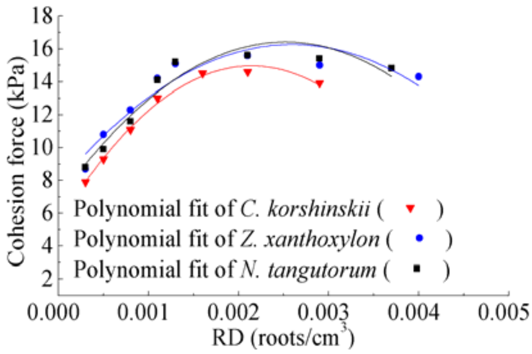
Figure 6 Relationship between cohesion force and depth for the three shrubs. (a) Cohesion force with depth for *C. korshinskii* (b) Cohesion force with depth for *N. tangutorum* (c) Cohesion force with depth for *Z. xanthoxylon*. The fitting equation between cohesion force and depth for *C. korshinskii*, *N. tangutorum* and *Z. xanthoxylon* are y=-0.0048x^2-0.0606x+14.638, R^2=0.9432, y=-0.009x^2+0.1167x+15.05, R^2=0.9656, and y=-0.0103x^2+0.1926x+14.4, R^2=0.9903.



(a) RAR for the three shrubs



(b) RLD for the three shrubs



(c) RD for the three shrubs

Figure 7 Relationship between cohesion force and the architectural indices for the three shrubs.

Table 6 Single root tensile resistance and tensile strength for the two herbs (C = *E. nutans;* D = *A. trachycaulum*) with growth periods of 10 months and 17 months

Plant	Growth period of 10 months					Growth period of 17 months				
	TGN	MRD	MTR	MTS	SN	TGN	MRD	MTR	MTS	SN
C	1	0.32±0.04d	6.62±1.20d	82.31±9.27a	20	1	0.46±0.06e	9.08±1.98c	54.64±3.27a	20
	2	0.36±0.04d	7.04±1.10b	69.16±7.52b	20	2	0.52±0.07d	9.94±1.86bc	46.80±4.33b	20
	3	0.48±0.07c	8.04±1.65c	44.43±4.60c	20	3	0.62±0.09c	12.04±2.53b	39.88±2.97c	20
	4	0.52±0.09c	9.16±2.10b	43.13±5.21c	20	4	0.68±0.10b	14.38±3.06a	39.60±4.39c	20
	5	0.60±0.07b	9.44±1.25ab	33.39±3.75d	20	5	0.76±0.08a	15.64±2.54a	34.48±2.70d	20
	6	0.74±0.08a	10.24±1.59a	23.81±1.85e	20	6	0.80±0.14a	16.08±4.66a	32.00±2.11e	20
	Mean	0.50	8.42	49.37	20	Mean	0.64	12.86	41.23	20
D	1	0.18	4.43	174.09	20	1	0.32	8.94	111.16	20
	2	0.24	4.84	106.99	20	2	0.40	9.56	76.08	20
	3	0.30	5.26	74.41	20	3	0.48	10.04	55.48	20
	4	0.36	5.88	57.77	20	4	0.52	10.68	50.29	20
	5	0.42	6.24	45.04	20	5	0.60	11.26	39.82	20
	6	0.48	6.96	38.46	20	6	0.66	12.08	35.31	20
	Mean	0.33	5.60	82.79	20	Mean	0.50	10.43	61.36	20

Notes: TGN = No. of test groups; MRD = Mean root diameter (mm); MTR = Mean tensile resistance (N); MTS = Mean tensile strength (MPa); SN = No. of samples. Values in the table are mean ± standard deviations; Figures followed by letters are significantly different at $p<0.05$.

months, highlighting their potential to improve hillslope stability with time. Slightly different temporal trends are evident for the two herb species analyzed in this study.

Mean root diameter, mean tensile resistance, and mean tensile strength for the two herbs increase from 10 to 17 months (Table 6).

The mean root diameter for *E. nutans* increased from 0.50 to 0.64 mm. The corresponding mean tensile resistance increased from 8.42 to 12.86 N. However, the mean tensile strength decreased from 49.37 to 41.23 MPa. Equivalent changes for the 10 ~ 17 month growth period for *A. trachycaulum* indicate an increase in mean root diameter from 0.33 to 0.50 mm, an increase in mean tensile resistance from 5.60 to 10.43 N, and a decrease in mean tensile strength from 82.79 to 61.36 MPa. The mean tensile resistance of the single root for the two herbs increases with root diameter, but the corresponding tensile strength decreases as root diameter increases. A significant power relationship between root diameter and tensile resistance and tensile strength of single roots is evident. As the two herbs planted in the test area have relatively strong roots in terms of tensile strength, their dense networks can markedly increase the corresponding shear strength of hillslope soils.

The two herbs have a fibrous root system. Results of direct shear tests and triaxial compression tests performed for a similar species, *Achnatherum splendens*, with a one year growth period, showed that shear strength of the rooted soil increased with root content (keeping moisture content constant, and under the same vertical pressure; Zhang and Hu (2013)). Compared to the cohesion force of non-rooted soil, the cohesion force of rooted soil for *A. splendens* is 13.48 kPa, with an increment of 5.39 kPa and an increase rate of 66.6% (Yu et al. 2012). Equivalent results for the cohesion force of the rooted soil for *C. korshinskii* is 11.26 kPa, with an increment of 3.17 kPa and an increase rate of 39.2%. In this instance, the cohesion force for rooted soil of *A. splendens* is greater than that of *C. korshinskii*. This indicates that some herbs can play an effective role in soil reinforcement.

3 Discussion

Results from this study indicate that the three shrubs and two herbs analyzed in this study are good candidates for loess hillslope soil reinforcement in the cold and semiarid environment of the Xining Basin.

3.1 Relationships between RAR, RLD and RD and depth

RAR, RLD and RD for the three selected shrubs decrease significantly with depth. RAR and RD decrease significantly for the three selected shrubs from the surface to 25 cm, but beyond this depth the decrease is much lower (i. e. there is an exponential relationship between RAR and RD with depth). RLD decreases notably beyond 25 cm depth. This is best expressed as a power relationship. Slightly differing trends with depth are evident for the three selected shrubs. RLD and RD for *N. tangutorum* are relatively larger at a depth of 0 ~ 15 cm, followed by *C. korshinskii* and *Z. xanthoxylon*. In the deeper layer of the slope from 30 to 50 cm, RLD and RD for *C. korshinskii* are relatively larger, followed by *Z. xanthoxylon* and *N. tangutorum*. While previous work by Mattia et al. (2005) and Preti and Giadrossich (2009) demonstrated a logarithmic relationship between RAR and depth, an exponential relationship is evident in this study. This may reflect the agrestal nature of plants studied by these other authors, but further investigation is required to explain these differences.

Root system architectural indices (RAR, RLD and RD) and depth increase with time for the growth period from 10 to 17 months, but results vary for the differing species considered in this study. Increases in RLD and RD are marginal relative to RAR. This is considered to reflect the significant increment in root diameter increment. This finding differs to those presented by McIvor et al. (2008), probably because the latter study considered horizontally excavated trees with a growth period of more than 5 years, while vertically excavated shrubs with a growth period of no more than 17 months were tested in this study. Similarly, differences in the relationship between RAR, RLD and RD with depth from findings shown by Baets et al. (2008a), Adhikari et al. (2013) and Abdi (2014) are considered to reflect differences in selected species.

3.2 Impact of RAR, RLD and RD on cohesion force

A power relationship describes the relationship between the cohesion force and RAR, RLD and RD in our study (Figure 7). This finding differs from an exponential relationship between cohesion force and RD demonstrated by Baets et al. (2008b), probably because of the different plant species considered and their root system architectures. The cohesion force of the rooted soil for the three shrubs with the growth period of 10 months initially increases with a corresponding increase in RAR, RLD and RD. However, as RAR, RLD and RD increase to a certain extent, the increase rate of cohesion force of the rooted soil starts to decline. This indicates that there is an optimal root content with which to maximize the cohesion force of the rooted soil. The maximum cohesion force for the rooted soil for *C. korshinskii* is 14.6 kPa. This is achieved with the values of 0.525%, 0.2135 cm/cm^3 and 0.0021 $roots/cm^3$ for RAR, RLD and RD, respectively, at a depth of 5 cm beneath the slope surface. As the cohesion force of the rooted soil for *N. tangutorum* and *Z. xanthoxylon* reaches the maximum value (15.6 kPa), their corresponding RAR are 0.714% and 0.817%, RLD are both 0.2135 cm/cm^3, and RD are both 0.0021 $roots/cm^3$, at a depth of 10 cm beneath the slope surface. Initial increases in root content beneath the slope surface increase the contact area between root and soil, increasing the bonding effect between roots and soil, so the cohesion force of the rooted soil increases (e.g. Li et al. 2015, among many authors). However, as the root content increases beyond the optimal root content, the bond between soil and roots is reduced by excessive roots, decreasing the cohesion force of the rooted soil. Slightly different results obtained by Comino and Marengo (2010) probably reflect the value of RAR (the optimal root content values are at least an order of magnitude higher in this study). Findings related to the optimal root content in this study indicate that RAR is influenced by the seeding/plant space, thereby affecting the maximum contribution by roots in increasing shear strength and the associated efficiency of roots in improving hillslope stability (as noted by Gray and Andrew 1982).

In the study, the optimal root contents for 10 month old samples of *C. korshinskii*, *Z. xanthoxylon* and *N. tangutorum* were 0.525%, 0.817% and 0.714% respectively. As the growth period increased to 17 months, the optimal root contents for *C. korshinskii* and *Z. xanthoxylon* were 0.925% and 1.260% respectively. The main causes leading to an increase in the optimal root content for the two shrubs could be attributed to changes in root number and mean tensile strength of roots. For example, as the growth period increased from 10 to 17 months, the optimal root content for *C. korshinskii* increased from 0.525% to 0.925%, the corresponding root diameter increased from 1.2 mm ~ 1.8 mm to 1.6 mm ~ 2.4 mm, root number in the rooted soil increased from 8 to 9, and the corresponding mean tensile strength of single root decreased from 22.18 to 20.18 MPa. Similarly, as the growth period increased from 10 to 17 months, the optimal root content for *Z. xanthoxylon* increased from 0.817% to 1.260%, the corresponding root diameter increased from 1.5 ~ 2.5 mm to 2.0 ~3.2 mm, the root number in the rooted soil decreased from 8 to 7, and mean tensile strength of single root decreased from 14.92 to 14.43 MPa. Similar conclusions regarding the relationship between the optimal root content and the influence of mean tensile strength of single root upon the cohesion force of rooted soil were documented by Li et al. (2015).

3.3 Temporal variability in indices and its impact upon shear strength

Root system architectural indices (RAR, RLD and RD) can be viewed as dynamic indices that document changing influences of root growth upon the cohesion force of soils. The maximum cohesion force of rooted soil for the selected shrubs with a growth period of 10 months in this study is 14.6 ~ 15.6 kPa (corresponding values for RAR range from 0.525% ~ 0.817%). The maximum cohesion force is at 5 ~10 cm beneath the ground surface. For the two shrubs with a growth period of 17 months, the maximum value in the cohesion force of the rooted soil is 17.6 kPa, with corresponding RAR values of 0.925% ~ 1.260%. A more notable increase in RAR was evident with extension of the growth period from 10 to 17 months, but increases in RLD and RD were trivial. This may reflect the sharp increase in root diameter, while the number and length/ unit volume of roots do not show a marked increase. For example, at 5 cm beneath the slope surface, the RAR of *C. korshinskii* with growth periods of 10 and 17 months are 0.525% and 0.925%, and the corresponding cohesion forces are 14.6 and 17.6 kPa (an incremental increase of 20.55%).

Few studies have examined temporal variation in RAR and RLD. Differences in variability over time reported here are similar to those reported by

Genet et al. (2008) who used a longer growth period than that used in this study.

3.4 A conceptual model outlining role of vegetation as an agent of hillslope stability in the Xining region

A conceptual model outlining the mechanical effect of roots for the three shrubs and two herbs upon slope protection by vegetation is shown in Figure 8. Selected species are well-adapted to the cold and dry conditions of this high altitude region, with strong roots enhancing resistance to tension and shear. Deep taproots are required to stabilize the thick, uniform soils of the Loess Plateau. At a 17 month growth period the roots of selected species extend to 60 cm; when fully grown, they typically extend to 3~5 m deep (Li et al. 2005; Niu 1998; Niu et al. 2003). These relatively fast growing species may assist soil reinforcement as the early stage of vegetation growth, potentially exerting a critical influence upon hillslope stability (e.g. Watson et al. 1999).

The conceptual model reflects the mechanical effect of the herb and shrub roots in hillslope protection. Rooted soil behaves as composite materials in which elastic roots of relatively higher tensile strength are embedded in a matrix of relatively plastic soil (see Pollen-Bankhead and Simon 2005; Wu 1976; Waldron 1977). Tractive forces between the roots and surrounding matrix add further strength to the soil. The mechanical effect incorporates the variation of root system architectural indices (RAR, RLD and RD) and cohesion force with depth. In the conceptual model, roots type (M) of herbs influence the reinforcement effect in topsoil, while shrub roots reinforce and anchor deeper parts of the soil, supporting findings presented by Baets et al. (2008a) and Zhou and Zhang (2003). Increases to shear strength markedly enhance hillslope stability.

Afforestation provides an effective tool to control soil erosion in the Loess Plateau region (e.g. Fu 1987, 2000, 2011; Zheng 2006). Findings from this study can be used to support infrastructure development and erosion control in the rapidly developing area near Xining. The enhanced mechanical properties of soils induced by the roots of shrubs and herbs are accompanied by improved hydrological and ecological effects, thereby providing a balance between hillslope engineering and ecological environmental protection strategies (e.g. Zheng 2006; Stokes et al. 2014). Results from

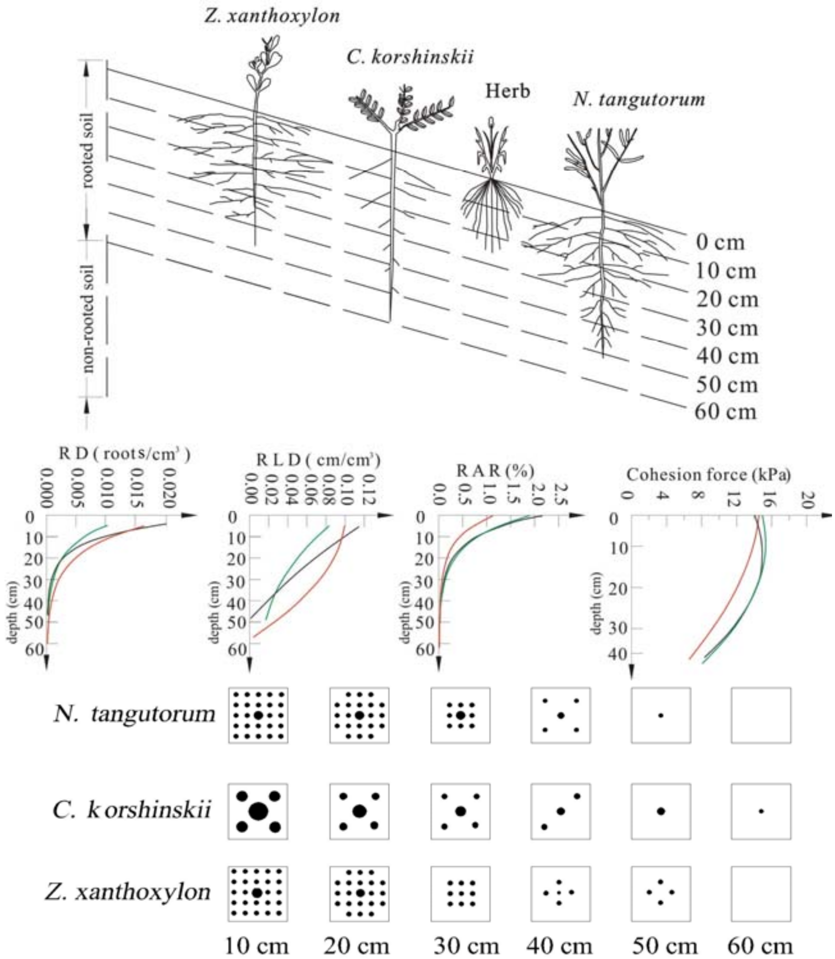


Figure 8 A conceptual model showing the influence of herb and shrub roots upon soil erosion and hillslope stability in the loess landscapes of the Xining region. Red lines indicate *C. korshinskii*; black lines indicate *Z. xanthoxylon*; green lines indicate *N. tangutorum*. As the two studied herbs have the same roots type (M), only one herb is presented in the model. The boxes in the model represent layers at different depths (0, 10, 20, 30, 40, 50 and 60 cm).

this study highlight the positive effect of young shrubs and herbs in managing soil erosion. Vegetative impacts are especially pronounced in the near-surface zone. Herb roots add to soil reinforcement, while shrubs enhance the anchorage effect of the soil.

4 Conclusion

This research has shown that several indigenous species have an excellent capacity to provide additional cohesion force for loess soils, thereby improving hillslope stability in the Xining region. The shear strength of rooted soil was significantly larger than that of non-rooted soil. An optimal root content is evident in terms of the impact of RAR, RLD and RD upon soil cohesion forces. RAR, RLD and RD decrease gradually with depth, reflecting growth characteristics such as the number, density and size of roots. Initially, cohesion force increases with root number. It then reaches an optimal point beyond which it drops. For the three shrubs with a growth period of 10 months, the optimal root number for *C. korshinskii, Z. xanthoxylon* and *N. tangutorum* is 8, with the corresponding RARs and depth being 0.525 % and 5 cm, 0.817 % and 10 cm and 0.714 % and 10 cm beneath the ground surface respectively. As the growth period increases from 10 to 17 months, the optimal root content for *C. korshinskii* and *Z. xanthoxylon* increases to 0.925% and 1.260% respectively. Over the growth period from 10 to 17 months, RAR increases more markedly than RLD and RD. The increase in RAR is more pronounced for *C. korshinskii* than it is for the other two species. A conceptual diagram summarizes the use of these findings to inform management of soil erosion in this region.

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