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Vertical root distribution and root cohesion of typical tree species on the Loess Plateau, China

ChaoBo ZHANG[1*], LiHua CHEN[2], Jing JIANG[1]

[1] College of Water Resources Science and Engineering, Taiyuan University of Technology, Taiyuan 030024, China;
[2] Key Laboratory of Soil and Water Conservation and Combating Desertification of Ministry of Education of China, School of Water and Soil Conservation, Beijing Forestry University, Beijing 100083, China

Abstract: Black locust (*Robinia pseudoacacia* L.) and Chinese pine (*Pinus tabulaeformis* Carr.) are two woody plants that are widely planted on the Loess Plateau for controlling soil erosion and land desertification. In this study, we conducted an excavation experiment in 2008 to investigate the overall vertical root distribution characteristics of black locust and Chinese pine. We also performed triaxial compression tests to evaluate the root cohesion (additional soil cohesion increased by roots) of black locust. Two types of root distribution, namely, vertical root (VR) and horizontal root (HR), were used as samples and tested under four soil water content (SWC) conditions (12.7%, 15.0%, 18.0% and 20.0%, respectively). Results showed that the root lengths of the two species were mainly concentrated in the root diameter of 5–20 mm. A comparison of root distribution between the two species indicated that the root length of black locust was significantly greater than that of Chinese pine in nearly all root diameters, although the black locust used in the comparison was 10 years younger than the Chinese pine. Root biomass was also significantly greater in black locust than in Chinese pine, particularly in the root diameters of 3–5 and 5–10 mm. These two species were both found to be deep-rooted. The triaxial compression tests showed that root cohesion was greater in the VR samples than in the HR samples. SWC was negatively related to both soil shear strength and root cohesion. These results could provide useful information on the architectural characteristics of woody root system and expand the knowledge on shallow slope stabilization and soil erosion control by plant roots on the Loess Plateau.

Keywords: root distribution; root cohesion; root extinction coefficient; soil erosion; soil reinforcement; Loess Plateau

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In the semi-arid regions of the Loess Plateau, the mean annual precipitation is low and the mean annual evaporation is relatively high (Zhou and Shangguan, 2007). The soil on the plateau is mainly formed from wind-deposited loess, which is susceptible to the forces of wind and water, and is one of the most erodible soils in the world (Laflen et al., 2000). Black locust (*Robinia pseudoacacia* L.) and Chinese pine (*Pinus tabulaeformis* Carr.), two typical tree species in arid and semi-arid regions (Yang et al., 2006; Luo et al., 2007; Zhen and Shangguan, 2007), were widely planted on the Loess Plateau in the past 20 years for conserving the soil and water and improving the ecological environments in this region.

Soils with vegetation are more resistant to erosion than those with no plants (De Baets et al., 2008). Experiments have verified that plant roots can increase soil shear strength by mechanical and hydrological effects (Greenway, 1987; Gray and Sotir, 1996; Gyssels et al., 2005). The most important mechanical effect is root reinforcement (Gray and Sotir, 1996), especially root cohesion (Waldron and Dakessian, 1981; Abe and Ziemer, 1991; Abernethy and Rutherfurd, 2001; Simon and Collison, 2002; Tosi, 2007; De Baets et al., 2008; Bischetti et al., 2009). Root cohesion is produced by the transfer of shear stress in the soil

*Corresponding author: ChaoBo ZHANG (E-mail: zhangchaobo@tyut.edu.cn)
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to tensile resistance in the roots (Wu et al., 1979; Fan and Su, 2008; Zhang et al., 2010). The cohesion can be evaluated by two parameters, i.e. root tensile strength and root cross-section area per unit soil area (Waldron, 1977; Wu et al., 1979). Generally, the mechanical effect of plant roots on soil shear strength is related to the specific characteristics of the root system (Abdi et al., 2010). The stress distribution of roots is ultimately determined by the morphological characteristics of roots (Stokes et al., 2008). Therefore, root distribution is an important consideration in the transfer mechanism of stress from the soil to the roots.

Research on tree roots is inherently laborious and time consuming because of the large soil volume contacted by the tree roots (Livesley et al., 2000). To our knowledge, few studies have focused on the root distribution of black locust and Chinese pine on the Loess Plateau (Liu et al., 1987; Li et al., 2004; Cao, 2006; Dong et al., 2007; Zhou and Shangguan, 2007). Furthermore, the root distribution of the tree species from these previous studies differed significantly. For example, the black locust on the Weibei Loess Plateau is shallow-rooted by the study of Liu (1987) while deep-rooted by the study of Zhao (2000). Roots are designed to anchor the plant to its substrate and to absorb nutrients and water (Robinson, 1991). The distribution characteristics of roots are influenced by the variations in environmental conditions.

Compared with above-ground biomass, knowledge of root biomass and its spatial distribution is considerably limited (Mokany et al., 2006). For implementing a reasonable management practice for soil erosion control, a thorough understanding of root distribution and competition below ground is required. Most of the previous researches on root cohesion on the Loess Plateau were different from those in North America (Schmidt et al., 2001; Roering et al., 2003), Asia (Nilaweera and Nutalaya, 1999; Fan and Su, 2008) and Europe (Mattia et al., 2005; Tosi, 2007; Bischetti et al., 2009). Although many studies have been conducted to improve the understanding of the effects of certain environmental factors on root cohesion in recent years, such as soil moisture content (Fan and Su, 2008), planting density (Loades et al., 2010), tree age and stand structure (Genet et al., 2008), researches on the vertical root distribution of tree species are still limited. To quantify root cohesion, *in situ* or in laboratory direct shear tests were usually performed (Campbell and Hawkins, 2003; Fan and Su, 2008). Given that Liu et al. (2006) started studying the shear strength of forest roots-loess composites using consolidated undrained triaxial compression tests, these tests are now be used in root cohesion studies (Zhang et al., 2010).

In this study, the vertical root distribution characteristics of black locust and Chinese pine on the Loess Plateau were analyzed, and the differences of the root distribution between the two species were determined. The effects of two typical root distribution (namely, horizontal root (HR) and vertical root (VR)) on root cohesion of black locust were also investigated using triaxial compression tests.

1 Study area and methods

1.1 Study area

Field experiments were conducted in May 2008 on a slope at the Tianshui Soil and Water Conservation Experimental Station (34°36′N, 105°42′E; 1,350 to 1,500 m asl) of the Yellow River Conservancy Commission in the Luoyugou watershed in Tianshui city, Gansu province, China (Fig. 1). The study area is characterized by a semi-arid continental climate, with warm summers and cold winters. The annual mean temperature is 10°C, and the mean annual precipitation is 534 mm with 80% occurring from May to October. The soil in the study area is typical loess with low-porosity. Pure stands of trees are evenly planted in the watershed to conserve soil and water. These forests have understory shrubs and few grasses. Five-year-old black locust and fifteen-year-old Chinese pine are widely distributed in the study area.

1.2 Root excavation

In this study, black locust and Chinese pine were investigated on a slope with a gradient of approximately 19° at the experimental station. The spacing between individual trees was 2.5 and 3.0 m for black locust and Chinese pine, respectively. Two sample plots were designed for each species, and each plot had an area of 20 m×20 m. Four uniform and healthy trees were selected randomly in the middle part of each plot. Soil removal from around the roots was accomplished with spades and small hand tools (e.g. hand pick, forks, screw drivers, forceps and needles). Manual

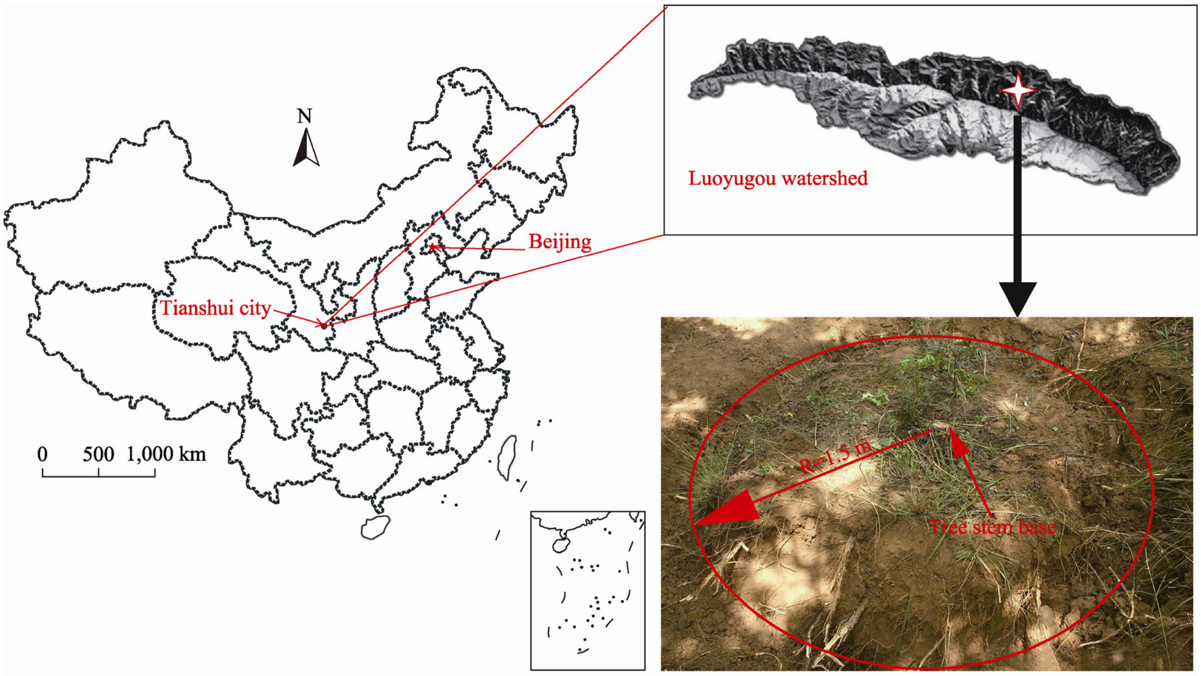

Fig. 1 The location and topography of the study area and the demonstration of root excavation

excavation was conducted on the root systems of black locust (eight individuals) and Chinese pine (eight individuals) for root distribution analyses. The excavation method of the entire root system was similar to the method described by Atkinson (2000). Roots with diameters of <3 and >3 mm were considered fine roots and coarse roots, respectively (Reubens et al., 2007). In the manual excavation of heavy clay soils, the lose of fine root parts with diameter of <1 mm was inevitable because the fine roots were difficult to separate from soil. Although parts of the fine roots were not sampled, the extent and branch of the whole roots could be directly reflected by the distribution of roots with diameters of >1 mm (other fine roots and coarse roots); thus, sufficient information on the mechanical properties of plants in terms of slope reinforcement was provided by this distribution (Reubens et al., 2007). Roots in different diameter classes of 1–3, 3–5, 5–10, 10–20 and >20 mm (abbreviated as D1, D2, D3, D4 and D5, respectively) were investigated. The stumps were not considered within these diameter classes.

Some respective measurements of black locust and Chinese pine were in the following: heights of 6.1±0.1 (mean±SE) and 3.9±0.2 m; stem base diameters of 7.6±0.4 and 11.6±1.3 cm; breast diameters of 5.6±0.4 and 8.8±1.0 cm. According to the study conducted by Liu et al. (2007), Chinese pine and black locust have tap and flat roots, respectively. In the study area, the root growth of the species was restricted because of the dry soil conditions. Given that the spacing between individual trees was only 2.5 and 3.0 m for black locust and Chinese pine, respectively, an inevitable overlap existed between the fine root parts of adjacent trees. The coarse roots were distributed mostly in a radius of 1.5 m, so this radius was chosen for root excavation (Fig. 1). A 1.5-m radius was sufficient to exhibit most of the roots, particularly the structures relevant to the mechanical reinforcement of soil. Generally, most roots of black locust and Chinese pine were found in the soil layer of 0–100 cm (Liu et al., 2007). Thus, the depth of root excavation in our study also reached only 100 cm. Soil layers at depths of 0–20, 20–40, 40–60, 60–80 and 80–100 cm (abbreviated as S1, S2, S3, S4 and S5, respectively) in the cylinder (1.5 m radius and 1.0 m height) was excavated. After excavation, the entire root system was rearranged into its original position. During excavation, some small parts of the roots were not easy to keep intact because of the compact soil surrounding the roots. Therefore, these small parts were cut from the roots and dug out from the soil, and then restored to their original positions in the root system using tapes. Root length was measured by a steel tape with 1-mm accuracy, and root diameter was measured at quarter points across the root length using a slide gauge with 0.02-mm accuracy. The angles between the roots and the horizontal plane were measured with a universal bevel protractor with an accuracy of 2 minutes. The roots of all diameter classes were dried in an oven at 70°C and weighed.

1.3 Root cumulative model

We used a vertical root distribution model basing on the following asymptotic equation for studying the characteristics of root distribution (Gale and Grigal, 1987):

$$Y=1-\beta^d. \quad (1)$$

Where Y is the cumulative root fraction (a proportion between 0 and 100%) from the soil surface to depth d (cm), and β is the fitted root extinction coefficient. β is the only parameter estimated in the model and provides a simple numerical index of root distribution. High β values (e.g. 98%) correspond to a greater proportion of roots at a deep soil layer, while low β values (e.g. 90%) imply a greater proportion of roots near the soil surface. The attainment of the maximum distribution of roots in both vertical and horizontal directions at an early age is verified (Coile, 1937). Although the root system size depends on tree age and root density, the root distribution model is established at a certain point in the early stage of root growth and is not changed after this stage. Thus, the influences of different ages of black locust and Chinese pine on the vertical root distribution patterns of the two species should be insignificant. The foliage types of plants should be noticed in the comparison, considering that black locust is a deciduous tree whereas Chinese pine is an evergreen tree.

Basing on the ratio of horizontally oriented roots to stem diameter, we used the following equation to calculate the competitive index (van Noordwijk and Purnomosidhi, 1995):

$$CI=\sum D_{hor}^2/DBH^2. \quad (2)$$

Where CI represents the competitive index, D_{hor} (cm) is the proximal diameter of the roots descending into the soil at an angle less than 45°, and DBH (cm) is the stem diameter at the breast height. CI can indicate the ability of roots to extend and compete for resources horizontally, and a greater CI indicates the plant has more horizontal roots.

1.4 Triaxial compression tests

Loess soil and black locust roots were both sampled from the field at the experimental station. Soil was collected from a soil profile with 100-cm depth using a spade. Roots were cut with scissors and placed in plastic bags, and then stored in a laboratory refrigerator at 4°C. Triaxial compression tests were conducted with a KTG Automatic Triaxial Compression System (Beijing Huakan Technology Co. Ltd., China) in a soil mechanics laboratory in 2008 (Zhang et al., 2010). Test samples were repacked in a cylinder-shaped sampler with 80 mm height and 39.1 mm diameter. All samples were tested under four soil water content (SWC) conditions of 12.7%, 15.0%, 18.0% and 20.0% with the corresponding soil wet density of 1.58, 1.61, 1.65 and 1.68 g/cm^3, respectively (the dry bulk density was 1.4 g/cm^3). In addition to the columns of soil-root composites, plain soil columns were also prepared as controls. Two distribution types of roots used in the soil-root composites to study the effects of different root distribution types on root reinforcement (Fig. 2): (1) one VR with 70 mm in length in the sample center; and (2) two HRs with 35 mm in length respective in the sample center. The diameter of the root was 5.1 mm. The consolidated–drained triaxial compression tests were conducted. Shear velocity was 0.012 mm/min in the tests.

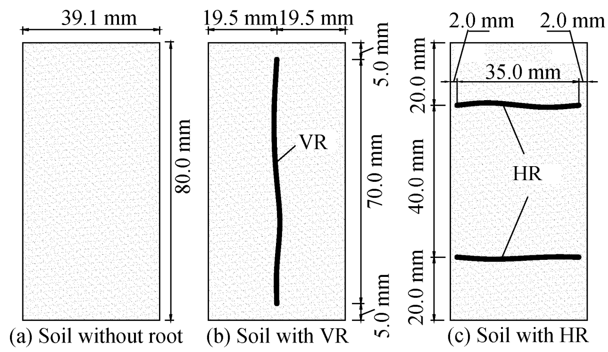

Fig. 2 Schematic of three types of soils. VR: vertical root; HR: horizontal root.

1.5 Root cohesion evaluation

The shear strength (τ_f, kPa) of a test sample, either plain soil or soil-root composite, is directly related to the normal stress (σ, kPa) acting on the shear plane when other physical properties of the sample are certain. The relationship between shear strength and normal stress was expressed by Coulomb's law (Waldron, 1977):

$$\tau_f = \sigma \tan\varphi + C. \quad (3)$$

Where φ (°) is the internal friction angle and C (kPa) is the integrated cohesion in a soil-root composite. The φ and C values in the soil-root composite differed from those in the plain soil. The presence of roots in soil produces a reinforced matrix wherein stress is transferred during the loading of pressure (Thorne, 1990). The transfer mechanism of stress from one component to another in the soil-root composite is similar to the transfer mechanism in the steel-reinforced concrete.

The integrated cohesion in a soil-root composite is equal to the sum of soil cohesion and root cohesion. Thus, the root cohesion was evaluated by the following equation:

$$C_r = C - C_s. \quad (4)$$

Where C_r (kPa) is the root cohesion and C_s (kPa) is the soil cohesion.

1.6 Statistical analyses

The data was analyzed using SPSS 15.0 (SPSS, USA). A regression analysis was used to fit Eq. 1 to the profile of cumulative root fraction (Y) from the soil surface to depth d. An independent samples t-test was used to test the differences of root length and root biomass between black locust and Chinese pine, and ANOVA was used to test the differences of root length and root biomass among different soil depths and root diameter classes. A least significant difference test was also used to control the familywise error rates after all comparisons were made. Differences were considered significant at $P<0.05$.

2 Results and discussion

2.1 Vertical root distribution of black locust and Chinese pine

Table 1 lists the root length in five root diameter classes for black locust and Chinese pine. With increasing root diameter, the mean root length for each species increased initially and then decreased. In addition to D5, the mean root length of black locust was significantly greater than that of Chinese pine in other four root diameter classes. The root lengths of both species were all greater in D3 and D4 than in other three diameter classes.

The percentage of total root length was equal to the root length in each diameter class divided by the total length of each species. With increasing root diameter, the percentage of total root length of both black locust and Chinese pine firstly increased and then decreased (Fig. 3a). For black locust, nearly half of total root length was concentrated in D3; whereas for Chinese pine, it was mainly distributed in D4. Very few percentage of total root length for black locust was concentrated in D5; however, nearly 25% of total root length for Chinese pine was concentrated in D5.

For the two species, the values of the average root length first increased and then decreased with increasing soil depth (Table 2). In S5, the average root length sharply decreased to 5.0% and 7.5% of total root length in black locust and Chinese pine, respectively. Among the five soil layers, the average root length was significantly highest in S2 for both species. Furthermore, the average root length in S2 was also significantly different from that in other four soil layers for each species.

Table 1 Root length in five root diameter classes for black locust and Chinese pine

Species	Item	Root diameter class				
		D1	D2	D3	D4	D5
Black locust	Mean root length (cm)	172.9^{a}	296.6^{a}	1,003.9^{b}	949.8^{b}	27.8^{a}
	Standard error	64.2	62.3	148.2	185.9	25.0
	Range of root length (cm)	20–507	90–630	557–1,602	300–1,672	0–202
Chinese pine	Mean root length (cm)	6.3^{a}	113.1^{ad}	331.0^{b}	531.3^{c}	282.6^{bd}
	Standard error	6.3	30.3	81.6	100.0	70.2
	Range of root length (cm)	0–50	0–225	126–767	230–918	14–521
	P	0.022	0.019	0.001	0.067	0.004

Note: D1, D2, D3, D4 and D5 represent roots in different diameter classes of 1–3, 3–5, 5–10, 10–20 and >20 mm, respectively. Different letters within a row denote significant differences between different root diameter classes at $P<0.05$. P values indicate the differences in root length between the two species in the same root diameter class.

With increasing root diameter, the average root biomass of black locust increased to the maximum value of 552.4 g in D4 and then decreased to 124.5 g in D5 (Table 3). However, the average root biomass of Chinese pine increased with increasing root diameter, except for a slight decline in D2. For black locust, the root biomass was significantly greater in D3 and D4 than in the other three classes, whereas for Chinese pine, it was significantly higher in D5 than in the other four classes.

Figure 3b shows the percentage of total root biomass (the root biomass in each diameter class divided by the total biomass of each species) in different root diameter classes for both species. With increasing root diameter, the percentage of total root biomass increased and then decreased for black locust, whereas it continually increased for Chinese pine. Roots with diameter of <5 mm constituted a small percentage of

Table 2 Average root length and percentage of total root length in five soil layers for black locust and Chinese pine

Species	Item	Soil layer				
		S1	S2	S3	S4	S5
Black locust	Mean root length (cm)	326.1^{ac}	1,102.5^{b}	492.9^{a}	238.6^{ac}	115.4^{c}
	Standard error	161.0	179.8	119.6	99.0	53.7
	Percentage of total root length (%)	12.7±5.3	52.4±7.9	21.9±5.1	9.0±2.9	4.0±1.6
Chinese pine	Mean root length (cm)	114.6^{a}	473.9^{b}	248.1^{ab}	151.8^{a}	80.7^{a}
	Standard error	56.2	184.0	50.8	39.9	29.0
	Percentage of total root length (%)	16.1±8.5	35.7±8.8	26.8±7.0	14.1±4.0	7.3±2.7
	P	0.235	0.028	0.081	0.429	0.579

Note: S1, S2, S3, S4 and S5 represent soil layers at depths of 0–20, 20–40, 40–60, 60–80 and 80–100 cm, respectively. Different letters within a row denote significant differences between different soil layers at $P<0.05$. *P* values indicate the differences in root length between the two species in the same soil layer.

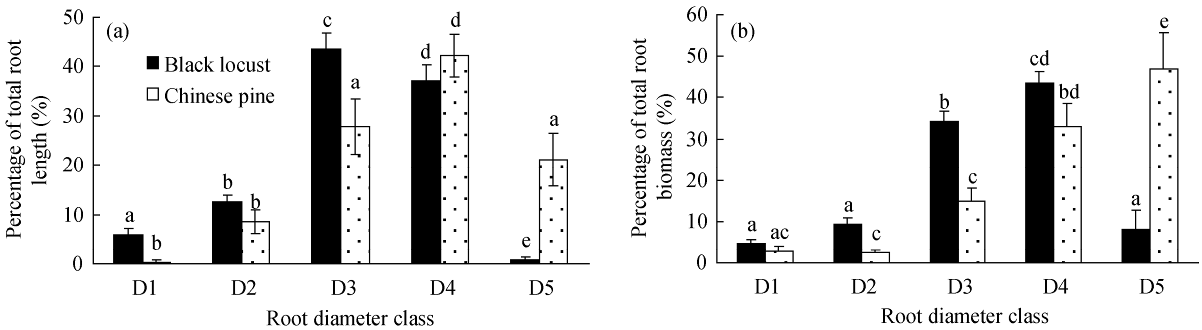

Fig. 3 Percentages of total root length (a) and biomass (b) for black locust and Chinese pine in different root diameter classes. Error bars indicate the standard error for the total root length and biomass at each root diameter class. Different letters denote significant differences in different diameter classes of each species and between the two species in the same root diameter class at $P<0.05$.

Table 3 Root biomass in five root diameter classes for black locust and Chinese pine

Species	Item	Root diameter class				
		D1	D2	D3	D4	D5
Black locust	Mean root biomass (g)	53.8^{a}	107.0^{a}	395.8^{b}	552.4^{b}	124.5^{a}
	Standard error	15.8	18.4	61.0	106.7	95.6
	Range of root biomass (g)	11.1–154.0	37.4–185.6	170.0–724.0	150.2–1,118.4	0.0–969.0
Chinese pine	Mean toot biomass (g)	25.2^{a}	19.7^{a}	128.7^{a}	338.6^{a}	818.8^{b}
	Standard error	6.3	5.1	11.3	47.8	293.8
	Range of root biomass (g)	7.4–55.7	5.5–48.0	68.7–157.6	78.6–513.9	40.9–2,048.8
	P	0.025	0.016	0.001	0.096	0.007

total biomass. Most of the root biomass was gathered between 5 and 20 mm diameters for black locust (78%) and in >10 mm diameter for Chinese pine (80%). The results showed that the coarse roots contributed more biomass to the total biomass than the fine roots.

The observed and fitted cumulative proportions of root length for black locust and Chinese pine with soil depths are shown in Fig. 4. Although the observed cumulative root fraction of both black locust and Chinese pine was relatively smaller than the fitted sample in the soil depth of 0–20 cm, the observed data well matched the fitted sample overall. Thus, the root distribution of the two species was simulated well by the vertical root distribution model (R^2=0.96 for black locust and R^2=0.90 for Chinese pine).

Deep rooting profile for the two species showed that 65.1% of black locust roots and 51.8% of Chinese pine roots were concentrated in the soil layer of 0–40 cm (Table 2). Further, 96.0% of black locust roots and 92.7% of Chinese pine roots were concentrated in the soil layer of 0–80 cm. According to the β values (96.2% and 97.2% for black locust and Chinese pine, respectively), a deeper rooting profile was shown in Chinese pine than in black locust. The *CI* was 1.20 and 0.68 for black locust and Chinese pine, respectively (Table 4).

More than 50% of total root length for both black locust and Chinese pine were centered in the soil depth of 0–40 cm (Fig. 4), which was consistent with the results of Schenk and Jackson (2002). Although black locust was 10 years younger than Chinese pine in this study, the roots of black locust were significantly longer than those of Chinese pine in all root diameter classes except for D5. Furthermore, more roots of black locust rather than of Chinese pine were observed in the soil depth of 0–60 cm (Table 2; Fig. 4). A significant difference existed in the root distribution between the two species. Black locust commonly has more roots than Chinese pine at the same age. Plant roots can play an essential role in slope stabilization and erosion control (Gyssels et al., 2005). Yang et al. (2007) studied the anti-erosion capability of soil below four kinds of shrubbery and found that the soil anti-erosion capability is positively correlated with root length in the soil layer of 0–20 cm. In this layer, the root length of black locust was significantly greater than that of Chinese pine, implying that black locust was preferably adaptive for soil erosion control in the study area.

Studies on the Loess Plateau have verified that water is the main limiting factor for vegetation growth (Yang and Shao, 2000). Thus, the competition for water between the roots of different trees in this arid region is astonishingly intense. A small value of *CI* in Chinese pine indicated that the roots of Chinese pine have more advantages in obtaining water than those of black locust.

More than 60% of black locust roots and 50% of Chinese pine roots were concentrated in the top soil layer of 0–40 cm. The largest portion of coarse root biomass located in the upper soil layer was also observed by other researchers (e.g. Danjon et al., 1999).

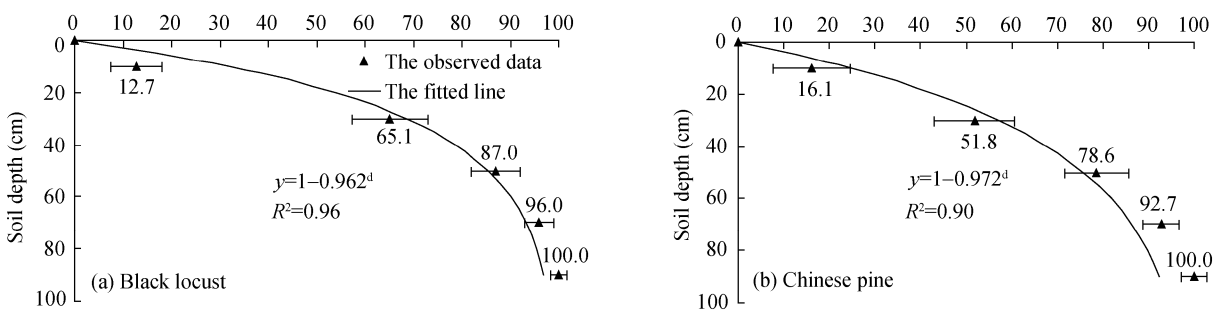

Fig. 4 Cumulative root fraction with soil depths for black locust (a) and Chinese pine (b)

Table 4 Variation in competitive indices of black locust and Chinese pine (mean±SE)

Species	*n*	*DBH* (cm)	DBH^2 (cm^2)	$\sum D^2_{hor}$ (cm^2)	*CI*
Black locust	8	5.62±0.48	33.19±5.50	40.70±8.85	1.20±0.14
Chinese pine	8	8.80±1.00	84.41±17.22	64.16±16.29	0.68±0.10

This root distribution pattern is important for soil reinforcement. A larger *CI* value indicates more root areas or roots spreading horizontally. Similar results have been reported in Indonesia. For example, according to the *CI* analysis of 19 five- to seven-year-old tree species, high and low *CI* values were found in shallow-rooted species and deep-rooted species, respectively (van Noordwijk and Purnomosidhi, 1995). The β and *CI* values in this study showed that our two sampled species were all deep-rooted plants and the root depth of Chinese pine was relatively deeper than that of black locust.

One possible reason for the existence of deep-rooted plants in arid and semi-arid regions is that the dry soil drives the plant roots to extend deeply for water and nutrients utilization. A deep-rooted pattern is usually found in situations wherein water is limited, such as in arid soil (Canadell et al., 1996). This root pattern is beneficial for obtaining below-ground resources and reducing competition with nearby plants. Chinese pine is a type of plant with short root length in the upper soil layer, and this root pattern shows a good capability of avoiding competition with adjacent individuals for resources.

In this study, the root patterns of the two species were investigated only in summer, and the effects of water and nutrient distribution in the soil on root distribution were not considered. Therefore, more information is still required on the temporal root distribution dynamics of both black locust and Chinese pine on the Loess Plateau.

2.2 Root cohesion of black locust

Table 5 summarizes the indices of shear strength, i.e. φ and *C*, of all samples obtained by the triaxial compression tests using the Mohr–Coulomb failure criterion. With increasing SWC, the *C* values of the three kinds of soil samples (soil without root, soil with HR and soil with VR) decreased. Furthermore, under the four SWC conditions, compared with the plain soil, the *C* values of the soil-root composites increased significantly, particularly in the soil with VR. By contrast, similar variations in φ values were not obtained. Under the SWCs of 12.7%, 15.0% and 18.0%, compared with the plain soil, the φ values of the soil-root composites decreased. However, under the 20.0% SWC condition, the φ values increased by 6% and 13% in the soil with VR and HR, respectively, compared with the plain soil.

Root cohesion was greater in the soil with VR than in the soil with HR. With SWC increasing from 12.7% to 20.0%, root cohesion decreased by 86% and 64% in the soil with VR and HR, respectively. Root cohesion was in the range of 4 to 35 kPa in the soil-root composites.

Mechanical soil reinforcement by roots is validated by root cohesion. Root reinforcement depends on the root tensile strength and root distribution in soils (Wu, 1976; Waldron, 1977). The most general and popular model for evaluating root cohesion is perpendicular root model (Wu, 1976; Waldron, 1977). Soil moisture can affect the measurements of root cohesion by different soil cohesion conditions. Soil moisture modifications by evapotranspiration and interception in the foliage can limit the accumulation of pore water pressures (Gray and Leiser, 1982). Pore water pressure plays an important role in the effective stress of soil and is useful in the prediction of soil shear strength (Terzaghi, 1936; Fredlund et al., 1978). Many studies have reported that soil cohesion decreases with increasing soil moisture content (e.g. Jimoh, 2005; Osman and Barakbah, 2006; Pollen, 2007; Fan and Su, 2008; Zhang et al., 2010). Soil moisture affects root cohesion by influencing the root failure mode (root breaking or pullout) in rooted soil. Root breaking is predominant in low-moisture soil, whereas root pullout is exhibited in high-moisture soil (Pollen, 2007).

Table 5 Root cohesion (C_r) and soil shear strength indices (C and φ) under four soil water content (SWC) conditions

Soil type	SWC											
	12.7%			15.0%			18.0%			20.0%		
	C (kPa)	φ (°)	C_r (kPa)	C (kPa)	φ (°)	C_r (kPa)	C (kPa)	φ (°)	C_r (kPa)	C (kPa)	φ (°)	C_r (kPa)
Soil without root	29	27.0	–	25	25.6	–	20	25.0	–	18	22.3	–
Soil with VR	64	23.0	35	53	22.7	28	30	23.6	10	23	23.7	5
Soil with HR	40	26.6	11	34	24.7	9	28	22.5	8	22	25.3	4

Root diameter can also affect root cohesion. Fine roots usually contribute to an increase in soil cohesion, whereas coarse roots tend to provide structural support against instability. Experimental measurement *in situ* or in the field is still an effective approach in evaluating root cohesion. Unlike direct test which only provides data for the upper soil layer and aims to detect the shear zone of composites, the triaxial compression test could study drain and stress research objects under different existing conditions (e.g. SWC and root distribution) without any hypothesis of potential failure plane, and provide another method to evaluate root cohesion.

The larger root cohesion in the soil with VR than in the soil with HR in this study could be explained by the perpendicular root model, which calculates root cohesion by using root tensile strength and root area ratio (RAR). RAR is defined as the fraction of the soil cross-sectional area occupied by roots per unit area (Gray and Leiser, 1982). More roots that grow horizontally indicate fewer RAR. Consequently, less root cohesion may be obtained. Therefore, VR can affect root cohesion as planting density (Loades et al., 2010). Similar to the results reported by Fan and Su (2008), the shear strength of soil in this study decreased with increasing SWC. However, root cohesion decreased with increasing SWC in this study, which is inconsistent with the results of Fan and Su (2008). In the two typical mechanical models (i.e. the perpendicular root model and fiber bundle model) for evaluating root cohesion, (Pollen and Simon, 2005), the effect of SWC on root cohesion is not included effectively. A high SWC may be fatal to the stability of vegetated slopes because of the possible sharp decrease in soil shear strength (Osman and Barakbah, 2006).

3 Conclusions

In this study, we attempted to show the overall vertical root distribution of black locust and Chinese pine in a semi-arid land on the Loess Plateau of Northwest China, and measured the root cohesion of black locust under different SWC conditions and root distribution types using triaxial compression experiments. The results showed that more than half of Chinese pine and black locust roots were distributed in the upper soil layer of 0–40 cm. The roots of black locust were significantly greater than those of Chinese pine in length and biomass. The roots of black locust and Chinese pine tended to spread horizontally and stab vertically, respectively, even though both two species were deep-rooted plants. The results of the root cohesion of black locust indicated that VR could produce greater root cohesion than HR under the same root length and root diameter. Root cohesion decreased with increasing SWC. SWC was important factor affecting root cohesion because it was negatively related to soil shear strength and root cohesion. These results are beneficial to the understanding of soil reinforcement by plant roots on the Loess Plateau.

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