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Root Distribution and Root Cohesion of Two Herbaceous Plants in the Loess Plateau of China

Qihong Yang [1], Chaobo Zhang [2,*], Shiming Yao [1] and Jing Jiang [2]

[1] Key Laboratory of the Regulation and Flood Control of Middle and Lower Reaches of the Yangtze River under Ministry of Water Resources, Yangtze River Scientific Research Institute, Wuhan 430010, China; yangqh@mail.crsri.cn (Q.Y.); yaoshiming@mail.crsri.cn (S.Y.)

[2] College of Water Resources Science and Engineering, Taiyuan University of Technology, Taiyuan 030024, China; jiangjing@tyut.edu.cn

* Correspondence: zhangchaobo@tyut.edu.cn; Tel.: +86-351-6111216

Abstract: In order to understand the root morphology distribution and mechanical properties of typical herbaceous plants, and to evaluate the ability of soil reinforcement by the plant roots, root morphology investigation, single root tensile test in laboratory and root cohesion evaluation by the Wu-Waldron model were carried out on two local representative herbaceous plants, *Kochia scoparia* (L.) Schrad and *Artemisia sacrorum* Ledeb. in the Loess Plateau of China. The results showed that the root morphological indexes (root number, single root diameter, root cross-sectional area, root surface area, root volume and root area ratio) of the two herbaceous plants decreased with the increase in soil depth, and the ratio of root to shallow soil layer was the highest in the 0–10 cm soil layer. The efficiency of root reinforcement could be higher in the shallow soil layer less than 10 cm. A positive correlation was observed between the root tensile force and root diameter in power function or exponential function, and a negative correlation was observed between the root tensile strength and root diameter in power function. The root cohesion of *Kochia scoparia* (2.73 kPa, or 0.92 kPa–1.37 kPa) was greater than that of *Artemisia sacrorum* (1.60 kPa, or 0.54 kPa–0.8 kPa), which could be used as the preferred herbaceous plant species for soil erosion control. The results could provide a scientific basis for selecting dominant species in the fields of ecological slope protection and soil and water conservation plant engineering in the loess area.

Keywords: herbaceous plant; root area ratio (RAR); root tensile strength; root cohesion; soil reinforcement

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1. Introduction

The Loess Plateau is located in the arid and semi-arid area of China, having only 200–700 mm precipitation and half of that in the summer [1]. The soil of the Loess Plateau is loose with vertical joints, which is easily eroded. The soil erosion modulus in most areas ranges from 1000 $t/km^{-2}a^{-1}$ to 5000 $t/km^{-2}a^{-1}$. The soil erosion modulus in Huangpuchuan Basin is the highest, which is close to 25,000 $t/km^{-2}a^{-1}$ [2,3]. The loose and porous texture of loess, uneven distribution of precipitation and unreasonable land use by humans leads to frequent geological disasters, such as slope destabilization, which aggravates soil erosion. Vegetation is the most active and effective factor to prevent soil erosion. Since as early as the 1960s, the United States has attached great importance to the role of slope ecological engineering in soil erosion and slope destabilization [4]. In recent years, the use of plants to prevent soil erosion, slope instability and other geological disasters has also been widely acknowledged by scholars worldwide [5–8].

The mechanical effect of plants on soil reinforcement is mainly manifested in that plant roots can transfer soil shear stress through their own tension and improve soil shear strength. Wu et al. [9] show that plant roots could improve soil shear strength mainly by improving soil cohesion, and have no obvious effect on the soil's internal friction angle. Therefore, the mechanical effect of soil reinforcement by roots can be explained

as the increase in the soil cohesion by roots, which is also called root cohesion [9]. Root cohesion depends on root morphology, including root diameter and root number, and root mechanical strength [10,11]. Generally, root cohesion increases with root number, root diameter and root tensile strength [12,13]. However, plants with the highest tensile strength in the root system do not necessarily have the strongest root reinforcement [14,15]. Root cohesion is simultaneously affected by root area ratio and root tensile strength [11].

Plants in different regions with different climatic conditions have different biological properties, which result in obvious differences in root morphology and biomechanical characteristics. The difference in the average root tensile strength is not regular between herbs and trees or shrubs. Herbaceous species could have greater or smaller root tensile strength than woody and shrub species [16–18]. Root tensile strength is dependent on species. Due to low investment, quick growth and good capacity of soil reinforcement, herbaceous plants are widely used in eco-engineering to produce obvious ecological, social and economic benefits. Herbaceous plants are susceptible to environmental stress, such as light, water, temperature, soil nutrition and soil texture, by changing the spatial distribution of roots [19,20].

There are not many comprehensive studies on the root cohesion of plants, especially herbaceous plants, in the loess region. For example, Huang et al. [21] simulated the root reinforcement of herbs in the Loess Plateau based on the asymptotic homogenization theory. They showed that the roots of herbs could modify the stress field of the shallow slope, indicating that more uniform shear stress existed in the root distribution zone and the slope stability could be improved. However, the root distribution and root cohesion were not specified. Root distribution related to root cohesion is reported mainly on woody plants in the Loess Plateau in the past decade [10,22,23]. In the past two years, herbaceous plants have been studied and the root distribution of several herbs introduced [24,25]. Root distribution characteristics including root area ratio, root number, root diameter, root cross-sectional area, root surface area and root volume have not been studied in detail. Moreover, few studies have focused on the root distribution of the two native herbaceous species on the Loess Plateau, *Kochia scoparia* (L.) Schrad and *Artemisia sacrorum* Ledeb, and tried to screen herbaceous plants to reinforce loess based on root cohesion. Therefore, it is necessary to study the root morphological distribution and mechanical properties of pioneer herbaceous plants in the loess area. The soil reinforcement performance of the plants such as root shear or tensile strength [26], root cohesion [27], root soil reinforcement index [28] and species importance values (SIV) [29] should be studied to screen the dominant species for soil bio-engineering in the loess area [30].

Therefore, this study aims (1) to investigate the root morphology, including root number, diameter, cross-sectional area, surface area, volume and root area ratio of two typical herbaceous plants *Kochia scoparia* and *Artemisia sacrorum* in the loess area, (2) to analyze the relationship between root tensile properties and root diameter by a single root tensile test in the laboratory and (3) to evaluate root cohesion using the Wu–Waldron model. The research results can provide a theoretical basis for the selection and planting of herbaceous species in the actual ecological soil reinforcement project in the loess area.

2. Materials and Methods

2.1. Study Area

The roots of *Kochia scoparia* and *Artemisia sacrorum* were investigated and sampled from a hilly slope in the Western Hill Ecological Park, Taiyuan City, Shanxi Province, China (37°84′ N, 112°46′ E). The study area has a warm temperate continental monsoon climate with long dry and cold winters, hot and humid summers, sharp temperature rises in spring and rapid cooling in autumn. The solar radiation is strong with rich light energy and heat there and the annual sunshine time can reach 2400~2600 h. The temperature varies widely from day to night. The annual average temperature is 9.5 °C. The rainfall is mainly concentrated in July to September and the annual average precipitation is about 470 mm [31]. The soil here is sandy loam (Table 1).

Table 1. Characteristics of the soil.

Location	Clay (g·100 g^{-1})	Silt (g·100 g^{-1})	Sand (g·100 g^{-1})	Texture Class
Western Taiyuan	15.2	28.3	56.5	Sandy loam

2.2. Root Morphological Investigation

The root morphology and root tensile characteristics of the two herbaceous plants, *Kochia scoparia* and *Artemisia sacrorum*, which are widely distributed in the study area, were studied. *Kochia scoparia* is an annual herbaceous plant and *Artemisia sacrorum* is a perennial herbaceous plant. The root morphological distribution was investigated on *Kochia scoparia* (five individuals) and *Artemisia sacrorum* (five individuals) with the whole-plant excavation method described by [14,32]. Soil columns with roots were dug out completely and put into sealing bags. The radius of the columns was 20 cm for *Kochia scoparia* and 30 cm for *Artemisia sacrorum* determined by the maximum horizontal distribution of the plant roots. The excavation depth was 40 cm as the soil below the depth was hard and the roots of the herbs were usually distributed up to the depth. The bags of soil columns were taken back to the laboratory under −4 °C storage [11]. The roots were then cleaned carefully in the laboratory every 5 cm layer from the top to the bottom. The number of roots in each layer was counted and recorded. The length of the roots was measured with a steel ruler with an accuracy of 1 mm. The root diameter was measured by an electronic vernier caliper with an accuracy of 0.01 mm. The root diameter of the roots in each soil layer was measured three times. The average value was considered as the root diameter used for the calculation of root cross-sectional area. *Kochia scoparia* had obvious lateral roots in addition to the main roots (Figure 1a), while *Artemisia sacrorum* had primary roots without obvious lateral roots (Figure 1b). Therefore, the primary roots and lateral roots were measured for *Kochia scoparia*, while only the primary roots were measured for *Artemisia sacrorum*. After the measurement of root diameter and root length in each layer, the root indexes, including root cross-sectional area s, root surface area S, root volume V and root area ration (RAR) in each layer were calculated using the following equations [18,33]:

$$s = \sum_{i=1}^{N} \frac{\pi D_i^2}{4} \quad (1)$$

$$S = \sum_{i=1}^{N} h\pi D_i \quad (2)$$

$$V = \sum_{i=1}^{N} h\frac{\pi D_i^2}{4} \quad (3)$$

$$RAR = \frac{AR}{As} \quad (4)$$

where N is the number of roots in each layer, D is the diameter of a single root (mm^2), h is the soil thickness of each layer (mm), Ar is the cross-sectional area of the roots on the shear plane (mm^2) and As is the total area of the soil shear surface (mm^2). The projection area of the maximum circular root distribution range on the horizontal surface was equal to As in this study.

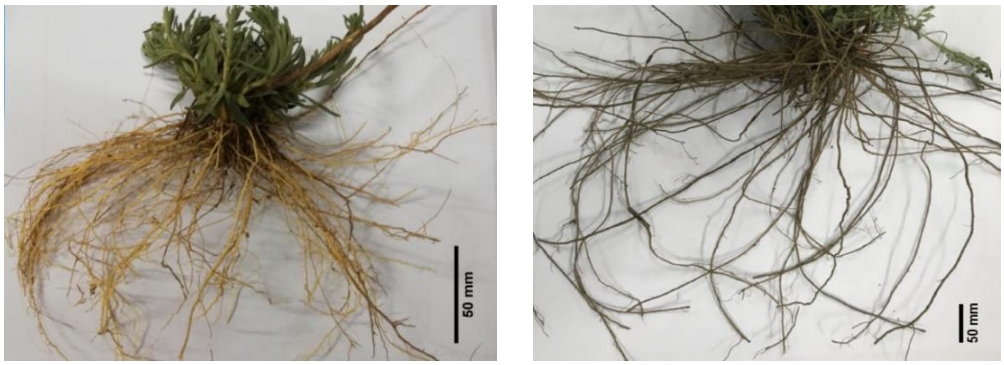
2.3. Root Tensile Tests

Root samples with good growth, undamaged appearance and complete diameter gradient were selected for the root tensile tests. A total of 68 root samples of *Kochia scoparia* and 32 root samples of *Artemisia sacrorum* were tested with the method by [14]. The WDW-5 electronic universal testing system (Changzhou Sanfeng Instrument Technology Co., Ltd., Changzhou, China) was used to determine the peak tensile force F (N) and tensile strength T_R (MPa) of the single root of *Kochia scoparia* and *Artemisia sacrorum*. A gauge length of

100 mm and strain rate of 100 mm·min^{-1} were set in the tests [34]. Before stretching, the diameter of the upper, middle and lower root was measured with an electronic vernier caliper. The average value was taken as the average root diameter of the root sample. The equipment automatically records the maximum tensile resistance of the root specimen when tensile failure occurs. In order to ensure the root activity, the collected root samples were measured within two days. The root tensile strength was calculated by the following formula [18]:

$$T_R = \frac{4F}{\pi D^2} \quad (5)$$

where T_R is root tensile strength (MPa), F is the maximum tensile force (N) and D is average root diameter (mm).



(**a**) *Kochia scoparia* (**b**) *Artemisia sacrorum*

Figure 1. Typical root morphology of herbaceous plants. (**a**) *Kochia scoparia*; (**b**) *Artemisia sacrorum*.

2.4. Root Cohesion Evaluation

The Wu–Waldron model is widely used to evaluate the root cohesion of plants [9,35]. The root cohesion (Cr) in root–soil composites is calculated by the formula [33]:

$$Cr = 1.2 \sum_{i=1}^{N} T_{Ri} \left(\frac{A_{Ri}}{A_S} \right) \quad (6)$$

where T_R is root tensile strength on soil shear surface (kPa) and $\frac{A_R}{A_S}$ is the root area ratio RAR. Based on the root tensile strength and root area ratio, the increased cohesion in the soil due to the presence of roots can be estimated. These two parameters are called the biotechnology root characteristic index [36].

2.5. Data Analysis

The data were analyzed using SPSS 20.0. Analysis of covariance (ANCOVA) was used to analyze the differences in the parameters of the root distribution under different soil depths. An independent-samples T-test was used to compare the difference in the mean values of the root parameters of the two plants. The significance was at the 0.05 level. Different lowercase letters indicate significant differences in the parameters between soil depths. The graphs were plotted using Excel 2013.

3. Results

3.1. Root Number

The number of roots of the two herbaceous plants was related with soil depth in exponential functions (*Kochia scoparia* $y = 154.66e - 0.564x$, $R^2 = 0.819$; *Artemisia sacrorum* $y = 136.34e - 0.561x$, $R^2 = 0.912$; Figure 2). The roots of *Kochia scoparia* were mostly distributed in the 0–30 cm soil layer. The number of roots increased first and then decreased with the increase in soil depth. The maximum average root number was 59 in the 5–10 cm soil layer. No significant difference in the number of roots was observed among the 0–15 cm

soil layers and among the 15–30 cm soil layers. The roots of *Artemisia sacrorum* were distributed in the 0–40 cm soil layer. The maximum average root number was 45 in the 0–5 cm soil layer. The average root number decreased with soil depth. The number of roots in the 0–15 cm soil layers was significantly greater than that in the 15–40 cm soil layers.

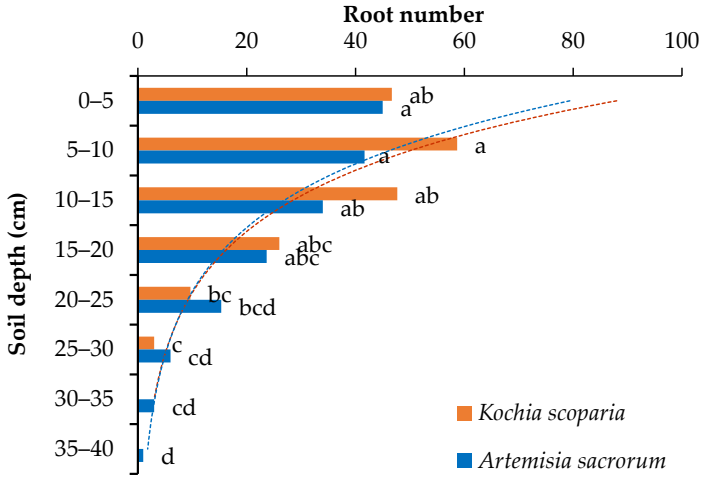


Figure 2. Variation of root number with soil depth (the different lowercase letters indicate significant differences in root number between the soil depths).

3.2. Root Diameter

The average root diameter of *Kochia scoparia* and *Artemisia sacrorum* decreased in power functions with soil depth. (*Kochia scoparia* $y = 0.6687x^{-0.495}$, $R^2 = 0.990$; *Artemisia sacrorum* $y = 0.7403x^{-0.28}$, $R^2 = 0.987$; Figure 3). The root diameter of *Kochia scoparia* ranged from 0.06 mm to 2.69 mm with an average diameter of 0.69 ± 0.06 mm in the 0–5 cm soil layer. The root diameter in 0–10 cm soil layers was significantly larger than that in 10–30 cm soil layers. The diameter of *Artemisia sacrorum* ranged from 0.06 mm to 2.19 mm. The maximum average root diameter was observed in 0–5 cm soil layer (0.75 ± 0.08 mm), which was significantly larger than that in 10–40 cm soil layers (0.47 ± 0.05 mm).

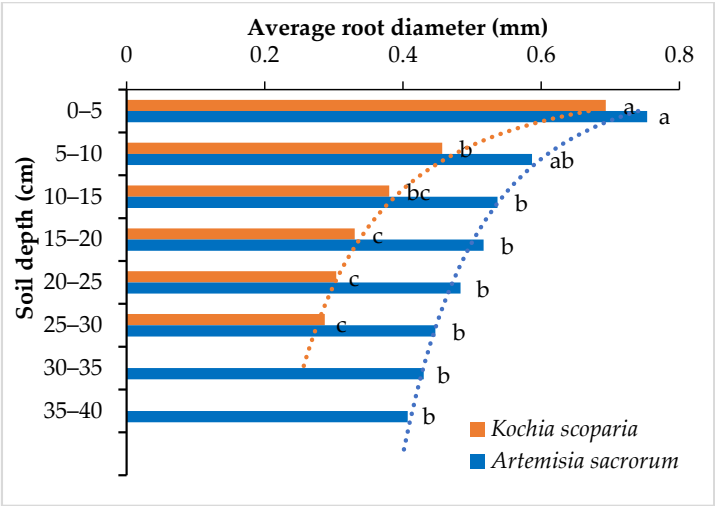


Figure 3. Variation of root diameter with soil depth (the different lowercase letters indicate significant differences in average root diameter between the soil depths).

3.3. Other Root Morphological Indexes

The root cross-sectional area, root surface area, root volume and root area ratio of the two herbaceous plants all decreased exponentially with the increase in soil depth (Table 2). The maximum root cross-sectional areas of *Kochia scoparia* and *Artemisia sacrorum* were

19.73 mm^2 and 21.67 mm^2 observed in the 0–5 cm soil layer, which was significantly greater than that in 10–40 cm soil layers (Figure 4a).

Table 2. Relationships between the root morphological indexes and soil depth for *Kochia scoparia* and *Artemisia sacrorum*.

Plant Species	Fitting Formula	Coefficient of Determination R^2
Kochia scoparia	$s = 70.668e^{-0.929h}$	0.974
	$S = 18{,}280e^{-0.744h}$	0.927
	$V = 3523.6e^{-0.928h}$	0.974
	$RAR = 0.0013e^{-0.916h}$	0.972
Artemisia sacrorum	$s = 61.696e^{-0.681h}$	0.949
	$S = 16{,}117e^{-0.612h}$	0.933
	$V = 3100.1e^{-0.682h}$	0.948
	$RAR = 0.0008e^{-0.695h}$	0.956

s is root cross-sectional area. S is root surface area. V is root volume. RAR is root area ratio. h is soil depth.

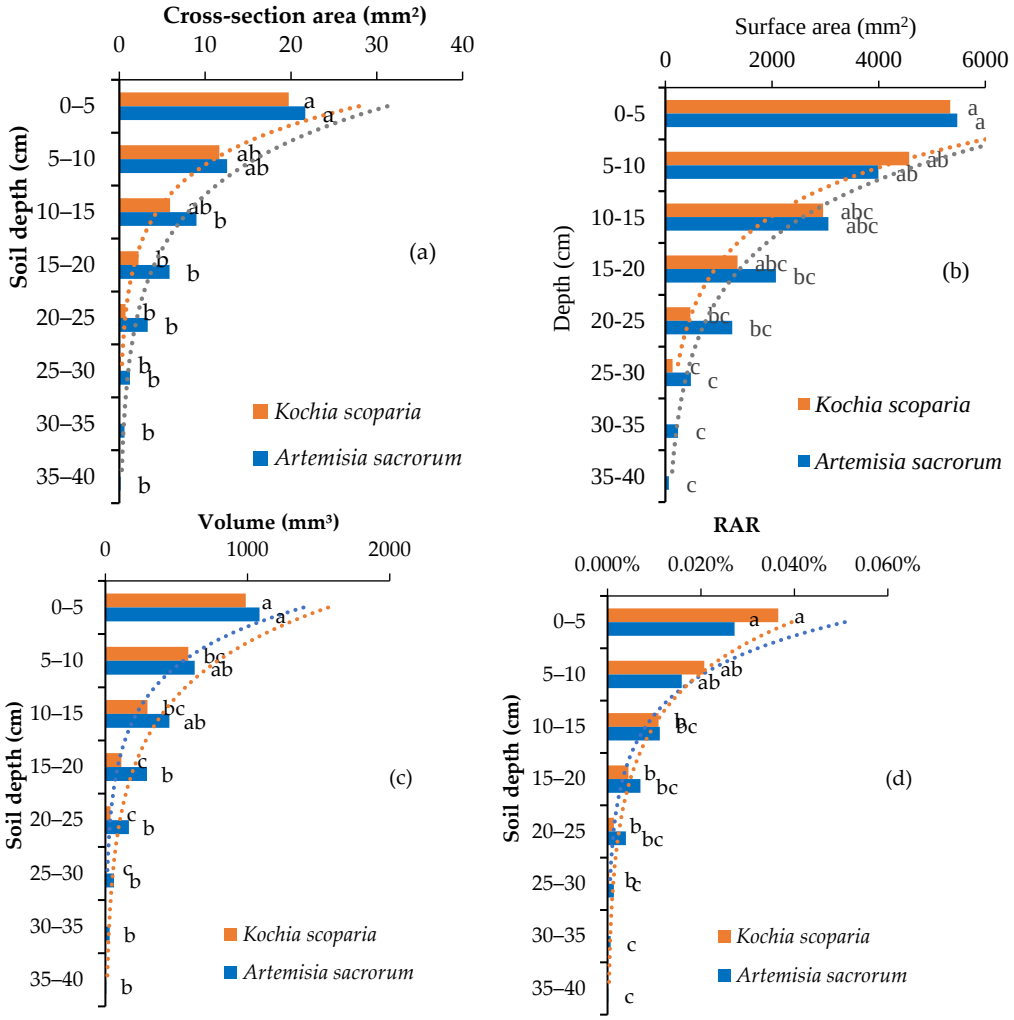


Figure 4. Variation of the root morphological indexes with soil depth. (**a**) Root cross-sectional area; (**b**) root surface area; (**c**) root volume; (**d**) root area ratio (the different lowercase letters indicate significant differences in the root morphological indexes between the soil depths).

The total root surface area of *Kochia scoparia* and *Artemisia sacrorum* was 14,827.30 mm^2 and 16,629.95 mm^2, respectively. The root surface area in the 0–5 cm shallow soil layer accounted for 36.02% (*Kochia scoparia*) and 32.92% (*Artemisia sacrorum*) of the total root surface area, and it was significantly greater than that in 25–40 cm soil layers (Figure 4b).

The total root volume was 2023.00 mm^3 and 2717.26 mm^3, respectively. In the 0–5 cm soil layer, root volume accounted for 48.77% (*Kochia scoparia*) and 39.88% (*Artemisia sacrorum*) of the total root volume. For *Kochia scoparia*, the root volume in the 0–5 cm soil layer was significantly higher than that in 5–30 cm soil layers. For *Artemisia sacrorum*, the root volume in the 0–15 cm soil layers was significantly higher than that in 15–40 cm soil layers (Figure 4c).

The root area ratio (RAR) reflects the proportion of root area in the soil, and it has an important effect on soil physical properties and the absorption of soil nutrients by roots. The RAR of *Kochia scoparia* was 0.0365% in the 0–5 cm soil layer and then decreased to 0.0004% in the 25–30 cm soil layer. The RAR of *Artemisia sacrorum* was 0.0272% in the 0–5 cm soil layer, and then decreased to only 0.0002% in the 35–40 cm soil layer. The RAR was significant greater in the 0–10 cm soil layers than in the soil layers below 10 cm (Figure 4d).

3.4. Root Tensile Properties

In the root tensile tests, 33 of the 68 *Kochia scoparia* root samples were successfully tested with a success rate of 48.53%. For *Artemisia sacrorum*, 26 out of the 32 root samples were successfully tested with a success rate of 81.25%. The root diameter of *Kochia scoparia* ranged from 0.34 mm to 1.45 mm with an average diameter of 0.70 mm, while the root diameter of *Artemisia sacrorum* ranged from 0.43 mm to 1.72 mm with an average diameter of 1.00 mm. the root tensile force increased and root tensile strength decreased with root diameter in power functions (Figure 5). The average root tensile force of the two herbaceous plants was 6.48 N (*Kochia scoparia)* and 12.40 N (*Artemisia sacrorum*), and the average tensile strength was 18.34 MPa (*Kochia scoparia*) and 15.84 MPa (*Artemisia sacrorum*).

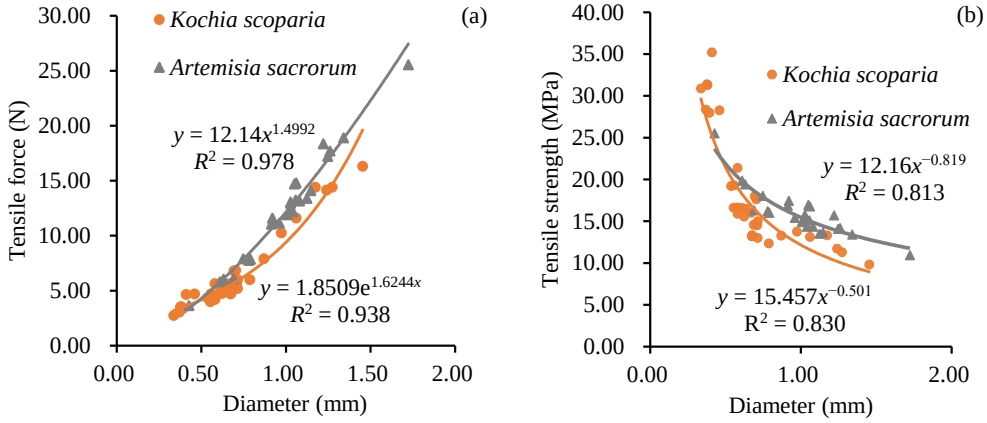


Figure 5. Root tensile properties of *Kochia scoparia* and *Artemisia sacrorum.* (**a**) Root tensile force; (**b**) root tensile strength.

3.5. Root Cohesion

The root cohesion of the two herbaceous plants decreased in logarithmic functions with soil depth (*Kochia scoparia* $y = -5.243 \ln x + 18.084$, $R^2 = 0.971$; *Artemisia sacrorum* $y = -6.81 \ln x + 19.595$, $R^2 = 0.953$; Figure 6). The maximum values appeared in the soil depth of 0–5 cm, in which the cohesion of *Kochia scoparia* was 8.04 kPa, while that of *Artemisia sacrorum* was 5.18 kPa. There was no difference in the cohesion between the two plants in different soil layers below a 10 cm soil depth. The cohesion of the 0–10 cm soil layer was significantly different from that of the 10–30 cm soil layer, and that of the 0–10 cm soil layer was significantly higher than that of the 10–40 cm soil layer. The average root cohesion of the two plants was *Kochia scoparia* (2.73 kPa) > *Artemisia sacrorum* (1.60 kPa)

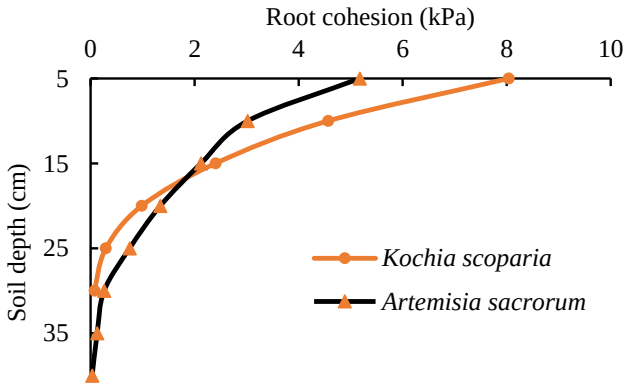


Figure 6. Root cohesion of *Kochia scoparia* and *Artemisia sacrorum*.

4. Discussion

4.1. Root Morphology and Soil Depth

Root indexes such as root number, root distribution depth, root surface area and root volume are important factors affecting soil shear strength [33]. In this study, the roots of the two plants were mainly distributed in the shallow soil layer less than 10 cm. There was no significant difference in the number of roots in the shallow soil layer of 0–10 cm, and the number of roots in the upper soil layer was more than that in the lower soil layer. The root number of *Kochia scoparia* increased first and then decreased with the increase in soil depth, which was similar to the root distribution of *Vetiveria zizanioides* (L.) Nash [37]. However, *Artemisia sacrorum* showed a decreasing trend. The reason might be that the taproot of *Artemisia sacrorum* was developed, and there were no obvious lateral roots. It is consistent with the research by Burylo et al. [38] on six species, including two tree species, *Pinus thunbergii* Parl. and *Quercus pubescens* Willd., two shrubby species, *Genista cinerea* D. C. and *Thymus serpyllum* L., and two herbaceous species, *Achnatherum splendens* (Trin.) Nevsk and *Aphyllantes monspeliensis*. The root number of *Kochia scoparia* and *Artemisia sacrorum* showed an exponential functional relationship with soil depth. The variation trend of the root diameter with soil depth was similar to that of root number. With the increase in soil depth, the average single root diameter decreased as a power function. The decrease in the root surface area can reflect the contact and connection between the root and the soil, and the root volume can reflect the growth status of the plant roots and the space occupied in the soil. The larger surface area and volume of the root result in larger contact area with the soil, a higher proportion of roots in the soil and a stronger root–soil bond. These two parameters decreased with the increase in soil depth. The variation pattern of the root surface area and root volume of *Kochia scoparia* and *Artemisia sacrorum* in the soil layer was the same as that of other herbaceous plants, such as *Artemisia desertorum* Spreng. Syst. Veg. [33], and was also similar to that of some shrub plants, such as *Nerium oleander* L. [8]. The root cross-sectional area, root surface area, root volume and root area ratio of *Kochia scoparia* and *Artemisia sacrorum* met the exponential function relationship with soil depth, and the determination coefficient of the fitting relationship was high ($R^2 > 0.9$). Other studies also showed that root density declined exponentially with soil depth [39], indicating that the relationship between these four morphological indexes of herbaceous roots and soil depth can be expressed by the exponential function. However, it should be noted that the distribution of root area ratio has significant spatial heterogeneity, and the factors such as plant category, growing climate and soil environment will affect the root area ratio of plants to different degrees. There may be an exponential functional relationship between root area ratio and soil depth [40] or a trend of increasing first and then decreasing [3]. Therefore, the root area ratio at different soil depths should be carefully applied to evaluate root cohesion.

4.2. Root Tensile Properties and Root Diameter

The tensile force of *Kochia scoparia* and *Artemisia sacrorum* showed a power function or an exponential function with the increase in root diameter (Figure 5), which was similar to

the results of the relationship between the root tensile force and the diameter of herbaceous plants such as *Paspalum notatum* Flugge [41], and also similar to that of shrub plants such as *Crataegus microphylla* C. koch and *Mespilus germanica* L. [42]. The tensile strength decreased with the increase in root diameter in the power function. This relationship also widely existed in other shrub plants such as *Rosa canina* (L.), *Cotoneaster dammeri* (C.K. Schneid) and *Juniperus horizontalis* (Moench) [27] and other trees such as *Fagus longipetiolata* Seem., *Tamarix ramosissima* Ledeb and *Larix decidua* Mill. [43].

The tensile force of *Kochia scoparia* was lower than that of *Artemisia sacrorum*, but the tensile strength was higher than that of *Artemisia sacrorum*, which was closely related to the root diameter. As the tensile force increases with the increase in the root diameter, and the maximum tensile strength decreases with the increase in root diameter. The average diameter of the root system of *Kochia scoparia* was smaller than that of *Artemisia sacrorum* in this study. Root tensile properties are also directly related with the content of chemical components in the roots. Generally, the content of cellulose and lignin in the roots is positively correlated with tensile strength, while the content of cellulose and tensile strength in the roots is significantly negatively correlated with diameter [44,45]. A higher content of cellulose and lignin in roots can result in greater root tensile strength. For example, the tensile force of *Carpinus betulus* L. (95.36 N) is greater than that of *Acer velutinum* Boiss. (64.15 N), and its tensile strength (43.31 MPa) is also greater than that of *Acer velutinum* (30.77 MPa) [42]. In fact, the differences of average root tensile strength between the two herbaceous plants in this study and that of some trees and shrubs are not obvious, even higher than that of some trees and shrubs. For example, the average tensile strength of *Kochia scoparia* (18.34 MPa) and *Artemisia sacrorum* (15.84 MPa) was higher than that of shrub species *Inula viscosa* L. (11.52 MPa) [18] and tree species *Fraxinus excelsior* (12.74 MPa) [42]. Therefore, the roots of herbaceous plants have a potential advantage in reinforcing shallow surface soil.

4.3. Root Cohesion and Soil Conservation

The root cohesion of *Kochia scoparia* and *Artemisia sacrorum* was mainly concentrated in the 0–10 cm soil layer. With the increase in soil depth, the root cohesion of the two plants decreased (Figure 6). This result was consistent with the research by Burylo, Hudek and Rey [38]. However, other studies showed that the root cohesion of *Lycium andersonii* A. Gray first increased and then decreased with the increase in soil depth [5], which may be due to the differences between plant species and soil conditions, resulting in different distribution laws of root tensile strength and root area ratio in the soil layer.

According to the Wu–Waldron model, the average root cohesion of *Kochia scoparia* and *Artemisia sacrorum* were 2.73 kPa and 1.60 kPa, respectively. However, the Wu–Waldron model assumes that the roots are tightly bound to the soil, and all roots break at the same time when the soil is shearing [9]. In fact, the root system does not reach the ultimate tensile strength at the same time when the soil is sheared. As a result, the Wu–Waldron model overestimated the soil reinforcement of the plant roots [46,47], which led to a larger calculation result of the root cohesion. Research has shown that the actual soil reinforcement effect of roots is only 34–50% of that calculated by the Wu–Waldron model [46,48,49], and its high value is positively correlated with root area ratio [50]. Therefore, in this study, the average root cohesion of *Kochia scoparia* may be 0.92 kPa–1.37 kPa, and that of *Artemisia sacrorum* may be 0.54 kPa–0.8 kPa.

The loess structure is loose and is easily scoured by water, which is liable to soil erosion and rainwater infiltration. Moreover, rainfall irrigation increases the soil water content of the slopes and leads to the deterioration of loess strength, and then induces loess landslide. The study proved that the root system can improve the shear strength of soil by exerting its own tensile characteristics. Chen [51] studied the difference in shear strength between the soil samples with roots and the unmodified loess through indoor direct shear and model tests. The results showed that the strain of the samples with roots reached the maximum shear strength, which was significantly higher than that of the samples without roots,

and the existence of roots increased the internal friction angle and cohesion of the loess. Su et al. [33] found that the root system of *Artemisia sacrorum* had a significant influence on the safety factor (Fs) of the loess slope. With the increase in soil depth, the roots had a gradually decreased influence on the slope Fs. In the upper 0–0.3 m range of the soil layer, the effect of roots was obvious, and the presence of roots could significantly improve Fs. Although some trees and shrubs have stronger roots than herbs, which results in better soil reinforcement [18], they are difficult to grow on steep slopes due to the need for growth conditions; they consume more water and nutrition than herbs [52,53]. Therefore, herbaceous plants are a competitive selection for loess slope ecosystem reconstruction and slope stability protection.

5. Conclusions

Based on the root morphology investigation, root tensile tests and the root cohesion evaluation of the two typical herbaceous plants, *Kochia scoparia* and *Artemisia sacrorum*, the main conclusions are as follows:

(1) The root morphological indexes of the two plants decreased with the root depth in the power functions (root diameter) or exponential functions (root number, root cross-sectional area, root surface area, root volume and root area ratio). These morphological distribution indexes can comprehensively reflect the root distribution in different soil depth. It can be inferred that *Kochia scoparia* and *Artemisia sacrorum* are suitable for strengthening and enhancing the stability of the shallow soil of the slope.

(2) The average tensile force of the roots of the two herbaceous plants was *Artemisia sacrorum* (12.4 N) > *Kochia scoparia* (6.48 N), and the average tensile strength was *Kochia scoparia* (18.34 MPa) > *Artemisia sacrorum* (15.84 MPa). The tensile force of *Kochia scoparia* and *Artemisia sacrorum* increased with the increase in the root diameter by the power function or exponential function, and the tensile strength was negatively correlated with root diameter by the power function.

(3) According to the Wu–Waldron model, the average root cohesion of the two herbaceous plants was *Kochia scoparia* (2.73 kPa) > *Artemisia sacrorum* (1.60 kPa). Considering the overestimation effect of the Wu–Waldron model, the average root cohesion was estimated to be 0.92 kPa–1.37 kPa for *Kochia scoparia* and 0.54 kPa–0.8 kPa for *Artemisia sacrorum*. The soil reinforcement effect of *Kochia scoparia* is obviously higher than that of *Artemisia sacrorum*, which can be considered the dominant herb species in the ecological slope protection project.

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