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Plant roots and anti-scourability of soils in the Shangshe Catchment, Dabie Mountains, Anhui Province, Eastern China

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Abstract The distribution of root biomass was studied in different soil layers (0–10, 10–20, 20–30, 30–40 cm) by means of a “study plot” method for various plant species in the Shangshe Catchment area in the Dabie Mountains, Anhui Province. The number and lengths of root samples were recorded. In each study plot, anti-scourability of soils in corresponding soil layers was measured with a C.C. Suoboliefu anti-scourability instrument. The results showed the following: 1) The root system was largely distributed in the 0–40 cm soil layer and the number of roots was the largest in the surface soil layer. Fine roots < 1 mm in diameter predominated in root length. 2) In the same section, the anti-scourability indices of the surface soil layer were larger than those of other soil layers in the various plant species. The tree root system, especially the fine roots < 1 mm in diameter, are highly instrumental in controlling soil losses. Correlation coefficients of length, number and density of fine roots and the anti-scourability index were 0.8173, 0.7159 and 0.6434, respectively. The length of fine root is a key factor in the anti-scourability soil index. This index is closely correlated with the non-capillarity of each soil type, indicating that forests have a strong soil stabilizing function, because their root systems improve physical soil properties and ultimately are responsible for the establishment of a bio-soil system with an anti-scourability index.

Keywords Shangshe Catchment, root system, soil anti-scourability index

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1 Introduction

The special topography and geomorphology of mountains provide specific boundary conditions and dynamic sources for confluence of rainfall, while the accompanying erosion of slopes, gullies and debris flow as a result of gravity inevitably endanger agriculture, water conservation facilities as well as the properties, livelihood and safety of people in mountainous areas (Wang and Xie, 1998). Ecological and environmental deterioration caused by soil and water losses inevitably affects the sustainability of economic and social development of mountainous and related areas. It is commonly acknowledged that “heavy or torrential rains in the entire catchment area, low ability in flood control and discharge in the middle and lower reaches and destruction of vegetation in the middle and upstream areas” (Cheng, 1999; Wu, 1999; Zhang et al., 1999; Zhan et al., 2000) were the major reasons for the catastrophic floods in the entire Yangtze River basin in 1998.

The Dabie Mountains are located in the border area of Hubei, Henan and Anhui provinces, with an area of 13800 km², of which 46% belongs to the Yangtze River basin and 54% to the Huai River basin (Yu and Shi, 1991). The Yangtze River widens in the middle and lower reaches with a considerable decrease in the gradient ratio, leading to easy sediment deposition. If floods do occur in the whole basin, its low ability in flood discharge below the middle reaches can easily lead to jacking with floods in the upper reaches, “causing successive increases of flood-water levels of subsequent floods much higher than those of previous floods under similar flow conditions” (Li and Ni, 1998), severely aggravating the persistence and dangers occasioned by floods. Therefore, it is of considerable importance to conduct a study in soil and water conservation and the hydrological effect of plants in the various land forms in the Dabie Mountains.

Plant roots are the main function carriers for the symbiont of a soil-vegetation ecosystem (Zhou and David, 1998). Its environmental improvement function

lies in two aspects: on the one hand, roots undergo extensive material exchange with the soil through rapid turnaround of large amounts of fine roots, contributing to the auto-fertilization function of forest soils; on the other hand, roots realize sand and soil stabilization functions through soil networks formed by the penetration of roots of different diameters. This theory has been fully validated in the study by Zhu (1982) on soil permeability and anti-scourability in the Loess Plateau and, for example, by the studies of Li et al. (1993) and Zhang et al. (1994) on the relationship between anti-scourability of soils and plant roots and the Jiang et al. (1979) study on factors affecting soil-scourability. But up to now, there has not been a systematic investigation into the relationship between different types of plant roots, the different ages of these same roots and anti-scourability of soils on the scale of a catchment area. Anti-scourability of root systems of different types of plants has yet to be verified by investigation on soil losses in a runoff field, at the level of a sub-catchment area and finally at catchment scales for different types of plants. In order for a systematic study to be conducted, we have established four-grade soil and water loss observation sites, since 1999, at catchment, sub-catchment, plot and micro-plot scales in different land forms in the Shangshe Catchment, Yuexi County of Anhui Province (Zhuang et al., 2004). At the same time we conducted studies on the relationship between plant roots in different land forms, roots of different ages of the same plants, anti-scourability and soil-permeability. Our investigation is part of this study. Based on correlation analyses between root features at various ages of different types of plants and physical soil properties and soil-stability functions, this study aims to expose the internal mechanism of soil stabilization functions in different types of plant roots in the Dabie Mountains. As well, we make comprehensive judgments on soil stabilization functions of different types of plants and provide a basis for the choice of plant types in the Changjiang conservation forests of the Dabie Mountains.

2 Research methods

2.1 Choice of different forest types and investigations of soil and roots

In the Shangshe Catchment, the following well managed stands were selected: a middle-aged Masson pine forest (*Pinus massoniana* Lamb) (A, 18 years old), a mature Masson pine forest (B, 41 years old), a middle-aged Chinese fir forest (*Cunninghamia lanceolata* (Lamb) Hook) (C, 10 years old), a mature Chinese fir forest (D, 18 years old) and a bamboo forest (*Phyllostachys edulis*) (E). All stands had a canopy density better than 0.8. We established 20 m×20 m study plots in stands A, B and D, a 15 m×20 m plot in C and in E a 10 m×20 m plot for tally

surveys. Basic conditions of the study plots are presented in Table 1.

Table 1 Basic conditions of five forest types

forest type	soil depth /cm	average height of tree/m	average diameter of tree at 1.3 m/cm	density /($\text{N} \cdot \text{hm}^{-2}$)
A	43	6.2	10.3	1250
B	62	13.5	23.8	750
C	45	8.3	12.1	1725
D	85	18.2	21.9	1325
E	85	16.6	9.2	1956

In each study plot, 1-m wide soil profiles with roots were dug, recorded as in conventional soil investigation methods where we observed the different layers, i.e., 0–10, 10–20, 20–30 and 30–40 cm for extraction of soil samples. Indices such as soil density in the different layers were analyzed in the laboratory. Soil samples of 25 cm×25 cm×10 cm were obtained from these different layers (0–10, 10–20, 20–30, 30–40 cm) with one replication. Roots were picked out and cleaned. The average dry biomass and length of plant roots in the different layers were measured in the laboratory.

2.2 Measurement of anti-scourability of soils

Anti-scourability of soils was measured with a C.C. Suoboliefu anti-scourability instrument. At 1 kg pressure and using a water column of 0.7 mm in diameter to strike soil layers for 1 min until water erosion points appeared, we calculated the anti-scourability index of the soil layer as the reciprocal of the mean value of the product of depth and width of every ten soil erosion points (Zhang and Hu, 1996). Because of the effect of litter and humus layers in forests, the anti-scourability of soils could present an unlimited range of values (Jiang, 1979; Ding et al., 2002); the litter layer was removed from the surface soil layer. The anti-scourability was measured in the different layers, i.e., 0–10, 10–20, 20–30 and 30–40 cm), where we also measured plant root density.

3 Results and analysis

3.1 Distribution characteristics of root profiles of different types of plants

Vertical distribution characteristics of the length and number of roots of different types of plants are listed in Fig. 1.

Figure 1 shows that root systems largely occur in the 0–40 cm soil layer. The length and number of roots less than 1 mm in diameter were larger in the surface soil layer than in the other soil layers. From our calculations, it is seen that

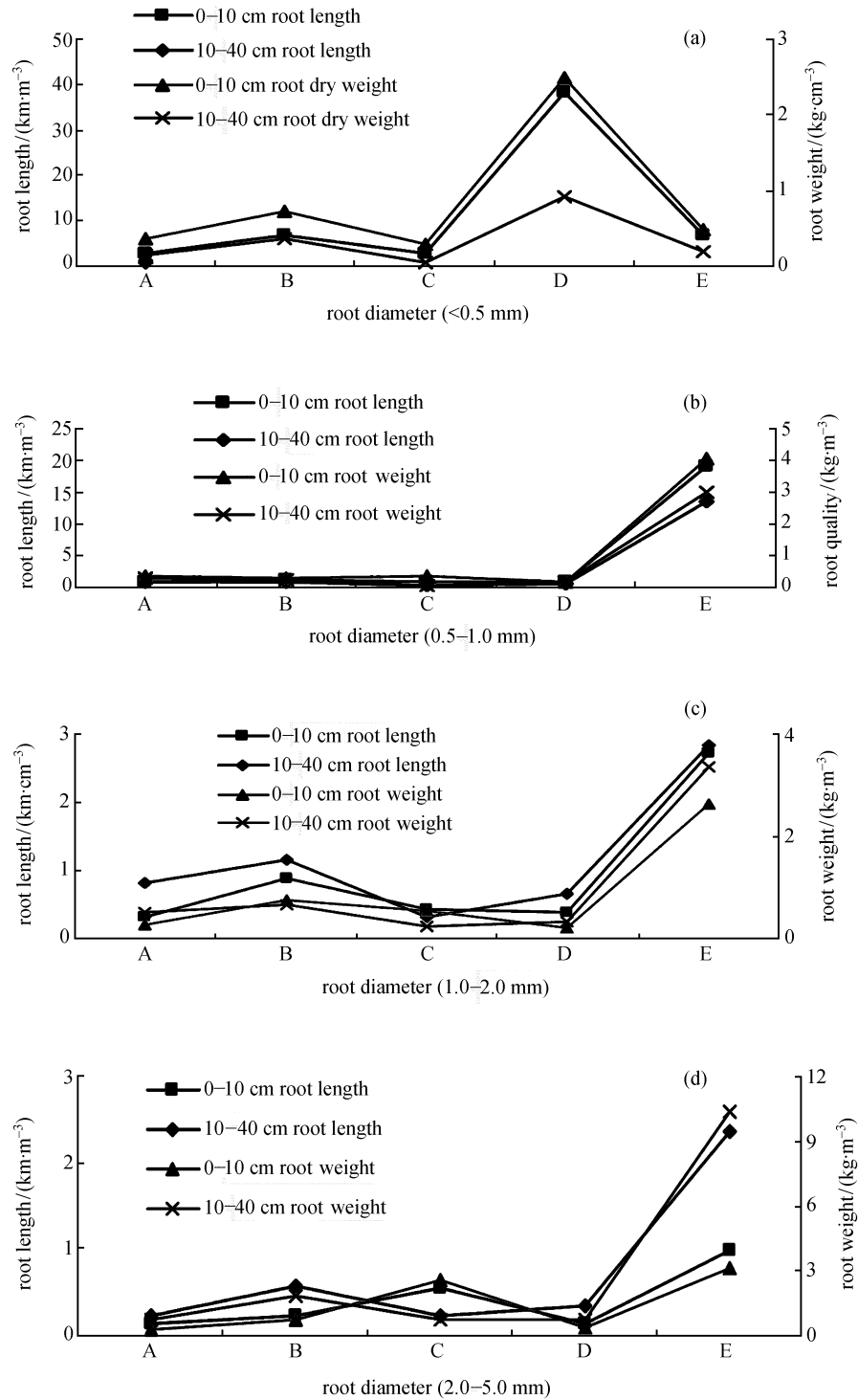


Fig. 1 Vertical distribution of length and weight of roots < 5.0 mm diameter at different scales

the total root length of plants in different forest types in the surface soil layer (0–10 cm) is classified in the following order: mature Chinese fir forest > bamboo forest > middle-aged Chinese fir forest > mature Masson pine forest > middle-aged Masson pine forest. Length ratios of roots of different diameters (< 0.5 mm: 0.5–1.0 mm: 1.0–

2.0 mm: 2.0–5.0 mm) were as follows: mature Chinese fir forest 1:0.4:0.01:0.004, middle-aged Chinese fir forest 1:0.2:0.1:0.04, bamboo forest 1:2.8:0.8:0.1, mature Masson pine forest 1:0.4:0.2:0.2 and middle-aged Masson pine forest 1:0.3:0.1:0.04. For all the forests except the bamboo forest, lengths of roots < 0.5 mm in

diameter predominated in the 0–10 cm soil layer. For the bamboo forest, lengths of root between 0.5–1.0 mm in diameter predominated in the surface layer. Their roots were 1.8 times longer than those of roots < 0.5 mm in diameter. Although roots in the 0–40 cm soil layer were, generally speaking, < 0.5 mm and between 0.5–1.0 mm in diameter and contributed weakly to the total forest biomass with the highest proportion in the total number of roots at 69.19%, they represented a good proportion of root lengths, with the highest at 97.33% and the lowest at 74.26%. The longer the roots, the wider their range, crisscrossing to form networks in the soil.

Our results show that the length and weight of roots < 1.0 mm in diameter in the 0–40 cm soil layer of the mature Chinese fir forest were much larger than those of the middle-aged Chinese fir forest, a condition also reflected, to a certain degree, in the mature Masson pine forest and the middle-aged Masson pine forest. Due to the enormous spatial variation in this mountainous area, this phenomenon needs to be verified by further investigations. In view of the two-side effects of the fir forest on soil fertility, we should take full advantage in practice of the fast-growth and high-yield functions of fir trees because the number of roots < 1.0 mm in diameter and their lengths in the surface soil layer can improve soil properties. Simultaneously, mixed forests should be established to overcome the defects of soil deterioration, caused by pure fir forests (Wu et al., 1994).

3.2 Plant roots and soil anti-scourability

3.2.1 Changes in anti-scourability of soils with various types of plants and different soil layers of the same plant

Anti-scourability of soils refers to the ability of soils to resist mechanical damage caused by agents such as runoff and wind and is affected by physical and chemical soil properties, the structure of soil profiles and biological factors (Zhang and Hu, 1996). A large number of studies (Jiang, 1979; Zhu, 1982; Ding, 2002) have demonstrated that plant roots, especially roots < 1.0–2.0 mm in diameter have a biodynamic function of stabilizing soil structures, increase the stability of water aggregates (> 2 mm) and the amount of organic matter content and, as well, endow the soil system with anti-scourability.

The measured values of anti-scourability in major types of plants in different soil layers in our study area are presented in Fig. 2. These show that anti-scourability of soils varies greatly with different types of plants or in different soil layers of the same plant and seem to adhere to some rules. For the same plant, anti-scourability in the surface soil layer (0–10 cm) was larger than in the subsoil layer, with a difference of 0.1842–0.6678. The difference between the upper and lower layers of the middle-aged

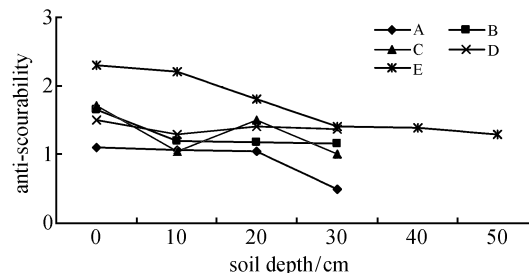


Fig. 2 Vertical distribution of anti-scourability at five types of forest

Chinese fir forest was the largest while that of the mature Chinese fir forest was the smallest. This is related to the number of roots in the surface soil layer, especially the large number of fine roots < 1.0 mm in diameter which have a powerful tensile capacity and elasticity, strengthening the anti-scourability together with other factors such as networks, root soil bonding, root biochemistry, etc. Jiang (1979) proposed three types of vertical distributions of anti-scourability of soils: a type that affects agricultural cultivation, which maintains strong anti-scourability in the crop root layer and a weak anti-scourability in the surface layer and below the root layer. A second type affects the soil formation process which maintains a strong anti-scourability in the clay layer and weak anti-scourability in the upper and lower layers. The third type affects biological growth which maintains strong anti-scourability in the surface soil layer and gradually weakens below the surface layer. Figure 2 suggests that anti-scourability of soils in different types of plants in the Shangshe Catchment fluctuates to a certain degree (e.g. soil anti-scourability at 1.0458 for mature Chinese fir forest in the 10–20 cm layer was lower than that in the 20–30 cm layer at 1.5084), but basically is in agreement with the type of vertical distribution affecting biological growth in which anti-scourability in the surface soil layer is the strongest and gradually weakens below the surface layer.

3.2.2 Correlation analysis of anti-scourability of soils and plant roots

A multiple linear stepwise regression analysis of the anti-scourability index (Y) in the various soil layers and the length, number and density of roots of different diameters in the corresponding layers, shows obvious linear relations between the length, number and density of roots < 1.0 mm in diameter and the anti-scourability soil index:

$$Y = 1.0872823 + 0.13749183X_1 + 0.51438240X_2 \quad R = 0.8173 \quad N = 22$$

$$Y = 1.15170742 + 0.00232108X_3 \quad R = 0.7159 \quad N = 22$$

$$Y = 1.1200 + 0.0000466X_4 \quad R = 0.6434 \quad N = 22$$

where X_1 (cm) represents the length of roots < 0.5 mm and X_2 (cm) root lengths between 0.5–1.0 mm in diameter, X_3 (g) is the weight of roots < 1.0 mm in diameter and X_4

(number of roots·m⁻²) represents density of roots < 1.0 mm in diameter.

Tests of the three regression models showed that their regression accuracies were 0.9999, 0.9998 and 0.9988, respectively, i.e., all greater than 0.99.

From this analysis, it can be concluded that the effect of plant roots on anti-scourability of soils is largely displayed as consolidation, networking, protection and blocking effects on soils by massive amounts of fine roots and hair roots. This has two reasons. In the first place, the number of roots per unit of volume is determined by root diameters. Roots with large diameters have low densities within a small contact area of the soil, so that they have a low ability in soil-absorption and soil-stability and do not necessarily play a decisive role in improving anti-scourability. Second, tough fibrous roots have small diameters, with a high density and large root lengths and play an indispensable role, compared with coarse roots, in soil improvement and the establishment of soil systems with anti-scourability (Li et al., 1993; Zhang et al., 1994). Since the above-ground biomass is related to below-ground biomass for the same plants, anti-scourability prediction of soils from the earlier regression equations is of great importance in predicting the soil erodibility factor of *K* (Wischmeier and Smith, 1965; Ruan and Wu, 2002; Zhang et al, 2008).

3.2.3 Correlation analysis of soil anti-scourability enhancement values and tree roots

The enhancement effect of tree roots on anti-scourability of soils actually refers to root intensification of its anti-scourability after eliminating the effect of anti-scourability of the soil layer without a root system. Zeng (1995) proposed in his “Study on Plant Root Intensification of Anti-Scourability in Purplish Soils of Guizhou” that anti-scourability enhancement values of soil layers with a root system was 84.55% higher than that of soil layers without a root system. Given our multiple stepwise regression analyses of the length, number and density of roots of

different diameter classes in the study plots, the anti-scourability enhancement of soil values (*Y*₁) can be derived from the following relationship:

$$Y_1 = 0.78172823 + 0.13749183X_1 + 0.5138240X_2 \quad R = 0.8713, N = 22$$

where *X*₁ represents the length of roots < than 0.5 mm and *X*₂ root lengths between 0.5–1.0 mm in diameter.

The relationship shows that roots < 0.5 mm and between 0.5–1.0 mm in diameter play a dominant role in intensifying anti-scourability of soils, because they have a much higher density than roots > 1.0 mm in diameter. Reflected in their root lengths, massive fine roots can demonstrate this mechanical networking effect on soils to the full.

3.3 Comprehensive analysis of soil stabilization function of root systems

A correlation matrix of 12 indices-root lengths (*X*₁–*X*₄), biomass (*X*₅–*X*₈), soil bulk density in a corresponding layer (*X*₉), capillary porosity (*X*₁₀), non-capillary porosity (*X*₁₁) and the anti-scourability soil index (*X*₁₂) of roots of the various diameter classes (< 0.5, 0.5–1.0, 1.0–2.0, 2.0–5.0 mm) in the surface soil layer (0–20 cm) of different types of plants is presented in Table 2. It shows that the distribution of the length of roots in the various diameter classes is correlated with the 0–20 cm soil layer. The correlation coefficients of the lengths of roots within the 0.5–1.0 mm diameter class and that of roots within the 1.0–2.0 and 2.0–5.0 mm diameter class are 0.96 and 0.88, respectively; correlation coefficients of the lengths of roots within the 1.0–2.0 mm diameter class and that of roots in the 2.0–5.0 mm diameter class are as high as 0.95; this implies that the distribution of roots in the different types of plants is quite similar to those of 0.5–5.0 mm in diameter. Roots < 0.5 mm in diameter are not very well correlated with other roots in root length and biomass, which suggests that the growth and distribution of the finest roots in the different types of plant are relatively independent.

Table 2 Correlation matrix

	<i>X</i> ₁	<i>X</i> ₂	<i>X</i> ₃	<i>X</i> ₄	<i>X</i> ₅	<i>X</i> ₆	<i>X</i> ₇	<i>X</i> ₈	<i>X</i> ₉	<i>X</i> ₁₀	<i>X</i> ₁₁	<i>X</i> ₁₂
<i>X</i> ₁	1.00	-0.07	-0.05	-0.11	0.99	-0.08	-0.11	-0.14	-0.56	0.34	0.07	0.40
<i>X</i> ₂	-0.07	1.00	0.96	0.88	-0.15	0.99	0.95	0.85	-0.25	0.38	0.26	0.39
<i>X</i> ₃	-0.05	0.96	1.00	0.95	-0.12	0.93	0.98	0.92	-0.25	0.46	0.11	0.37
<i>X</i> ₄	-0.11	0.88	0.95	1.00	-0.19	0.82	0.98	0.99	-0.06	0.35	-0.03	0.20
<i>X</i> ₅	0.99	-0.15	-0.12	-0.19	1.00	-0.15	-0.19	-0.21	-0.55	0.37	0.03	0.43
<i>X</i> ₆	-0.08	0.99	0.93	0.82	-0.15	1.00	0.90	0.78	-0.25	0.42	0.27	0.46
<i>X</i> ₇	-0.11	0.95	0.98	0.98	-0.19	0.90	1.00	0.96	-0.17	0.37	0.11	0.26
<i>X</i> ₈	-0.14	0.85	0.92	0.99	-0.21	0.78	0.96	1.00	-0.02	0.29	-0.03	0.13
<i>X</i> ₉	-0.56	-0.25	-0.25	-0.06	-0.55	-0.25	-0.17	-0.02	1.00	-0.13	-0.67	-0.38
<i>X</i> ₁₀	0.34	0.38	0.46	0.35	0.37	0.42	0.37	0.29	-0.13	1.00	-0.40	0.79
<i>X</i> ₁₁	0.07	0.26	0.11	-0.03	0.03	0.27	0.11	-0.03	-0.67	-0.40	1.00	-0.02
<i>X</i> ₁₂	0.40	0.39	0.37	0.20	0.43	0.46	0.26	0.13	0.38	0.79	-0.02	1.00

Table 3 Principal component analysis

principal component	characteristic root	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8
1	6.27	0.02	0.38	0.39	0.37	0.00	0.37	0.38	0.35
2	3.37	0.47	-0.10	-0.08	-0.14	0.50	-0.08	-0.14	-0.17
3	2.10	-0.18	-0.11	-0.05	0.04	-0.15	-0.11	-0.04	0.04
principal component	X_9	X_{10}	X_{11}	X_{12}	difference	ratio	accumulative contribution rate		
1	-0.10	0.23	0.03	0.21	2.90	0.48	0.48		
2	-0.26	0.33	-0.06	0.37	1.27	0.26	0.74		
3	0.54	0.31	-0.65	0.08	1.28	0.16	0.90		

Soil bulk density is negatively correlated with the length and biomass of roots of the various diameter classes; the absolute value of correlation coefficients decreases with an increase in diameter. Both capillary porosity and non-capillary porosity are positively related to the length and biomass of roots in the various diameter classes, but their correlation coefficients are small, implying that different types of plants have their own special ways to improve physical soil properties. The anti-scourability soil index is positively related to the length and biomass of roots in the various diameter classes, with higher correlation coefficients of about 0.4 for roots within the 0.5–1.0 and 1.0–2.0 mm diameter classes and correlation coefficients of 0.2–0.3 for other roots. The anti-scourability index is positively and significantly correlated with non-capillary porosity with a correlation coefficient of 0.93, which fully shows that different types of plants share similar improvements in soil structure and enhancing anti-scourability of soils.

Table 3 presents the result of a principal component analysis of the 12 indices in the surface soil layer (0–20 cm) of different types of plants. It shows that the first principal component contributed 48%, the second 26% and the third 16% of the total variation in the model, i.e., the first three components together account for 90%. In the first principal component, the variables X_2 , X_3 , X_4 , X_6 , X_7 and X_8 all have large positive coefficients; therefore, the first principal component reflects the comprehensive characteristics of the length and biomass of roots between 0.5–5.0 mm in diameter in the various soil types. In the second principal component, X_1 , X_5 and X_{12} have large positive coefficients while X_2 , X_3 , X_4 , X_6 , X_7 , X_8 and X_9 have negative coefficients; therefore, the second principal component reflects a comparison of characteristic values and the anti-scourability soil index of roots < 0.5 mm in diameter with the length, biomass and soil bulk density of roots with diameters between 0.5–5.0 mm in the various soil types. In the third principal component, X_9 and X_{11} have the largest coefficients but opposite in signs; therefore, this third component reflects the comparison between soil non-capillary porosity and soil bulk density.

4 Conclusions

1) In the same section, the values of the anti-scourability index of surface soil layer were larger than those of other soil layers in different types of plants.

2) Anti-scourability of soils is closely related to tree root features, especially length, number and density of roots < 1 mm in diameter. Their correlation coefficients are, respectively, 0.8173, 0.7140 and 0.6434.

3) In the 0–20 cm soil layer of different types of plants, the correlation coefficients of the length of roots with diameters between 0.5–1.0 mm was 0.96 and that of roots between 1.0–2.0, 2.0–5.0 mm in diameter 0.88. The correlation coefficient of the length of roots between 1.0–2.0 mm in diameter and that of roots between 2.0–5.0 mm in diameter reached 0.95, which shows that the distribution of root in different types of plants was quite similar within the entire range of diameters between 0.5–5.0 mm. Roots < 0.5 mm in diameter were not very well correlated with other roots in root length and biomass, which suggests that the growth and distribution of the finest roots in different types of plants were relatively independent and specific.

4) Anti-scourability of soils in different types of plants was highly correlated with non-capillary soil porosity, which suggested that different types of plants shared a similarity of improving soil structures and establishing soil systems with anti-scourability through their root systems.

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