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Effect of *Cynodon dactylon* community on the conservation and reinforcement of riparian shallow soil in the Three Gorges Reservoir area

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Abstract

Introduction: Riparian vegetation plays a crucial role in soil conservation and riverbank reinforcement. The Three Gorges hydrologic project has significantly changed the pattern of water-level fluctuation and riparian environment, which significantly influenced plant community development and its effect on soil conservation and riverbank protection. *Cynodon dactylon*, a perennial grass with developed root system and creeping stems, has become a dominant riparian species in the Three Gorges area after the completion of the dam. We aimed to characterize how the soil-root system under the *C. dactylon* community responded to environmental changes and effects of the soil-root system on shallow soil conservation and riverbank reinforcement through field investigation and laboratory test.

Methods: We conducted a field survey and experimental research. Quadrates of a natural *C. dactylon* community were set up on a riverbank along an altitude gradient. Plants were sampled randomly for the measurements of spatial structure and tensile strength of roots. Soil erosion resistance, soil scour resistance, and shear strength of sampled soil-root systems and control soil were tested in the laboratory.

Results: Roots of the *C. dactylon* community significantly increased soil erosion resistance, soil scour resistance, and shear strength, enhancing the stability of shallow soil and riverbank. Due to water-level fluctuation, *C. dactylon* at lower altitudes was subjected to less time exposed to air. As a result, the soil-root systems at lower altitudes were characterized by reduced biomass with reduced capacity for soil reinforcement as measured through erosion resistance, soil scour resistance, and shear strength. The correlation analysis indicated that root biomass had a significant positive linear correlation with the enhancement of erosion resistance and scour resistance, and shear strength, respectively.

Conclusions: Roots of the *C. dactylon* community effectively enhanced the stability of riparian shallow soil and riverbank. The fluctuation in water level caused the difference of root growth as the exposed time of plants decreases with the decrease of altitude. The difference of root structure resulted in the variation of the soil-root system in soil conservation and reinforcement.

Introduction

The riparian plant community is a significant factor influencing the occurrence and progress of riverbed and erosion (Brooks and Lake 2007; Pollen 2007). Riverbanks with a well-established plant community are less prone to bank failure (Hubble 2004; Wang et al. 2009; Greenwood et al. 2004). Restoring and maintaining the riparian plant community can conserve soil and control or prevent riverbank failure as well as preserve riverside habitats (Norris et al. 2006; Hubble et al. 2010). The riparian plant community performs its function in soil conservation and slope protection through the cohesion and reinforcement of the soil-root system matrix (Mickovski et al. 2009; Schwarz et al. 2012). The capacity of the soil-root system on soil conservation and reinforcement is characterized by soil erosion resistance, soil scour resistance, and shear strength (De Baets et al. 2006, 2007; Pollen 2007; Genet et al. 2008). A large number of studies showed that the effects of the

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soil-root system on soil conservation and reinforcement were significantly related to the characteristics of plant and soil including plant species, plant age, soil type, and soil moisture (Reubens et al. 2007; Xu and Zeng 2008; Stokes et al. 2009; Fan and Lai 2014). Among these characteristics, root structure and distribution were directly related to the enhancement of the soil-root system on soil conservation (Mickovski and van Beek 2009; Ji et al. 2012; Ghestem et al. 2014). Changes in the spatial distribution of plant community and plant roots caused by environmental changes influence significantly the effects of plant roots on slope stabilization (Cammeraat et al. 2005; Normaniza et al. 2008; Burylo et al. 2012).

The Three Gorges Project, one of the largest water conservancy and hydropower projects in the world, has significantly altered the region's riparian environment by forming 400-km^2 riparian belts around the reservoir with water-level fluctuation (from 145 to 175 m) and the reverse seasonal fluvial pattern (exposure in summer and inundation in winter) (Chen and Xie 2007). The traumatic change of dry and wet cycles causes stresses of riparian plants and leads to the degradation of the plant community. The composition and structure of plant communities degrade and become simple in the particular ecological environment (Chen and Xie 2009; Lu et al. 2010; Liu et al. 2011). The quick and frequent drawdown of water level exacerbates water erosion and scouring (Xu et al. 2009). These changes increase soil erosion, bank collapse, and landslide endangering ecological safety in the reservoir area. Restoring riparian vegetation can effectively improve the ecological environment in the Three Gorges Reservoir region (Wang et al. 2004; Xu et al. 2009). *Cynodon dactylon* is a common riparian plant species in the Three Gorges Reservoir area (Liu et al. 2011) and has become a dominant species with a strong ability to adapt to flooding and drought since the Three Gorges Project was finished (Chen et al. 2010). In this paper, a field survey and experimental research were conducted to (1) evaluate the differences in root system biomass and other root system characteristics of the *C. dactylon* community with altitude, (2) evaluate the effect of the root system of the *C. dactylon* community on several soil conservation and soil strength characteristics which are known to have an impact on slope stability, and (3) examine the relationship between root system biomass and these same soil conservation and soil strength characteristics, thereby allowing a consideration of the relationship between water-level fluctuation and the capacity of *C. dactylon* to contribute to slope stability and riverbank protection in the Three Gorges Reservoir area.

Methods

Field experimental design

The field experiment was set up on the riparian bank of the Xiangxi River, a branch of the Yangzi River in the Three Gorges Reservoir region. Five quadrates (10×10 m^2) of a natural *C. dactylon* community were set up on a riverbank along an altitude (elevation above sea level) gradient only from 155 to 175 m at 5-m intervals as the exposed time of plant communities below 155 m was too short to recover adequately when the field investigation was carried out. The soil was classified as tidal sandy soil derived from river alluvium with sandy loam texture. Five subquadrates (1×1 m^2) were arranged randomly in each main quadrate. Plants were sampled randomly in each subquadrate for the measurements of spatial structure and tensile strength of roots. In addition, the soil-root system was sampled using a soil sampler (diameter 8 cm, depth 15 cm) in each subquadrate. The samples were wrapped with plastic and brought back for the measurement of soil erosion resistance, soil scour resistance, and shear strength in the laboratory.

Determination of root tensile strength and root system structure

The Diti method was used to test the tensile strength of roots (Yang et al. 2007):

$$P = 4F/\pi D^2 \quad (1)$$

where *F* and *D* represent the maximum tensile resistance and diameter of the section of the root, respectively, which were tested using a stress recorder and vernier caliper in the field. *P* representing the root tensile strength was calculated according to formula (1). Five plants were sampled randomly in each subquadrate to measure the tensile strength of roots in the field, and another ten plants to measure root length, root surface area, and number of root furcations in the laboratory. Then, the sampled plants were divided into ground and underground parts from the root collar, dried to a constant mass at 60°C in an oven, and weighed to test their biomass.

Characterization of the soil-root system in soil conservation and reinforcement

Enhancement of soil scour resistance of the soil-root system was measured using the method of scouring soil samples with hydraulic flume based on the following calculation (Xu and Zeng 2008; Burylo et al. 2012):

$$\mathrm{Ev} = (C_1 - C_2)/C_2 \quad (2)$$

where Ev is the enhancement of root scour resistance of the soil-root system (the increasing multiple in scour resistance is due to root presence). Its value and range depend on root biomass, root texture and distribution of related species, plant growth, and environmental condition. C_1 and C_2 represent the scour resistance coefficients of the soil-root system and control sample, respectively.

The measurement unit of the scour resistance coefficient is the amount of water (L) to flush out 1 g of saturated sample soil. The scour resistance coefficient was tested using the method described by Xu and Zeng (2008). Five soil-root system samples and one control sample were tested repeatedly at each altitude gradient. The roots of each sample were separated and dried to a constant mass at 60°C in an oven, and weighed to test their biomass for the relationship analysis between scour resistance and root structure.

Enhancement of soil erosion resistance of the soil-root system was measured using the method of collapse resistance in static water and calculated as follows (Xu and Zeng 2008; Burylo et al. 2012):

$$\mathrm{Ce} = (V_1 - V_2)/V_2 \quad (3)$$

where Ce is the enhancement of erosion resistance of the soil-root system ranging from 0 to 1. V_1 and V_2 are the detachment rate of the soil-root system sample and control soil sample, respectively. Detachment rate was measured using the weight of disintegrating water-saturated soil in unit time represented by $V = M/t = (M_1 - M_2)/t$ (g/min). The detachment rate of samples was tested using the method described by Burylo et al. (2012). Five soil-root system samples and one control sample were tested repeatedly at each altitude gradient. The roots of each sample were separated and dried to a constant mass at 60°C in an oven, and weighed to test their biomass for the relationship analysis between erosion resistance and root structure.

Soil shear strength of the soil-root system was measured based on the Mohr-Coulomb law (Xu and Zeng 2008; Burylo et al. 2012):

$$\tau_f = \sigma \tan\varphi + C \quad (4)$$

where C is the effective soil cohesion (kPa), including the cohesion among soil particles and the cohesion between soil particles and roots; σ is the effective stress force that is normal to the slope (kPa); and φ is the effective angle of shear resistance (°). Soil shear resistance indices (C, φ) are determined according to the τ-σ curve. Soil shearing stress (τ) was calculated by the formula $\tau = KR$ and tested using a strain-controlled direct shear apparatus. The quantum ring rate coefficient of determination (K) is set as 2.5 kPa/0.01 mm, and the unit of dial test indicator readings (R) was set as 0.01 mm. Each sample of the soil-root system was cut into four cylindrical testing samples (diameter 8 cm, depth 2 cm) which was put into a shear box and saturated with water for the determination of shearing stress. Five samples were tested repeatedly at each altitude gradient. The roots of each sample were separated and dried to a constant mass at 60°C in an oven, and weighed to test their biomass for the relationship analysis between shear strength and root structure.

Data analysis

One-way analysis of variance (ANOVA) was performed to determine the structure of roots and the effects of the soil-root system on soil conservation and slope protection. The altitudinal gradient was used as an independent factor, and root structure indexes (root biomass, root length, root area, and number of root furcation) and soil reinforcement indexes (root tensile strength, enhancement of soil erosion resistance, enhancement of soil scour resistance, and shear strength) as dependent factors. The Duncan test method was conducted for multiple comparisons to test the significance level of each parameter among treatments when the main effect was significant. The relationship of spatial distribution between root structure and the performance of the soil-root system in soil conservation and slope protection was uncovered by linear analysis of root biomass with enhancement of soil erosion resistance, enhancement of soil scour resistance, and shear strength, respectively. All analyses were conducted using SPSS software (13.0).

Results

The spatial structure of roots

The structure and distribution of roots changed with altitude (Table 1). Root length, root area, number of root furcation, and root biomass of *C. dactylon* plants increased significantly with the increase of altitude ($P < 0.05$) and reached the maximum at an altitude of 175 m. Their root length, number of root furcation, root area, root biomass, and plant biomass at 175 m increased by 26.6%, 121.3%, 166.2%, 113.5%, and 207.4%, respectively, compared to those at 155 m. However, the difference was not significant within low altitudes (155 and 160 m) and middle upper altitudes (165, 170, and 175 m) ($P > 0.05$).

Soil enhancement and spatial variation of the soil-root system

The roots of *C. dactylon* plants had good tensile strength and enhanced effectively the performance of soil in soil reinforcement and slope protection. The average soil detachment of the soil-root system of *C. dactylon* decreased 32.0% in contrast to the control soil, and the soil scour resistance coefficient and shear strength of the soil-root system increased 315.4% and 21.1%, respectively (Figure 1).

The tensile strength of roots and performance of the soil-root system in soil conservation and reinforcement changed along with the altitude gradient (Figure 2). The tensile strength, enhancement of soil erosion resistance, enhancement of soil scour resistance, and shear strength of the soil-root system at 175 m were about 40.39%,

Table 1 Characteristics of *C. dactylon's* root system at various elevations

Elevation (m)	Root length (mm)	Root area (cm^2)	Number of root furcation	Root biomass (g)	Plant biomass (g)
155	65.598 ± 2.691b	7.970 ± 0.540b	1,120 ± 102b	0.052 ± 0.006b	0.720 ± 0.100c
160	69.634 ± 3.449b	8.275 ± 0.849b	1,684 ± 295ab	0.063 ± 0.009ab	0.852 ± 0.115c
165	79.356 ± 3.190a	13.440 ± 2.519ab	1,794 ± 247ab	0.069 ± 0.021ab	1.451 ± 0.333bc
170	80.626 ± 3.377a	13.928 ± 2.912ab	1,945 ± 387ab	0.101 ± 0.010ab	1.849 ± 0.217ab
175	83.033 ± 3.456a	17.638 ± 2.216a	2,981 ± 523a	0.111 ± 0.015a	2.214 ± 0.280a
Total	*F* = 5.542; significance = 0.000	F = 4.073; significance = 0.014	F = 3.940; significance = 0.016	F = 3.288; significance = 0.014	F = 7.830; significance = 0.000

Values are expressed as mean ± SE; means followed by the same letter(s) within each column are not significant at $P < 0.05$.

125.29%, 374.09%, and 23.84%, respectively, more than those at an altitude of 155 m. The tensile strength of *C. dactylon* roots was significant among the upper (175 and 170 m), middle (160 and 165 m), and middle lower (155 m) parts ($P < 0.01$), while the internal difference within each part was not significant. The enhancement of soil scour resistance differed significantly between each altitude. The enhancement of soil erosion resistance differed significantly among the upper (175 m), upper middle (170 and 165 m), and middle lower (160 and 155 m) parts ($P < 0.01$). The shear strength differed significantly among the upper middle (175, 170, and 165 m) and middle lower parts (160 and 155 m) ($P < 0.01$), while the internal difference within each part was not significant. Soil indicators as gradients increased due to the soil-root systems at high gradients which had more exposure time to develop.

Relationship between root biomass and soil enhancement of the soil-root system

The tensile strength of roots and enhancement of soil scour resistance, and the enhancement of soil erosion resistance and shear strength of the soil-root system had a non-linear correlation and rectilinear correlation with root biomass, respectively (Figure 3). The enhancement of soil erosion resistance, shear strength, enhancement of soil scour resistance of the soil-root system, and tensile strength of roots increased with the increase of root biomass. However, the tensile strength of roots and enhancement of soil scour resistance of the soil-root system increased slowly when root biomass of each seedling was over 0.10 g and root biomass of the soil-root system was over 1.2 g/cm^3. It indicated that increase of biomass promoted the performance of the soil-root system in soil conservation and slope reinforcement.

Discussion

Root enhancement

Roots of shrub and herbaceous plants usually concentrate within a 30-cm soil layer where much soil erosion usually takes place (Ding et al. 2002); therefore, a well-grown plant community can effectively enhance soil reinforcement and slope reinforcement by increasing the soil erosion resistance, soil scour resistance, and

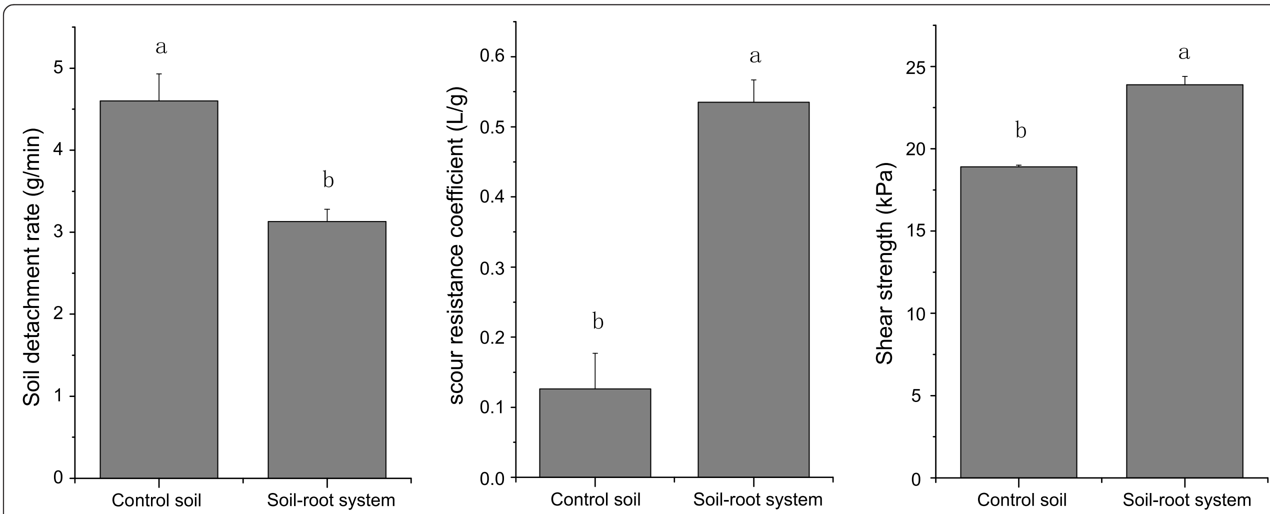

Figure 1 Effects of soil-root system (*C. dactylon*) on soil detachment rate, scour resistance coefficient, and shear strength.

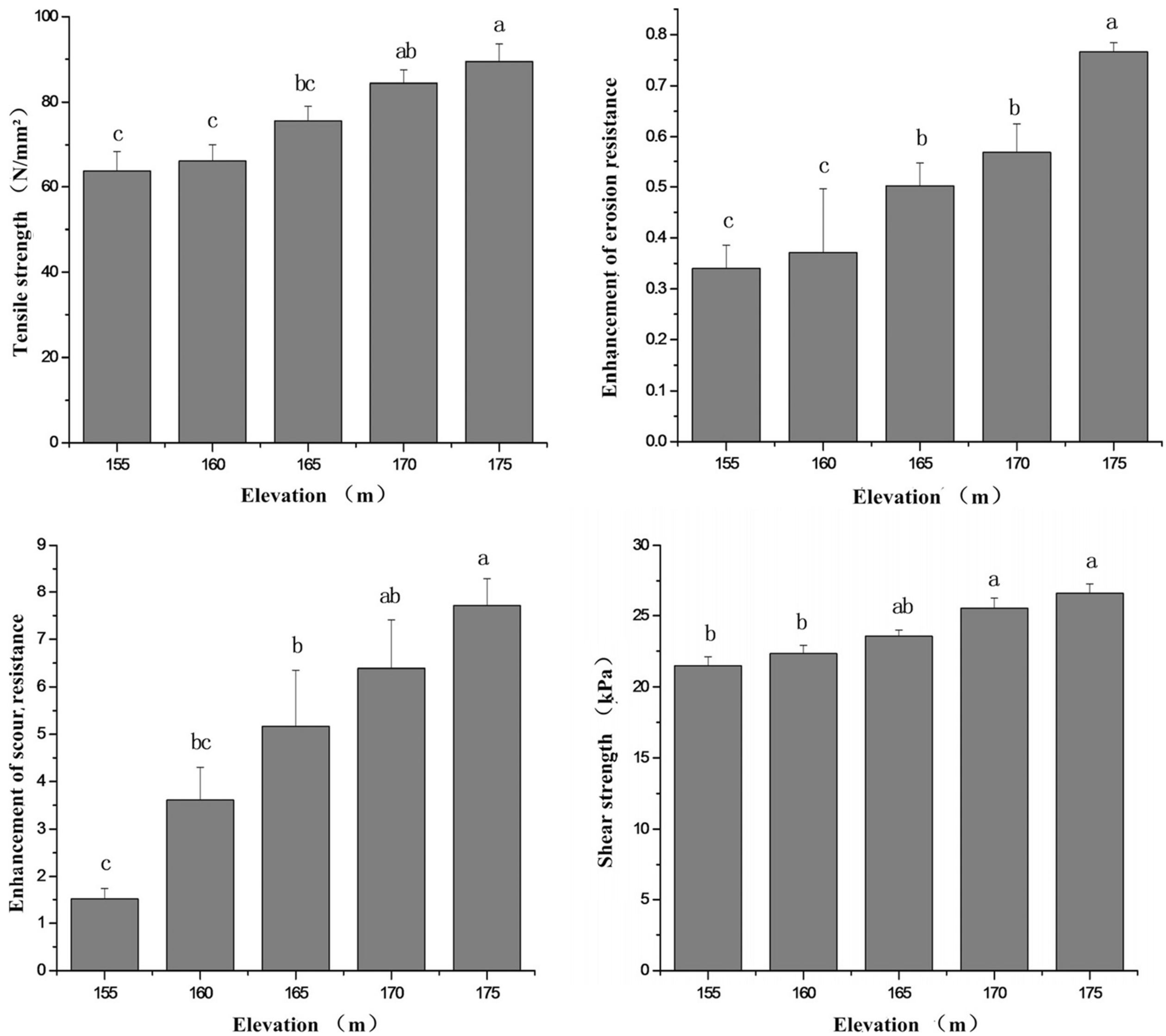

Figure 2 The spatial variation of root tensile and soil enhancement of the soil-root system (mean ± SE).

shear strength of riparian soil through cohesion and reinforcement of the root system (Hubble et al. 2010; Comino and Druetta 2010; Schwarz et al. 2010). The soil-root system's theory is that the soil-root system with a spatial distribution and structure can increase the shear strength of soil through associative root networks which reinforce soil layers by towing obliquely and anchoring vertically (Schmidt et al. 2001; Stokes et al. 2008; Fan and Su 2008). Plant roots can also affect physical and chemical properties of soil related to soil erosion which further promote soil stability (Gyssels et al. 2005). The enhancement of plant roots differs significantly for plant species (Docker and Hubble 2008; Abdi et al. 2009; Zhang et al. 2014). Xu et al. (2011) reported that *Triarrherca sacchariflora* had the best enhancement on anti-scouring among the five species they tested. Our study found that *C. dactylon* performed well for enhancement of shallow soil conservation and riverbank stability. Soil erosion resistance, soil scour resistance, and shear strength of the soil-root system were significantly improved with *C. dactylon.*

Spatial variation of root enhancement

The spatial dynamics of the root system was related to the interaction between plant roots and soil, making the effects of plant roots on soil conservation and slope protection change with the spatial dynamics of the root system and ecological environment (Stokes et al. 2008).

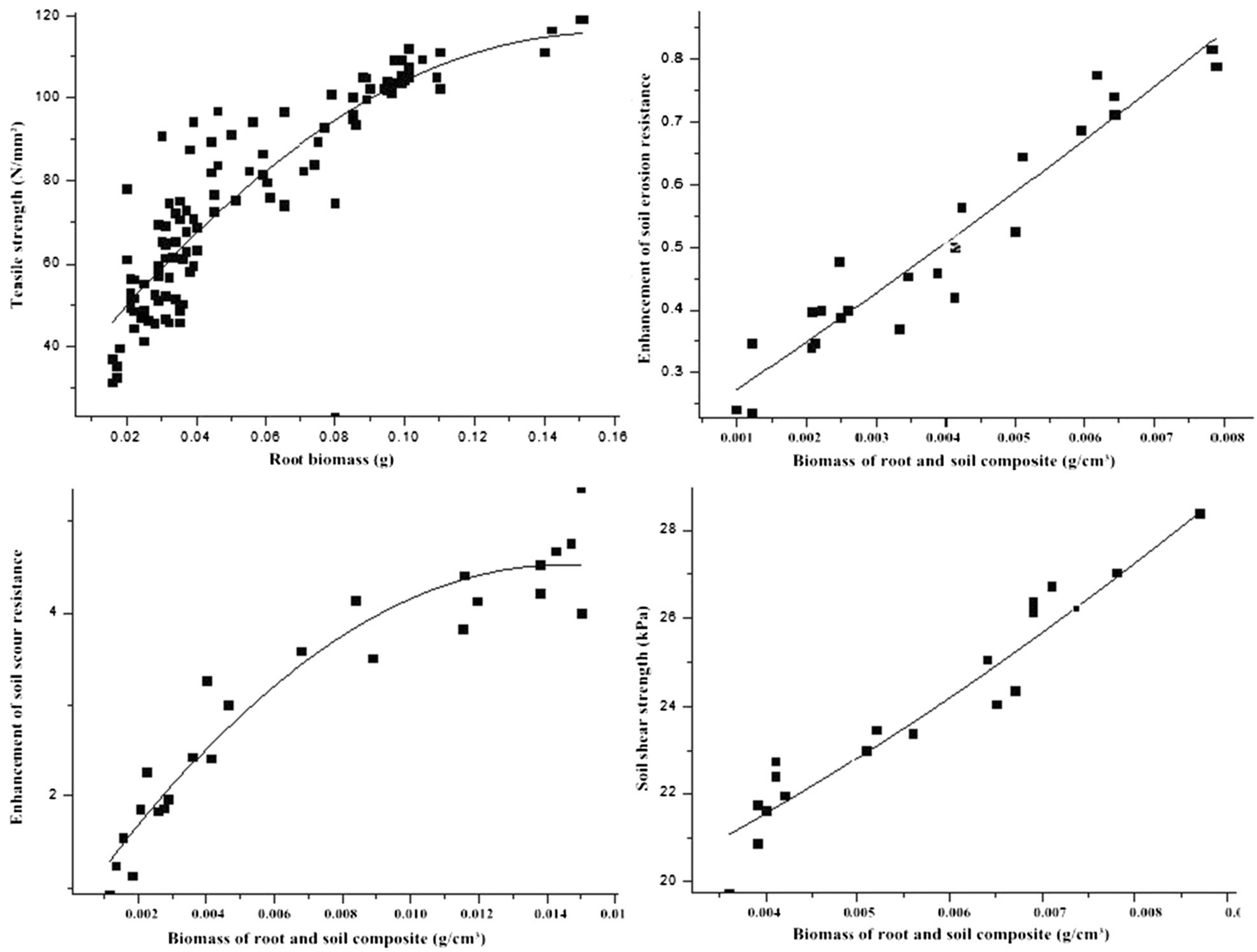

Figure 3 The linear relationship between root biomass and soil reinforcement and slope protection of the soil-root system.

The fluvial pattern in the Three Gorges Reservoir area has changed from summer inundation with winter exposure to summer exposure with winter inundation (a reverse seasonal fluctuation) for electricity production and flood control. The water level reaches 175 m from mid-October to January, then gradually declines to 160 m in March and April, and finally to 145 m from June to October. The water drawdown significantly affected the growing period of the *C. dactylon* community and resulted in the spatial difference of root growth and distribution. Both Cazzuffi et al. (2006) and Tosi (2007) reported that the spatial structure of riparian plants changed with the change of ecological environment during their growth and development which further induced the change of the soil-root system in soil conservation and slope protection. The distribution of root length, root area, root bifurcation number, and root biomass of *C. dactylon* showed significant differences among altitudes, and increased with increasing altitude. Plants at 175 m grow best, as this altitude has extended the drawdown period for plants to grow. The linear analysis of root biomass with enhancement indexes suggested that the enhancement of the soil-root system on soil conservation and slope stability increased with the increasing root biomass. The spatial variations of root biomass make the performance of soil conservation and reinforcement of the soil-root system change along with altitude gradient. Therefore, it can be concluded that this change was related to amplitude and reverse seasonal fluctuation in the Three Gorges Reservoir region.

Conclusions

The results of our study showed that the roots of the *C. dactylon* community effectively enhanced the stability of riparian shallow soil and riverbank. The tensile strength, enhancement of soil erosion resistance, enhancement of soil scour resistance, and shear strength of the soil-root system of *C. dactylon* were significantly higher than those of the control soil. However, the enhancement effect of *C. dactylon* roots changed along with the riparian altitude gradient in the Three Gorges Reservoir area. The tensile strength, enhancement of soil erosion resistance, enhancement of soil scour resistance, and shear strength of the soil-root system at 175 m were about 40.39%, 125.29%, 374.09%, and 23.84%, respectively, more than those at an altitude of 155 m. The biomass of soil-root systems was related significantly with the soil erosion resistance, soil scour resistance, and shear strength. The spatial variation of roots made the performance difference of the soil-root systems. The fluctuation in water level caused the difference of root biomass and structure, as the exposed time of plants decreased with the decrease of altitude in the Three Gorges Reservoir area. The difference of root biomass and structure resulted in the variation of the soil-root system in soil conservation and reinforcement.

The riverbank in the Three Gorges Reservoir covers 400 km^2 with a length of over 2,000 km. The change of fluvial pattern has caused the degradation of vegetation and reduction of the soil-root system in soil conservation and slope reinforcement. Most riparian shrub and herb species disappear as they cannot adapt to the new fluvial pattern (Chen and Xie 2010; Lu et al. 2010). The vegetation degrades toward the annual herb community in the Three Gorges Reservoir area. The wave and fluctuation of water level caused frequent soil slide and collapse (Xu et al. 2009). The riverbank is facing the danger of becoming 'bare bald' like most other reservoirs of large water conservancy and hydropower projects. Riparian plant species selection for riverbank restoration in the Three Gorges Reservoir area should have not only a good ability in soil conservation and reinforcement but also a good adaptation to the new fluvial pattern. *C. dactylon* with good adaptation to flooding and the ability of clonal propagation is one of the few perennial herbs to adapt to the changed environment (Chen et al. 2010). Restoring the *C. dactylon* community and taking full advantage of its effect on soil conservation and slope protection can effectively reduce soil erosion and enhance riverbank stability.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
JZ, MZ and JW were the major persons involved in the field and laboratory experiments. JZ and FC have analyzed and interpreted the experimental data and primarily drafted the manuscript. All authors approved the final draft of this manuscript.

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