J. Mt. Sci. (2018) 15(7): 1498-1509 e-mail: jms@imde.ac.cn http://jms.imde.ac.cn
https://doi.org/10.1007/s11629-017-4719-y

Soil nutrients in relation to vertical roots distribution in the riparian zone of Three Gorges Reservoir, China

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Citation: Zhong RH, Hu JM, Bao YH, et al. (2018) Soil nutrients in relation to vertical roots distribution in the riparian zone of Three Gorges Reservoir, China. Journal of Mountain Science 15(7). https://doi.org/10.1007/s11629-017-4719-y

Abstract: Since the impoundment of the Three Gorges Reservoir (TGR), the riparian zone has been subjected to numerous environmental changes. This study was conducted to recognize the distribution of grass roots and its impacts on soil nutrients in the water level fluctuation zone of TGR. Roots of four predominant herbaceous plants in the study area, specifically, *Cynodon dactylon*, *Hemarthria altissima*, *Hemarthria compressa*, and *Paspalum paspaloides*, and their corresponding relation with soil nutrient contents were investigated. Root surface area density was determined with WinRHIZO, and the relationships of root distribution with soil depths and soil nutrient contents were studied. The results indicates that most roots are distributed in the top soil layer of 0-10 cm. Estimated root surface area density for the selected grass species ranges from 0.16 to 13.44 cm^2/cm^3, and decreases exponentially with an increase in soil depth. Soil organic matter and total nitrogen contents are significantly lower on bare control area than the corresponding values on the grasslands. Total nutrient contents on grasslands of *C. dactylon* and *H. compressa* are higher than those of other grass areas. Root length density and root surface area density are significantly correlated with soil organic matter and total nitrogen content for the four grasslands. The present results suggests that plant roots have significant effects on the distribution of soil nutrients in soil profiles in the riparian zone along the TGR. Nevertheless, additional investigations are needed to reveal the specific interactions between plant roots distribution, soil nutrients and water level fluctuations.

Keywords: Roots distribution; Soil nutrients; Water level fluctuations; Riparian zone; Root surface area density; Root length density

Received: 12 October 2017
Revised: 25 January 2018
Accepted: 26 April 2018

Introduction

Roots system (especially fine roots) is the fundamental part of plant for water absorption and nutrients acquisition, hence have important influence on plant growth and survival (Bloom et al. 1985; Jobbágy and Jackson 2001; Kochsiek et al. 2013). Faster growth rates combined with longer longevities of fine roots derived from greater belowground absorptive surface area regulate the turnover rate (Kochsiek et al. 2013). Rapid acquisition of nutrients in the rhizosphere or mutative nutrients supply rates develop faster turnover of fine roots, and then would induce more active roots reply to varying nutrients availability (Hodge et al. 2009). Due to the higher specific root length, fine roots allow larger absorptive area per unit biomass, enabling faster rates of root turnover (Aerts and Chapin. 1999; Metcalfe et al. 2008; Ostonen et al. 2007). Roots improve soil properties, whereas; the development of root systems is influenced by diverse soil properties (Gregory 2006). Thus, quantifying the distribution of roots with soil depths is essential for understanding the interactions of root, plant and soil characteristics in particular for explaining how plant roots affect moisture and nutrients acquisition (Sainju and Good 1993; Bloom et al. 1985; Jobbágy and Jackson 2001). However, the detailed influences of roots on soil nutrients vary along location and environmental conditions. Specifically, in the riparian zone; soil nutrients are affected by soil property, plant roots and submergence.

Actually, soil nutrients are essential for many biological processes in the riparian zone. These processes have important impacts on the distribution and diversity of macrophytes (Peintinger et al. 2007; Wang et al. 2016; Wilcox and Nichols, 2008), phytoplankton (Brauns et al. 2008; Geraldes and Boavida, 2005) and benthic communities (e.g., invertebrates and fishes) (Brauns et al. 2008; McEwen and Butler. 2010; Richardson et al. 2002) which depend on the riparian area as the habitat for survival and reproduction. Consequently, soil degradation due to water level fluctuations (WLFs) directly controls the quality of habitat in the reservoir riparian zone (Zhao et al. 2014). Generally, WLFs have significant influence on physical and chemical characteristics of soil from the riparian zone, particularly affecting the soil nutrients cycle. Therefore, any changes in the soil-water interface will affect the soil nutrient dynamics (Abrahams 2008; de Vicente et al. 2010; Hofmann et al. 2008). In recent years, numerous investigations have reported the influence of inundation on soil nutrient dynamics. Research from Abrahams (2008) showed that WLFs affects the concentrations of soil organic matter and nutrients, and fine particle proportion of the substrate, which results in low nutrient levels of sandy or stony substrate in the water level fluctuation zone (WLFZ). Meanwhile, the study of De Vicente et al. (2010) found that WLFs potentially improve the availability of phosphorus in the water body, whereas diminishes the sediment's phosphate absorption capacity after few years of wet-dry cycles. In contrast, Zhang et al. (2012) examined the fractions of phosphorus, phosphate sorption and release for soils in the WLFZ of Three Gorges Reservoir (TGR). Specifically, in this case, Phosphate sorption reached equilibrium in 12 h and Fe/Al–P and OP were main release portions. Certainly, after the full operation of TGR, the fate of phosphorus in sediment has changed, the sediment has been a phosphorus "sink" since the full impoundment of the TGR (Wu et al. 2016). Ye et al. (2012) investigated soil nitrogen dynamics in the littoral zone of TGR and indicated that WLFs have significant influence on the process of nitrification and the soil inorganic N concentration declined after WLFs. An investigation at Manwan Reservoir of Lancang River demonstrated that submersion increased soil pH, TP, and TK concentration, though reduced the concentration of soil total carbon (TC) and total nitrogen (TN); yet, long-term flooding increased the soil C/N ratio (Zhao et al. 2014).

The Three Gorges Dam, is the largest hydropower project in the world, with a catchment area of approximately 1.0×10^6 km^2, the TGR has a total water storage capacity of 39.3 billion m^3 (Fu et al. 2010). Since the fully operational TGR in 2008, the reservoir has suffered a wide range of water level fluctuations from an altitude of 145 m to 175 m. It is mainly operated to maintain the low level in the wet season (May–September) and high level in the dry season (October–April). Consequently, an artificial riparian region with a vertical elevation difference of 30 m and a total area of 349 km^2 has been created (Tang et al. 2014; Ye et al. 2011). However, since the first appearance of TGR artificial riparian zone in 2003, it has experienced significant eco-environment degradation (Xu et al. 2013). The regulation of water level and changed hydrological process together with wave action and extreme rainfall events have caused disappearance of pre-dam terrestrial plants and emergence of a new vegetation community (Yang et al. 2012, 2013b; Zhang et al. 2013; Zhao et al. 2007), pronounced bank erosion and intensive sedimentation in the riparian zone (Bao et al. 2010, 2012, 2015; Tang et al. 2014) and other environmental challenges (Fu et al. 2010; Li et al. 2013b; Yang and Lu 2013; Yuan et al. 2013; Zhang and Lou 2011). Among these environmental consequences, soil degradation and the response of plants to the dramatic change in post-dam construction hydrological regime represent cause for concern in the case of the riparian zone of TGR. Recently, several investigations have reported soil nutrient dynamics (Ye et al. 2012, 2013a, 2014; Zhang et al. 2012), soil heavy metal pollution (Ye et al. 2011, 2013b), soil erosion and sedimentation (Bao et al. 2012; Tang et al. 2014), and plant physiological and ecology responses (Yang et al. 2012; Zhang et al. 2013) in the WLFZ of TGR. However, little information is available concerning root depth distribution and its influence on soil nutrients in the littoral zone of TGR. The aim of the present study is to: (1) clarify the vertical roots distribution with soil depths; (2) investigate the soil nutrient changes with the depth of soil layers; and (3) identify the interaction between roots and soil nutrient concentrations.

1 Materials and Methods

1.1 Study site

We selected the riparian zone at Shibao town, Zhong County of Chongqing city, right bank of the Yangtze River, as the sampling site (30°24'53''N, 108°10'25''E; Figure 1). Local climate is typical moist semi-tropical monsoon with an annual mean temperature of 18.2°C and an annual average rainfall of 1150 mm (Zhong et al. 2016). The major proportion of precipitation occurs during May to September. The dominated soil of the study area is purple soil (He 2003). According to Tang et al. (2014), a silty soil texture dominated the sampling site. Based on the investigation from Lu et al. (2010), before the impoundment of TGR, the vegetation of the riparian zone was very rich, and dominated species including therophyte (*Digitaria ciliaris*, *Leptochloa chinensis*, and *Setaria viridis*), perennials (*C. dactylon*, *Capillipedium assimile* and *H. altissima*) and ligneous plants (*Ficus tikoua*, *Pterocarya stenoptera*, and *Vitex negundo*) (Ye et al. 2013b). Nevertheless, the biodiversity severely diminished due to the submersion. After the flooding, some annual plants (e.g., *Echinochloa crusgalli* and *Bidens tripartita*) and flooding-tolerant species (e.g., *C. dactylon*) have become the predominant species (New and Xie 2008; Zhang et al. 2013).

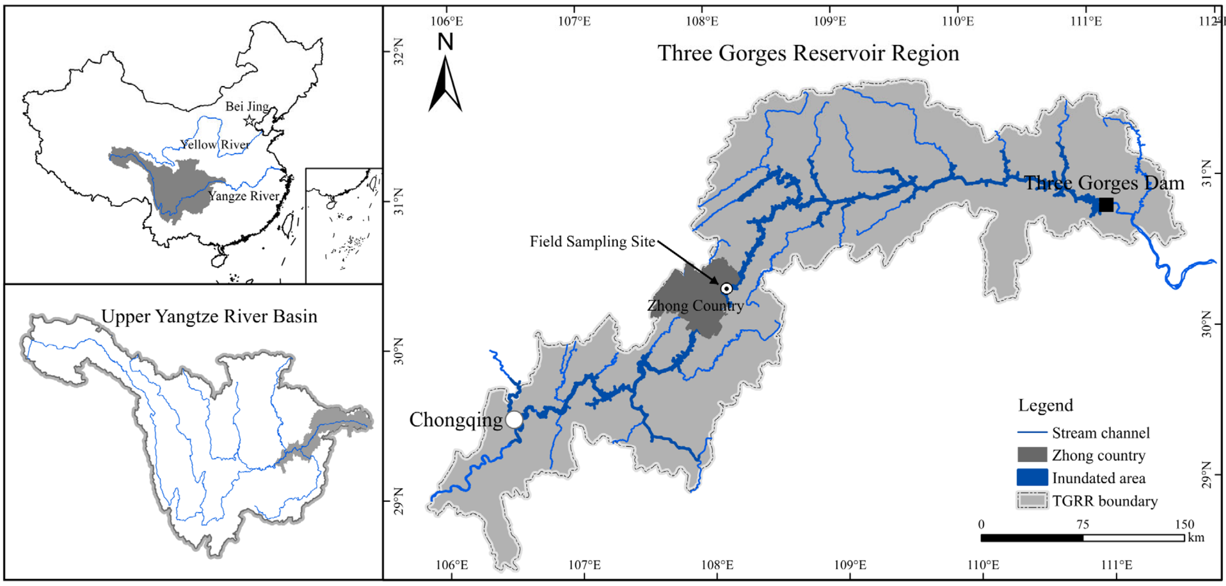

Figure 1 Location of the study area and the sampling site in Zhong County in the Three Gorges Reservoir area.

1.2 Sampling and laboratory measurements

This research investigated root distribution and corresponding soil nutrients content of three plantation species (i.e., *Hemarthria altissima*, *Hemarthria compressa* and *Paspalum paspaloides*) and one native grass (i.e., *Cynodon dactylon*). Field sampling was conducted in May 2014 when the water level of TGR receded and the riparian zone was mostly exposed. Sampling was carried out on the flat terraces with elevation of 170~175 m. Each grass species is now well developed in the WLFZ of TGR. An area of bare land was defined as the experimental control (CK).

Detailed field sampling and laboratory measurements are carried out by following the methods described by Zhong et al. (2016). However, in this investigation, the root surface area density (RSAD, cm^2/cm^3) was instead of the root length density (RLD, cm/cm^3) for describing roots distribution.

The RSAD (cm^2/cm^3) was calculated by dividing total root surface area (*A*, cm^2) by the volume of the soil occupied by roots (*V*, cm^3) (Kokko et al. 1993). The surface area of single root cylinder (A_r) is calculated by root radius (*R*) and length (*L*) using the equation:

$$A_r = 2\pi RL \tag{1}$$

For each individual soil cylinder, the total root length was multiplied by the root length per diameter class. Thus, RSAD at different soil depth classes (every 5 cm) was estimated using the following equation:

$$RSAD = \sum 2\pi R_i L_i / V \tag{2}$$

where, R_i is mean diameter of a representative diameter class *i*, L_i is the total root length of a representative diameter class *i*, and *V* is volume of the root-permeated soil core (cm^3).

1.3 Determination of soil nutrients

In this study, the $K_2Cr_2O_7$–H_2SO_4 digestion method was used to determine the soil organic carbon (SOC) (Bai et al. 2005). Soil organic matter (SOM) content was calculated by multiplying SOC concentration with the Van Bemmelen factor of 1.724 (Tan 2005). TN was determined by the K370 Kjeldahl method. Perchloric-acid digestion followed by ammonium-molybdate colorimetry was taken to measure the total soil phosphorus (TP) and FP 640 flame photometry method was implemented to determine the total soil potassium (TK).

1.4 Statistics analysis

Many studies indicated that the root amount declines with an increase in soil depths, presenting a negative exponential relationship (Eq.(3)) (Han et al. 2009; Li et al. 2005; Nosalewicz and Lipiec. 2014). Thus, power law equation between root parameter and soil depths has been fitted as follows:

$$y = a \times exp^{-bx} \tag{3}$$

where, *x* is soil depths and *y* is the measured root parameter, i.e. RSAD. The coefficient "*a*" represents the theoretical root length or surface area density at the depth zero and the coefficient "*b*" is the rate of the decrease in root index with soil depths.

The relationships between the soil nutrients content and root distribution with soil layers was tested using the Pearson correlation analysis. In addition, the Kruskal–Wallis nonparametric H-test was used to test if there are significant difference between the RSAD and soil nutrients content according to species, soil depths and re-vegetation measures. A nonparametric test was used given the small sample numbers and non-normal distributions of the data. In addition, an analysis of covariance (ANCOVA) with soil depth as a covariate was performed to test for soil nutrient significant differences between the grass species (Tukey HSD procedure). The values of soil nutrient contents were log transformed before this analysis to meet the prerequisite assumptions of normal distributions for this particular statistical procedure. All statistical analysis was performed using SPSS 23.0 and plotted with OriginPro 2016.

2 Results

2.1 Roots distribution with soil depths

The RSAD of different grasses were tested at 0-30 cm soil depth for every 5 cm. Figure 2 showed most roots were developed in the topsoil of 10 cm

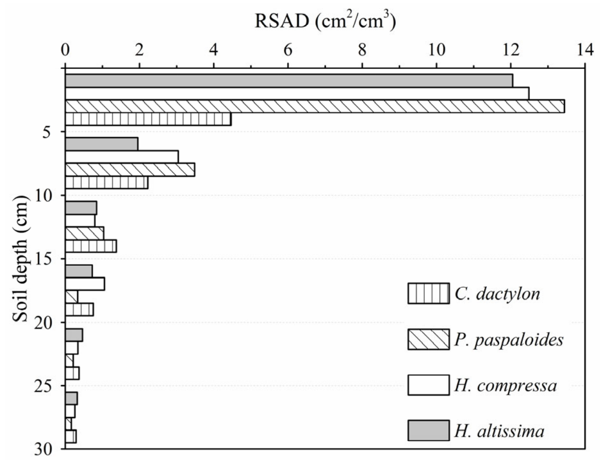

Figure 2 Mean root surface area density (RSAD) at each depth for the grasses studied.

Table 1 Regression equation exponents and correlation between RSAD (cm²/cm³) and soil depth (cm) for the different grass species.

Species	*a*	*b*	Correlation index (R^2)	*p*
H. ltissima	65.948	0.340	0.988	**
H.compressa	48.263	0.270	0.989	**
P. aspaloides	50.669	0.265	0.999	**
C. dactylon	5.205	0.124	0.995	**

Note: ** indicates the significant level $p < 0.01$

Table 2 Soil nutrients differences between grass re-vegetation types (ANCOVA, Tukey HSD test, $\alpha = 0.05$).

Soil nutrient	Revegetation types	Difference*
Total nitrogen	Plantation	A
	Natural	A
	CK	AB
Total soil phosphorus	Plantation	A
	Natural	A
	CK	A
Total soil potassium	Plantation	A
	Natural	A
	CK	A
Soil organic matter	Plantation	A
	Natural	A
	CK	AB

Note: *Different letters indicate significant differences between revegetation types.

layer, and the Kruskal–Wallis H-test result revealed the RSAD decrease significantly with increasing soil depths ($p<0.01$). The maximum RSAD estimated at the top soil layer (0-5 cm) was 13.45 cm²/cm³ for *P. paspaloides*, followed by 12.49 cm²/cm³ for *H. compressa*, 12.05 cm²/cm³ for *H. altissima* and 4.47 cm²/cm³ for *C. dactylon*. The RSAD for all studied grasses was nearly 0 at the soil depth up to 30 cm. Mean RSAD was 1.58 cm²/cm³ for *C. dactylon* and 2.95 cm²/cm³ for the other three grass species. RSAD for *C. dactylon* was significantly higher than the other grasses ($p<0.01$). Significant differences between species within the different soil layers were observed according to the Kruskal–Wallis H-test ($p<0.05$).

The exponential relationship between root distribution and soil depth was tested. As expected, a decrease of RSAD with increasing root depth following the exponential relationship described by Eq.(2) was observed. The values coefficients a, b and their statistical significance relationships are given in Table 1. This relationship was consistent for all grass species. All the species studied have good fitted power curves with adjusted R^2 values higher than 0.97 (Table 1). The values of a, b within plantation species were greater in terms of RSAD than the corresponding values of the natural recovery species (*C. dactylon*). These results indicate that re-vegetation types appreciably modify vertical root distribution but in different ways for grass root length and surface area.

2.2 Soil nutrient changes with soil depths

The SOM concentrations decreased significantly with increasing soil depths ($p<0.01$), and significant differences ($p<0.05$) were detected between the control and grassland plots (Table 2). In contrast, Table 2 shows no remarkable difference observed between the natural recovery (i.e., *C. dactylon*) and the plantation plots. In addition, the SOM of *H. compressa* plot was generally higher as compared to *H. altissima* and *P. paspaloides* (Figure 3d). TP concentrations with soil depth showed a slight decrease but this was not statistically significant, and TP contents varied markedly with soil depths under *H. compressa* as compared to the other grassland uses (Figure 3b). TK concentration was relatively higher in the soils of *C. dactylon* and *H. compressa* plots with respect to the other land uses (Figure 3c) but not significantly different with soil depths among the different grass species plots (Table 2).

2.3 Relationship between root distribution and soil nutrient concentrations

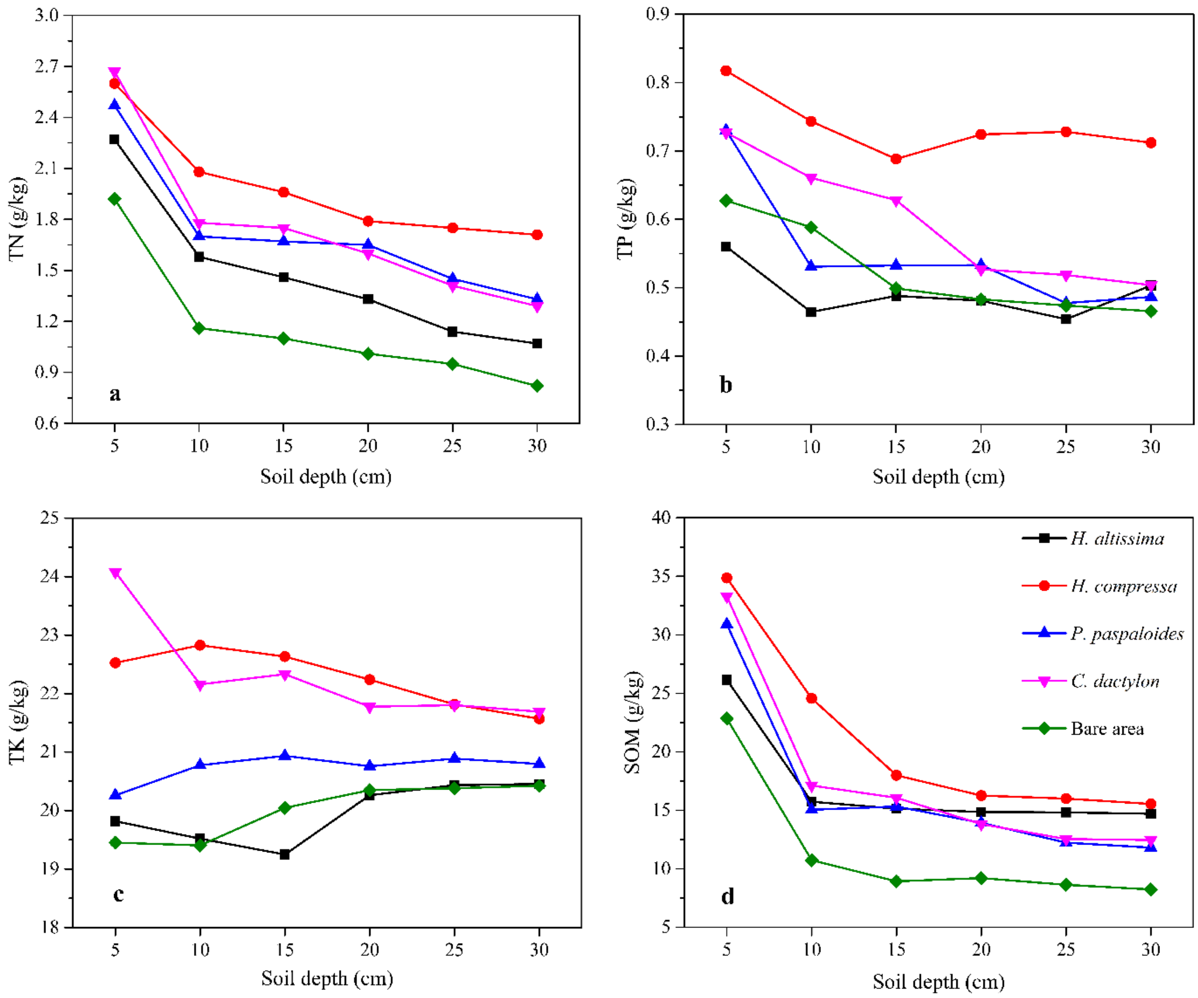

Figure 3 Mean soil nutrient contents (a: TN, b: TP, c: TK, d: SOM) for each grass species at different soil depths. TN = Total nitrogen; TP = Total soil phosphorus; TK = Total soil potassium; SOM = Soil organic matter.

As presented in Table 3, RSAD, SOM, TN and TP were significantly and positively correlated ($p<0.01$) for all species. SOM and TP concentrations were also positively correlated, but not statistically significantly. In addition, the respective concentrations of SOM and TK and that of TN and TK were negatively correlated. In contrast, the concentrations of TP and TK were not significantly correlated.

The concentrations of SOM and TN were significantly and positively correlated with RSAD (Table 3). The TP content also had a positive correlation with root density except for *H. altissima* land. The TK contents were otherwise not correlated with RSAD, and negative correlations were observed between TK and root distribution for the plots of *H. compressa* and *P. paspaloides,* except in the case of plot *C. dactylon* that showed a significant positive correlation between the TK and root distribution.

3 Discussion

3.1 Roots distribution with soil depths

The high density of grass roots resulted in high RSAD in the topsoil (0-10cm), whereas, the RSAD decreased with an increase in soil depth. A larger root surface area is useful for up taking available soil nutrients (Wang et al. 2006). The present study revealed that the RSAD was significantly different for grasses studied at different soil depths ($p<0.05$). The most probable factors for explain this difference are the environmental heterogeneity and genetic diversity (Zhong et al. 2016). There are numerous environmental reasons, such as climate, soil properties and altitudes that have significant

Table 3 Pearson correlation coefficients between soil nutrients and root distribution

Species	Items	RSAD	SOM	TP	TK	TN
H. altissima	RSAD	1	0.999**	0.588	-0.099	0.906*
	SOM		1	0.622	-0.074	0.923*
	TP			1	0.46	0.871
	TK				1	0.207
	TN					1
H. compressa	RSAD	1	0.919*	0.915*	0.200	0.908*
	SOM		1	0.900*	0.493	0.956*
	TP			1	0.115	0.771
	TK				1	0.564
	TN					1
P. paspaloides	RSAD	1	0.983**	0.968**	-0.757	0.977**
	SOM		1	0.992**	-0.694	0.993**
	TP			1	-0.611	0.999**
	TK				1	-0.642
	TN					1
C. dactylon	RSAD	1	0.988**	0.924*	0.974**	0.970**
	SOM		1	0.951*	0.991**	0.994**
	TP			1	0.961**	0.971**
	TK				1	0.985**
	TN					1
Bare area	SOM	–	1	0.831	0.479	0.992**
	TP	–		1	0.479	0.853
	TK	–			1	0.382
	TN	–				1

Notes: **, * mean significant difference at 0.01 levels and at 0.05 levels, respectively. RSAD = Root surface area density; SOM = Soil organic matter; TP = Total soil phosphorus; TK = Total soil potassium; TN = Total nitrogen.

effects on the morphology of root system and root distribution with soil depths (Coutts et al. 1999; Genet et al. 2005). Besides, soil physical and chemical properties, for example, soil structure and texture (Quine et al. 1991), soil bulk density (Gyssels et al. 2005), soil moisture and nutrients level (Hodge 2004), and water level fluctuations can strongly control root systems growth. Nevertheless, in this current investigation, all root samples were collected at a few meters' distance from each other. Accordingly, changes of environmental and soil properties differences cannot be responsible for the observed variability in RSAD. On the other hand, the interspecific relationships (Craine 2006) and the genetic diversity of different species (Burylo et al. 2011) might explain the differences in RSAD.

Statistical tests showed that, RSAD decreased following an exponential law (Table 1) with an increase in soil depth. These relationships have been observed by many authors (Han et al. 2009; Li et al. 2013a; Li et al. 2005; Nosalewicz and Lipiec 2014). The values of *a* and *b* herein are mostly higher than the corresponding estimates reported for wheat by Nosalewicz and Lipiec (2014), several other grasses from the Loess Plateau (Han et al. 2009) and as well as several herbs (Li et al. 2013a). These differences might be attributed to the species and environmental heterogeneity. However, in the present study, the most critical environmental factor may be the seasonal submergence of the riparian zone since this is likely to have a crucial consequence on plants in both the growth of above ground and roots development. Root samples for the present study were only collected at the attitude of 170 m to 175 m in the WLFZ; hence, more investigations are needed to identify the influence of water inundation on roots at different altitudes and in different locations.

3.2 Soil nutrients distribution under different vegetation cover

The concentrations of soil nutrients were different for each grass species. SOM and TN contents decreased with increasing soil depths. These results can be explained by the decomposition and conversion of plant residues and humus at the surface soil layer and fine root turnover in the deep soil layer (Matamala et al. 2003; Wang et al. 2006; Yang 2008). Values of SOM and TN from the grass lands were significantly higher compared to CK but no significant differences were detected among the grass species (Figure 2, Table 1). For TP contents, there was a slight decline with soil depth but this was not significant, and no substantial difference was observed between the grasslands and the CK. Trend of TK contents with depth also was not obvious, and no significant difference was detected between the grasslands and the CK. However, the concentrations of TP and TK on the lands of *C. dactylon* and *H. compressa* were generally higher than the other land types. The variability of TP and TK can be explained by the fact that P and K are strongly determined by parent material, soil water and temperature conditions and the degree of soil development on account of their inorganic forms (Matamala et al. 2003; Wang et al. 2006; Yang 2008). The present finding indicates that vegetation restoration (including artificial recovery and natural restoration) in the riparian zone have significant influence on soil nutrients cycling. The current investigation provides useful information for species selection in the future re-vegetation actions in the WLFZ of the TGR and similar areas in the Yangtze River Basin.

3.3 Influence of water level fluctuations on soil nutrient contents and roots distribution

River damming and followed the impoundment of reservoir changed the pre-dammed reaches with natural river flow regime into an artificial lacustrine system (Xu et al. 2011; Bao et al. 2015). Due to the fact that, reservoirs adopt the maximum level impounding operation pattern in dry season for power generation and then release the stocked water to the minimum water level during the inundation season for flood control (termed as "impounding the clear water and discharging the muddy water"), that has consequently formed a drastic WLFs. (Shao et al. 2008; Zhang and Lou 2011; Tang et al. 2014). Particularly for large reservoirs, e.g. the Three Gorges Reservoir, the extent of WLFs can reach tens of meters. These extreme WLF would lead to the ecosystems imbalance (aquatic and terrestrial) in the riparian zone and geomorphology and bring about the vegetation redistribution, species diversity loss, bank erosion and sedimentation, and other biogeochemical processes in the riparian zone (Riis and Hawes 2002; Furey et al. 2004; Leira and Cantonati 2008; Wang and Yin 2008; Bao et al. 2015). Consequently, as mentioned previously, WLFs would affect soil physicochemical properties, particularly affecting the soil nutrients cycling from the riparian zone. Changes in the soil-water interface will cause the soil nutrient level dynamics. Therefore, after the impoundment of TGR, the robust WLFs have resulted in significant changes on physical and chemical characteristics of soil and ecosystems in the riparian zone. For this reason, the influence of WLFs on the soil nutrient contents in the riparian zone of TGR has also been reported by many researchers. SOM contents observed in the present investigation generally fall in the same order of magnitude of those results reported from the WLFZ of TGR by several previous studies, i.e. Wang et al. (2010), Ye et al. (2013b, 2014), but are higher than those values reported by Chang et al. (2011), Guo et al. (2012) and Zhang et al. (2012). In general, the TN contents reported in this study are higher than the results reported by Wang et al. (2010), Chang et al. (2011), Guo et al. (2012), Zhang et al. (2012) and Ye et al. (2013b, 2014). TP concentrations reported here fall in the range of values reported by Chang et al. (2011) at the same sampling sites, and TP contents reported by Zhang et al. (2012) in the mid-section of TGR as well as those in Ye et al. (2014) investigation for plantation and natural recovery areas. The TP concentrations measured by this study are slightly lower than those reported in Wang et al. (2010) and Ye et al. (2013b) for different sites along the riparian zone of TGR. TK concentrations were similar to the results reported by Chang et al. (2011) and Ye et al. (2013b) for varying sites across the riparian zone of TGR, and higher than the results presented by Wang et al. (2010) and Ye et al. (2014). The differences of soil nutrient contents between the present investigation and previous studies in the WLFZ of TGR (Wang et al. 2010; Chang et al. 2011; Guo et al. 2012; Zhang et al. 2012; Ye et al. 2013b, 2014) may be attributed a range of factors including the submersion and inundation periods. The different sampling periods for all the investigations cited above might explain the differences. In addition, as mentioned before, we only collected the soil samples at the altitude of 170 m to 175 m of the riparian zone where flooding time is relatively short lived. Actually, the water inundation time duration has important influence on soil nutrients cycling and plant growth, at different sampling elevations is changed (Tang et al. 2014). Thus, the dissimilar soil nutrient levels between this study and other similar investigations in the riparian zone of TGR can partly be explained by the difference of submergence intensity.

Widespread attention has been diverted to the consequences of submergence on plant ecosystem in WLF zones. Generally, WLFs of TGR have resulted in the decrease or loss of plant diversity and the reconstruction of community structure (New and Xie 2008; Yang et al. 2012; Ye et al. 2013; Zhang et al. 2013), alteration of plants physiological and biochemical response (Wang et al. 2016; Zhang et al. 2016; Lin et al. 2016; Lei et al. 2018), and thereby habitat fragmentation and Landscapes changing (Fu et al. 2010; Zhang and Lou 2011; Li et al. 2013; Xu et al. 2013; Yuan et al. 2013). Therefore, many re-vegetation strategies in the riparian zone of TGR were proposed, such as the dike-pond system (Li et al. 2011; Willison et al. 2013), the modified pond-land terrace land/water use system (Chen et al. 2014), and others riparian vegetation restoration engineering (Peng et al. 2014; Yang et al. 2015). However, these investigations and suggestions lack the consideration of WLFs affects on roots system that called for detail investigations to understand the influences of water flooding on soil nutrients and roots distribution. In spite of this, the findings of this study imply re-vegetation in the riparian zone (including artificial recovery and natural restoration) would minimize the negative impacts of large dams on fluvial ecosystems.

3.4 Interaction of grass root distribution and soil nutrients

The results from this investigation indicated a significant correlation between root distribution and SOM, TN and TP (Table 3), and the concentrations of TN and SOM from grasslands were obviously higher compared to those from bare land (Figure 3). Root is the primary organ for plants absorbing water and nutrients during growth (Bloom et al. 1985; Kochsiek et al. 2013). A large proportion of nutrition for plant growth is provided via root turnover. However, in turn, the soil nutrient levels limit roots development. Thus, in general, RSAD distribution in the soil profile is significantly and positively correlated with SOM, TN and TP contents. The relationship between root distribution and TK was different in the different plots studied by this investigation. In the case of plots for *C. dactylon*, significantly and positive correlation was observed between TK and root distribution, which implies the presence of roots providing more K to the soil. In contrast, a negative correlation between TK and root density was observed for plots of *H. altissima* and *P. paspaloides*, which implies more K from root turnover is required to support the growth of these two species.

4 Conclusions

Root distribution and corresponding soil nutrients in the riparian zone of TGR were examined. Roots were generally confined to the topsoil layer (0-10 cm), and then decreased significantly with increasing soil depths ($p<0.01$). An exponential relationship between root distribution and soil depth was observed. The results presented here improve our knowledge on the biological characteristics of grass species growing in the WLFZ of TGR. SOM and TN concentrations decreased significantly with increasing soil depth ($p<0.01$), and statistical differences ($p<0.05$) were observed between the bare control area and the sampled grass lands. In contrast, no significant trends were observed for TP and TK with soil depth, but in general, higher values of TP and TK were found in the soils of the *C. dactylon* and *H. compressa* plots compared to the others. The correlation analysis indicated that the plant roots significantly influenced the contents of SOM, TN and TP. The present study demonstrates that plants and especially plant roots play an important role in controlling soil nutrients level in the riparian zone of TGR. The findings of this study imply re-vegetation in the riparian zone, including artificial restoration and natural recovery to decrease the negative impacts of large dams on fluvial ecosystems, although the conclusion must be further verified through additional controlled experiments. Furthermore, the affects of water level fluctuation should be investigated in greater detail. So far, the present results are helpful for species selection in the implementation of future re-vegetation actions in the riparian zone of the TGR and similar regions of the Yangtze River Basin.

Acknowledgements

Financial support for this study was jointly provided by the National Natural Science Foundation of China (Grant Nos. 41601296, 41571278 and 41771321), China Postdoctoral Science Foundation (Grant No. 2016M592720), Applied Basic Research Foundation of Yunnan Province (Grant No. 2016FD011), and Sichuan Science and Technology Program (2018SZ0132). The authors are thankful to all persons involved in the field investigation and data preparation of this project.

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