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Assessing heavy metal pollution in the water level fluctuation zone of China's Three Gorges Reservoir using geochemical and soil microbial approaches

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Abstract The water level fluctuation zone (WLFZ) in the Three Gorges Reservoir is located in the intersection of terrestrial and aquatic ecosystems, and assessing heavy metal pollution in the drown zone is critical for ecological remediation and water conservation. In this study, soils were collected in June and September 2009 in natural recovery area and revegetation area of the WLFZ, and geochemical approaches including geoaccumulation index (I_{geo}) and factor analysis and soil microbial community structure were applied to assess the spatial variability and evaluate the influence of revegetation on metals in the WLFZ. Geochemical approaches demonstrated the moderate pollutant of Cd, the slight pollutant of Hg, and four types of pollutant sources including industrial and domestic wastewater, natural rock weathering, traffic exhaust, and crustal materials in the WLFZ. Our results also demonstrated significantly lower concentrations for elements of As, Cd, Pb, Zn, and Mn in the revegetation area. Moreover, soil microbial community structure failed to monitor the heavy metal pollution in such a relatively clean area. Our results suggest that revegetation plays an important role in controlling heavy metal pollution in the WLFZ of the Three Gorges Reservoir, China.

Keywords Heavy metal · Geochemical approach · Soil microbial community structure · Water level fluctuation zone

Introduction

Heavy metals widely exist in water, soil, and plant in riparian zone, the intersection of terrestrial and aquatic ecosystems on earth surface. Most of them, i.e., mercury (Hg), cadmium (Cd), lead (Pb), chromium (Cr), and arsenic (As), generally existing at low concentrations, can cause damage to the environment when their accumulations exceed certain levels (Li et al. 2006; Zhang et al. 2009a). Concentrations of heavy metal in the riparian environment can be easily altered by human activities (Mays and Edwards 2001; Zhang et al. 2009b). Therefore, it is desirable to determine the anthropogenic impacts on the concentrations and spatial variations of heavy metals and evaluate their pollution status in the riparian zone for ecological remediation and water conservation.

To better evaluate heavy metal pollution in soil, monitoring data are usually interpreted using geochemical approaches including enrichment factor and geoaccumulation index (I_{geo}), and multivariate statistical techniques (i.e., factor analysis, FA) (Birth 2003;

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Censi et al. 2006; Zhang et al. 2009a; Li et al. 2010). Geoaccumulation index (I_{geo}) is widely used to evaluate anthropogenic influence on heavy metal pollution, which could well estimate the extent of metal pollution by comparing current concentration with pre-industrial levels (Idris 2008). FA allows identifying the possible pollutant sources in soil and reducing the dimensionality of a data set (Yu et al. 2008; Amaya et al. 2009).

Soil microbial community structure is an important and meaningful indicator of soil quality and thus also receives worldwide attention for assessing heavy metal pollution (Demoling and Baath 2008). Composition of microbial communities has often been proposed to be an easy and sensitive indicator of anthropogenic effects on soils (Renella et al. 2005). Previous studies have revealed that both short-term and long-term exposures to heavy metals result in the reduction of soil microbial community (Lasat 2002; Khan et al. 2008). However, some studies also reported the limitation of microbial parameters for evaluating soil heavy metal pollution especially in slight metal pollution area and their results varied (Liao and Xie 2007; Lazzaro et al. 2008). Therefore, combining soil microbial community structure with geochemical approaches might be more reasonable to evaluate heavy metals pollution (Wang et al. 2010).

With the completion of the Three Gorges Dam in 2008, the newly formed water level fluctuation zone (WLFZ) results in various ecological problems including loss of previous vegetation and soil erosion in an area of 350 km^2 in the Three Gorges Reservoir (New and Xie 2008). To restore the riparian ecosystem, revegetation projects have been carried out in some areas in recent years. The changes of natural environment together with human activities could alter the heavy metal distribution and pollution status in the riparian zone soil (Mays and Edwards 2001; Zhang et al. 2009b). Previous studies showed that heavy metal pollution was present in the WLFZ (Li et al. 2005; Yu et al. 2006). Discharge of industrial and domestic sewage into the Three Gorges Reservoir reached 1.15×10^9 tons in 2008, of which 85% of the sewage had received some level of treatment before discharge (State Environmental Protection Administration of China 2009). In addition to the local waste discharge, many areas are used for commercial harbors, i.e., Wanzhou and Zigui Harbors. However, little information is available on the evaluation of heavy metal pollution in the WLFZ during the drying period after the completion of the Three Gorges Dam.

In this study, we combined the geochemical approach (i.e., geoaccumulation index, I_{geo}) with soil microbial community structure technique to evaluate heavy metal pollution in the WLFZ of the Three Gorges Reservoir, China. The objectives were twofolds: (1) to examine the differences of heavy metals between natural recovery area and revegetation area; (2) to evaluate the pollution status using the geochemical approach and soil microbial community structure technique.

Materials and methods

Site description

Three Gorges Reservoir region (29°16′ to 31°25′N, 106° to 111°50′E) lies in a 600-km valley from Yichang to upstream Chongqing (Fig. 1). Climate in this region belongs to southeast sub-tropic monsoon. Annual mean temperature is 16.5°C to 19°C and annual precipitation is about 1100 mm with 80% taking place from April to October. After rising to 173 m by 2008 and 171 m by 2009, the water level of Three Gorges Reservoir reached a maximum of 175 m in winter of 2010 and would fluctuate from 145 m above sea level (a.s.l.) in summer (May to September) to 175 m a.s.l. in winter (October to April) thereafter.

With the Three Gorges Dam fully functioning in 2010, the Three Gorges Reservoir inundates a total area of 1,080 km^2 with formation of the WLFZ with a total area of 350 km^2 (Zhong and Qi 2008). Due to the inundation, various ecological problems arise, i.e., loss of previous vegetation and soil erosion (New and Xie 2008). To restore the riparian ecosystem, revegetation projects have been carried out in three areas including Zhongxian, Wanzhou, and Zigui in recent years.

Before submergence, vegetation in the WLFZ was dominated by annuals, i.e., *Setaria viridis*, *Digitaria ciliaris*, and *Leptochloa chinensis*, perennials including *Cynodon dactylon*, *Hemarthria altissima*, and *Capillipedium assimile*, and woody plants such as *Ficus tikoua*, *Pterocarya stenoptera*, and *Vitex negundo* (Lu et al. 2010). However, the reversal of submergence time with half a year (May–September) exposed in summer and another half (October–April) submerged in winter, and prolonged inundation

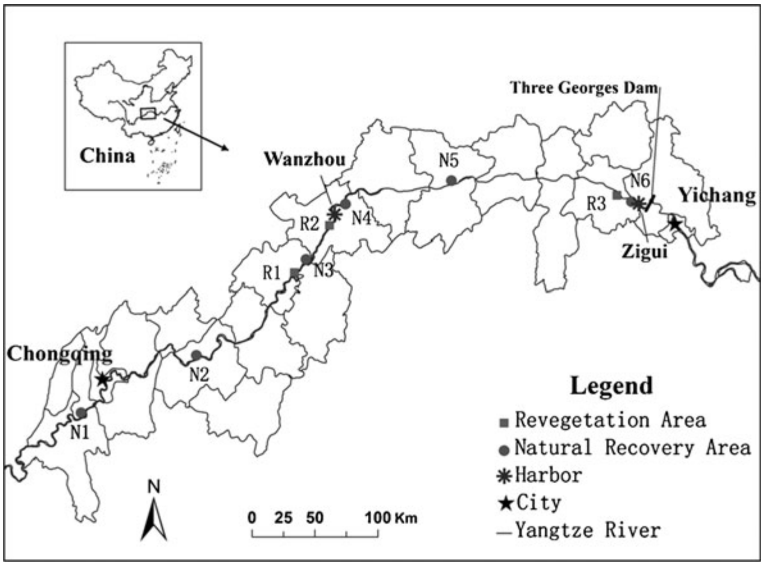

Fig. 1 Schematic diagram of sampling sites in the water level fluctuation zone of Three Gorges Reservoir, China

duration resulted in loss of previous vegetation and only the annual plants such as *S. viridis, D. ciliaris,* and *L. chinensis* are dominant species with the average cover of 60% in the natural recovery area of the WLFZ (Lu et al. 2010). In the revegetation area, three vegetation types (herbs, shrubs, and trees) were planted along the elevation from 155 to 175 m. In general, herbs such as *C. dactylon* and *Hemathria sibirica* were planted between the elevations of 145–155 m with the mean coverage of 95%. Shrubs including *Hibiscus syriacus*, *Morus alba,* and *Salix variegatee* were planted between the elevations of 155 to 165 m with the mean cover of 70%. Trees such as *Salix chaenomeloides* and *Taxodium distichum* were planted between the elevations of 165 to 175 m with the average cover of 90%. All those plants could tolerate summer exposure and winter submergence (Lu et al. 2010).

Soil sampling

Field surveys were conducted in June 2009 and September 2009 when the WLFZ was all exposed to the air. Soil samples were collected in six natural growth areas (N1-6) and three revegetation areas (R1-3) based on the geographical properties in the WFLZ from the upstream to downstream in the Three Gorges Reservoir (Fig. 1). In each area, three sampling sites were randomly selected along the elevation from 145 to 175 m. In N1, samplings were only collected between the elevations of 165 to175 m due to the high water level during the sampling period. At each sampling site (1 × 1 m), five soil samples of the 0–20-cm soil layer were collected and then well mixed to form a composite sample. Samples were sealed in plastic bags and stored at 4°C for soil heavy metal analyses and at −20°C for soil microbial community structure analyses.

Heavy metal analysis

Soil pH was measured in a 2:1 (*g*/*g*) soil to water solution using Fisher Scientific AR15 (Waltham, MA) pH probe. Soil organic matter was determined by potassium dichromate titrimetric solution with the method detection limit (MDL) of 0.5 gkg^{-1}. The particle-size was determined by wet sieving and by sedimentation using the pipette sampling technique (Rinklebe and Langer 2006). For metal analysis, total sediment digestion was performed in Teflon vessels following the classical open digestion procedures with a mixture of concentrated $HF–HClO_4–HNO_3$ (i.e., 10 mL HNO_3, 5 mL HF and 5 mL $HClO_4$) (State Environmental Protection Administration of China 2002). All procedures were carried out as described by Li et al. (2010). Concentrations of metals in solutions were determined using flame atomic absorption spectrometry (Analytik Jena AAS vario6, Germany) for Cr, Cd, Pb, Cu, Zn, Fe, and Mn, and cold vapor AAS for Hg with the MDL of 0.02 mg/kg (Zhang et al. 2009a). As was determined by diethyl disulfide and carbamate silver colorimetric method with the MDL of 0.05 mg/kg (GB15618-1995). Quality control procedures, including internal quality control using reference materials and regular participation in interlaboratory comparisons, were employed to monitor the validity of the test results. A good agreement was observed between the data analyzed and those certified by the reference material and the analytical precision was within ±10% (Ye et al. 2011).

Soil microbial community structure analysis

The total number of culturable heterotrophic bacteria, actinomycetes, and fungi were numerated using the plate counting technique. Soil (10 g fresh weight) was weighed into 300-mL Erlenmeyer flasks containing 90 mL of sterile monopotassium phosphate buffer (K_2HPO_4 (0.65 g), KH_2PO_4 (0.35 g), and $MgSO_4$ (0.10 g) in 1 L water) and shaken for 15 min at 250 rpm. From each soil extract, 100-fold dilutions were prepared in test tubes containing 9 mL buffer. The total number of culturable heterotrophic bacteria was numerated using plate counts made on tryptone soya agar (Oxoid, Basingstone, Hampshire, England) amended with 0.1 g/L cyclohexamide. The colony-forming units (cfu) of fungi and actinomycetes were numerated using plate counts made on rose Bengal agar (Oxoid) amended with 30 mg/L streptomycin sulfate for fungi, while glycerol casein agar was amended with 0.05 g/L cyclohexamide for actinomycetes (Khan et al. 2010). The plates were inoculated with 100 μL soil suspension and cultivated at 25°C in constant-temperature incubator for 1 week to form visible colonies of heterotrophic bacteria, fungi, and actinomycetes. Control plates of respective media without soil suspension were also included to check any possible contamination.

Data analysis

Geoaccumulation index (I_{geo})

The geoaccumulation index (I_{geo}) (Müller 1969) has been applied to evaluate soil heavy metal pollution by comparing current concentration with pre-industrial levels (Loska and Wiechuła 2003). The I_{geo} can be calculated using the following equation:

$$I_{\text{geo}} = \log_2(C_n/1.5B_n) \tag{1}$$

where C_n is the measured concentration of the examined metal (n) in soil and B_n is the background concentration of the metal (n). The background matrix correction factor due to lithogenic effects was considered using a constant of 1.5. In this study, B_n, the local background value was suggested by Tang et al. (2008) (Table 1). The reference

Table 1 Concentration of metals and soil pH in the water level fluctuation zone of the Three Gorges Reservoir (unit in milligrams per kilogram except Fe and Mn in grams per kilogram and pH)

		pH	Hg	As	Cr	Cd	Pb	Cu	Zn	Fe	Mn
Natural recovery area	*N*	32	32	32	32	32	32	32	32	32	32
	Minimum	5.28	0.06	1.09	15.50	0.27	17.41	13.13	48.63	8.75	0.10
	Maximum	8.45	0.75	9.31	66.13	0.78	70.14	69.39	139.73	33.05	0.89
	Mean	7.56*	0.12	4.41*	39.47	0.48*	37.10*	30.73	83.38*	24.97	0.48*
	S.E.	0.18	0.02	0.43	2.00	0.03	2.33	2.66	4.67	0.76	0.04
Revegetation area	*N*	18	18	18	18	18	18	18	18	18	18
	Minimum	4.94	0.06	1.17	17.56	0.24	19.74	13.60	48.25	19.44	0.16
	Maximum	8.06	0.96	3.97	65.38	0.46	35.91	50.80	84.69	30.11	0.58
	Mean	6.41	0.19	2.78	42.89	0.33	27.77	23.33	67.34	23.44	0.30
	S.E.	0.21	0.06	0.20	2.97	0.01	1.09	2.63	2.67	0.65	0.03
BV			0.05	5.84	78.03	0.13	23.88	25.00	69.88		
GS			≤0.15	≤15	≤90	≤0.20	≤35	≤35	≤100		

Independent-samples *T* test was performed for the metals and the non- parametric Mann–Whitney U test was used for pH and Hg to compare the differences between the natural recovery areas and revegetated areas

S.E. standard error, *d.f.* degrees of freedom; *BV* background values for the Three Gorges Reservoir region (Tang et al. 2008), *GS* grade one of environmental quality standards for soil (State Environmental Protection Administration of China 1995)

$*p<0.01$

values of Fe and Mn were 29,400 and 583 mg/kg, respectively (China National Environmental Monitoring Center 1990). Müller (1981) distinguished seven classes of geoaccumulation index from class 0 ($I_{geo} \leq 0$) to class 6 ($I_{geo} > 5$; Table 2). The highest class (class 6) reflects at least 100-fold enrichment over the background values (Zhang et al. 2009b).

Statistical analysis

Independent-samples *T* test was performed to compare the differences in soil characteristics, soil metals, and microbial communities between the natural recovery areas and revegetated areas. Normality and homogeneity of data were examined by the Kolmogorov–Smirnov and Levene tests, respectively. Logarithmic transformation was needed for bacteria and fungi. The non-parametric Mann–Whitney U's test was used for pH and Hg, as they were not normally distributed. Pearson's correlation analysis was used to test the relationships among soil pH, metals, and soil microbial communities. FA was used to identify the source types of pollutants in the soil. Kaiser–Meyer–Olkin (KMO) and Bartlett's sphericity test were conducted to examine the suitability of the data for FA (Helena et al. 2000). All the processes were performed using SPSS 13.0 for windows.

Results

Distribution of metals and soil characteristics

All the metals except Hg, Cr, Cu, and Fe showed significant variations between the natural recovery area and revegetation area in the WLFZ ($p < 0.01$) with higher values in natural recovery area (Table 1). China's Environmental Quality Standard for Soils (GB 15618-1995) specified three grades for metals (State Environmental Protection Administration of China 1995). Compared to levels of grade one, Cd and Pb in natural recovery area, and Hg and Cd in revegetation area were exceeded the standard values (Table 1). Overall, Hg, Cd, and Pb in all the study areas and Cu and Zn in natural recovery area were higher than background values (Table 1). No significant variability existed in the soil characteristics including soil organic matter and soil granule composition between the natural recovery area and revegetation area ($p < 0.05$; Table 3).

Table 2 Müller's classification for geoaccumulation index (Müller 1981)

I_{geo}	Class	Pollution status
>5	6	Extremely polluted
4–5	5	Heavily to extremely polluted
3–4	4	Heavily polluted
2–3	3	Moderately to heavily polluted
1–2	2	Moderately polluted
0–1	1	Unpolluted to moderately polluted
<0	0	Unpolluted

The average values of geoaccumulation index (I_{geo}) for As, Cr, Pb, Cu, Zn, Fe, and Mn were below zero, while I_{geo} (Hg), I_{geo} (Cd) were above zero in all the areas and the I_{geo} (Cd) in natural recovery area were greater than 1(Fig. 2). Further, Pearson's correlation analysis demonstrated significantly positive relationships among soil pH, As, Cd, Pb, Cu, Zn, Fe, and Mn ($p < 0.05$; Table 4).

Soil microbial community structure

No significant variability existed in the soil microbial communities including bacteria, fungi, and actinomycetes between the natural recovery area and revegetation area ($p < 0.05$; Fig. 3). Pearson's correlation analysis demonstrated that the number of bacteria and actinomycetes were significantly positive with pH and Cd (Table 4).

Discussion

Spatial variations of heavy metal distribution

The significantly spatial differences of most metals in the WLFZ ($p < 0.01$; Table 1) indicated the influence of human activities on metals (Mays and Edwards 2001). In the revegetation area, plants with higher biomass could absorb and accumulate metals, resulting in the lower concentration of metals in soil (Zhang et al. 2009a). Moreover, revegetation could reduce the value of soil pH (Table 1; Ma and Jiao 2005), and consequently increase the solubility of heavy metal in soil

Table 3 Soil characteristics for natural recovery and revegetation areas in the water level fluctuation zone of the Three Gorges Reservoir (mean±SE)

Characteristics	Natural recovery area	Revegetation area
Soil organic matter (g/kg)	10.17±0.96	9.93±0.50
Gravel (%) (>0.25 mm)	9.54±2.41	9.16±1.92
Coarse sand (%) (0.05–0.25 mm)	31.18±2.40	29.69±1.69
Fine sand (%) (0.01–0.05 mm)	13.41±0.73	12.42±0.70
Silt (%) (0.005–0.01 mm)	31.76±1.49	33.03±0.88
Fine silt and clay (%) (0.001–0.005 mm)	5.08±0.47	4.87±0.40
Clay (%) (< 0.001 mm)	9.04±1.02	10.82±1.02

There were no significant differences between the recovery and revegetation areas

solution while decrease the absorbability of soil particles, resulting in lower concentration of metals in soils (Yin et al. 1997; Table 4). The higher metals (i.e., Cd, Pb, and Zn) in the natural recovery area can be attributed to the rapid developments of industry and urbanization around these sites (N1-6) (Li et al. 2005; SEPA 2009).

Pollution assessment using geochemical approaches

The averaged I_{geo} for As, Cr, Pb, Cu, Zn, Fe, and Mn in all the areas were lower than zero (Fig. 2), suggesting that the WLFZ was not polluted by these metals (Table 2; Müller 1981). However, the average values of I_{geo} (Hg) and I_{geo} (Cd) were above the zero, especially I_{geo} (Cd) in natural recovery area were greater than 1, indicating that Cd was a moderate pollutant and Hg was a slight pollutant in the WLFZ (Fig. 2; Table 2; Müller 1981; Gargouri et al. 2011). High volume of water in the Yangtze River can significantly dilute relatively smaller amount of contaminants from nearby cities and traffic exhaust in the river, leading to the WLFZ free of being polluted by most metals (Zhang et al. 2009b). Frequent water transport in the WLFZ might have made the whole watershed contaminated by the vehicle exhaust containing Hg (SEPA 2009). The contamination of Cd in all the study areas could be attributed to the large amount of industrial and domestic wastewater from nearby cities (Censi et al. 2006; Li et al. 2010). The frequent material exchange between river and the riparian zone during the submergence period also made the contaminants (i.e., Cd) accumulating in the WLFZ (Qiao et al. 2007).

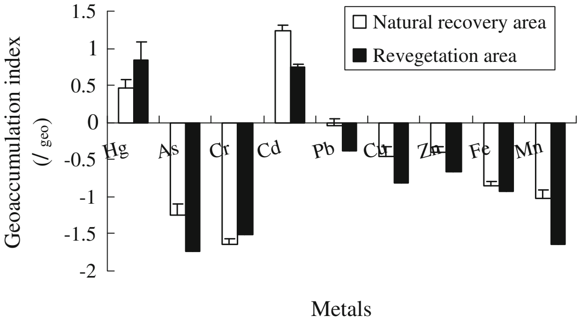

Fig. 2 Geoaccumulation index (I_{geo}) values of metals in the water level fluctuation zone of the Three Gorges Reservoir (mean±SE)

FA extracted four factors with eigenvalue greater than 0.5 accounting for 88% of the total variance (Table 5). Factor 1, accounting for 53% of variance with the highest loadings of As, Cd, Pb, Zn, and Mn and medium loading of Cu (Table 5), could be considered as industrial and domestic sources (Zhang et al. 2009a). Industrial and domestic wastewater from nearby cities contributed large amount of Cd, Pb, Cu, and Zn to the soil, leading to the contents of these metals in the natural recovery area higher than the background values (Table 1). Factor 2, accounting for 15% of total variance with the highest loadings of Fe (Table 5), could be regarded as natural source (Li et al. 2010). The I_{geo} (Fe) less than zero indicated that Fe originated from the natural rock weathering and the WLFZ was not polluted by Fe (Table 2; Fig. 2; Müller 1981). Factor 3, with the highest loadings of Hg (Table 5), could be regarded as the traffic source (Liu 1997). The pollution of Hg in all sites was correlated to the traffic exhausts from the frequent water transportation in the Three Gorges Reservoir region (SEPA 2009). Factor 4, which had the highest loadings of Cr and accounted for 7% of the total variance, could be considered as another crustal source (Zhang and Liu

Table 4 Pearson correlation coefficients among soil microbial community, metals, and soil parameters

	pH	Hg	As	Cr	Cd	Pb	Cu	Zn	Fe	Mn
pH	1.00									
Hg	−0.13	1.00								
As	0.66**	−0.06	1.00							
Cr	0.34*	−0.33*	0.37**	1.00						
Cd	0.65**	−0.18	0.79**	0.40**	1.00					
Pb	0.68**	0.03	0.88**	0.33*	0.71**	1.00				
Cu	0.33*	−0.18	0.37**	0.36*	0.53**	0.46**	1.00			
Zn	0.70**	0.03	0.73**	0.36*	0.57**	0.93**	0.57**	1.00		
Fe	0.26	−0.03	0.10	0.14	0.06	0.31*	0.45**	0.52**	1.00	
Mn	0.51**	0.01	0.68**	0.16	0.65**	0.74**	0.63**	0.74**	0.56**	1.00
Bacteria	0.30*	0.13	0.19	0.21	0.32*	0.12	−0.16	0.03	−0.21	−0.03
Fungi	−0.22	0.02	−0.13	−0.05	0.02	−0.11	0.05	−0.15	−0.03	−0.02
Actinomycetes	0.30*	0.02	0.26	0.35*	0.30*	0.19	−0.25	0.10	−0.16	0.00

*$p<0.05$; **$p<0.01$

2002). The concentration of Cr lower than background values and I_{geo} (Cr) less than zero could be contributable to natural rock weathering (Table 1; Fig. 2; Müller 1981).

The total factor scores interpreted the total pollution level and sources (Zhang et al. 2009a). The higher the factor scores, the higher the factor's influence (Bu et al. 2010). The natural recovery area was distinguished from revegetation area by factor score 1, which were most likely polluted by industrial and domestic wastewater (Table 5). Factor score 4 was significant to the condition of revegetation area, reflecting the influences of natural factor from natural rock weathering (Table 5). Overall, the integrated factor scores recognized the natural recovery area as a region of comparatively high pollution (Table 5).

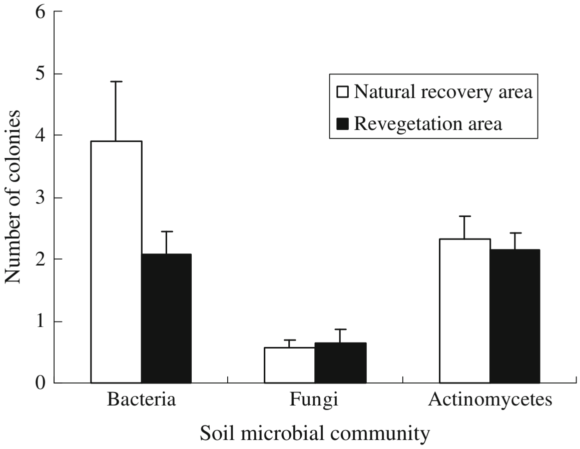

Fig. 3 Microbial population groups in natural recovery and revegetation areas (unit in 10^5 cfu/g except fungi in 10^4 cfu/g). There were no significant differences between the recovery and revegetation areas

Pollution assessment using soil microbial community structure

Soil biological characteristics are recognized as much more dynamic and sensitive than soil physicochemical properties to environmental changes (Hinojosa et al. 2004). However, reports also showed the limitation of microbial parameters for evaluating soil heavy metal pollution especially in slight metal pollution area (Liao and Xie 2007; Lazzaro et al. 2008). In this study, although the natural recovery area was more polluted compared to the revegetation area, there were no significant variabilities in the soil microbial communities including bacteria, fungi, and actinomycetes between the natural recovery area and revegetation area ($p<0.05$; Fig. 3). Suhadolo et al. (2004) had found that a higher concentration of metals did not always reduce microbial communities because some microbes may prosper even under heavy metal-polluted conditions. Based on the results obtained by geochemical approaches, the WLFZ was

Table 5 Rotated components of metals in the water level fluctuation zone of the Three Gorges Reservoir, China

Variable	Factor 1	Factor 2	Factor 3	Factor 4	
Hg			0.92		
As	0.93				
Cr				0.89	
Cd	0.87				
Pb	0.94				
Cu	0.58				
Zn	0.85				
Fe		0.92			
Mn	0.83				
Eigenvalues	4.74	1.35	1.19	0.65	
Percent of variance	52.65	14.95	13.25	7.17	
Cumulative percentage	52.65	67.59	80.84	88.01	
Area	Factor score 1	Factor score 2	Factor score 3	Factor score 4	Total factor score
Natural recovery area	0.34	0.02	−0.16	−0.27	0.16
Revegetation area	−0.61	−0.04	0.29	0.48	−0.29

Extraction method: principal component analysis; Rotation method: Quartimax with Kaiser normalization. Only factors loading values greater than 0.50 were presented

moderately polluted by Cd, but we also found that the number of bacteria and actinomycetes were significantly positive with Cd (Table 4), which could partly explain that higher content of soil metal may not play some part in reducing microbial number.

Comparison of the two assessment approaches

Geochemical techniques by I_{geo} and FA illustrated the moderate pollutant (i.e., Cd) and the slight pollutant (i.e., Hg) in the WLFZ. It also identified the pollutant sources including industrial and domestic wastewater, natural rock weathering, traffic exhaust, and crustal materials. Soil microbial community failed to monitor the soil heavy metal pollution. Some microbes were capable of tolerating heavy metal contamination (Suhadolo et al. 2004; Wang et al. 2010), thus microbial parameters had difficulties in extrapolating the meaningful toxic variables, i.e., Cd in this study. Therefore, combined use of geochemical technique and soil microbial community structure approach should be adopted to evaluate the pollution status in the WLFZ of Three Gorges Reservoir. Moreover, other indicators should be used in the further investigation, like soil populations or toxicity tests or metal bioaccumulation in vegetation, which could better evaluate metals bioavailability.

Conclusion

The concentrations of heavy metal (As, Cd, Pb, Zn, and Mn) demonstrated significant variations between the natural recovery area and revegetation area, with lower levels in the revegetation area, suggesting the effectiveness of revegetation project on controlling heavy metal pollution in the WLFZ. The geoaccumulation index (I_{geo}) and FA revealed moderate pollutants, i.e., Cd and the slight pollutant (i.e., Hg) in the WLFZ, and identified pollutant sources of industrial and domestic wastewater, natural rock weathering, traffic exhaust, and crustal materials. Nevertheless, soil microbial community failed to monitor the soil heavy metal pollution. Thus, combining the geochemical technique with soil microbial community structure approach could be a reliable approach to assess heavy metal pollution in the WLFZ of Three Gorges Reservoir, China. Moreover, other indicators, like soil populations or toxicity tests or metal bioaccumulation in vegetation, should be used in the further investigation to better evaluate metals bioavailability.

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