RESEARCH ARTICLE

Plant communities in relation to `flooding and soil characteristics in the water level fluctuation zone of the Three Gorges Reservoir, China

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Abstract With the filling of the Three Gorges Reservoir, original vegetation in the water level fluctuation zone (WLFZ) between the elevations of 145 and 175 m disappeared due to the reversal of submergence time (winter flooding) and prolonged inundation duration (nearly half a year). To better understand the relationships between the environmental factors and recovered plant communities for reconstructing floristically diverse riparian zone, we conducted a field survey in 11 sites in the WLFZ in June 2010, and vegetation composition, flooding characteristics, heavy metals, and soil major nutrients were determined. Consequently, the canonical correspondence analysis was used to investigate the relationships between plant species composition and flooding characteristics, heavy metal contamination, and soil nutrients. Results demonstrated that vegetation in the WLFZ was dominated by annuals, i.e., *Echinochloa crusgalli* and *Bidens tripartita*, and perennials including *Cynodon dactylon*, and plant species richness and diversity were negatively associated with flooding duration, heavy metal contamination, and nutrients including total phosphorus, available phosphorus, available potassium, and nitrate. Our results suggest that plant species, recovering mainly through soil seed bank and regeneration of remnant individuals, have been influenced by the combined effects of environmental factors.

Keywords Canonical correspondence analysis · Heavy metals · Flooding · Soil nutrient · Vegetation

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Introduction

Vegetation restoration in riparian zone has increasingly concerned the governments and ecologists since vegetation degeneration has resulted in serious environmental issues and the loss of ecological services (Langer et al. 2008). Many studies have focused on the factors influencing plant diversity in the riparian zone and found that the presence and abundance of species are, to a great extent, determined by a wide variety of environmental factors (i.e., flooding, soil contamination, and nutrient supply) (Aerts et al. 2003; Schipper et al. 2011). Therefore, it is critical to understand the relation between the environmental factors and plant diversity for reconstructing floristically diverse riparian zone.

Plant species diversity and evenness are strongly determined by soil nutrient supply (Aerts et al. 2003). Correlative studies have shown a humped-back relationship between number of species and major soil nutrients like nitrogen (N), phosphorus (P), and potassium (K) (Janssens et al. 1998). Braakhekke and Hooftman (1999) suggested higher plant species diversity with a balanced resource supply ratio. For the most commonly growth-limiting nutrients (N and P), the supply ratios must be between 10 and 14 to achieve highest biodiversity (Aerts et al. 2003). Concerning the P and K, the highest number of species is found at 5–8 mg/100 g extractable P and 20 mg/100 g extractable K (Janssens et al. 1998). Thus, for restoration or maintenance of plant community diversity, the soil chemical characteristics have to be appropriate. Other characteristics such as soil pH and organic matter can also influence plant species composition since they are moreover closely related to the N, P, and K availability in the soils (De Deyn et al. 2004).

Plants are sensitive to surpluses of particular trace elements, with certain sensitive species showing signs of toxicity at low heavy metal concentrations (Kabata-Pendias and Pendias 2001). In a landscape, riparian zone is an effective

sink for heavy metals due to its integration and accumulation of pollutants from both the terrestrial and aquatic environments (Ye et al. 2011). As a result, heavy metal concentrations in the riparian zone soils commonly exceed environmental quality standards, indicating potential toxicological risks for plants (Leuven et al. 2005).

For plants in riparian zone, periodical flooding is often considered an extremely important environmental factor (Lenssen and De Kroon 2005). As the floodwaters move onto the riparian zone, the soils become anaerobic, resulting in strongly reduced oxygen availability for plant roots. This creates major stress particularly for plants without specific traits to adapt to these conditions and could thus limit their distribution (Banach et al. 2009). In addition to this direct impact, flooding could influence plant species distribution indirectly by changing soil characteristics like pH and nutrients status (Beumer et al. 2008).

With the completion of the Three Gorges Dam in 2008, the Three Gorges Reservoir inundates a total of area of 1,080 km^2. The water level of the reservoir fluctuates from 145 m a.s.l in summer (May to September) to 175 m in winter (October to April), resulting in formation of the water level fluctuation zone (WLFZ) with a total area of 350 km^2 in the reservoir (Ye et al. 2011). The reversal of submergence time (winter flooding) and prolonged inundation duration (nearly half a year) result in loss of previous vegetation, and annual plants such as *Setaria viridis, Digitaria ciliaris*, and *Leptochloa Chinensis* currently are dominant species (Lu et al. 2010a). Vegetation restoration in the WLFZ has become an increasing concern in recent years (Ye et al. 2012a); thus, it is important to understand the formation of naturally recovered vegetation in the WLFZ. The present study aimed to assess relationships between plant communities and environmental factors including periodic flooding and soil chemical characteristics in the WLFZ. We tried to answer the following questions: (1) How is plant species composition in the WLFZ related to soil chemistry? (2) How does short-term periodic flooding affect plant species composition?

Materials and methods

Study sites

The WLFZ of the Three Gorges Reservoir region (29°16′–31° 25′ N, 106–111°50′ E) is located in a 600 km valley from Yichang to upstream Chongqing, a transitional zone from the Tibetan Plateau in the west to the east rolling hills and plains of China's subtropical region (Fig. 1). Its annual mean temperature is 3.4–7.2 °C in January and 28–30 °C in July. Annual mean precipitation is about 1,100 mm with 80 % falling in April to October. Zonal soil is composed of red soil, yellow soil, and mountain yellow soil (Zhao et al. 2007; Ye et al. 2011).

With the Three Gorges Dam fully functioning in 2010, the water level in the reservoir fluctuates from 145 m in summer to 175 m in winter. The reversal of flooding time and prolonged submergence duration have dramatically altered the hydrological regime in the WLFZ. Before submergence, vegetation in the WLFZ was dominated by annuals, i.e., *Setaria viridis, D. ciliaris*, and *Leptochloa chinensis*; perennials including *Cynodon dactylon, Hemarthria altissima*, and *Capillipedium assimile*; and woody plants such as *Ficus tikoua, Pterocarya*

Fig. 1 Schematic diagram of sampling sites in the water level fluctuation zone of Three Gorges Reservoir, China
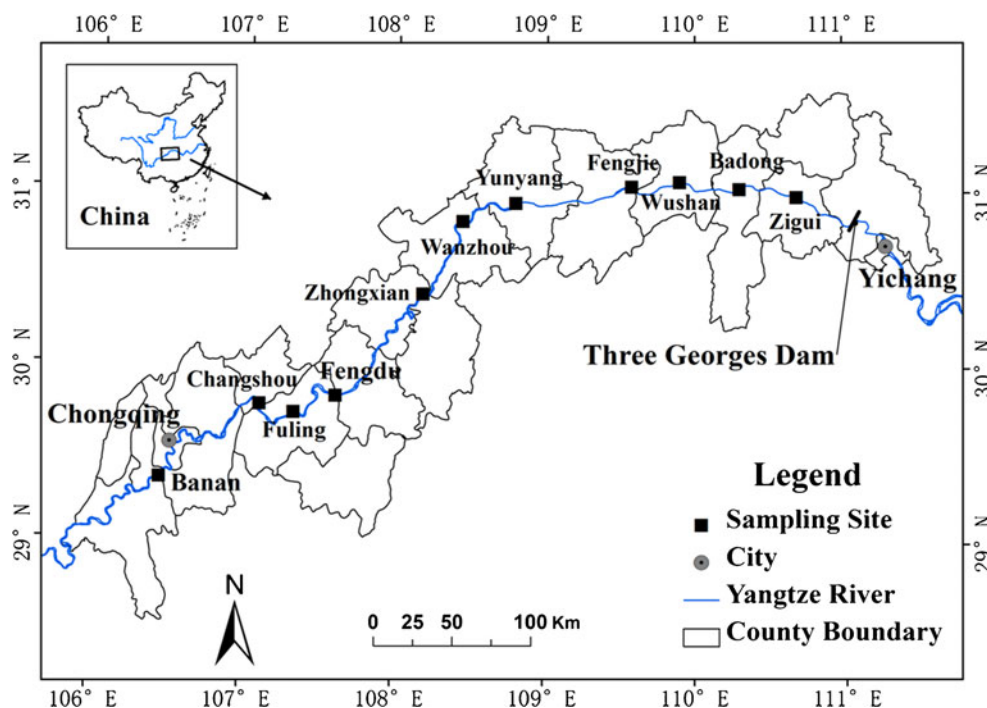
stenoptera, and *Vitex negundo* (Lu et al. 2010a; Ye et al. 2011). However, after the prolonged submergence, the number of plant species is strongly reduced and annual plants, i.e., *Echinochloa crusgalli* and *Bidens tripartita*, and perennials including *C. dactylon* are dominant species.

Field work and laboratory analysis

Field surveys were conducted in June 2010 when the reservoir's water level was 145 m, and the WLFZ was exposed to the air after submergence. We selected 11 sampling sites based on the geographical characteristics of the WLFZ from upstream to downstream in the Reservoir (Fig. 1). In order to examine the impact of flooding duration on plant community, a survey of vegetation and soil was conducted in three sections of elevation from 145 to 175 m (i.e., bottom, 145–155 m; middle, 156–165 m; and top, 166–175 m) in each sampling site. However, survey was only carried out between the elevations of 166–175 m in Banan because of high water level during the sampling period.

Four 1×1 m herb quadrats and four 5×5 m shrub quadrats were investigated in the three sections of each sampling site. Vascular plant species in the quadrats were identified according to Van der Meijden (2005); the cover of each species was estimated according to the Braun-Blanquet method (Braun-Blanquet 1932) on 10×10 m areas. At each stand, plant species richness and diversity were determined. Five diversity indices were used to assess the vegetation community, and they were Patrick richness index (S) (Patrick 1949), Shannon–Wiener heterogeneity index (H) (Shannon and Weaver 1949), Simpson heterogeneity index (D) (Simpson 1949), Pielou evenness index (J) (Pielou 1966), and Alatalo evenness index (E) (Alatalo 1981). The species importance values were calculated by the relative density, relative frequency, and relative dominance (relative dominance of herb and shrub were estimated from cover).

One sampling plots (1×1 m each) was randomly selected in each section of each sampling site. At each plot, we collected five top soil samples (i.e., 0–20 cm), and the samples were well mixed to form a composite sample. Thus, a total of 31 composite samples were collected, and all the samples were sealed in plastic bags and stored at 4 °C for analysis.

To analyze heavy metal (i.e., Hg, As, Cr, Cd, Pb, Cu, and Zn) in soil, 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 $HClO_4$) (Ye et al. 2012b). Concentrations of metals in solutions were determined using flame atomic absorption spectrometry (Analytikjena AAS vario6, Germany) for Cr, Cd, Pb, Cu, and Zn, and cold vapor AAS for Hg with the method detection limit (MDL) of 0.02 $mg\,kg^{-1}$ (Zhang et al. 2009). As was determined by diethyl disulfide and

carbamate silver colorimetric method with the MDL of 0.05 $mg\,kg^{-1}$, recommended by the State Environmental Protection Administration of China (GB15618-1995) (SEPA 1995).

Soil organic matter content (by the $K_2Cr_2O_7$ titration method after digestion), total nitrogen (TN) (by the Kjeldahl method), total phosphorus (TP) (molybdenum blue colorimetry), total potassium (TK) (flame photometry), available phosphorus (AP) [by 0.5 M $NaHCO_3$ extraction (1:20) colorimetric method], and available potassium (AK) [by 1 M NH_4OAC extraction (1:20) flame photometry], were determined. NO_3–N was extracted with pure water and measured by phenol disulfonic acid spectriphotometric method. NH_4–N was extracted from fresh soil samples with a 2 M KCl solution and concentration was determined by indophenol blue colorimetry. Soil pH was measured in a 2:1 (by weight) soil/water solution using Fisher Scientific AR15 (Waltham, MA, USA) pH probe. Soil moisture was measured by drying 10–20 g subsamples of soil for 24 h at 105 °C and subtracting the sample dry weight from its initial weight. The average flooding duration (sum of days per year) was derived from daily river water level data (http://xxfb.hydroinfo.gov.cn/).

Statistical analysis

Cannonical correspondence analysis (CCA) was carried out using the ordination program CANOCO (version 4.5, ter Braak and Smilauer 2002) to investigate the relationship between vegetation and environmental factors. Montecarlo test (1,000 permutations) was employed to determine the significance of the obtained canonical axes. Species occurring at least three stands were employed in CCA. Soil metals were highly correlated with each other (Ye et al. 2011, 2012b); a principal component analysis (SPSS 13.0) was executed on the soil heavy metal concentrations to reduce the amount of variables while preserving the variation. The first principal component accounted for almost 60 % of the variation in the soil metal concentrations. Thus, the remaining components were discarded, and for each sampling site, the soil metal concentrations were replaced by the site score on the first component (Schipper et al. 2011). To account for the impacts of flooding and soil nutrients on plant communities, other 12 soil variables were included as additional environmental factors: elevation, flooding duration, TN, TP, TK, AP, AK, NH_4–N, NO_3–N, pH, OM, and soil moisture.

Nonparametric Kruskal–Wallis test was performed to investigate the effects of elevation and sampling sites on species diversity and environmental factors. Partial correlation analysis was used to test the relationship between the environmental variables and diversity indices. All the processes were performed using SPSS 13.0 for windows.

Results

Site conditions

The soil nutrient concentrations of OM, AK, and NH_4–N, showed significantly spatial variation among the 11 sampling sites ($p<0.05$) (Table 1). Significant site variation was also found in the metals of As, Cd, Pb, and Cu (Table 1). Most of the soil nutrient and metals showed decreasing trends with the rising of elevation, and only the NO_3–N contents was significant difference among the three elevations (Table 1).

Species richness and diversity varied significantly among the sites and the elevations. The diversity indexes of S, H, and D decreased significantly with the elevation increased (Table 1). Only the Ea index showed significant site variation (Table 1). No significant difference of the J index was found either among the sites or the elevations.

Partial correlation results showed that the indexes of S, H, and D were significantly negatively correlated with elevation, flooding duration, Hg, Zn, NO_3–N, and AK, and positively correlated with NH_4–N, TK, and Pb ($p<0.05$) (Table 2). The J index was significantly negatively correlated with Hg and NO_3–N, and the Ea index was significantly negatively correlated with Hg only.

Plant community characteristics

A total of 38 herbaceous species were identified (Appendix 1) and annual plants, i.e., *E. crusgalli* and *B. tripartita*, and perennials including *C. dactylon* are dominant species (Fig. 2). The 13 environmental variables yielded a significant ($p=0.01$) ordination with four axes explaining in total 32.9 % of the variation in the plant species. The first ordination axis (F ratio$=3.013$, $p=0.002$), which explained most

Table 1 Environmental factors and plant community characteristics in the water level fluctuation zone of the Three Gorges Reservoir

	145–155 m ($n=10$)	156–165 m ($n=10$)	166–175 m ($n=11$)	Kruskal–Wallis test for sampling sites		Kruskal–Wallis test for elevation intervals	
				χ^2	p value	χ^2	p value
Elevation (m)	147.10±1.19	160.60±1.34	170.45±1.76	2.282	0.994	24.726	0.000**
Flooding duration (days)	267±5	136±10	59±14	2.382	0.992	24.751	0.000**
pH	7.80±0.18	8.06±0.06	7.68±0.25	17.778	0.059	2.458	0.293
OM (g/kg)	23.33±2.04	25.93±6.69	19.53±3.05	21.635	0.017*	2.763	0.251
Soil moisture (%)	26.20±2.97	19.09±2.62	18.64±2.95	17.347	0.067	5.040	0.080
TN (g/kg)	0.86±0.07	1.09±0.23	0.73±0.08	12.582	0.248	3.468	0.177
TP (g/kg)	0.86±0.06	0.81±0.04	0.67±0.06	16.682	0.082	5.498	0.064
TK (g/kg)	20.20±0.76	20.13±0.81	20.27±1.30	13.758	0.184	0.566	0.754
AP (mg/kg)	15.25±3.36	16.39±3.35	8.81±1.97	9.596	0.477	3.934	0.140
AK (mg/kg)	96.78±8.98	95.37±10.14	92.28±7.36	24.685	0.006**	0.139	0.933
NH_4–N (mg/kg)	6.82±1.47	6.49±1.09	5.65±0.48	18.637	0.045*	0.058	0.972
NO_3–N (mg/kg)	11.81±1.44	9.14±1.62	5.76±0.72	12.371	0.261	8.746	0.013*
Hg (mg/kg)	0.12±0.02	0.21±0.12	0.09±0.02	11.076	0.352	1.336	0.513
As (mg/kg)	13.21±0.90	11.13±1.41	11.36±1.16	21.769	0.016*	2.290	0.318
Cr (mg/kg)	46.12±3.28	43.12±3.31	40.86±2.28	18.169	0.052	1.193	0.551
Cd (mg/kg)	0.35±0.06	0.33±0.05	0.36±0.06	23.858	0.008**	0.151	0.927
Pb (mg/kg)	40.37±5.50	31.71±2.81	30.30±3.42	20.661	0.024*	2.379	0.304
Cu (mg/kg)	33.55±6.30	22.46±4.99	19.92±5.40	19.081	0.039*	5.335	0.069
Zn (mg/kg)	88.99±8.46	77.04±5.35	70.17±6.00	17.427	0.065	4.670	0.097
S	5.40±2.03	14.20±2.11	15.36±1.96	8.726	0.558	13.047	0.001**
H	1.21±0.24	2.37±0.16	2.49±0.11	8.790	0.552	13.068	0.001**
D	0.61±0.06	0.88±0.02	0.90±0.01	8.976	0.534	12.971	0.002**
J	0.91±0.02	0.93±0.01	0.93±0.01	16.177	0.095	1.116	0.572
Ea	0.87±0.02	0.86±0.02	0.86±0.01	19.089	0.039*	0.462	0.794

Values are the mean±SE in which SE is the standard error

OM soil organic matter, *TN* total nitrogen, *TP* total phosphorus, *TK* total potassium, *AP* available phosphorus, *AK* available potassium, *S* Patrick richness index, *H* Shannon–Wiener heterogeneity index, *D* Simpson heterogeneity index, *J* Pielou evenness index, *Ea* Alatalo evenness index

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

Table 2 Partial correlation coefficients between soil characteristics and diversity indices of vegetation in the water level fluctuation zone of the Three Gorges Reservoir

	S	H	D	J	Ea
Elevation	−0.726**	−0.808**	−0.793**	−0.369	−0.043
Flooding duration	−0.736**	−0.826**	−0.818**	−0.295	−0.049
Soil moisture	−0.099	−0.129	−0.167	0.115	0.198
pH	0.210	0.480	0.599*	0.136	−0.116
TN	0.197	0.398	0.498	0.163	−0.133
TP	0.155	−0.027	−0.137	0.481	0.358
TK	0.769**	0.781**	0.676*	0.022	−0.094
AP	−0.004	0.137	0.112	−0.130	−0.084
AK	−0.824**	−0.837**	−0.769**	−0.360	0.063
NH_4–N	0.522	0.641*	0.663*	0.239	0.009
NO_3–N	−0.660*	−0.647*	−0.531	−0.705*	−0.251
OM	0.298	0.047	−0.302	−0.301	−0.208
Hg	−0.334	−0.301	−0.208	−0.688*	−0.658*
As	0.227	0.283	0.362	0.181	0.041
Cr	−0.172	−0.416	−0.461	0.080	0.067
Cd	−0.294	−0.336	−0.320	0.307	0.424
Pb	0.637*	0.626*	0.485	−0.514	−0.575
Cu	0.365	0.550	0.553	0.320	0.127
Zn	−0.722**	−0.735**	−0.616*	−0.101	0.144
Fe	0.205	0.266	0.132	−0.547	−0.578
Mn	0.492	0.454	0.327	0.415	0.401

S Patrick richness index, *H* Shannon–Wiener heterogeneity index, *D* Simpson heterogeneity index, *J* Pielou evenness index, *Ea* Alatalo evenness index, *OM* soil organic matter, *TN* total nitrogen, *TP* total phosphorus, *TK* total potassium, *AP* available phosphorus, *AK* available potassium

*p<0.05; **p<0.01

of the variation in species composition, was associated mainly with flooding duration, elevation, TP, AP, NO_3–N, and metals (Fig. 2a). The second ordination axis of the CCA was associated mainly with TN, NH_4–N, TK, and AK (Fig. 2a). Most of the herbaceous species were situated in the positive part of the second ordination axis (Fig. 2a). The lower elevation sites (145–155 m) were separated from higher elevation sites (156–175 m) and appeared to be associated with deeper and longer flooding duration, and higher content of TP, AP, and metals (Fig. 2b) while with lower herbaceous species (Fig. 2c).

Discussion

Plant species composition and diversity in the WLFZ

The pre-dam vegetation (New and Xie 2008) failed to persist under the new conditions, and the species richness and diversity were significantly lower due to the great hydrological changes by the Three Gorges Dam construction. Before submergence, there were 392 vascular plants, mostly temperate species, and the vegetation was dominated by 36 species in the WLFZ (Zhong and Qi 2008). However, after submergence, vegetation in the WLFZ was dominated by annuals, i.e., *E. crusgalli* and *B. tripartita*, and perennials including *C. dactylon*. Meanwhile, the species richness and diversity, i.e., *S*, *H*, and *D* were much lower in elevation of 145–155 m with longer flooding duration (Table 1).

Secondary vegetation in wetland could recover through four main processes: regeneration of remnant individuals, germination from the soil seed bank, sprouting from cut or crushed roots and stems, and seed dispersal from other areas (Tucker et al. 1998). In the WLFZ, annuals mainly recovered from the soil seed bank, which could complete their life cycles and form seed bank during the drawdown, and perennials recovered through regeneration of remnant individual and could tolerate the flooding stress via physiological or morphological traits (Lu et al. 2010b). Meanwhile, the plant species composition and diversity were also influenced by the environmental factors including flooding, soil chemical characteristics in the WLFZ.

Flooding

Segregation of plant species along a hydrological gradient is a well-described phenomenon (Van Eck et al. 2004; Voesenek et al. 2004; Schipper et al. 2011). For plant communities in the WLFZ of the Three Gorges Reservoir, flooding characteristics played an important role in plant species composition (Table 2; Fig. 2a). After the Three Gorges Reservoir filling, this newly formed ecotone was changed from the previous terrestrial to a novel hydrological regime, which is the opposite of the natural one, with post-dam flooding occurring in winter rather than summer. Plant species adapted to previously terrestrial habitats have disappear and few species are expected to survive in the novel habitats with half a year under inundation as deep as 30 m (New and Xie 2008). Moreover, tolerance to flooding strongly differs between plant species and has been shown to range from 90 to over 200 days of total submergence (Lu et al. 2010b).

Due to such differences in flooding tolerance, different elevation with varying flooding duration was generally well reflected by variations in species richness and diversity (Table 1 and 2). Flood-sensitive species are usually restricted to higher elevation of the floodplain, where the impacts of flooding are limited, while more tolerant species persist at lower sites, where flooding is more frequent or prolonged (Lenssen and De Kroon 2005). The CCA results presented here agree well with flooding tolerance differences as observed by Lu et al.
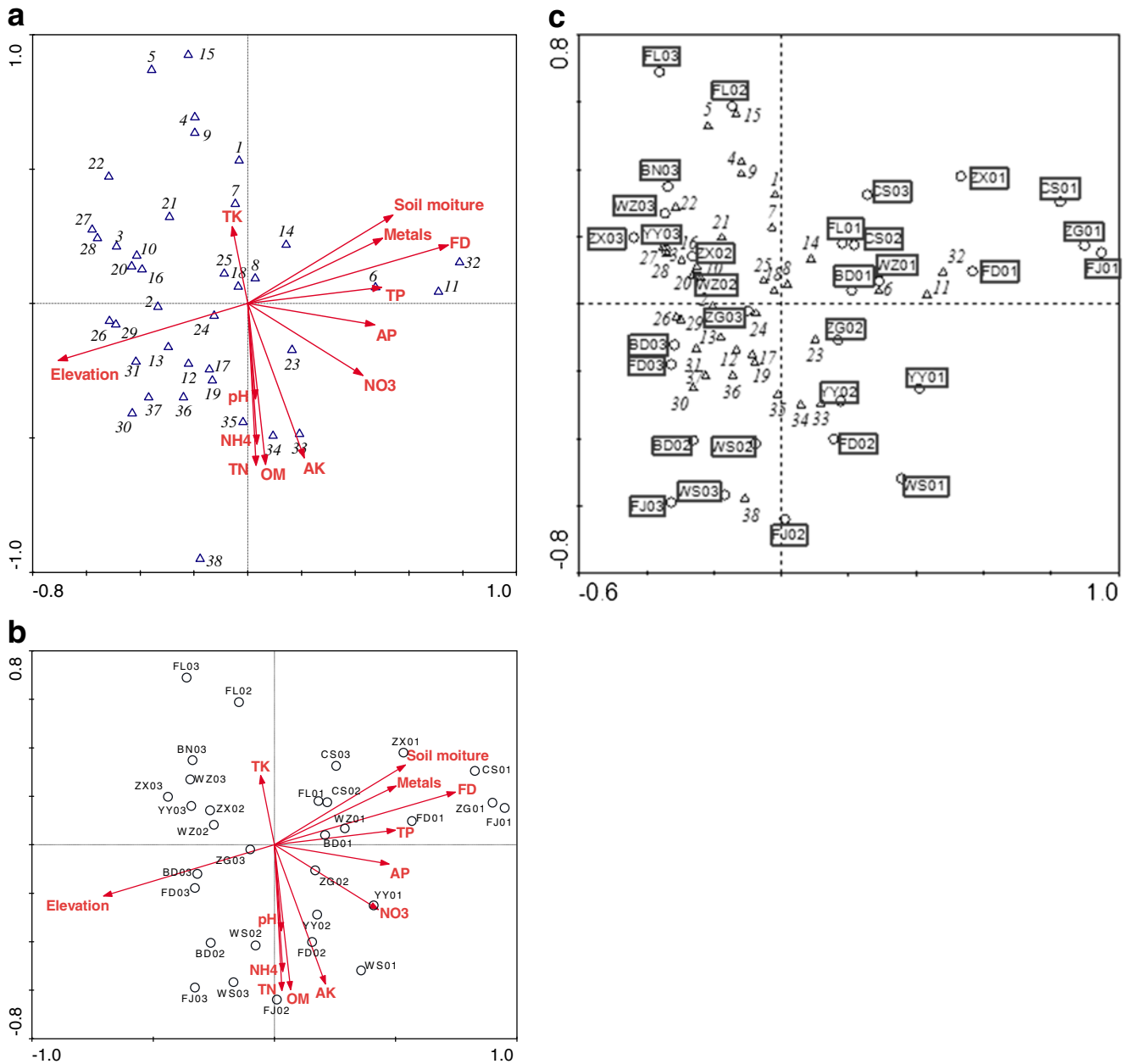
Fig. 2 Location of plant species and environmental variables (**a**), sampling sites and environmental variables (**b**), and sampling sites and plant species (**c**) in the water level fluctuation zone of Three Gorges Reservoir defined by the first two axes in the canonical correspondence analysis. Environmental variables: *TN* total nitrogen, *TP* total phosphorus, *TK* total potassium, *AP* available phosphorus, *AK* available potassium. Flooding duration (FD): 03, 166–175 m; 02, 156–165 m; 01, 145–155 m. Locations: *BN* Banan, *CS* Changshou, *FL* Fuling, *FD* Fengdu, *ZX* Zhongxian, *WZ* Wanzhou, *YY* Yunyang, *FJ* Fengjie, *WS* Wushan, *BD* Badong, *ZG* Zigui. Plant species names are indicated using the numbers. Full names can be found in Appendix 1

(2010a). Species identified as flooding-tolerant, like *C. dactylon*, *Cyperus compressus* and *Alternanthera philoxeroides*, were positively associated with flooding duration in the CCA, whereas more sensitive species, like *Alopecurus aequalis*, *Gnaphalium hypoleucum* and *Lindernia ruellioides*, indeed showed a negative relationship to flooding duration (Fig. 2a).

Heavy metal contamination

The significantly negative associations between heavy metal concentrations and species richness and heterogeneity ($p < 0.05$) (Table 2) indicated that soil heavy metal contamination had played an important role in regulating plant species composition in the WLFZ. Higher heavy metal contents in

Changshou, Zhongxian, and Fengjie due to long-time agriculture practice (SEPA 2009; Ye et al. 2011; 2012b) were associated with lower plant species in these areas (Fig. 2c). Moreover, the elevation was positively correlated with species richness and diversity in the partial correlation analysis (Table 2), while the lower elevation sites (145–155 m) appeared to be associated with lower herbaceous species (Table 1). Such contrasting relationships indicated that metals could play some role in the vegetation diversity in the WLFZ. Yet, the significantly spatial variation of heavy metals among the sampling sites did not cause obviously spatial variation in species richness and diversity (Table 1) (Ye et al. 2011; 2012b). Hence, it seemed unlikely that single metal concentrations induced the observed significant differences in plant species composition and richness; rather, a combined effect of multiple metals and other factors, including soil nutrients, elevation, and so on, may have been attributable to the relationships.

Soil nutrient

Soil nutrient concentrations could strongly affect plant species diversity and evenness (Aerts et al. 2003). Previous study demonstrated that plant species with high diversity were at balanced N/P ratios between 10 and 14 (Roem and Berendse 2000). The increase of N supply in a N-limited grassland (e.g., N/P ratio<10) may lead to an increase in biodiversity (Roem and Berendse 2000). In the present study, the mean N/P ratios was 1.2 ± 0.1 (Table 1), indicating N-limiting soil in the WLFZ. Hence, plant species were positively associated with TN and NH_4–N, while negatively correlated with TP and AP in the CCA (Fig. 2a). Moreover, excess of NO_3–N is known for its negative effect on the diversity of plant communities and even when it is in small quantities (Aerts et al. 2003). The available soil phosphorus could be a limiting factor of NO_3–N supply by two sources, i.e., the symbiotic fixation of atmospheric nitrogen by legumes and the mineralization of the organic matter of the soil (Janssens et al. 1998; Aerts et al. 2003). A similar mechanism appeared evidently in this study that the heterogeneity and evenness of species were significantly negatively correlated with NO_3–N ($p<0.05$) (Table 2).

Species richness of riparian vegetation generally tends to increase with the increased available K before reaching the optimum content (200 mgK/kg soil) (Janssens et al. 1998). The mean content of AK in the study area was 94.7 ± 4.9 mg/kg<200 mg/kg. Although the heterogeneity and evenness of species were significantly positively correlated with the TK, the CCA together with partial correlation analyses presented the evenness of plant species was negatively associated with AK (Table 2; Fig. 2a). This suggested that the negative relationship between species richness and AK in the study area may be mediated by other factors, such as soil contamination, flooding duration, and so on (Wassen et al. 2005; Stewart and Pullin

2008). Thus, a combined effect of multiple stressors may explain the relationship as observed here more reasonably.

Conclusion

The variations in plant species composition were related with flooding characteristics, heavy metal contamination and soil nutrients by using canonical correspondence analysis (CCA) in the WLFZ of the Three Gorges Reservoir. Plant species richness and diversity showed significantly negative relationships with flooding duration, the level of heavy metal contamination and nutrients including TP, AP, AK, and NO_3–N, while positively correlated with TK and NH_4–N. Moreover, a more integral approach is needed when assessing impacts of stressor on plant communities, by including other relevant environmental agents rather than focusing on single stressor in isolation.

Appendix 1

Table 3 The distribution of plant species in the study area in the water level fluctuation zone of Three Gorges Reservoir (03, 166–175 m; 02, 156–165 m; 01, 145–155 m)

Numbers	Species	Sampling sites
1	*Imperata cylindrica*	Banan 03; Changshou 02; Fuling 01, 02
2	*Oxalis corniculata*	Banan 03; Fuling 01, 03; Fengdu 03; Zhongxian 02, 03; Wanzhou 02, 03; Yunyang 03; Fengjie 02, 03; Badong 02, 03; Zigui 02, 03
3	*Clinopodium chinense*	Banan 03; Fuling 01; Fengdu 03; Zhongxian 02, 03; Wanzhou 02, 03; Yunyang 03
4	*Commelina diffusa*	Banan 03; Fuling 01, 02, 03
5	*Humulus japonicus*	Banan 03; Fuling 01, 02, 03
6	*Alternanthera philoxeroides*	Banan 03; Changshou 01, 03; Fuling 01, 03; Fengdu 01, 02, 03; Zhongxian 01; Wanzhou 02; Yunyang 02; Fengjie 02;
7	*Chenopodium ambrosioides*	Banan 03; Changshou 03; Fuling 01, 02; Zhongxian 02; Yunyang 02, 03

Table 3 (continued)

Numbers	Species	Sampling sites
8	*Echinochloa crusgalli*	Banan 03; Changshou 02, 03; Fuling 01, 02; Fengdu 02; Zhongxian 02; Wanzhou 02; Yunyang 03; Fengjie 02; Zigui 02
9	*Gynura crepidioides*	Banan 03; Fuling 01, 02
10	*Erigeron annuus*	Banan 03; Fuling 01, 02, 03; Zhongxian 02, 03; Wanzhou 02, 03; Yunyang 03; Fengjie 03; Wushan 03; Zigui 03
11	*Cynodon dactylon*	Changshou 01, 02, 03; Fuling 02, 03; Fengdu 01, 02, 03; Zhongxian 01; Wanzhou 01; Yunyang 01, 02, 03; Fengjie 01, 02; Wushan 01; Badong 01; Zigui 01
12	*Bidens tripartita*	Fuling 01, 02, 03; Fengdu 02, 03; Zhongxian 02; Wanzhou 01, 02, 03; Yunyang 02, 03; Fengjie 02, 03; Badong 02, 03; Zigui 02, 03
13	*Corydalis saxicola*	Fuling 02; Fengdu 02, 03; Zhongxian 03; Fengjie 03;
14	*Polygonum lapathifolium*	Changshou 02, 03; Fuling 01, 02; Fengdu 02; Zhongxian 01, 02; Wanzhou 02; Yunyang 02
15	*Herba Polygoni*	Changshou 03; Fuling 02, 03;
16	*Youngia japonica*	Changshou 03; Fuling 03; Fengdu 02, 03; Zhongxian 02; Wanzhou 02, 03; Yunyang 03
17	*Solanum nigrum*	Changshou 03; Fuling 01, 02; Zhongxian 02; Wanzhou 03; Yunyang 03; Fengjie 02, 03; Wushan 01, 02, 03; Zigui 03
18	*Melilotus officinalis*	Changshou 02; Zhongxian 02; Wanzhou 03; Badong 02; Zigui 02
19	*Setaria viridis*	Fuling 01, 03; Fengdu 02, 03; Zhongxian 02, 03; Wanzhou 01, 02, 03; Fengjie 02, 03; Wushan 01, 02, 03; Badong 01, 02, 03; Zigui 02, 03
20	*Artemisia annua*	Fuling 03; Fengdu 02, 03; Zhongxian 02, 03; Wanzhou 03; Yunyang 03, Fengjie 02; Wushan 01, 02; Badong 02, 03;
21	*Eriochloa villosa*	Fuling 03; Zhongxian 02, 03; Zigui 02, 03
22	*Alopecurus aequalis*	Fuling 02; Zhongxian 02, 03
23	*Xanthium sibiricum*	Fuling 01; Fengdu 01, 02, 03; Zhongxian 01, 02, 03; Wanzhou 01; Yunyang 02, 03; Fengjie 01, 02, 03; Badong 01, 02; Zigui 02
24	*Lindernia crustacea*	Fuling 01; Fengdu 02; Zhongxian 02, 03
25	*Digitaria cruciata*	Fuling 01; Zhongxian 02; Yunyang 03; Zigui 02, 03

Table 3 (continued)

Numbers	Species	Sampling sites
26	*Daucus carota*	Fengdu 03; Zhongxian 02, 03; Wanzhou 03; Fengjie 03; Badong 03; Zigui 03
27	*Lindernia ruellioides*	Zhongxian 02, 03; Yunyang 03
28	*Gnaphalium hypoleucum*	Zhongxian 03; Wanzhou 02; Yunyang 03
29	*Artemisia atrovirens*	Zhongxian 02, 03; Wanzhou 02, 03; Yunyang 03; Fengjie 03; Wushan 03
30	*Dendranthema indicum*	Zhongxian 02, 03; Yunyang 03; Fengjie 02, 03; Wushan 03
31	*Commelina communis*	Zhongxian 02; Yunyang 03; Badong 02, 03; Zigui 02
32	*Cyperus compressus*	Zhongxian 01; Wushan 02; Zigui 01, 02
33	*Aeschynomene indica*	Zhongxian 01; Fengjie 02; Wushan 03
34	*Amaranthus retroflexus*	Wanzhou 02; Yunyang 02; Wushan 01; Badong 02; Zigui 02;
35	*Leptochloa panicea*	Wanzhou 02; Fengjie 02; Zigui 02
36	*Acalypha australis*	Wanzhou 02; Yunyang 03; Fengjie 02, 03; Badong 02; Zigui 02
37	*Stellaria media*	Yunyang 03; Wushan 02, 03; Badong 03
38	*Phytolacca Americana*	Fengjie 02, 03; Badong 02

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