

Plant community characteristics and their responses to environmental factors in the water level fluctuation zone of the three gorges reservoir in China

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Received: 17 August 2012 / Accepted: 1 April 2013 / Published online: 16 April 2013
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Abstract The annual water level regulating of the Three Gorges Reservoir prolonged the submerged duration (from 2 to 8 months) and resulted in the reversal of natural flood rhythms (winter submerged). These changes might alter plant community characteristics in the water level fluctuation zone (WLFZ). The aim of this study was to determine the plant community characteristics in the WLFZ and their responses to the environmental factors (i.e., annual hydrological regulation, topographic characteristics, soil physical properties and soil nutrients). The height, coverage, frequency and biomass of each plant species and the soil properties at each elevation zone (150, 155, 160, 165 and 170 m) were measured from March to September in 2010. Univariate two-factor analysis and redundancy analysis (RDA) were used to analyze the spatial and temporal variations of the community characteristics and identify the key environmental factors influencing vegetation. We found that 93.2 % of the species analysed were terrestrial vascular plants. Annual herbs made up the highest percentage of life forms at each altitude. The differences in the species number per square metre, the Shannon–Wiener diversity index and the biomass of vegetation demonstrated statistical significance with

respect to sampling time but not elevation. The most dominant species at altitudes of 150, 155, 160, 165 and 170 m were *Cynodon dactylon*, *Cyperus rotundus*, *Digitaria sanguinalis*, *Setaria viridis* and *Daucus carota*, respectively. The concentrations of soil nutrients appeared to be the lowest at an altitude of 150 m, although the differences with respect to elevation were not significant. The results of the RDA indicated that the key factors that influenced the species composition of vegetation were elevation, slope, pH and the concentration of soil available phosphorus.

Keywords Three Gorges Reservoir · Submergence · Soil properties · Dominant species · Diversity

Introduction

River systems around the globe are increasingly affected by damming to satisfy increasing demands for hydroelectricity, flood mitigation and reliable water supplies (O'Connor 2001). The impoundment of dams can significantly alter river flow, shorelines, sediment and aquatic fauna and can result in the loss of original riparian vegetation (Merritt and Wohl 2006; New and Xie 2008; Willison et al. 2013). Alteration of hydrological regimes due to the operation of reservoirs may be the main mechanism affecting shoreline vegetation (Nilsson and Berggren 2000; Ye et al. 2013b). Other factors (e.g., flooding, soil nutrients and soil contamination) influenced by dams also have the potential to change the surrounding plant community (Aerts et al. 2003). However, there is very little information about the vegetation responses to annual hydrological regime regulation, topographic characteristics, soil physical properties or soil nutrients in the impoundment areas of reservoirs.

Responsible editor: Zhihong Xu

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The Three Gorges Dam (TGD), the largest hydropower project in the world, was initiated in 1994. The first impoundment occurred in June 2003, and the water level of the Three Gorges Reservoir (TGR) rose from approximately 60 to 135 m above the original riverbank. The second impoundment occurred in October 2006, and the water level rose to 156 m. The Three Gorges Dam reached its design-maximum reservoir water level of 175 m (574 ft) for the first time on October 26, 2010, which resulted in the formation of a water level fluctuation zone (WLFZ) with an area of 302.0 km². The WLFZ is the exposed region between the high and low water levels along the bank of a reservoir (Wantzen et al. 2008). Compared with other reservoirs, the WLFZ of the TGR has a longer submergence period. The zones at altitudes of 150 and 170 m are submerged for 8 months and nearly 2 months, respectively. In addition, the hydrological regime of the TGR is the exact opposite of the natural flood rhythms of the Yangtze River (Fan et al. 2012). The water level is maintained at 145 m in summer (from June to September) and at 175 m in winter (from October to December).

Before the implementation of the TGR, the main vegetation types in the zone below an elevation of 175 m were trees (e.g., *Pinus massoniana* and *Cupressus funebris*), shrubs (e.g., *Vitex negundo*, *Securinega suffruticosa* and *Myricaria laxiflora*) and herbs (*Imperata cylindrica*, *Arthraxon hispidus* and *Cynodon dactylon*) (Chen et al. 2008). The filling of the TGR may have resulted in the loss of pre-existing vegetation and the formation of novel plant communities. However, several studies have focused only on plant species composition (Wang et al. 2012), heavy metal (Ye et al. 2013a), soil major nutrients (Ye et al. 2013b) and eco-friendly utilisation mode of resources (Yuan et al. 2013) in the WLFZ. Studies of other physical and chemical soil properties have not been reported, and little is known about the WLFZ of the TGR. The variation in vegetation in the WLFZ is caused by complex interactions involving the hydrological regime, topographic characteristics, soil nutrients and contamination. Most plants in the WLFZ of plain reservoirs such as lakes are hydrophytes or helophytes because of the relatively short submergence time and low water level variations (Crivelli and Grillas 1995; Miranda and Hodges 2000). The plants in the WLFZ of valley-dammed reservoirs in the southwest of China, such as the Ertan reservoir in Sichuan province, could not survive because of the steep slopes. The WLFZ of the TGR has complicated topographical characteristics and a special hydrological regulating regime. For the WLFZ managers, further studies on the important factors influencing the vegetation may contribute to greater understanding and better prediction of the successional trends of the plant community, which may be essential for managing the plant community, protecting the WLFZ habitat and restoring the WLFZ ecosystem function.

Our specific objectives were as follows: (1) to confirm the plant community characteristics in the WLFZ after implementation of the TGR, (2) to confirm how much nitrogen and phosphorus is released by the death and the decomposition of vegetation after winter submergence and (3) to determine the effects of annual hydrological regime regulation and soil properties on the plant community in the WLFZ.

Study area and methods

Study area

The Xiaojiang River is the tributary with the largest area of the WLFZ in the TGR in China (Fig. 1). The main stream belonging to the TGR is 117.5 km in length. The WLFZ in the Xiaojiang River is located at 30°49′–31°41′ N, 107°56′–108°54′ E. The area of the WLFZ is 48.02 km², which accounts for 15.9 % of the total WLFZ in the TGR. The average annual temperature is 18.6 °C. The average annual precipitation is 1,100–1,500 mm, most of which occurs between April and October. The soil types in the five transects from the Qukou transect to the Shuangjiang transect are yellow soil, yellow soil, red soil, red soil and red soil. The duration of submergence is higher at lower elevations. For example, the submerged time at altitudes of 150, 155, 160, 165 and 170 m were 256, 200, 147, 116 and 57 days, respectively, between October 2009 and June 2010.

Vegetation sampling

Vegetation surveys were performed along five transects (Fig. 1) between March and September in 2010. The width of each transect ranged from 30 to 60 m. These surveys were performed during flood-regulation periods. The water level fluctuated primarily between 145 and 150 m. The water level only rose to 172.5 m (566 ft) between 2008 and 2009. Therefore, we divided each transect into five elevation zones (150, 155, 160, 165 and 170 m). Three square vegetation sampling plots (1 × 1 m) were located at 10- or 20-m intervals along each elevation zone of each transect. The water levels in each of the months from March to September were 156.7, 154.4, 154.4, 147.5, 150.9, 153.1 and 162.4 m, respectively. Due to the submersion of some elevation zones in different months, the number of plots in the months from March to September was 45, 60, 60, 75, 45, 45 and 30, respectively. A total of 390 plots were sampled. We measured the height, coverage, frequency and above-ground biomass of each plant species in each plot. Based on the plant life forms, the plants were sorted into five groups: perennial herbs, annual herbs, climbing plants, shrubs and



Fig. 1 Schematic diagram of sampling transects in the WLFZ

trees. Based on their dependence on water, the plants were classified into three groups: hydrophytes, mesophytes and xerophytes. Plant samples were oven-dried at 65 °C and analysed for dry weight. The nitrogen and phosphorus concentrations in 36 species were analysed (Bao 2005).

Environmental factors

The slopes of the transects were measured with an inclinometer and were classified into six grades (I through VI) : <5°, 6–15°, 16–25°, 26–35°, 35–45° and >45°. After plants had been removed, the soil depth (SD) was measured with a soil auger (Arbeláez and Duivenvoorden 2004). The soil density (0–20 cm) was investigated using the cutting ring method. Three random topsoil samples (0–20 cm) were collected and then mixed to form a composite sample at each elevation zone of each transect. A total of 120 mixed samples were sealed in plastic bags and brought to the laboratory. These soil samples were dried at 70 °C for chemical analysis. We measured the soil pH and contents of soil organic matter (SOM), total nitrogen (TN), available nitrogen (AN), total phosphorus (TP), available phosphorus (AP), total

potassium (TK) and available potassium (AK), using methods described by Bao (2005).

Data analysis

The relative height (RH), relative coverage (RC), relative frequency (RF) and relative biomass (RB) of each plant species were expressed as the percentages of the height, coverage, frequency and biomass, respectively, of all species recorded. The sum of the above four relative variables of a species was called the importance value index (IVI = RH + RC + RF + RB) (Jerry et al. 2002; Zhang 2011). The relative IVI of each plant species was expressed as the percentage of the IVI for all species recorded. The IVI, which ranged from 0 to 4, represented the relative importance or dominance of a plant species in a plot zone. We calculated the number of species (R) per square metre for each plot and the Shannon–Weiner diversity index (H'):

$$H' = - \sum_{i=1}^s P_i \ln P_i$$

where P_i is the relative IVI of the i th species ($i = 1$ to s) and s is the total number of species. Dominance was used to describe the degree of

predominance of a plant species in an ecological community. $Y_i = P_i \times f_i$, where Y_i is the dominance of the i th species at the elevation of the transects, P_i is the relative IVI of the i th species, and f_i is the frequency of the i th species. Dominant species were defined as those with dominance values ≥ 0.02 (Peng et al. 2011; Zhang 2011).

A univariate two-factor analysis of variance of the general linear model was performed to determine whether there was a significant interaction effect between sampling time (months) and elevation. The significances of differences in the means of species richness, fresh weight, coverage and soil properties were compared using Tukey's test. When comparing the soil nutrients in the different transects, the mixed samples from all elevations were used as replicates for each transect. The statistical analyses described above were performed using SPSS 16.0.

A preliminary detrended correspondence analysis of the IVI of the species at each elevation of each transect revealed that the gradient lengths were < 3.0 , indicating that the majority of the species exhibited linear responses to underlying environmental variation, which justified the use of linear multivariate methods. Thus, we identified the key environmental factors influencing the vegetation by redundancy analysis (RDA) using the Canoco 4.5 software package (Leps and Smilauer 2003; Michael et al. 2012). The scaling of the ordination focused on inter-species correlations, and a Monte Carlo permutation test based on random permutations was conducted to test the significance of the eigenvalues of the first canonical axis. The species data were log-transformed to reduce the effects of extreme values, and the environmental data were square-root transformed (Leps and Smilauer 2003; Gazer 2011).

Results

Species composition

A total of 146 vascular plant species were identified, belonging to 116 genera of 38 families. The plant families with the largest number of species in the studied area were Asteraceae ($N=25$, 17.1 %), Poaceae ($N=24$, 16.4 %), Fabaceae ($N=10$, 6.8 %), Polygonaceae ($N=8$, 5.5 %), Cyperaceae ($N=5$, 3.4 %) and Lamiaceae ($N=5$, 3.4 %). A total of 107 dicot (73.3 %), 36 monocot (24.7 %) and 3 fern (2.0 %) species were recorded in the sampling sites.

The life forms present at the highest percentage at each altitude were annual herbs. The percentages of annual herbs at the altitudes of 150, 155, 160, 165 and 170 m were 71.4, 68.1, 57.0, 53.0 and 56.0 %, respectively. The less frequent life forms (mostly at the altitude of 170 m) were climbing

plants (*Ficus tikoua*, *Paederia scandens*, *Vitis amurensis*, *Pueraria phaseoloides* and *Cayratia japonica*), shrubs (*Boehmeria nivea*, *Lespedeza davidii*, *Lespedeza cuneata* and *V. negundo*) and trees (*Morus alba*, *Albizia kalkora* and *Broussonetia papyrifera*).

We found that 93.2 % of the plant species present were terrestrial vascular plant species ($N=136$) in the study sites, whereas only 10 hydrophytes or helophytes—*Equisetum arvense*, *E. debile*, *Polygonum hydropiper*, *Oryza sativa*, *Ranunculus sceleratus*, *Alternanthera philoxeroides*, *Oenanthe javanica*, *Centella asiatica*, *Beckmannia syzigachne* and *Ludwigia prostrata*—were identified in the abandoned pits, ponds and paddy fields.

Dominant species

The vegetation distribution and the IVI of the dominant plant species varied with elevation (Table 1). The dominant species exhibiting the highest IVI values at the altitudes of 150, 155, 160, 165 and 170 m were *C. dactylon* (1.42 ± 0.66), *Cyperus rotundus* (0.81 ± 0.67), *Digitaria sanguinalis* (0.62 ± 0.67), *Setaria viridis* (0.55 ± 0.69) and *Daucus carota* (0.97 ± 0.42), respectively. The IVI of *X. sibiricum*, *C. dactylon*, *C. rotundus* and *P. hydropiper* were negatively correlated with elevation, whereas the IVI of *Artemisia annua* and *D. carota* were positively correlated with elevation.

Plant diversity

The species number per square metre (R) ranged from 3 to 23, with an average of 10, in the WLFZ. The mean R was the highest during July (12.5 ± 4.3) and was lower in June, May, April, August, September and March in descending order (Fig. 2a). The mean R at the altitude of 165 m was the highest (10.7 ± 4.8) and was lower at the altitudes of 170, 160, 155 and 150 m in descending order (Fig. 2b). The significance values for sampling time and for the interaction of sampling time and elevation, but not for elevation alone, were < 0.05 . Therefore, the differences in R exhibited statistical significance with respect to sampling time ($F=14.285$, $p<0.01$) and sampling time \times elevation ($F=2.687$, $p<0.05$) but not with respect to elevation.

The Shannon–Wiener diversity index (H') values ranged from 1.64 to 3.41, with an average of 2.93, in the WLFZ. The average H' was highest ($3.18.0 \pm 0.11$) during July and was lower in May, June, April, August, September and March in descending order (Fig. 2c). The average H' was highest (3.12 ± 0.11) at the altitude of 170 m and was lower at 165, 160, 155 and 150 m in descending order (Fig. 2d). However, there were no significant differences in H' with respect to sampling time, elevation or sampling time \times elevation.

Table 1 Distribution and importance value index (IVI) of the dominant species

Dominant species	150 m	155 m	160 m	165 m	170 m
<i>Xanthium sibiricum</i>	ABDE(0.40±0.09)	AB(0.41±0.31)	D(0.13±0.09)	D(0.17±0.14)	0.07±0.03
<i>Bidens pilosa</i>	ABE(0.16±0.03)	ABCD(0.21±0.08)	ABCDE(0.19±0.05)	BC(0.12±0.07)	AE(0.13±0.11)
<i>Eclipta prostrata</i>	BD(0.12±0.06)	BCDE(0.21±0.09)	BCE(0.12±0.05)	0.06±0.01	0.00±0.00
<i>Artemisia annua</i>	0.00±0.00	0.05±0.01	0.07±0.01	E(0.12±0.13)	BDE(0.43±0.24)
<i>Gnaphalium affine</i>	0.00±0.00	D(0.07±0.04)	CE(0.14±0.11)	BCE(0.15±0.05)	CDE(0.12±0.04)
<i>Comnyza canadensis</i>	0.00±0.00	0.05±0.04	ABC(0.33±0.23)	BCDE(0.50±0.45)	ABCDE(0.31±0.14)
<i>Digitaria sanguinalis</i>	D(0.17±0.09)	ADE(0.18±0.09)	ABCDE(0.62±0.67)	AC(0.34±0.44)	0.07±0.01
<i>Cynodon dactylon</i>	ABCE(1.42±0.66)	BC(0.53±0.57)	BD(0.36±0.35)	AB(0.25±0.18)	BC(0.30±0.08)
<i>Setaria viridis</i>	0.02±0.00	C(0.06±0.03)	BCD(0.18±0.07)	BCD(0.55±0.69)	BD(0.32±0.17)
<i>Echinochloa crusgali</i>	ABC(0.38±0.12)	AC(0.18±0.11)	ABC(0.26±0.07)	A(0.30±0.27)	AC(0.19±0.18)
<i>Alternanthera philoxeroides</i>	0.09±0.01	ABE(0.25±0.15)	0.04±0.01	0.13±0.09	0.04±0.00
<i>Acalypha australis</i>	B(0.10±0.01)	ABDE(0.15±0.01)	B(0.05±0.04)	ABD(0.09±0.03)	AB(0.09±0.05)
<i>Cyperus rotundus</i>	ABCDE(1.08±0.94)	ABDE(0.81±0.67)	BDE(0.28±0.18)	CE(0.14±0.11)	AE(0.18±0.16)
<i>Polygonum hydropiper</i>	ABE(0.22±0.12)	ACE(0.19±0.14)	C(0.20±0.18)	D(0.13±0.02)	C(0.06±0.01)
<i>Daucus carota</i>	0.00±0.00	0.00±0.00	BE(0.15±0.12)	BDE(0.44±0.29)	ABCDE(0.97±0.42)
<i>Oxalis corniculata</i>	B(0.02±0.05)	0.02±0.02	BE(0.08±0.03)	BDE(0.12±0.02)	ABCDE(0.11±0.04)
<i>Clinopodium chinense</i>	0.00±0.00	0.02±0.03	E(0.08±0.04)	C(0.20±0.13)	B(0.08±0.05)
<i>Equisetum arvense</i>	0.00±0.00	A(0.04±0.08)	A(0.03±0.07)	0.00±0.00	0.00±0.00
<i>Solanum nigrum</i>	0.00±0.00	0.00±0.00	CD(0.06±0.07)	D(0.07±0.09)	(0.02±0.03)
<i>Imperata cylindrica</i>	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	C(0.11±0.24)

Values are capital letters (mean±SE) where the letters from A to E represent transects of Qukou, Yanglu, Gaoyang, Huangshi and Shuang jiang, respectively. The mean is the average IVI of species of five transects, and the SE is the standard error

Plant biomass

The fresh weight of vegetation ranged from 5.1 to 3,513.0 g m⁻², with an average of 627.2 g m⁻². The average fresh weight was highest (1,294.2±774.3 g m⁻²) during September and was lower in August, June, July, May, April and March in descending order (Fig. 3a). The average fresh weight was highest (721.9±614.5 g m⁻²) at the altitude of 170 m and was lower at 165, 150, 160, 165 and 155 m in descending order (Fig. 3b). Differences in the fresh weight were significant with respect to sampling time ($F=12.77$, $p<0.01$) but not with respect to elevation or sampling time×elevation. The fresh weight ($N=120$, $r=-0.227$, $p<0.05$) and the coverage ($N=120$, $r=-0.429$, $p<0.001$) were also highly negatively correlated with the slope (Fig. 4a, b). The dry weight of vegetation varied from 4.8 to 920.5 g m⁻², with an average of 162.1 g m⁻², from March to September in 2010. Differences in the dry weight also demonstrated statistical significance with respect to sampling time ($F=11.018$, $p<0.01$) but not elevation or sampling time×elevation.

Environmental factors

The soil depth ranged from 7.6 to 73.0 cm, with an average of 29.91 cm. Differences in the soil depth ($F=9.874$, $p<0.01$) and

soil density ($F=3.176$, $p<0.05$) were significant with respect to elevation. The average soil depth was greatest at slopes <5°. Differences in the soil depth were significant with respect to slope ($F=9.293$, $p<0.01$; Fig. 4c). The soil density ranged from 0.79 to 1.9 g m⁻³, with an average of 1.35 g m⁻³. The average soil density was highest at slopes of >45°. Differences in the soil density were significant with respect to slope ($F=2.664$, $p<0.05$; Fig. 4d). The average concentrations of SOM, TN, AN, TP, AP, TK and AK, but not soil pH, were lowest at the altitude of 150 m, although the differences with respect to elevation were not significant (Table 2). The differences in the average concentrations of SOM, TN, AN, TP and TK, but not pH, AP and AK, were significant with respect to sampling time. Differences in the concentrations of all soil nutrients were significant with respect to the different transects investigated.

The RDA of species and environmental variables

The ordination analysis revealed the environmental gradient in the area. The results of the RDA showed that elevation was the best explanatory variable (Table 3, Fig. 5). The conditional effects indicated the following: (1) the contributions of elevation ($F=8.29$, $p<0.01$), slope ($F=2.46$, $p<0.05$), pH ($F=2.27$, $p<0.05$) and AP ($F=1.95$, $p<0.05$) were significant during the forward selection; (2) the

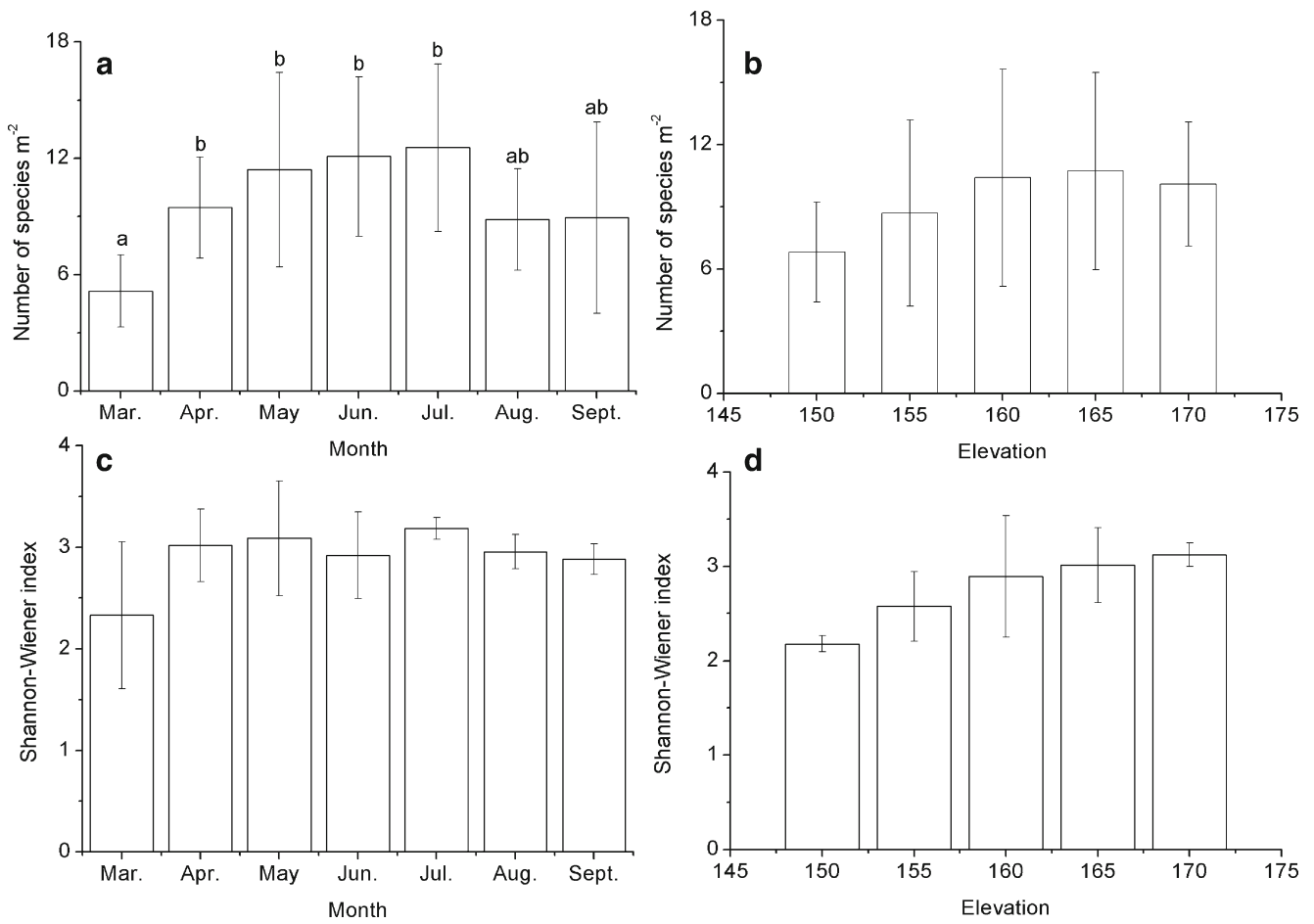


Fig. 2 Number of plant species per square meter and Shannon–Wiener diversity index with respect to sampling time (a, c) and elevation (b, d). Means(±SE) without shared letters are significantly different from each other ($p < 0.05$)

contributions of the remaining variables were not significant. The RDA results also showed that there was a strong correlation between vegetation and environmental factors, with species–environment correlations of 0.979 on the first axis and 0.808 on the second axis. The eigenvalues for the

first four RDA axes were 0.287, 0.099, 0.087 and 0.071. The cumulative percentage variance of species–environment relations of the first axis and second axis were 40.4 and 54.3 %, respectively. The sum of all the RDA canonical eigenvalues was 0.711.

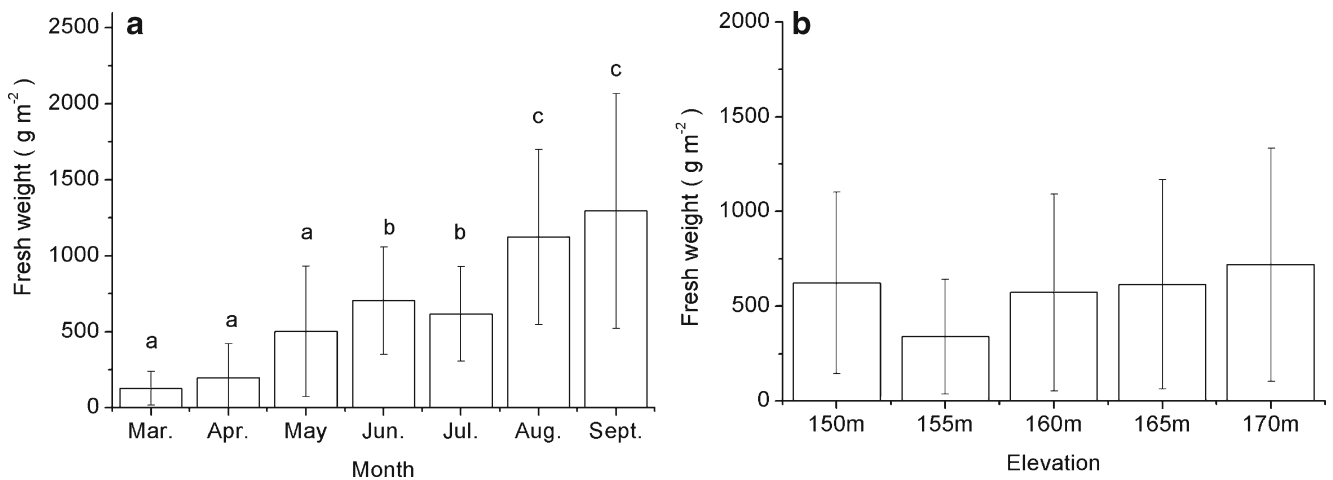


Fig. 3 Fresh weight with respect to sampling time (a) and elevation (b)

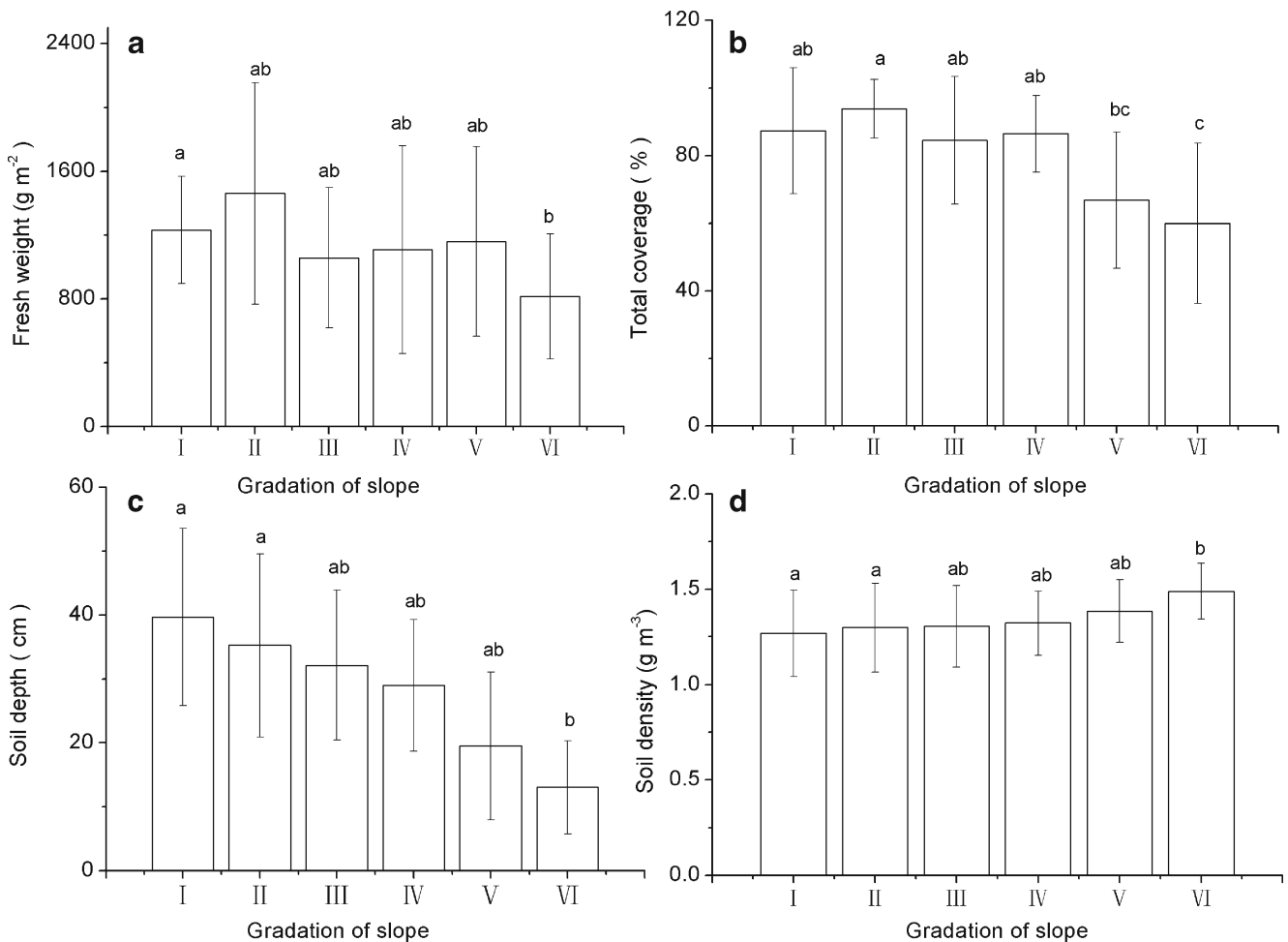


Fig. 4 Fresh weight (a), coverage (b), soil depth (c) and soil density (d) with respect to slope. The slopes were classified into six grades (I through VI) : <math><5^\circ</math>, $6\text{--}15^\circ$, $16\text{--}25^\circ$, $26\text{--}35^\circ$, $35\text{--}45^\circ$ and $>45^\circ$. Means without shared letters differ ($p<0.05$)

Nitrogen and phosphorus contents in 36 species

The nitrogen and phosphorus contents in the different species varied (Fig. 6). The nitrogen contents in the plants ranged from 5.02 (*Rumex acetosa*) to 34.75 g kg⁻¹ (*Chenopodium ambrosioides*), with an average of 13.04 g kg⁻¹. The phosphorus contents in the plants ranged

from 1.62 (*Hemarthria altissima*) to 5.90 g kg⁻¹ (*Eclipta prostrata*), with an average of 3.86 g kg⁻¹. The dry weights varied from 176.9 to 556.9 g m⁻², with an average of 307.6 g m⁻² in September 2010. Therefore, the nitrogen and phosphorus released from the vegetation that died and decomposed during submergence varied from 0.89 to 7.3 g m⁻² and from 0.29 to 3.29 g m⁻² respectively.

Table 2 Soil chemical properties varied with elevations of the WLFZ

Altitude	150 m	155 m	160 m	165 m	170 m
pH	8.29±2.12	6.87±0.87	6.83±0.84	6.89±0.88	6.85±1.13
SOM (g kg ⁻¹ dw)	12.56±4.51	16.05±9.50	15.03±6.04	13.71±4.03	13.79±3.53
TN (g kg ⁻¹ dw)	0.23±0.03	0.25±0.07	0.39±0.2	0.42±0.24	0.43±0.20
AN (mg kg ⁻¹ dw)	27.31±14.23	28.80±11.55	35.35±13.3	35.97±13.85	37.44±13.68
TP (g kg ⁻¹ dw)	0.23±0.04	0.36±0.12	0.37±0.15	0.34±0.19	0.34±0.18
AP (mg kg ⁻¹ dw)	7.09±4.80	7.45±3.82	16.32±16.51	13.58±20.42	11.10±12.31
TK (g kg ⁻¹ dw)	2.99±1.61	4.38±2.00	5.57±3.67	6.58±3.67	6.45±3.52
AK (mg kg ⁻¹ dw)	44.88±27.31	62.21±35.91	93.01±51.69	80.28±47.71	76.37±36.72

Values are the mean±SE in which SE is the standard error. SOM Soil organic matter, TN total nitrogen, AN available nitrogen, TP total phosphorus, AP available phosphorus, TK total potassium, AK available potassium

Table 3 Marginal and conditional effects obtained from the summary of forward selection

Marginal effects		Conditional effects			
Variable	Lam.	Variable	Lam.	p value	F
Elevation	0.26	Elevation	0.26	0.002	8.29
Soil density	0.12	Slope	0.08	0.012	2.46
Soil depth	0.09	pH	0.06	0.016	2.27
Slope	0.07	AP	0.06	0.030	1.95
TN	0.06	Soil depth	0.04	0.070	1.85
pH	0.06	TP	0.04	0.166	1.43
TP	0.05	AN	0.04	0.086	1.59
AN	0.05	TK	0.03	0.228	1.25
TK	0.04	Soil density	0.03	0.280	1.19
AP	0.04	AK	0.03	0.276	1.19
AK	0.04	TN	0.02	0.332	1.12
SOM	0.02	SOM	0.02	0.660	0.71

SOM Soil organic matter, TN total nitrogen, AN available nitrogen, TP total phosphorus, AP available phosphorus, TK total potassium, AK available potassium

Discussion

Characteristics of vegetation in relation to environmental factors in the WLFZ

Among the different environmental variables (topographic and soil variables) studied, elevation was found to be the main factor that influenced the distribution and the important value index of species in the WLFZ. After the filling of the TGR, the original vegetation, especially trees and shrubs, could not survive because they could not tolerate the winter submergence and summer drought (New and Xie 2008). In the present study, we found that a few shrubs (*B. nivea*, *L. davidii*, *L. cuneata* and *V. negundo*) and trees (*M. alba*, *A. kalkora* and *B. papyrifera*) only appeared at the altitude of 170 m. The main vegetation type at the five elevations was herbs. The dominant species with the highest important value index at the altitudes of 150 and 155 m were perennial herbaceous plants (*C. dactylon* and *C. rotundus*). However, the dominant species at elevations >160 m were annual herbs, including *D. sanguinalis* and *D. carota*. The previous studies have also reported that *C. dactylon* was the dominant species at lower elevations, whereas *Comniza canadensis* was dominant at an elevation of 170 m in the WLFZ in the TGR (Wang et al. 2012; Ye et al. 2013b). A number of studies have also shown that relatively flood-tolerant species are found mainly at lower elevations and

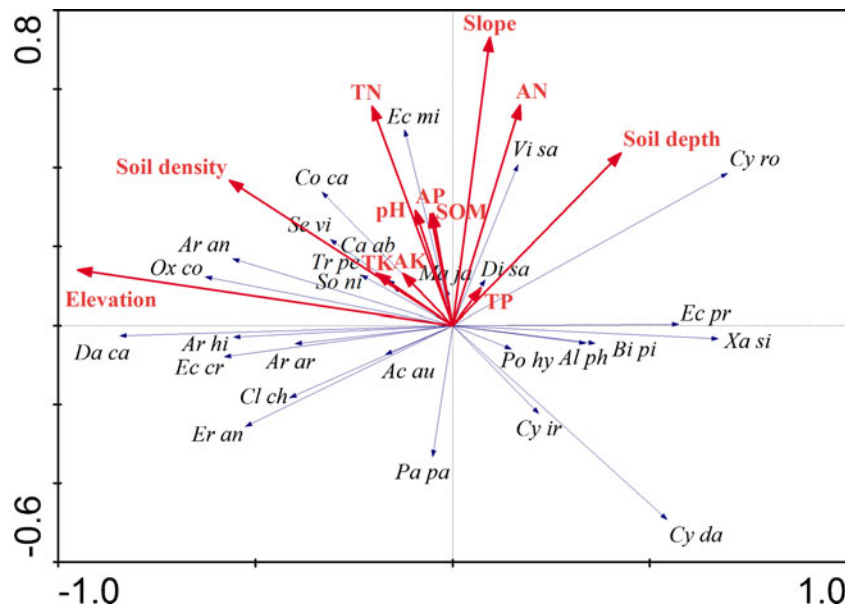


Fig. 5 Ordination diagram showed the result of RDA analysis of the important value index of species and environment variables. SOM Soil organic matter, TN total nitrogen, AN available nitrogen, TP total phosphorus, AP available phosphorus, TK total potassium, AK available potassium. Only species shown were those with >3 % fit. Ar an, *Artemisia annua*; Al ph, *Alternanthera philoxeroides*; Ac au, *Acalypha australis*; Ar ar, *Artemisia argyi*; Ar hi, *Arthraxon hispidus*; Bi pi, *Bidens pilosa*; Ca

ab, *Carpesium abrotanoides*; Cl ch, *Clinopodium chinense*; Co ca, *Comniza canadensis*; Cy da, *Cynodon dactylon*; Cy ro, *Cyperus rotundus*; Da ca, *Daucus carota*; Di sa, *Digitaria sanguinalis*; Ec pr, *Eclipta prostrata*; Ec cr, *Echinochloa crusgali*; Gn af, *Gnaphalium affine*; Ma ja, *Mazus japonicas*; Se vi, *Setaria viridis*; Tr pe, *Trigonotis peduncularis*; Ox co, *Oxalis corniculata*; Po hy, *Polygonum hydropiper*; Vi sa, *Vicia sativa*; Xa si, *Xanthium sibiricum*

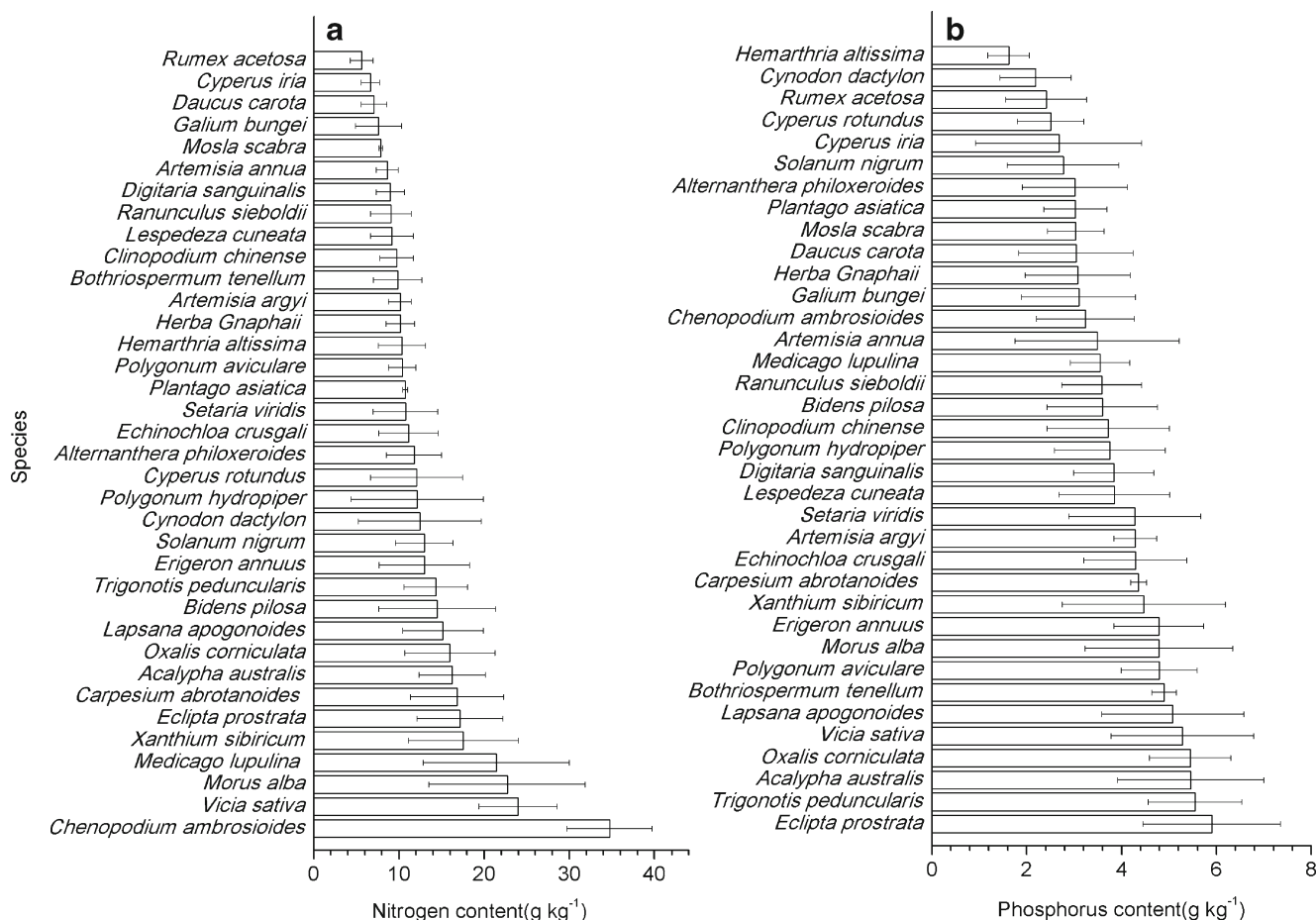


Fig. 6 Nitrogen (a) and phosphorus (b) contents in the different species varied

that relatively flood-sensitive species are found mainly at higher elevations (Van Eck et al. 2004; Lesnssen and De Kroon 2004). This species distribution pattern might be caused by several synthetic attributes (e.g., the inundation water depth, the tolerant flooding capacity, the life form, the dispersal mode and the inter-specific competition).

Several perennial herbs, such as *C. dactylon*, *C. rotundus* and *H. altissima*, are able to survive the submerged period because of their dormant tubers or rhizomes. These species may have evolved morphological, physiological and biochemical adaptations to oxygen deficiency. For example, *C. dactylon*, *C. rotundus* and *Rumex palustris* develop higher underground biomass, photosynthetic capacity and amylase activity (Peña-Fronteras et al. 2009; Hong et al. 2011; Jie et al. 2012). Recently, considerable progress has been made in terms of understanding the molecular aspects governing these responses to flooding. Oxygen-sensing mechanisms in *Arabidopsis* and rice have been found to be mediated by an N-end rule pathway. SUB1A, a gene responsible for tolerance of complete submergence, was found only in some low-yielding rice varieties in India and Sri Lanka (Gibbs et al. 2011; Francesco et al. 2011). Because *C. dactylon* and *C. rotundus* are able to tolerate complete

submergence for 7 months, they may also have underlying molecular mechanisms that will be discovered in the future.

The annual herbs of the WLFZ at >160 m, such as *X. sibiricum*, *B. pilosa*, *E. prostrata*, *C. canadensis* and *P. hydropiper*, had short life cycles (Kolar and Lodge 2001). In addition, the exposed time of the WLFZ at >160 m was at least 200 days. Thus, these species may rapidly attain maturity before being submerged. In addition, seed dispersal by wind, water, animals and humans may be an important factor (Merritt and Wohl 2006). For example, the seeds of the dominant plants, such as *C. canadensis* and *Bidens pilosa*, are dispersed by wind (Dauer et al. 2006).

Slope is also a key factor influencing plant community characteristics. In general, the steeper the slope of the WLFZ, the greater the amount of soil loss was resulting from erosion by water waves and rainfall (Marden et al. 2005). This effect is a potential threat to the existing and growing plants. Several measures for soil and water conservation should be considered in vegetation restoration efforts.

A total of 136 terrestrial vascular plant species were found in the study sites. In general, hydrophytes or helophytes could not survive because of continuous exposure of the WLFZ in summer. Only a few hydrophytes or

helophytes were found in the abandoned pits, ponds and paddy fields that held water. Seeds, tubers, or rhizomes of the most herbaceous terrestrial plants could sprout and grow quickly once the WLFZ was exposed. Therefore, the pattern of herbaceous terrestrial plants being the most abundant life form might not vary during the early stages of succession.

Soil properties and their influence factors in the WLFZ

The pH of the soil was found to be highest at the altitude of 150 m, with an average of 8.29. In general, the pH of soil increases with increasing soil moisture, especially for acidic soil types (Huang 2000). Flooding simulation experiments have shown that the soil pH of acidic soil might increase after flooding events (Sun et al. 2007; Valenzuela-Encinas et al. 2009). Because the submergence period is the longest at the elevation of 150 m, it is likely that the soil pH increases with soil moisture, indicating that the soil type is most likely acidic.

The concentrations of nitrogen and phosphorus appeared to be lowest at the elevation of 150 m, although the differences with elevation were not significant. The long-term submergence in winter and the high frequency of floods in summer may result in this pattern, as soil nutrients may be released when submerged and soil that serves as a nutrient source may be scoured by repeated flooding. Qiu and McComb (1996) reported that the concentration of total N was reduced after long-term submergence. However, different inundation periods and water depths in the WLFZ did not play a significant role in current soil development (Wang et al. 2012). In addition, the variation in available phosphorus was greater than of the variation in total phosphorus. Soil nutrients, especially available nutrients, are also affected by the parent types of soil, plant uptake and rainfall (Bardgett and Wardle 2003; Knoepp and Vose 2007). For example, the soil nitrogen contents in different vegetation restoration types are higher in shrub soils than in herb soils (Ye et al. 2012). The concentration of dissolved reactive phosphorus increases significantly with increasing rainfall intensity (Shiqaki et al. 2007).

Practical implications

The filling of the TGR resulted in loss of the original vegetation, especially trees and shrubs. The current plant species with high economic value should be chosen in the process of vegetation restoration. For example, the flood-tolerant edible hydrophytes in a dike-pond system may provide economic returns for farmers (Willison et al. 2013). The chemical constituents (xanthanolides, kaurene glycosides and essential oils) in *X. sibiricum* and *C. rotundus* have anti-oxidant, anti-bacterial, anti-inflammatory and anti-tumour properties (Han

et al. 2007; Jin et al. 2011). The sesquiterpene artemisinin, derived from *A. annua*, has received attention due to its anti-malarial properties and its potential for curing some cancers (Arsenault et al. 2008). The acetone extract from *A. annua* possesses good insecticidal properties (Khosravi et al. 2011). *M. alba* has been reported to be a potential source of protein for ruminant livestock (Doran et al. 2007). Therefore, the above-described plants should be prioritised in vegetation restoration efforts.

In winter inundating season, the nitrogen and phosphorus released from the vegetation in the WLFZ ranged from 0.89 to 7.3 g m⁻² and from 0.29 to 3.29 g m⁻², respectively. The death and decomposition of vegetation may result in secondary pollution during submergence. Harvesting herbs with high nitrogen and phosphorus contents might effectively remove nitrogen and phosphorus from the WLFZ. To avoid secondary pollution, this vegetation should be harvested before it is submerged. The harvesting of several economically valuable herbs may reduce the cost of vegetation restoration. The economic and ecological benefits of harvesting of several plant species, such as *M. alba*, *H. altissima* and *C. dactylon*, should be considered.

However, there are many uncertainties that cannot be answered by our study because the WLFZ is only 2 years old, and the plants and soil in the WLFZ are likely to continue to be in stages of acclimation. Therefore, long-term investigations and observations should be continued in this area to identify and monitor changes in the characteristics of the plant communities and soil properties.

Conclusions

A total of 146 species of vascular plants were found in the WLFZ. There were no significant differences in the number of species per square metre, the biomass or the biodiversity index at different elevations. The dominant species of plants varied with elevation. The dominant species, exhibiting the highest important value index, at the altitudes of 150, 155, 160, 165 and 170 m were *C. dactylon*, *C. rotundus*, *D. sanguinalis*, *S. viridis* and *D. carota*, respectively. Soil depth and soil density were significantly different at different elevations, but differences in soil pH values, the concentrations of SOM, TN, AN, TP, AP, TK and AK were not. Therefore, different inundation periods and water depths may only result in different dominant species at different elevations and may not play a significant role in the chemical properties of the soil. In winter inundating season, the released nitrogen and phosphorus from the vegetation varied from 0.89 to 7.3 g m⁻² and from 0.29 to 3.29 g m⁻² respectively. The results of the RDA indicated that the main factors influencing the vegetation characteristics were the

elevation, the slope, the pH and the concentration of soil available phosphorus.

Acknowledgements This study is supported by the National Natural Science Foundation of China (grant no. 50979061), Major Science and Technology Program for Water Pollution Control and Treatment (grant no. 2013ZX07104-004) and the Key Technologies R&D Program (grant no. 2012BAC06B04). We also thank Dr. Qingfeng Wang, Xiaojie Pan, Xiaojuan Chen and Xi Zou for the comments on early draft of this manuscript.

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