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The effects of the reverse seasonal flooding on soil texture within the hydro-fluctuation belt in the Three Gorges reservoir, China

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Abstract
Purpose The formation of the large hydro-fluctuation belt at the altitude of 145–175 m, following the construction of the Three Gorges Dam, developed from the terrestrial system in the Three Gorges reservoir. This research mainly concerned the effects of the resultant reverse seasonal flooding on soil texture.
Materials and methods Four field experimental plots were designed with sample belts and quadrats at the head, middle, and tail sections of the reservoir area. Stratified soil samples were collected, followed by analysis of soil structure and soil grain size of the collected samples.
Results and discussion The reverse seasonal flooding significantly changes texture and nutrient of riparian soil. The percentages of silt and clay formations were greatest at the lower hydro-fluctuation belt, followed by the middle and upper hydro-fluctuation belt, respectively. The percentage of silt and clay particles at 150 m was greater than that of 170 m by 18.12%. Conversely, the percentage of sand particles at the upper hydro-fluctuation belt ranked the highest, and followed by the middle and lower hydro-fluctuation belt, respectively. The percentage of sand particles at 170 m was higher than that at 150 m by 19.72%. Soil texture type changed with increasing altitude gradient, from silt loam, loam, then to sandy loam. Reverse seasonal flooding also promotes silt and clay permeation, and deposition from surface soil to subsurface soil, increasing homogeneity in grain structure between soil layers. This change in soil texture is associated with changes in soil nutrients. The content of soil organic matter, total nitrogen, total phosphorus, and total potassium varied significantly among soil texture types, with loam having the highest soil nutrient concentration and sandy loam having the lowest.
Conclusions The reverse seasonal flooding promotes the deposition of clay and silt within the hydro-fluctuation belt, inducing the total texture change of loam to silt loam. However, the structures and attributes of soil texture varied along the altitude gradient, as the exposed and submersed season and time span of riparian soil changed with the increase of altitude.

Keywords Soil composition · Soil nutrient · Soil grain size · Spatial distribution · The Three Gorges project

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1 Introduction

Soil texture is a critical indicator of soil physical properties, characterizing soil composition of different sized mineral particles (Neyshabouri et al. 2011; Wang et al. 2014). These soil particles form soil aggregates by combining with organic matter through cementation and agglomeration. The formation of aggregates increases organic matter stability and reduces their rate of decomposition. The size and percentage of soil particles significantly influence the size and quantity of soil aggregates, as well as their integration with organic matter (Ahmadi et al. 2011). From previous studies, there is a clear dependency of soil organic matter on soil particle size (Crawford et al. 1993; Zheng et al. 2011), in that high relative percentages of smaller particles (clay and silt) in soil result in reduced organic matter decomposition rates and higher organic matter content (Lin and Li 2001). Predictably, organic content is commensurately lower with high soil concentrations of larger particles such as sand (Christensen and Straw 1986; Wang et al. 2007). As such, soil texture is thought of as a critical factor in determining soil fertility due to its consequences on soil nutrient content and aeration conditions (Wang et al. 2003; Xu et al. 2013).

Soil texture is determined primarily by the soil's stable parent material types. In addition to these basic properties, soil texture can also be modified dramatically by specific environmental factors (Wang et al. 2003; Wang et al. 2009; Fu et al. 2012). Flooding is an important environmental factor which has crucial effects on changes of soil texture and soil nutrients in riverbank ecosystem (Neill 1995; Hefting et al. 2004; Yang et al. 2006). Some previous studies indicated that flooding could promote soil particles depositing on riverbanks and improve soil physical and chemical properties (Banach et al. 2009; Lee et al. 2014; Lu et al. 2016). However, other studies suggested that flooding induced the degradation of soil texture as it washed away much smaller soil particles (Campbell et al. 2002). It was thought that the variances of flooding pattern and riverbank altitude contributed to the different research results (Saint-Laurent et al. 2014; Ye et al. 2014).

With the construction of the Three Gorges project in China, the water level in the reservoir area has been greatly raised, and a large number of terrestrial ecosystems (from altitude 145 to 175 m) have been transformed into a riparian ecosystem, forming a new hydro-fluctuation belt of over 400 km^2. The amplitude and rhythm of flooding changed dramatically, with amplitude increasing from 10 to 30 m, and flooding rhythm reversing from "summer submersion-winter exposure" to "summer exposure-winter submersion." Due to the disturbance caused by this reverse seasonal flooding, the riparian environment was changed dramatically. These brought about the further, significant degradation of the riparian ecosystem, resulting in the loss of complexity within the composition and structure of the plant community (Lu et al. 2007, 2010). Along with decreased soil nutrient quality, a spatial heterogeneity of soil nutrient content also appeared (Guo et al. 2012). We hypothesize that the reverse seasonal flooding also correspondingly impact the soil texture within the hydro-fluctuation belt in the Three Gorges reservoir area. We selected four typical sections along Yangtze river in the Three Gorges reservoir area as case study plots, with soil samples collected along the elevation gradient from each plot, and the particle size composition of soils samples was tested. The effects of the reverse seasonal flooding on soil texture were elucidated by analyzing the changes in soil texture with altitude gradient and soil depth. Coordinated changes in soil nutrient were also analyzed in conjunction with the spatial distribution of soil nutrient characteristics.

2 Materials and methods

2.1 Research plots

Four field experimental plots were allocated along the Yangtze river in the Three Gorges reservoir area, located in Zigui and Xingshan counties in the Hubei province, and Wanzhou city and Zhongxian county in the Chongqing municipal (Fig. 1). The general environmental conditions in the four field plots are as follows:

(1) Zigui hydro-fluctuation belt at 30°38′58″ N and 110°18′23″ E. Average annual temperature is approximately18.9 °C, with an average annual rainfall of 1100 mm and average annual sunshine time of 1631.5 h. Soil texture type is Haplic alisol 30 cm thick, with a riverbank slope of about 30°. The plant habitat is composed primarily of grass dominated by *Setaria viridis*, *Rumex dentatus*, and *Digitaria ciliaris* etc.

(2) Xingshan hydro-fluctuation belt at 31°06′26″ N and 110°55′47 E. Average annual temperature is approximately 15.3 °C, with an average annual rainfall of 1050 mm, and an average annual sunshine time of 1682.8 h. The soil texture type is Haplic luvisol 30 cm thick, with a riverbank slope of about 28°. The plant habitat is composed of grass dominated by *Cynodon dactylon*, *Psapalum distichum*, and *Rumex dentatus*.

(3) Wanzhou hydro-fluctuation belt at 30°43′31 N and 108°25′43″ E. Average annual temperature is about 17.7 °C, with an average annual rainfall of 1243 mm, and an average annual sunshine time of 1484.4 h. The soil texture type is Haplic luvisol 40 cm thick, with a riverbank slope of about 25°. The plant habitat comprised grass dominated by *Cynodon dactylon*, *Alternanthera philoxeroides*, and *Setaria viridis.*

(4) Zhongxian hydro-fluctuation belt at 30°24′51″ N and 108°18′29″ E. Average annual temperature is about 18.2 °C, with an average annual rainfall of 1200 mm and an average annual sunshine of 1327.5 h. The soil type is Haplic luvisol 50 cm thick, with a riverbank slope of about 22°. The plant habitat is dominated by *Hemarthria sibirica*, *Cynodon dactylon*, and *Polygonum viscosum*.

2.2 Quadrat design and sample collection

The field experiment was conducted on March 2014 following flood recession and the reappearance of the hydro-fluctuation belt in the Three Gorges reservoir area. Seven sample belts were designed at each plot along the elevation gradient within the altitudes of 150–180 m at an altitude

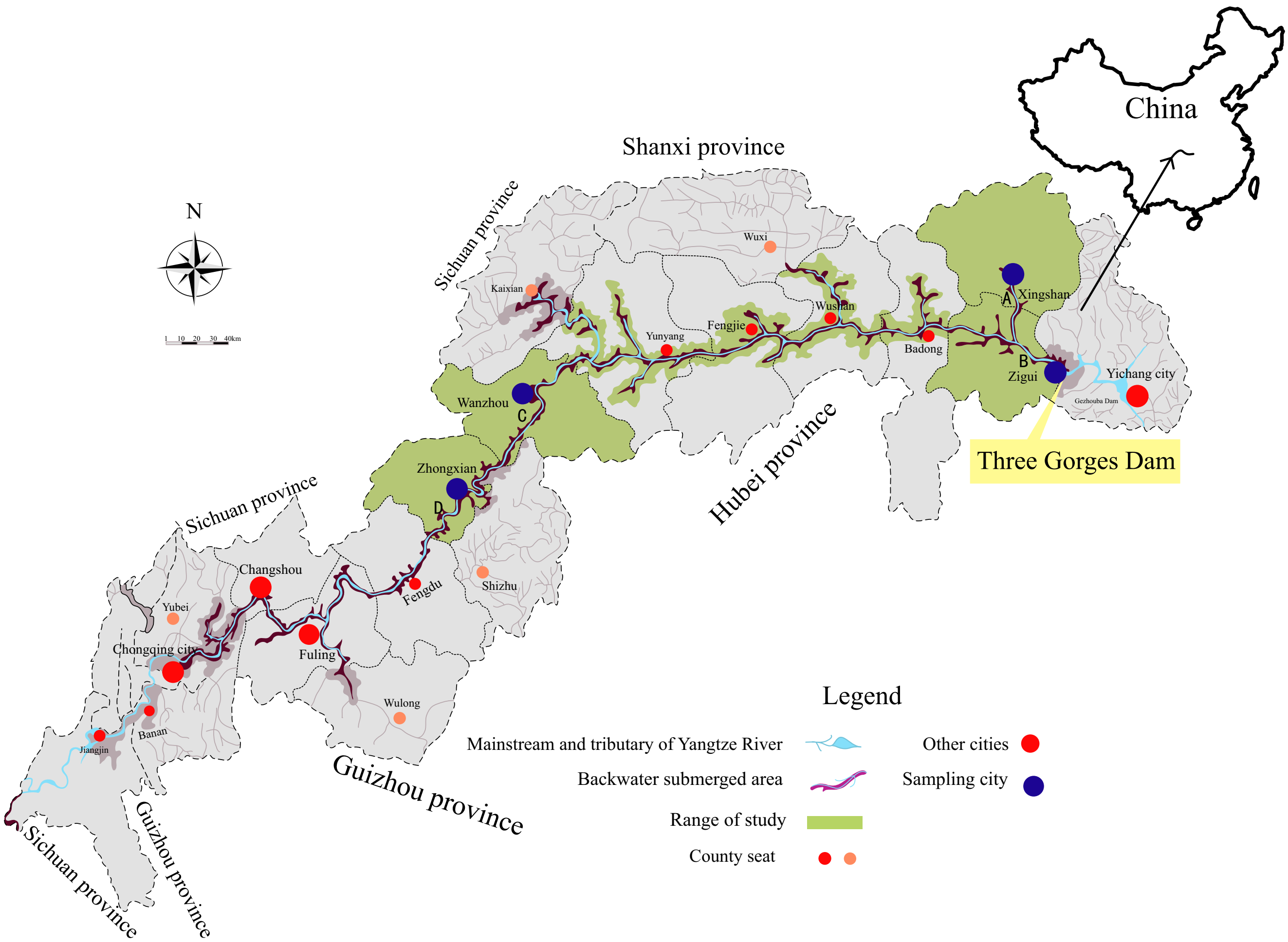

Fig. 1 Distribution of the field experimental plots in the Three Gorges reservoir area

distance of 5 m. Ten quadrats (1 × 1 m^2) were arranged randomly within each sample belt. Riverbank within the altitude of 150–175 m was designated as the hydro-fluctuation belt, with the non-hydro-fluctuation belt above 175 m used as a control. Soil was sampled at the center and four corners in each quadrat using a soil collector (diameter in 8 cm, length in 15 cm) before soil litters were cleaned. Each collected soil column was divided into three sections (0–5, 5–10, and 10–15 cm) as the soil samples to represent varying soil depths. Five hundred and twenty-five soil samples were collected from each plot.

2.3 Determination of soil texture and soil nutrient

Soil samples were air-dried in a laboratory. Debris was removed from the samples, with stones and other impurities removed with 10 and 100 mm sieves one after another after being crushed and ground. The sieved soil samples were kept in plastic bags and stored in a refrigerator at 4 °C. One section of each sample was used in determining soil texture, and the rest used for measuring the soil chemical properties. The composition of soil particle size was analyzed using a TopSizer laser particle size analyzer. Soil particles less than 2 μm in size were classified as clay, particles between 2 and 20 μm as silt, and particles of 20–2000 μm m in size as sand. Soil organic matter content was tested through the method of potassium dichromate oxidation-heated externally. Total nitrogen concentrations were tested using the Kjeldahl determination, total phosphorus tested using the method of acid fusion-Mo sb colorimetry, and the total potassium tested using the method of NaOH melting-lame photometry.

2.4 Data analysis

ANOVA analysis (one-way ANOVA) was applied using the altitude gradient and soil depth as dependent variables and soil particles as an independent variable in order to analyze the variance of soil texture along altitude gradient. The Turkey test was employed when the effect of a single factor was significantly different between treatment groups in order to obtain further data. The soil texture type of soil samples was classified according to the international soil texture classification standard (Christensen and Straw 1986). The effect of flooding on soil texture was uncovered through the analysis of changes in soil particle composition and soil texture type along altitude gradient. The relationship between the changes of soil texture and soil nutrient was further discussed. All data were analyzed using SPSS19.0 software.

3 Results

3.1 Effects of flooding on composition and type of soil texture

The reverse seasonal flooding induced a significant change in soil texture composition, with soil percentages of clay, silt, and sand changing significantly ($P < 0.01$) (Table 1). Compared with the non-flooding, the percentage of soil clay and silt in hydro-fluctuation belt increased by 8.45 and 7.58% respectively, while the percentage of sand decreased by 7.47%. The soil texture type changed completely from loam to silt loam along with the change of soil particle size composition.

3.2 The changes of soil texture along an altitude gradient

The soil particle size composition changed significantly along an altitude gradient ($P < 0.01$) (Table 2), with a corresponding change taking place in soil texture type. In the lower hydro-fluctuation belt (150–155 m), the percentage of the clay and silt ranged within 53.97 to 55.68%, and the soil texture was classified as a silt loam; in the middle hydro-fluctuation belt (160–165 m), the percentage of the clay and the silt ranged from 51.91 to 52.84%, the soil texture belonged to loam; in the upper hydro-fluctuation belt (170–175 m), the percentage of the clay and silt in soil decreased slightly, ranging from 47.14 to 52.16%. The soil texture of most soil samples was loam, but that of a few soil samples collected from 170 m were characteristic of sandy loam, in which the percentage of sand particles was over 55.0%.

3.3 The change of riparian soil texture with soil depth

The particle size composition of riparian soil changed significantly in relation to soil depth ($P < 0.01$). The percentage of clay and silt in soil increased with soil depth, while the percentage of sand decreased. The soil texture type of topsoil was loam within the riverbank, while that of middle layer soil and subsoil was silty loam. However, the change in soil particle size composition in relation to soil depth differed significantly between the hydro-fluctuation belt and non-hydro-fluctuation belt (Table 3). In the hydro-fluctuation belt, the percentage of clay and silt in topsoil was 8.72 and 5.68% lower, respectively, than that of middle layer soil, and 12.09 and 73.69% lower than that of subsoil. The percentage of sand in topsoil was higher than that of the middle layer soil and subsoil by 7.30 and 9.74%, respectively. In the non-hydro-fluctuation belt, the percentage of clay and silt in topsoil was 12.50 and 9.73% higher than that of middle layer soil and 18.14 and 14.16% higher than that of subsoil. The percentage of sand in topsoil was higher than that in the middle layer soil and subsoil by 8.18 and 20.81%, respectively. The reverse seasonal flooding reduced the difference in soil particle size composition between topsoil, middle layer soil, and subsoil.

3.4 Nutrient characteristics of different soil texture in hydro-fluctuation belt

There were significant discrepancies in soil nutrient content between the three soil texture types that appeared in the hydro-fluctuation belt ($P < 0.01$) (Table 4). The soil nutrient of loam ranked the highest, followed by silty loam and sand loam. The soil content of organic matter, total nitrogen, total phosphorus, and total potassium of loam was higher than that of silty loam by 12.54, 17.64, 12.12, and 10.03%, respectively, and higher than that of sand loam soil by 46.11, 34.24, 46.05, and 66.61%.

4 Discussion

4.1 The effect of the reverse seasonal flooding on soil texture

Soil texture type was influenced by the internal factor of soil parent material, as well as by many external factors such as climate, water, vegetation etc. in the process of wetland evolution and recovery (Zheng et al. 2011; Wolf et al. 2011). The conditions of change in soil texture are difficult to isolate due to the influence of flooding in wetlands (Wang et al. 2005; Hossler and Bouchard 2010). While some studies suggest that flooding increased the percentage of clay particles and porosity of soil, leading to overall improvement soil texture (Lu et al. 2007; Hossler and Bouchard 2010; Lee et al. 2014), other studies indicate that flooding increased sand particle

Table 1 The effects of the reverse seasonal flooding on soil texture

Riverbank	Clay particle (%)	Silt particle (%)	Sand particle (%)	Soil texture type
Hydro-fluctuation belt	7.44 ± 0.11a	46.29 ± 0.46a	46.36 ± 0.24b	Silty loam
Non hydro-fluctuation belt	6.86 ± 0.14b	43.03 ± 0.31b	50.10 ± 0.51a	Loam
F; *p*	24.15; <0.01	19.57; 0.00	15.91; <0.01	

Different letters in the columns indicate significant differences ($P < 0.05$). The following tables are the same

Table 2 The changes of soil texture along an altitude gradient within the hydro-fluctuation belt

Altitude (m)	Clay (<2 μm) (%)	Silt (2~20 μm) (%)	Sand (20~2000 μm) (%)	Soil texture
150	7.69 ± 0.41^{a}	47.99 ± 2.14^{a}	44.32 ± 1.96^{f}	Silty loam
155	7.71 ± 0.39^{a}	46.27 ± 3.15^{b}	46.03 ± 2.64^{e}	Silty loam
160	6.93 ± 0.57^{b}	44.90 ± 3.53^{c}	48.16 ± 2.74^{d}	Loam
165	6.80 ± 0.28^{c}	44.11 ± 2.54^{d}	49.09 ± 3.17^{c}	Loam
170	6.21 ± 0.46^{d}	40.93 ± 3.78^{f}	52.86 ± 3.41^{a}	Loam, sand loam
175	6.11 ± 0.61^{e}	41.95 ± 4.17^{e}	51.95 ± 3.25^{b}	Loam
F; *p*	40.51;<0.01	6.67;<0.01	11.32;<0.01	

percentage, soil bulk density, and soil substrate concentration, inducing soil texture degradation (Campbell et al. 2002). The reverse seasonal flooding caused the riparian soil to experience periodical inundation, exposure, scour, and elution, accompanied by a series of changes in soil oxygen, water content, temperature, and soil microorganism content and metabolism in the Three Gorges reservoir area (Du and Gao 2011). These factors eventually resulted in a dramatic change in riparian soil texture. Our studies indicate that the 6-year disturbance caused by the reverse seasonal flooding significantly changed the soil texture in the hydro-fluctuation belt. The percentage of clay and silt particles increased significantly while the percentage of sand particles decreased significantly. The riparian soil texture completely transitioned from loam to silt loam. Since the river wetland is highly open, much of the flushed soil particles from the riverbank flowed downstream (Noe et al. 2013). This deposition of clay and silt particles from the upstream riverbank and terrestrial system over hydro-fluctuation belt resulted in the significant change in riparian soil texture, under the rain and flood conditions.

This data implicates reverse seasonal flooding in inducing riparian soil changes along the altitude gradient in flooding intensity, flooding frequency, exposure, and submersion season and time span in the hydro-fluctuation belt. Soil in the middle and upper hydro-fluctuation belts suffered a high degree of flooding at high frequency and experienced long-term exposure, while soil in the lower hydro-fluctuation belt was only slightly disturbed by flooding at a lower frequency and experienced long-term submersion. Under the influence of the reverse seasonal flooding, much of the smaller soil particles were washed away in the middle and upper hydro-fluctuation belt and deposited in the lower hydro-fluctuation belt. The percentage of clay and silt particles in the lower hydro-fluctuation belt was high, while the percentage of sand particles was lower in the middle and upper hydro-fluctuation belts. This varying presence of sand further differentiated soil texture along altitude gradient. The soil texture in lower hydro-fluctuation belt changed from loam soil to silt loam soil. Du and Gao (2011) conducted detailed research on the distribution of soil particle size in the Three Gorges reservoir by taking Zhongxian as a case study. Their research results coincided with our research results from the four field experimental plots. The reverse seasonal flooding also affected the differentiation of soil texture between soil layers in the riparian zone. While the percentage of clay and silt increased, the percentage of sand decreased with soil depth in both the hydro-fluctuation belt and the non-hydro-fluctuation belt. However, the reverse seasonal flooding reduced the degree of these differences in soil composition between soil layers in the hydro-fluctuation belt.

4.2 The changes of soil nutrient associated with the variation of soil texture

The variation of the soil texture was often associated with changes in the chemical composition of soil in wetland evolution and recovery (Campbell et al. 2002; Lu et al. 2007). It is thought that soil particle size is closely related to the retention

Table 3 Changes of riparian soil texture with soil depth

Riverbank	Soil depth (cm)	Clay (<2 μm) (%)	Silt (2~20 μm) (%)	Sand (20~2000 μm) (%)	Soil texture type
Hydro-fluctuation belt	0~5	6.91 ± 0.41^{c}	44.18 ± 0.24^{c}	48.92 ± 0.62^{a}	Loam
	5~10	7.57 ± 0.34^{b}	46.84 ± 0.31^{b}	45.59 ± 0.57^{b}	Silty loam
	10~15	7.86 ± 0.32^{a}	47.86 ± 0.26^{a}	44.58 ± 0.42^{c}	Silty loam
F; *p*		44.24;<0.01	24.76;<0.01	81.78;<0.01	
Non hydro-fluctuation belt	0~5	6.86 ± 0.04^{c}	43.03 ± 0.54^{c}	50.11 ± 0.49^{a}	Loam
	5~10	7.84 ± 0.46^{b}	47.67 ± 0.35^{b}	46.32 ± 0.39^{b}	Silty loam
	10~15	8.38 ± 0.39^{a}	50.13 ± 0.41^{a}	41.48 ± 0.26^{c}	Silty loam
F; *p*		40.51;<0.01	6.67;<0.01	11.32;<0.01	

Table 4 The interrelation between soil texture and soil nutrients

Soil texture	Organic matter Mean ± SE (g/kg)	Total nitrogen Mean ± SE (g/kg)	Total phosphorus Mean ± SE (g/kg)	Total potassium Mean ± SE (g/kg)
Loam	15.97 ± 0.35a	0.98 ± 0.03a	1.11 ± 0.02a	9.43 ± 0.19a
Silty loam	14.19 ± 0.28b	0.85 ± 0.04b	0.99 ± 0.03b	8.57 ± 0.23b
Sand loam	10.93 ± 0.21c	0.73 ± 0.03c	0.76 ± 0.02c	5.66 ± 0.14c
F; *p*	34.24; <0.01	18.65; <0.01	27.21; <0.01	25.15; <0.01

of soil nutrients. Soil particles of different sizes, including clay, silt, and sand, have different effects on soil organic matter and nutrient content (Zhou et al. 2009). The percentage of smaller soil particles, including the clay and the silt, has a positive correlation with soil nutrient content, as the presence of small particles increases surface area and cohesion, leading to a higher capacity to adsorb and retain soil nutrients. In contrast, a higher percentage of the sand leads to lowered organic matter content, as the large size particle increased soil looseness and permeability, promoting the formation and transformation of organic matter (Wu et al. 2004; Zhang et al. 2012). Bi et al. (1997) reported that soil organic matter and total nitrogen were concentrated mainly in clay particles, as did total phosphorus and total potassium, even though there was little difference among soil particles.

Flooding was a critical factor regarding the changes in soil texture and soil nutrient in wetland succession; flooding patterns determined the changing trend of soil texture and soil nutrient (Hefting et al. 2004; Zheng et al. 2011). The reverse seasonal flooding resulted in spatial variation of soil texture along the altitude gradient in the Three Gorges reservoir area. Silt loam, which had the highest percentage of clay and the silt, was distributed in the lower hydro-fluctuation belt, while loam with relatively lower percentages of clay and silt was distributed in the middle and upper hydro-fluctuation belts. The sand loam, which has the highest percentage of sand, only appeared in some parts of the upper hydro-fluctuation belt. This change in soil texture resulted in a coordinated change in soil nutrient content. Our research results suggest that the loam soil ranked the highest in soil nutrient content, with excellent soil particle size composition and good permeability. In comparison, silty loam had a lower soil nutrient content, with the highest percentage of small size particles and poor permeability, while sandy loam had the lowest soil nutrient content and the highest percentage of sand particles. These results are in accordance with the soil nutrient characteristics of soil texture, as well as the spatial distribution characteristics of soil nutrients in the Three Gorges reservoir area (Wang et al. 2015; Wang et al. 2016). These studies also suggest that the reverse seasonal flooding caused a loss of soil nutrients and induced an irregular spatial distribution of soil nutrients in that the highest concentrations of soil nutrient were predominantly distributed to the middle hydro-fluctuation belt (Chang et al. 2011; Shen et al. 2016).

5 Conclusions

The reverse seasonal flooding resulted from the construction of the Three Gorges dam influences significantly the soil texture and soil nutrient within the hydro-fluctuation belt in the Three Gorges reservoir area. The soil texture is totally changed from loam to silt loam with the deposition of clay and silt within the hydro-fluctuation belt, while a spatial variation of soil texture occurrences from silt loam, loam, then to sand loam with increasing altitude gradient. This change in soil texture is associated with changes in soil nutrients. The content of soil organic matter, total nitrogen, total phosphorus, and total potassium varied significantly among soil texture types. An irregular spatial distribution of soil nutrient occurrences in that the highest concentrations of soil nutrient were predominantly distributed to the middle hydro-fluctuation belt.

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