Spatial and temporal dynamics of nutrients in riparian soils after nine years of operation of the Three Gorges Reservoir, China

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Abstract

The construction and operation of the Three Gorges Reservoir (TGR), the largest hydropower dam in the world, has had significant consequences for the hydrology of riparian zones along the Yangtze river. Little is known about how such changes in hydrology might affect the levels of nutrients and organic matter (OM) in riparian soils. We conducted a nine-year study on the spatio-temporal dynamics and dominant environmental correlates of nutrients and OM in riparian soils along a 600 km section of the Yangtze. These soils have been exposed to a disrupted hydrological regime since the TGR's establishment in 2008. Vegetation surveys were also conducted from 2012-2016 to assess relationships between soil chemical properties and vegetation community properties under altered hydrology. Across the stream gradient, concentrations of total potassium (K) increased by 54% since the TGR's establishment. The opposite occurred for SOM and available K, concentrations of which were 35% and 33% lower in 2016, respectively, than those of 2008. The rate of increase in total K tended to be more rapid at the middle section of the stream gradient. Moreover, concentrations of SOM, total N, total K, and available phosphorus (P) and K tended to be particularly high at the middle section. The spatio-temporal distributions of nutrients were strongly positively related to the contents of fine soil particles (i.e., silt and clay). Moreover, the aboveground biomass was negatively correlated with the nutrient dynamics. Our results indicate that the control of the nutrient release in the middle reaches and lower elevations where fine particles tend to accumulate, will be essential for maintaining the health of aquatic and riparian

ecosystems upstream of the TGR.

Keywords: Nutrient distribution patterns; Hydrological conditions; Soil particle size; Riparian zone; Three Gorges Reservoir

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1. Introduction

Riparian ecosystems are the zones of transition between terrestrial and aquatic ecosystems. Riparian soils can act as sinks for, or sources of, nutrient pollutants that are derived from industrial waste discharge and domestic and agricultural runoff (Hantush et al., 2013). The tendency for riparian soils to retain or release nutrients such as nitrogen (N), phosphorus (P), and potassium (K) are largely dependent on soil characteristics including particle size (Cotovicz et al., 2014) and redox conditions (Meynendonckx et al., 2006), and on the characteristics of plant and soil microbial communities (e.g. Ye et al., 2017). These factors are in turn influenced by hydrological processes which can be drastically altered by anthropogenic activities, such as the construction and operation of dams and reservoirs (Sun et al., 2018). A thorough understanding of how the biogeochemical properties of riparian soils are affected by anthropogenic disturbance will be essential for the effective management and conservation of riparian ecosystems and associated watersheds.

Hydrological dynamics (e.g., the frequency and timing of flooding or drought) have significant effects on the biogeochemical properties of riparian soils (Baldwin & Mitchell, 2000). In particular, flooding is an active driver of soil physico-chemical conditions and sedimentation processes, which in turn regulate soil nutrient dynamics by affecting the processes of sorption, desorption and nutrient transport (Cook, 2007). Brovelli et al. (2012) reported that the nutrients deposited during floods were typically associated with fine sands that contain fine organic matter. Moreover, by stimulating the mineralization of organic matter and the production of inorganic nutrients, inundation during floods can result in losses or gains of N, P and K, and transformations of N and P (Bai et al., 2005). For example, frequent flooding can reduce the soil's ability to retain P and promote losses of N via coupled

nitrification-denitrification (Bai et al., 2007; Kerr et al., 2010). Hydrology also influences plant community composition and biomass, with consequent implications for the amounts of nutrients retained or lost from the ecosystem via processes associated with primary production and decomposition (Baldwin & Mitchell, 2000; Berhongaray et al., 2013; Hefting, et al., 2005). Overall, there are likely numerous interrelated properties and processes that underpin the responses of soil biogeochemistry to altered hydrological conditions, and much remains unknown. Thus, studies that occur over large spatial and temporal scales, and thus incorporate a wide range of environmental and hydrological conditions, will be essential to unravelling these complex relationships.

Dams represent one of the most significant anthropogenic hydrological disturbances to rivers worldwide (Ye et al., 2015; Gao et al., 2016). The construction of dams can alter sediment deposition conditions and the adsorption and retention of nutrients in the reservoir (Cunha et al., 2014). Friedl & Wüest (2002) demonstrated that dams act as physical barriers, limiting the natural transfer of water and reducing the water flow velocity, thereby extending sediment residence times and thus facilitating greater rates of nutrient deposition. However, various uncertainties remain regarding the adverse environmental and ecological consequences of dams (Wu et al., 2015; Gao et al., 2016), and further studies are warranted.

The Three Gorges dam in China, located in the mainstream of the Yangtze River, is the largest hydroelectric project in the world. The Three Gorges Reservoir (TGR; 29°16' - 31°25' N, 106°20' - 111°50' E) was fully completed in 2008 and has an area of 1080 km² (Ye et al., 2015). Since the impoundment of the TGR, the hydrological conditions and biogeochemistry of the upstream riparian areas have undergone marked changes (Zhang et al., 2012; Wu et al., 2016). Specifically, the

water velocity has decreased with average value between 0.2 and 0.3 m s⁻¹ (Hu et al., 2013) and with a maximum observation lower than 0.5 m s⁻¹ (Bao et al., 2015). Moreover, since 2008 water levels throughout the TGR watershed have generally fluctuated between a base level of 145 m above sea level (a.s.l) during the wet season (May to September) and a peak level of 175 m a.s.l. during the dry season (October to April) (Bao et al., 2015). Thus, the construction and operation of the TGR has resulted in the formation of an unnatural ‘water level fluctuation zone’ (hereafter ‘WLFZ’) that covers an area of 350 km² (Ye et al., 2011). The spatial distribution of sediments also changed, with higher sediment deposition in the reaches from Fuling to Fengjie (Hu et al., 2013; Bao et al., 2015; Li & Zhang, 2015).

Over the last few decades, and before the full operation of the TGR, the transportation and dynamics of nutrients throughout the WLFZ have received considerable research attention (Wang et al., 2009; Zhang et al., 2012; Huang et al., 2015). However, few studies have investigated the responses of soil nutrients to the altered hydrologic and geochemical conditions in the TGR’s WLFZ since full operation commenced in 2008. Moreover, prior investigations have not been carried out over spatial and temporal scales large enough to capture regional-level heterogeneity or long-term effects. Thus, we investigated the long-term (nine-year) spatial and temporal patterns of soil nutrients along a 600 km section of the TGR’s WLFZ after repeated anti-seasonal drying-wetting cycles. Our objectives were to (1) determine the spatio-temporal distribution of nutrients and OM in riparian soils subjected to an unnatural hydrological regime and (2) identify the dominant environmental correlates of soil nutrients and OM in the TGR WLFZ. This information will be invaluable for the development of optimal ecological management practices for the TGR region and elsewhere.

2. Materials and methods

2.1. Site description

The TGR is situated in the main channel of the Yangtze River from Yichang to Chongqing (Fig. 1). Detailed geomorphological characteristics of the WLFZ have been described by Ye et al. (2013) and Bao et al. (2015). The TGR has a humid subtropical monsoon climate with an average annual temperature of 16–19°C and precipitation of 817–1361 mm. Around 80% of precipitation occurs between April and October (MEP, 2014). The temporal dynamics of air temperature and rainfall in the study region for the duration of experiment (2008 to 2016) are shown in Figure S1. Air temperatures vary from upstream to downstream, with higher values in the middle reaches (Fig. S1). The slopes of the WLFZ become steeper and the area of water level fluctuation decreases gradually from upstream to downstream toward the TGR (Fig. 1; Bao et al., 2015). In 2001, before the TGR's construction, the riparian vegetation communities in the area featured 83 families and 240 genera, including 405 vascular plant species (Wang et al., 2002). These plant communities were generally dominated by *Setaria viridis*, *Leptochloa Chinensis*, *Digitaria ciliaris*, *Ficus tikoua*, *Cynodon dactylon*, *Pterocarya stenoptera*, and *Vitex negundo* (Ye et al., 2013).

2.2. Sample collection

The sampling sites spanned the entire TGR mainstream, from upstream at Banan to the dam area at Zigui (Fig. 1 and Table S1). In September of 2008 (before the TGR was operational), and in June and September of 2009 to 2016, surface soil samples (0–20 cm) were collected from thirteen selected sampling sites during 17 sampling events (Fig. 1). At each sampling site three plots (1 m² each) were established, with

each plot representing an interval of elevation from 145 to 175 m a.s.l. (145-155 m, 155-165 m, and 165-175 m). At each plot, a composite sample was formed from the mixture of five top soil samples (0-20 cm). However, in Banan, soil samples were only collected at the highest elevation of 165-175 m due to the high water level during the sampling period. We were unable to collect 119 of the planned samples (mainly in September from 2010 to 2011) because the sampling sites were inundated at these times. Therefore, a total of 510 composite samples were collected and these were stored at 4°C before chemical analysis.

2.3. Field measurements and chemical analysis

The vegetation attributes for each plot were quantified in June and September of 2012-2016. Plant species in the quadrats (5 m × 5 m) were identified according to Van der Meijden (2005). The coverage of each species was estimated according to the Braun-Blanquet method (Braun-Blanquet, 1932). Plant diversity was quantified with the Shannon-Wiener heterogeneity index (H) (Shannon and Weaver, 1949). The above ground biomass was obtained by harvesting all plants to the soil level (Ye et al., 2014).

Analytical methods of soil nutrients were described in detail by Ye et al. (2015). In brief, soil organic matter (SOM) was determined by potassium dichromate titrimetric solution with the method detection limit (MDL) of 0.5 g kg⁻¹. Total N was analyzed by the Kjeldahl method. Total P and available P were measured by molybdenum-antimony anti-spectrophotometric method with the MDL of 0.01 mg kg⁻¹. Total K and available K were determined by flame photometric method with the MDL of 0.01 mg kg⁻¹. To determine the contents of ammonium (NH₄⁺-N) and nitrate (NO₃⁻-N), 20 g of fresh soil were extracted with 100 ml extractant (0.4 M KCl) for 1 h,

then the filtered solution was analyzed for $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ on a continuous flow auto analyzer (Skalar-40) (Keeney & Nelson, 1982) with the MDL of 0.05 mg kg^{-1} . To determine the soil pH, a 2:1 (by weight) soil to water solution was measured with a Fisher Scientific AR15 (Waltham, MA) pH probe. The particle-size was determined by the pipette sampling technique (sand: $> 0.25 \text{ mm}$; silt: $0.05\text{-}0.001 \text{ mm}$; clay: $< 0.001 \text{ mm}$) (Rinklebe et al., 2006). Quality control procedures, including internal quality control using reference materials and regular participation in inter-laboratory comparisons, were used to ensure validity of the test results.

2.4. Statistical analysis

Regression analysis was used to examine the spatial and temporal trends in soil nutrients, key soil properties and plant community characteristics. Analysis of variance (ANOVA) was used to identify significant differences in the mean levels of soil nutrients, soil properties and plant community characteristics among different sampling times, sites, and elevation intervals. Pearson's correlation and linear regression analyses were used to assess the relationships between soil nutrients and environmental factors. Spearman correlation analysis was used to investigate the relationships between soil properties and plant community characteristics. We used Principal Component Analysis (PCA) to evaluate the patterns of variation in soil and environmental characteristics in September 2008 (representing pre-flooding conditions), June 2012 (representing conditions mid-way through our trial), and September 2016 (at the end of our trial, representing properties after nine years of repeated anti-seasonal wet-dry cycles). In the PCA biplots we grouped sampling sites based on position in the 600 km stream gradient, with sites from Banan to Fuling classed as the upper reaches of the stream gradient, sites from Fengdu to Fengjie

classed as the middle reaches, and sites from Wushan to Lanlingxi classed as the lower reaches. Redundancy analysis (RDA), a linear canonical community ordination method, was used to investigate the main controlling factors on the spatial and temporal distributions of nutrients. The significance of the relationships between the ordination and explanatory variables were evaluated with a Monte Carlo permutation test. The effects of environmental factors on nutrients were tested using the Forward Selection method. For PCAs and RDAs we used the average of the three elevation intervals (i.e., 145-155 m, 155-165 m and 165-175 m) for each sampling site as single observations. All the analyses were performed using SPSS 19.0 for Windows except the RDA which was performed using Canoco 5.0.

3. Results

3.1. Spatial and temporal variation in soil nutrient levels

All soil nutrients measured showed significant trends in spatial variation in the WLFZ ($p < 0.05$), with higher contents of SOM, total N, total K, available P, available K and $\text{NH}_4^+\text{-N}$ in the middle reaches (Fengdu to Fengjie) than in the upper (Banan to Fuling) and lower (Wushan to Lanlingxi) reaches (Fig. 2). On average, concentrations of total P exhibited a significant declining trend towards the TGD, with total P decreasing from $0.82 \pm 0.04 \text{ g kg}^{-1}$ at Banan to $0.62 \pm 0.04 \text{ g kg}^{-1}$ at Lanlingxi. The opposite was true for total N : total P ratios (hereafter ‘N:P ratios’; Fig. 2). Soil OM levels, available K concentrations, and N:P ratios declined over time. In 2008, the average SOM content was $21.14 \pm 1.88 \text{ g kg}^{-1}$, the average available K concentration was $81.15 \pm 4.74 \text{ mg kg}^{-1}$, and the average soil N:P ratio was 2.65 ± 0.31 . These values declined over time (Fig. 3) such that in 2016 the average SOM content was $14.73 \pm 0.66 \text{ g kg}^{-1}$, the average available K concentration was $67.31 \pm 3.16 \text{ mg kg}^{-1}$, and

the average soil N:P ratio was 1.32 ± 0.07 . The variation in most soil nutrients was large during the first four years (2008-2011) (Fig. 3). In addition, concentrations of TP, TK and AP were lower at the highest elevation (165-175 m) than at the lower elevations (145-155 m and 155-165 m; Fig. 4).

Finally, PCA indicated that the middle reach sites (sites from Fengdu to Fengjie), with higher contents of silt and most nutrients, were separated from the upper (i.e., sites from Banan to Changshou) and lower reach sites (i.e., from Badong to Lanlingxi) in 2016. This effect was not present in 2008 (before flooding) or in 2012 (after four-year impoundment) (Fig. 5).

3.2. Potential drivers of spatial and temporal variation of soil nutrients

Soils were 47% silt on average, but soil textural properties varied over time and throughout the watershed (Figs. S3-S4). Silt and clay contents were higher in the middle reaches than in the upper and lower reaches (Fig. S3). Soil pH and moisture showed a decreasing trend from upstream to downstream (Fig. S3) and pH also increased gradually from 2008 to 2016 (Fig. S4). Silt content and soil moisture were lower at the high elevations than at the low and middle elevations (Fig. S5). All nutrients were positively correlated with silt and clay (Table S4). Silt content explained 18% of variation in SOM, 16% for total N, 25% for total K and 27% for available K. Clay content explained 18% of the variation in available K (Fig. 6). Sand was strongly related to total and available K, accounting for 22% and 23% of their variation, respectively (Tables S4 and 1). Soil nutrients were also strongly correlated with air temperature, rainfall, pH and soil moisture (Table S4).

82.2% of the variability in the spatial distribution of soil nutrients was explained by RDA axes 1 (53.3%) and 2 (28.9%). Air temperature, silt and sand were correlated

with RDA axis 1, while clay and soil moisture contributed significantly to RDA axis 2 (Fig. 7a). The samples were clearly grouped into two parts (Fig. 7a). Samples in the middle reaches were closely associated with all the nutrients, air temperature, silt and clay, which suggested that these environmental parameters have strong influence over nutrient levels at the middle reach sites (Fig. 7a). Samples from the upper reach sites were closely linked to sand and rainfall (Fig. 7a). Air temperature, clay, and sand explained 44.1%, 20.7%, and 8.1% of spatial variation in nutrient levels, respectively (Table 1). 56.4% of the variability in the temporal patterns of soil nutrients was explained by RDA axes 1 (42.6%) and 2 (13.8%). Silt and soil moisture were associated mainly with RDA axis 1, and RDA axis 2 was closely associated with pH, sand, and rainfall (Fig. 7b). Samples collected in September of 2008, 2010 and 2011, and in June 2011 were distinctly separated from the rest of the samples (Fig. 7b). Silt, soil moisture, and pH accounted for 31.3%, 13.1%, and 9.1% of temporal variation in soil nutrient levels, respectively (Table 1).

3.3. Relationships between soil properties and vegetation characteristics

After nine-years of anti-seasonal flooding and periods of prolonged submergence, the number of plant species decreased sharply, with only 55 vascular plant species belonging to 50 genera of 21 families remained in 2016, dominated by annual plants including *Bidens tripartita* and *Echinochloa crusgalli*, and perennials such as *C. dactylon*. The aboveground biomass showed an increasing trend from upstream to downstream (Fig. S2a). Meanwhile, plant species diversity, aboveground biomass and plant coverage showed significant temporal dynamics, and only the plant diversity presented a decreasing trend from 2012 to 2016 (Fig. S2d-f). These plant parameters had higher values at the upper elevation plots than lower elevation plots (Fig. S2g-i).

Most of the soil nutrients including total N, total P, available P and K showed negative relationships with plant aboveground biomass, plant diversity and coverage (Table S5).

4. Discussion

The levels of soil nutrients and OM in the riparian zone of the TGD WLFZ varied greatly in both space and time, yet there were clear trends in this variation that can guide future management and restoration efforts. In particular, the strongly decreasing gradient in soil total P from upstream to downstream (Fig. 2), along with the rapid enrichment of most nutrients in the middle reaches following the establishment of the TGR (Fig. 3), suggest that riparian zones in the middle reaches of the Yangtze river are particularly sensitive to the changes in hydrology, sedimentary conditions, and land uses associated with increasing human activity in the region. However, there is a clear need for ongoing monitoring of nutrients and their ecological impacts over the entire TGR watershed, given that concentrations of total K tend to increase over time when averaged over the total 600 km stream gradient and that total P levels were highest at upstream sites.

4.1. Possible factors controlling the spatial variations of nutrients

Our results are consistent with previous studies and support the view that changes in hydrology (e.g. flow velocity) following dam establishment can have substantial effects on the distribution and transfer of nutrients in riparian zones (Cunha et al., 2014; Sun et al., 2018). However, our study provides the valuable new insight that such effects are likely driven by changes in the mobility of sand, silt, and clay, respectively, throughout the TGR watershed, as has been observed for heavy metal

contaminants elsewhere (Fremion et al., 2016). The full operation of the TGR has markedly slowed the water flow velocity compared with that prior to the impoundment. This can increase sedimentary residence times, thereby leading to greater rates of sediment deposition and facilitating the adsorption of nutrients to fine particles (Cotovicz et al., 2014; Fremion et al., 2016; Sun et al., 2018). Given that silt and clay particles have longer suspension times, these particles and associated adsorbed nutrients can be transported further downstream under the new hydrological regime.

Here we note that there were more fine particles (silt and clay) deposited in the middle reaches than in the upper and lower reaches (Fig. S3). Thus, it seems reasonable that sites in the middle reaches (especially from Fengdu to Fengjie) were influenced particularly strongly by the operation of the TGR because of their larger river area, gentler slopes, and lower water flow velocities, which together facilitated rapid accumulation of fine sediments (Fig. 1; Bao et al., 2015). This could, in turn, account for the higher accumulation of nutrients in soils from Fengdu to Fengjie (Fig. 2). Soil organic matter, total N, total K, available P and K showed similar spatial distributions to silt and clay (Figs. 2 and S3), and soil clay content was able to explain 21% of spatial variation in soil nutrient levels (Table 1). These results further indicate that the fine-grained particles have high nutrient absorption capacity and, as a result, contribute to the accumulation of nutrients in soils of the middle reaches of the TGR watershed.

At the same time, the topographical characteristics and vegetation of the WLFZ are likely vital factors for determining the spatial variation in soil nutrients. Bao et al. (2015) showed that the geomorphologic patterns of the WLFZ vary from upstream to downstream. The slopes of the WLFZ are steepest close to the TGR (Fig. 1), and the

WLFZ area also decreases gradually from upstream to the dam. As a result, the upper-middle reaches, with their wider areas and gentler slopes, are better suited for anthropogenic activities. On the other hand, the soil in the lower reaches was possibly more easily eroded due to the steep slopes (Fig.1), leading to losses of nutrients and OM from soil to water during wave erosion and storm events (Bing et al., 2016; Sun et al., 2018). All of these processes are likely to have contributed to the declining levels of total and available P in soils from upstream to the TGR (Fig. 2).

Interestingly, air temperature was found to be a key factor for the spatial dynamics of nutrients, explaining 44% of variation (Table 1). Variation in temperature can regulate soil nutrient forms and availability by affecting the soil physicochemical conditions (e.g. pH), plant uptake of nutrients, and microbial activities (Xiao et al., 2012a). For example, higher temperatures promote soil moisture evaporation which drives upward flow of nutrients in the soil solution (Xiao et al., 2010). Moreover, increased temperatures accelerate the mineralization of SOM and can, therefore, increase the availability and mobility of nutrients (Lahti et al., 2002). In the present study, air temperature showed significant spatial variation, especially in August, with higher temperatures in the upper-middle reaches (Fig. S1). This was strongly associated with higher levels of soil nutrients in those areas (Fig. 2). Therefore, our results could provide a reference point for evaluating the potential effects of climatic warming and hydrological changes on soil nutrient dynamics.

Finally, vegetation in the WLFZ plays an important role in nutrient cycling directly via plant uptake, decomposition, and deposition of alluvial materials, and indirectly through stimulation of microbial processes in the rhizosphere (Hefting et al., 2005; Wang et al., 2016; Xiao et al., 2017). Thus, the higher aboveground biomass in the lower reaches might have contributed to the lower accumulation of soil nutrients

in those areas due to high levels of plant uptake (Fraser et al., 2004; Figs. 2 and S2). Similarly, the low levels of plant diversity, aboveground biomass and coverage associated with low levels of plant uptake in the lower elevations of 145-155 m might have led to the higher level of soil nutrients (e.g., total P, total K and available P) in these areas (Figs. 3 and S2). Meanwhile, these results could be partly explained by the fact that the low plant coverage associated with long-term inundation can promote natural chemical weathering and thus increase the availability (and extractability) of some soil nutrients (Wang et al., 2013). Thus, vegetation biomass is likely acting as an important sink of nutrients, and this highlights the need to conserve and promote the riparian vegetation native to the area.

4.2. The effects of altered hydrodynamics on soil nutrients

Inundation frequency has been regarded as an important regulatory factor for soil nutrient levels due to its role in shaping soil texture and sorption-desorption processes (Woodward et al., 2015). In our study, concentrations of total P, total K and available P in soil were highest at 145-155 m a.s.l., which had the longest flooding duration (286 days per year versus 237 days for 155-165 m and 169 days for 165-175 m) (Fig. 4). These results contrast sharply with those of previous studies (Kerr et al., 2010; Xiao et al., 2012b), which found that higher inundation frequency increased nutrient (e.g. P) loss and reduced the sorption capacity of nutrients. We suggest that in our study the high nutrient levels associated with the longest inundation durations can be explained by high rates of deposition of fine sediment particles (i.e. silt) in the areas between 145 and 155 m with gentle slopes (Fig. S5; Bao et al., 2015).

Together our results indicate that the accumulation of nutrients in the WLFZ was underpinned to a great extent by the transportation and sedimentation of fine particles.

Indeed, silt content accounted for 31% of temporal variation in nutrient levels, particularly total K and available K (Table 1; Fig. 6). Venterink et al. (2002) have illustrated that the release of K in soils is mainly dependent on physical adsorption to clay particles and observed increases in K adsorption after drainage of soil. However, leaching of available K and the erosion of the deposited fine particles in the WLFZ could have been accelerated by summer rainfall, thus leading to the observed declines in the levels of available K (Fig. 3). Moreover, the middle reach from Fengdu to Fengjie, with higher contents of silt and nutrients, was separated from the upper and lower reaches after the nine-year inundation (in 2016), compared to that before flooding (in 2008) and after four-year impoundment (in 2012) (Fig. 5). These results suggest that, after nine years of full operation of the TGR, more fine particles have been deposited in the middle reaches of the WLFZ, leading to significant accumulation of nutrients from Fengdu to Fengjie (Figs. 2 and S4; Wu et al., 2016).

However, sediment particle size is unlikely to be the only important driver of the spatial and temporal distributions of soil nutrients and OM observed in our study. The anti-seasonal hydrology and repeated drying and wetting cycles are also likely to have had strong effects on soil pH, soil moisture and soil anoxic-aerobic conditions, all of which influence nutrient solubility, forms and sorption-desorption processes (e.g. Bing et al., 2016; Table 1). For instance, the alternating aerobic-anaerobic conditions associated with the repeated wetting-drying cycles could affect microbial activities and consequently nutrient dynamics (Woodward et al., 2015). Similarly, alternating aerobic-anaerobic conditions can accelerate the decomposition of soil OM (Fierer & Schimel, 2002). Such an effect could explain the declining levels of SOM from 2008 to 2016 (Fig. 3). Moreover, the effects of repeated wetting and drying on soil N dynamics remain a debated topic (Woodward et al., 2015). Baldwin & Mitchell (2000)

reported that frequent wetting and drying cycles result in the loss of soil N storage by the coupling of nitrification and denitrification. On the contrary, Woodward et al. (2015) found long-term enrichment or no changes in soil N contents after repeated wetting-drying cycles. Our results suggest that alternation of inundation and drying can affect the forms of N rather than facilitate its loss or accumulation (Fig. 3).

Similarly, hydrodynamics were likely a key controlling influence for temporal dynamics of P in the riparian zone (Wu et al., 2016), but it is difficult to predict whether the repeated wetting-drying cycles contributed to an increase or decrease in soil P concentrations based on our current data (Fig. 3). This is not surprising given that the response of soil P to the hydrological changes depends on many factors, including sedimentary conditions, local agricultural activities, vegetation and topography (Gao et al., 2016; Sun et al., 2018). For instance, the operation of TGR likely promoted the transportation and sedimentation of the fine particles and then accelerated the accumulation of P in the WLFZ. At the same time, the use of phosphate fertilizer and organophosphorus pesticides has increased by an annual average rate of ca. 5%, with approximately 7% of the fertilizer and 9% of the pesticides lost in run-off each year (Gao et al., 2016). Thus, a large amount of these pollutants could have entered the WLFZ and the Yangtze river during the wet season, and some of the accumulated soil P might be released to the TGR through the processes of dissolution, diffusion and exchange during the high water-level period of the dry season (Xian et al., 2013). Moreover, soil moisture also showed positive relationship with the contents of total P and available P, accounting for 13% of variation temporally in soil nutrients (Tables 1 and S4). Thus, the temporal dynamics of soil moisture might have contributed to the temporal variation in P levels by regulating the mobility and bioavailability of P (Figs. 3 and S4; Hernandez-Soriano &

Jimenez-Lopez, 2012). Finally, deposition of sediment and accumulation of nutrients (total P and available P) were also observed in the low and middle elevations of the WLFZ which had relatively gentle slopes (Figs. 4 and S5) and account for nearly 67% of the total area of WLFZ (Yuan et al., 2013). The higher concentration of P in the WLFZ might drive the release of P from the sediment to water during the high water level period of the dry season. The irregular and complex distribution of P from 2008 to 2016 is likely underpinned by some combination of all of these mechanisms, and perhaps others that remain unknown (Fig. 3).

The middle reaches, from Fengdu to Fengjie, and the low (145-155 m) and middle elevations (155-165 m) of the WLFZ tended to act as a sink for nutrients, which have important consequences for water quality and ecosystem health. The higher enrichments of soil nutrient in the middle reaches, were likely due to the gentle slopes and particularly large water level fluctuation area characteristic of the middle reaches, both of which would have facilitated sediment deposition (Figs. 2 and S3). The anti-seasonal variation in water levels upstream of the TGR could result in the removal of fine size particles from the WLFZ and, in doing so, promote the release of accumulated soil nutrients into the TGR. Therefore, the leaching and release of nutrients from soil to water should receive special attention in the middle reaches of the TGR watershed.

5. Conclusions

Our study provides one of the first long-term, large-scale investigations of the spatio-temporal dynamics of nutrients in riparian soils in an area subject to immense pressure from increasing human activities. Several trends emerged regarding the spatial distribution and temporal dynamics of nutrients in riparian soils of the TGR

WLFZ. Soil nutrient levels tended to be higher and accumulated more rapidly in the middle reaches of the TGR watershed. The concentration of total K increased from 2008 to 2016, while the concentrations of SOM and available K declined over the same period. Variation in nutrient levels appeared to be driven by soil physiochemical properties that are themselves influenced by hydrology and anthropogenic activities, including sediment size, pH, soil moisture, air temperature and vegetation. However, the annual hydrological cycle, which drives frequent alternation of erosion and deposition events, makes the biogeochemical processes in the WLFZ extremely dynamic and complex. Thus, it is challenging to predict future dynamics of soil nutrients throughout the TGR watershed. Even so, our study provides valuable information about the long-term biogeochemical influence of the TGR's construction and operation. From a management perspective, our results indicate that the release of nutrients from sites where sediments tend to accumulate, such as areas with gentle slopes or long inundation durations, should be given priority.

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Conflict of interest

The authors declare that there are no conflicts of interest.

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Table 1 RDA results showing the proportion of spatial and temporal variance of soil nutrients explained by single key explanatory variables.

Explanatory variables	% variance explained	<i>P</i> value	F ratio
Spatial			
Air temperature	44.1	0.00	7.1
Clay	20.7	0.01	4.7
Sand	8.1	0.08	2.5
Rainfall	5.9	0.09	2.2
Silt	7.7	0.15	2.0
Soil moisture	4.4	0.20	2.0
pH	1.3	0.61	0.5
Temporal			
Silt	31.3	0.00	6.8
Soil moisture	13.1	0.02	3.3
pH	9.1	0.05	2.5
Sand	2.4	0.56	0.7
Clay	2.6	0.52	0.7
Air temperature	2.6	0.57	0.7
Rainfall	1.2	0.84	0.3

Figure Captions

Fig. 1. The study area in the water-level-fluctuation zone of Three Gorges Reservoir, China.

Fig. 2. The spatial dynamics of soil nutrients from upstream to downstream in the water level fluctuation zone of the Three Gorges Reservoir. Data were mean values of years 2008 to 2016 ($n=39$). Regression analysis was used to investigate the spatial distribution pattern for each parameter and one-way ANOVA was used to examine the differences in NO_3^- -N among the different sampling sites. TGD = Three Gorges Dam.

Fig. 3. The temporal dynamics of soil nutrients from 2008 to 2016 in the water level fluctuation zone of the Three Gorges Reservoir. Data were mean values of 13 sampling sites ($n=30$). Regression analysis and one-way ANOVA were used to investigate the temporal distribution of soil nutrients.

Fig. 4. Soil nutrients compared among three elevation intervals in the water level fluctuation zone of the Three Gorges Reservoir. Values are means $\pm$ SE. Different letters indicate statistically significant differences among the three elevation intervals (differences significant where $p < 0.05$; $n = 153$ for 145-155 m; $n = 156$ for 155-165 m; $n = 201$ for 165-175 m).

Fig. 5. PCA analyses for soil nutrients and environmental variables at all sampling sites in (a) September 2008 (pre-flooding), (b) June 2012 (mid-way through the experiment) and (c) September 2016 (after nine years of repeated flooding). Red circles represent the upper reach sites, green circles represent the middle reach sites, and purple circles represent the lower reach sites. Sampling sites from the upstream Banan to the dam area Lanlingxi: 01, Banan; 02, Changshou; 03, Fuling; 04, Fengdu; 05, Zhongxian; 06, Wanzhou; 07, Yunyang; 08, Fengjie; 09, Wushan; 10, Badong; 11,

Zigui; 12, Lanlingxi; 13, Xingshan.

Fig. 6. Relationships between soil silt content (%; with silt used as a representative variable for particle size) and soil nutrient concentrations (n=510).

Fig. 7. Biplots of hybrid of RDA analyses for soil nutrients and environmental factors in spatial (a) and temporal (b) distributions. Blue arrows represent nutrients and the red arrows represent influencing factors. Arrow length represents the degree of influence of each influencing factor on soil nutrients. Red circles represent the upper reach sites, green circles represent the middle reach sites, and purple circles represent the lower reach sites. Sampling sites from the upstream Banan to the dam area Lanlingxi: 01, Banan; 02, Changshou; 03, Fuling; 04, Fengdu; 05, Zhongxian; 06, Wanzhou; 07, Yunyang; 08, Fengjie; 09, Wushan; 10, Badong; 11, Zigui; 12, Lanlingxi; 13, Xingshan.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Graphical abstract

Highlights

- ▶ Nine-year study of riparian soil nutrients across a 600 km stream gradient.
- ▶ Nutrients accumulated most in the middle of the stream gradient.
- ▶ OM and available K decreased but total K increased over time.
- ▶ Nutrient dynamics were strongly positively related to the contents of silt.
- ▶ Aboveground biomass was negatively correlated with nutrient distributions.

ACCEPTED MANUSCRIPT