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Dam Effect on Soil Nutrients and Potentially Toxic Metals in a Reservoir Riparian Zone

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The unique hydrological regime of Three Gorges Dam (TGD) has brought enormous challenges to the riparian zone (RRZ), which plays an important role in regulating sediment and nutrient transport into the Yangtze River. The soil in a RRZ is one of the key factors that affect the water quality. After 4 years of winter-flooding, the concentration of soil nutrients and potentially toxic metals between the flooded reservoir RRZ and adjacent non-flooded upland (Upland) are examined. There are two main results: First, soil organic carbon and soil available potassium concentration were significantly lower in RRZ than in Upland. Soil total nitrogen (TN) concentration showed the same trend, but with no significance. Soil available phosphorus concentration is significantly higher in RRZ. Second, the concentrations of all the tested potentially toxic metals (Cd, Cr, Cu, Pb, Zn), their geoaccumulation index (I_{geo}) values and potential ecological risk index (E_i) values are significantly higher in RRZ than in Upland. Cd had the highest I_{geo} and E_i values in RRZ. The present results indicated that the flood–dry–flood cycle caused by TGD has changed the soil nutrient concentrations and increased the potentially toxic metal concentrations. There is a cross-contamination risk of the soil in RRZ, perhaps related to fertilization. As the last protective barrier for the Yangtze River, soil potentially toxic metals pollution control should deserve a considerable attention in the RRZ formed by TGD.

1. Introduction

The Three Gorges Dam (TGD), the largest hydraulic project in China, has had a dramatic impact on the hydrology of the Yangtze River. In a typical year, the water level of the Yangtze River falls from 175 m above sea level (asl) in winter to 145 m asl in summer. The seasonal water level changes have formed a new reservoir riparian zone (RRZ) with an area of 348 km^2.[1] This new hydrological regime, quite different compared to the previous natural water level fluctuation, has brought enormous challenges to ecosystem in this RRZ, including: 1) bio-diversity reduction and riverscape aesthetics deterioration; 2) soil erosion and frequent geological hazards; and 3) serious environmental pollution, including reservoir bank pollution and amphibious cross contamination.[2]

RRZs (sometimes also called riparian buffer strips) are located at the intersection of terrestrial and aquatic ecosystems, and they play an important role in regulating sediment and nutrient transport into larger river courses.[3,4] In riparian buffer zones, soil, vegetation, and hydrology are key factors that affecting the water quality.[4] Soil features including soil organic matter content, soil chemical-physical characteristics, soil pH, and soil potentially toxic metal content have large effects on sorption–desorption processes and microbial activities, and thus regulate soil nutrient dynamics and influence water quality.[5,6] Therefore, it is essential to characterize soil nutrient and soil potentially toxic metal dynamics in the RRZ for an improved assessment of environmental quality.[7]

Recent research has clearly shown that hydrological regime regulated by dams can affect RRZ function and soil nutrients and potentially toxic metals within riparian ecosystem all over the world: 1) Hydrological regime influenced the microflora which would led to the decomposition of organic matter, and thus the release of nutrients such as nitrogen and phosphorus.[8] 2) Hydrological regime changed the efficiency of plant utilizing the soil nutrients, and thus leaded to the change of soil nutrients in RRZ. 3) The flooding period of RRZ provides an anaerobic reduction environment, which would stimulate the potentially toxic metal changing from less stable fraction to more stable fraction leading to a high level of concentrations in riparian soil, especially Cd.[9–12]

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To date, studies of dam effect on soil nutrients and potentially toxic metals in the RRZ of the Three Gorges Reservoir Area (TGRA) have focused on limited temporal and spatial extents.[13–15] There were also a number of studies focused on 2008–2009, before the TGD was fully functioning in 2010 and the formation of the riparian strip in 2011.[16–18] Zhao et al.[19] has reviewed the dam effect on sediments in this RRZ, found that: As, Cd, Hg, Cr, Cu, Ni, Pb, and Zn exhibited a higher probability to exceed the background values after damming, especially Cd. As the last protective barrier for the Yangtze River, it's vital to evaluate the potential ecological risk of soil potentially toxic metals (especially Cd) in this RRZ for water security.

To address the effects of the TGD subsequent to the formation of the RRZ, in 2012, soil samples were collected all over the RRZ of TGRA during the dry period of the flood–dry–flood cycle. The major objectives of this study were to: 1) examine the differences in soil nutrient and potentially toxic metal concentrations between RRZ soil and adjacent non-flooded upland soil and 2) evaluate the pollution status and potential ecological risk of potentially toxic metals from soil in the RRZ of TGRA.

2. Experimental Section

2.1. Study Area

The TGRA comprises roughly 58 000 km^2 area, the part of Yangtze River basin between Chongqing and Yichang City (where the TGD is located). The region is characterized by a humid subtropical monsoon climate. Annual mean temperature is 15–19 °C. The average precipitation is about 1250 mm $year^{-1}$, with the majority of rain occurs during May to September. TGD has raised water levels to 156 m in winter 2006 and 2007, 173 m in 2008 and 171 m in 2009. With the TGD fully functioning in 2010, the water level reached 175 m in winter, and thus the current RRZ of TGRA was first formed in summer 2011 (**Figure 1**).

The most common soil type in the TGRA is a high sandy soil, known locally as "purple soil," these soils are distributed in Fuling, Fengdu, Zhongxian, Wanzhou, and surrounding areas (**Figure 2**). Less common is a high clay soil, known locally as "yellow soil," which is distributed in Wulong, Fengjie, Badong, and surrounding areas (Figure 2). The purple soil is an early weathering product of Jurassic rocks and contains 18% clay, 30% silt, and 52% sand and is classified as an Orthic Entisol in the Chinese Soil Taxonomic System, a Regosol in the FAO Taxonomy, or an Entisol in the USDA Taxonomy.[20] Yellow soil is rich in goethite and formed on the red clay of Quaternary Period.

Because of their important water quality implications, Chinese government had formulated the national environmental quality standard for potentially toxic metal background values in soils (GB-15618-1995), and Tang et al.[21] had provided the background values for soils of the TGRA.

2.2. Field Sampling and Sample Treatments

Field surveys were conducted in July 2012, when the RRZ was not flooded. Sampling sites were set up in 10 areas along both sides (south bank and north bank) of the Yangtze River in Zigui, Badong, Wushan, Fengjie, Yunyang, Wanzhou, Zhongxian, Fengdu, Fuling, and Jiangjin (Figure 2). A 120 soil samples were collected below 200 m asl including reservoir RRZ (RRZ, flooded for about 160–270 days annually, 155–167 m asl, suffered 4 years of winter-flooding in July 2012) and adjacent non-flooded upland (Upland, never flooded, 175–200 m asl). In each sampling site, three sampling quadrats were randomly selected in RRZ and three other quadrats were randomly selected in the nearby Upland. In each quadrat (2×2 m^2), the quincunx distribution

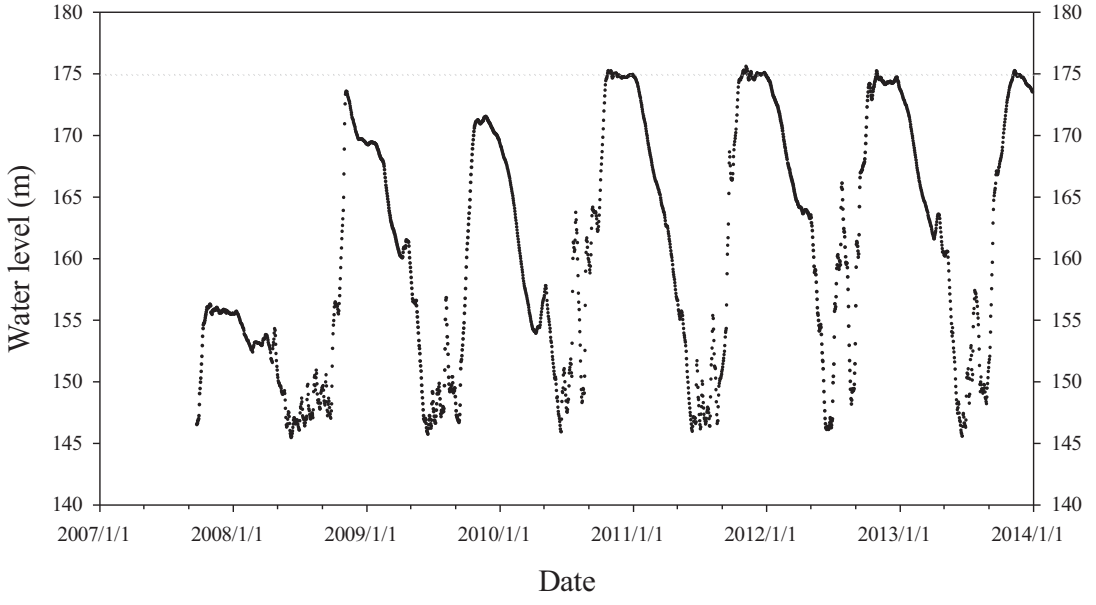

Fig. 1. Annual water fluctuations at the Zhongxian site from 2007 to 2013.

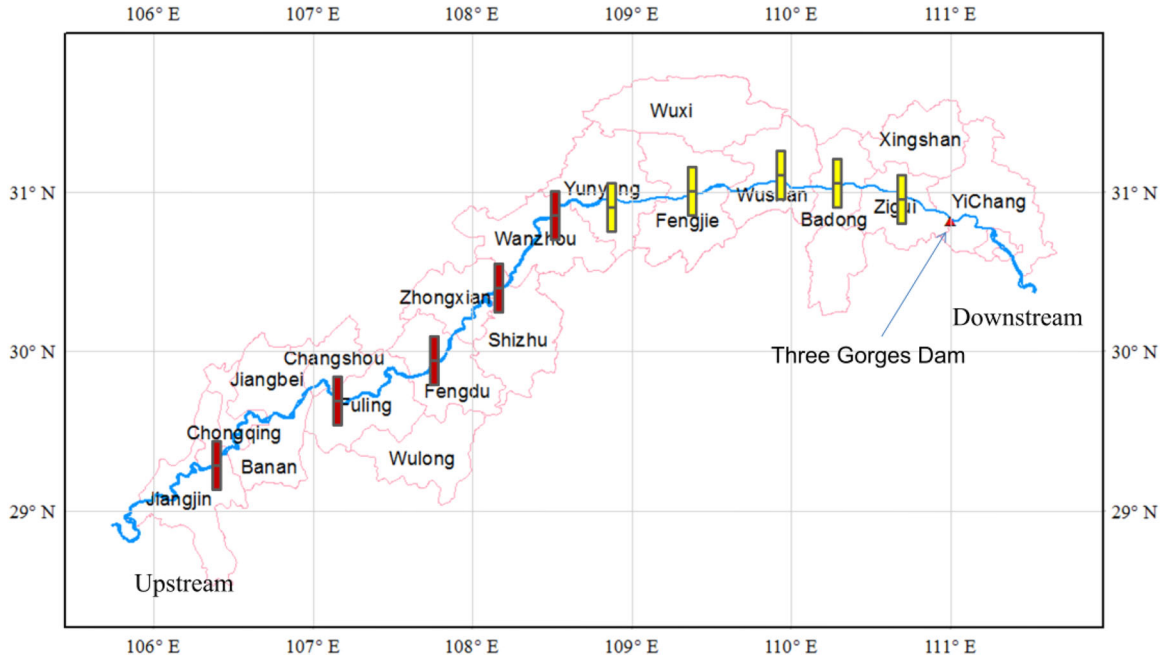

Fig. 2. Sampling sites in the Three Gorges Reservoir Area, China. Yellow column represents yellow soil and red column represents purple soil.

point method was used to collect soil samples: Soil samples in four angles and the middle were collected, and then mixed the five soil samples as one soil sample. In the same time, soil type of each quadrat was recorded. All soil samples were collected from 0 to 10 cm soil layer. Soil samples were air-dried, and then passed through a 2 mm polyethylene sieve for soil organic carbon (SOC) and pH analyses, and a 0.25 mm polyethylene sieve to analyze the concentration of soil total nitrogen (TN), soil total phosphorus (TP), soil total potassium (TK), soil available phosphorus (AP), soil available potassium (AK), and potentially toxic metals (Cd, Cr, Cu, Pb, Zn).

The potassium dichromate oxidation-outer heating method was used to analyze SOC based on the standard LY/T1237-1999,[22] and a pH meter was used for pH analysis. TN was analyzed using a Kjeldahl apparatus (Kjeltec 2200, Auto Distillation Unit, FOSS, Sweden) following the standard GB7173-87.[23] UV-vis spectrophotometry (UV-2550, UV-vis spectrophotometer, Shimadzu, Japan) was used to measure TP,[24] AP,[25] and TK.[26] Potentially toxic metals (Cr, Cu, Zn, Cd, Pb) and AK were analyzed by inductive coupled plasma emission spectrometry (ICP-OES, iCAP 6300, Thermo Scientific, USA) based on the $HNO_3/HF/HClO_4$ digestion-ICP method.

2.3. Data Analyses

2.3.1. The Geoaccumulation Index (I_{geo})

The geoaccumulation index (I_{geo}) introduced by Müller[27] was used to evaluate soil potentially toxic metal pollution by comparing current concentration with previous levels. I_{geo} is mathematically expressed as:

$$I_{geo} = \log_2(C_n/kB_n) \quad (1)$$

where C_n (mg kg^{-1}) is the concentration of the examined metal (n) in soil and B_n (mg kg^{-1}) is the background concentration of the metal (n). The background matrix correction factor (k) due to lithogenic effects was considered using a constant of 1.5. In TGRA, the local background value is 78.03 mg kg^{-1} for Cr, 25.00 mg kg^{-1} for Cu, 69.88 mg kg^{-1} for Zn, 0.134 mg kg^{-1}1 for Cd, 23.88 mg kg^{-1} for Pb.[21] To provide an overall assessment of geoaccumulation, Müller[27] proposed seven categories for pollution levels based on I_{geo} values (**Table 1**).

2.3.2. The Potential Ecological Risk Index (RI)

Hakanson[28] has put forward an approach to quantify the potential ecological risk index of multiple factors (RI) which is widely used. The toxicity of potentially toxic metals and their response to the environment were calculated following the equations:

Table 1. Müller's classification for I_{geo}.[27]

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

$$RI = \Sigma_i^n E_i \quad (2)$$

$$E_i = T_i \cdot \frac{C_i}{C_0} \quad (3)$$

where E_i is the individual coefficient reflecting the potential ecological risk for metal i, C_i ($mg\,kg^{-1}$) is the measured concentration for metal i, and C_0 ($mg\,kg^{-1}$) is the background value for metal i, which is the same as B_n in Equation (1). T_i is the toxic-response factor for a given substance, which accounts for the toxic requirement and the sensitivity requirement: 2 for Cr, 5 for Cu and Pb, 30 for Cd, and 1 for Zn.[28] According to E_i and RI values, Hakanson[28] defined five potential ecological risk levels (**Table 2**).

2.3.3. Statistical Analyses

Paired *t*-test analyses were conducted to test differences in properties between Upland and RRZ soils. The differences in properties among soil types and flooding situations were tested by the LSD post-hoc tests. All statistical analyses were carried out using SPSS version16.0.

3. Results

3.1. Soil Nutrients

SOC was significantly lower in RRZ than in Upland, TN showed the same trend, although not significant. SOC decreased by 23%, while TN decreased by 14%. AP was significantly higher in RRZ, with an increase of 72%; while AK was significantly lower in RRZ, with a decrease of 31%. Meanwhile, TP and TK showed no significant difference between these two sites (**Table 3**). In Upland, SOC and TN showed significant differences between purple soil and yellow soil; while in RRZ, only TN showed significant difference between soil types (**Figure 3**).

3.2. Potentially Toxic Metal Concentrations and Pollution Assessments

The concentrations of all tested potentially toxic metals (Cd, Cr, Cu, Pb, Zn) were significantly higher in RRZ than Upland soils. Cd, Cr, Cu, Pb, and Zn increased 26, 15, 70, 18, and 32%, respectively (Table 3). In RRZ, the concentrations of all tested potentially toxic metals were higher than the national environmental quality standard for soils of China (GB-15618-1995), as well as back ground value for soil of TGRA.[20] Especially Cd in RRZ ($0.38\,mg\,kg^{-1}$), which is 1.9 times of the national standard ($0.134\,mg\,kg^{-1}$, GB-15618-1995) and 2.8 times of the local back ground value. In the RRZ, all five potentially toxic metals were significantly higher in purple soil than yellow soil; while in the Upland soils, only Pb showed significant difference between purple soil and yellow soil (Figure 3). All five potentially toxic metals were significantly correlated with each other in the TGRA, and Cr, Cu, and Zn were negatively correlated with pH (**Table 4**).

Table 2. The classification of potential ecological risk coefficient of single-factor (E_i) and potential ecological risk index of multiple factors (RI) suggested by Hakanson.[22]

E_i	Ecological risk level of single-factor pollution	RI	General level of potential ecological risk
<40	Low risk	<150	Low risk
40–80	Moderate risk	150–300	Moderate risk
80–160	Considerable risk	300–600	Considerable risk
160–320	High risk	≥600	Very high risk
≥320	Very high risk		

Table 3. Comparisons of mean values of soil properties in RRZ and Upland sites, which were tested by paired *t*-test.

	Mean ± SE		
	Upland	RRZ	*p*-value
SOC ($g\,kg^{-1}$)	10.54 ± 1.02	8.09 ± 0.52	**0.026**
TN ($g\,kg^{-1}$)	0.96 ± 0.07	0.82 ± 0.05	0.070
TP ($g\,kg^{-1}$)	0.86 ± 0.04	0.895 ± 0.04	0.432
TK ($g\,kg^{-1}$)	17.43 ± 0.67	18.546 ± 0.47	0.067
AP ($mg\,kg^{-1}$)	5.15 ± 0.59	8.8535 ± 0.89	**0.002**
AK ($g\,kg^{-1}$)	1.27 ± 0.10	0.8853 ± 0.046	<**0.001**
pH	7.11 ± 0.00	7.60 ± 0.00	0.053
Cr ($mg\,kg^{-1}$)	98.53 ± 3.00	112.91 ± 2.35	<**0.001**
Cu ($mg\,kg^{-1}$)	31.68 ± 2.42	53.76 ± 3.97	<**0.001**
Zn ($mg\,kg^{-1}$)	89.17 ± 4.66	117.27 ± 5.40	<**0.001**
Cd ($mg\,kg^{-1}$)	0.30 ± 0.03	0.38 ± 0.030	**0.033**
Pb ($mg\,kg^{-1}$)	31.51 ± 2.75	37.29 ± 2.350	**0.050**

Bold values indicate significance at $p \leq 0.05$.

All I_{geo} values of the five tested potentially toxic metals were significantly higher in RRZ than in Upland soil: Cd, Cr, Cu, Pb, and Zn increased 153, 76, 160, 103, and 121%, respectively (**Figure 4**). The I_{geo} values of potentially toxic metals decreased in the order of Cd > Cr > Zn > Pb > Cu for Upland soil, the order is Cd > Cu > Zn > Pb > Cr for RRZ soil (Figure 4). In Upland soil, only Cd was in class 1, other four potentially toxic metals were in class 0 (Table 1). However, in RRZ soil, Cd, Cu, Zn, and Pb were in class 1, only Cr was in class 0 (Table 1). I_{geo} indicated that Upland soil was unpolluted by Cr, Cu, Zn, and Pb; unpolluted-moderately polluted by Cd, while RRZ soil was unpolluted by Cr; unpolluted-moderately polluted by Cd, Cu, Zn, and Pb. All the I_{geo} values were <1, suggesting that RRZ soil and Upland soil were both below the moderately polluted level.

The E_i values of Cr, Cu, Zn, Cb were significantly higher in RRZ than in Upland soil, while the E_i value of Pb showed no significant difference between two sites. Cd, Cr, Cu, Pb, and Zn increased 28, 14, 70, 18, and 31%, respectively (**Figure 5**). The E_i values of Cr, Cu, Zn, and Pb were <40 in both Upland soil and RRZ soil, suggesting that they were at the low ecological risk level of single-factor pollution. The E_i value of Cd was 67 in Upland soil, and 86 in RRZ soil, indicating that the ecological risk level of Cd pollution is moderate in Upland soil and considerable in RRZ soil (Table 2). For the five examined potentially toxic metals, their RI value was under 150 both in

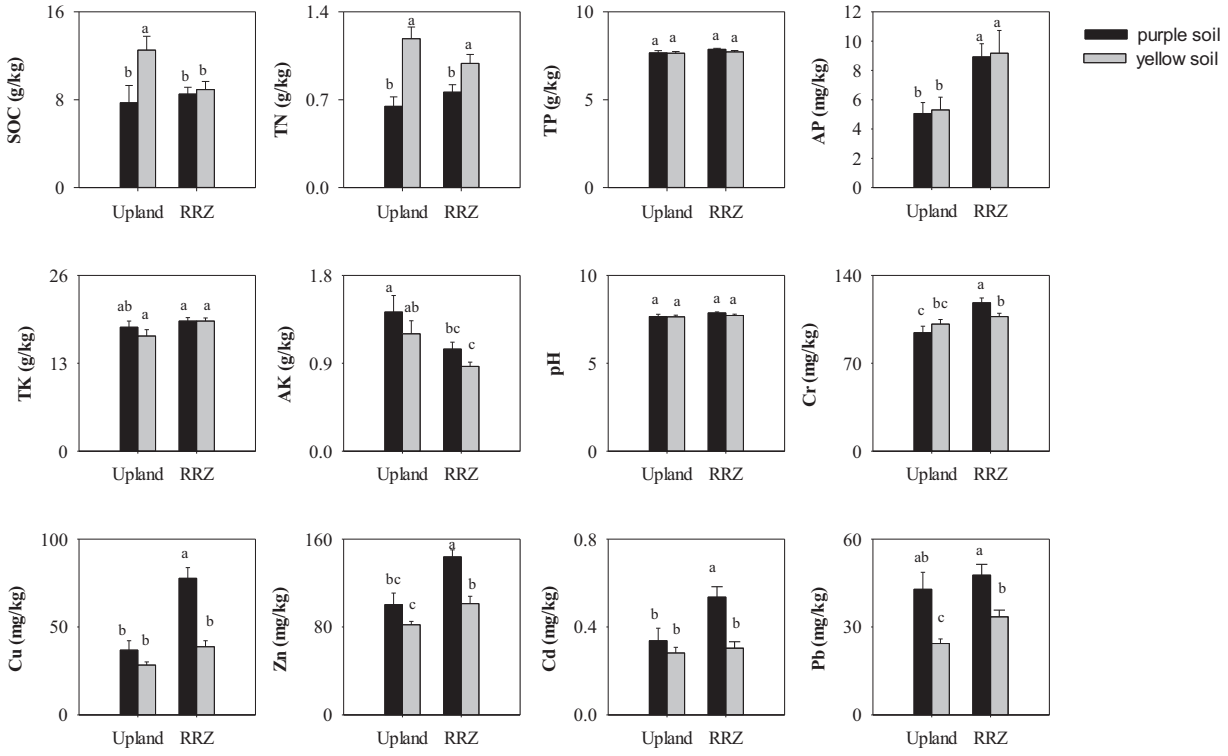

Fig. 3. LSD post-hoc tests of soil properties between different soil types and flooding situations. Errors bars represent ± SE. Bars marked with the same letter do not differ significantly at the 0.05 level from LSD post-hoc tests.

Upland soil and RRZ soil (84 in Upland, 109 in RRZ), indicating that they had a low general ecological risk level (Table 2).

4. Discussion

4.1. The Flood–Dry–Flood Cycle Has Changed Soil Chemistry

The effects of the TGD on soil chemistry are complex, including effects on nitrogen, SOC, and potentially toxic metals. The flood–dry–flood cycle caused by TGD has decreased the concentration of SOC and TN (Table 3), which were positively correlated with each other (Table 4). One explanation for this linked decline would be if soil nitrogen mainly exists in form of organic nitrogen in the soil.[29] The decrease of SOC and TN may be attributed to several mechanisms: 1) SOC may be leached from the soil profile during the extended period of flooding. The loss of soil carbon might also be due to the high slope in RRZ, which may lead to soil erosion shortly after the flooding period.[30] 2) The long flooding period offers a good environment for anaerobic microorganism to increase the rates

Table 4. Pearson correlation coefficients for soil properties at the TGRA.

	TN	pH	TP	AP	TK	AK	Cr	Cu	Zn	Cd	Pb
SOC	**0.818**	−0.004	0.122	**0.355**	**0.328**	**0.372**	−0.068	0.037	0.121	**0.282**	0.126
TN	1	0.012	−0.05	**0.284**	**0.334**	**0.287**	−0.012	−0.034	0.046	**0.238**	0.084
pH		1	−0.146	−0.042	−0.144	−0.095	**−0.195**	**−0.158**	**−0.191**	−0.141	−0.082
TP			1	**0.477**	0.031	0.000	**0.457**	**0.393**	**0.454**	**0.327**	0.144
AP				1	**0.301**	**0.235**	**0.224**	**0.355**	**0.404**	**0.344**	**0.241**
TK					1	**0.248**	0.143	0.106	**0.349**	**0.193**	**0.271**
AK						1	**−0.231**	0.004	0.066	**0.183**	0.151
Cr							1	**0.563**	**0.605**	**0.302**	**0.247**
Cu								1	**0.85**	**0.678**	**0.598**
Zn									1	**0.693**	**0.606**
Cd										1	**0.764**

All tests were one-tailed. Bold values indicate correlations with $p \leq 0.05$. Units of soil properties are shown in **Table 3**.

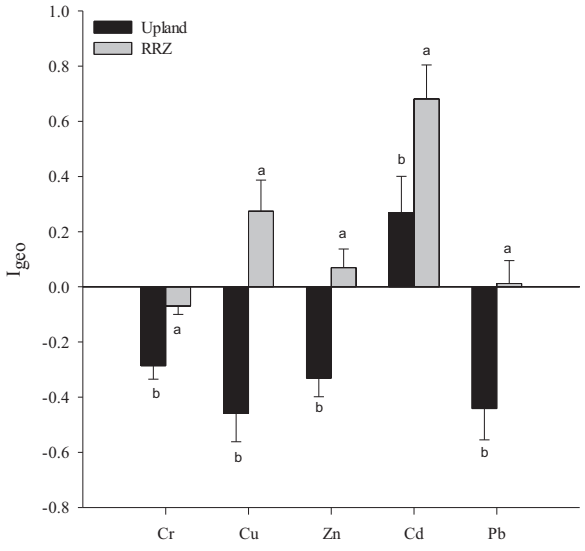

Fig. 4. Comparisons of mean values of I_{geo} of potentially toxic metals in RRZ and Upland sites, which were tested by paired *t*-test. Errors bars represent ± SE. Different letters signify a significant difference at $p = 0.05$.

of their denitrification, which would convert nitrate to N_2 or/and N_2O and released to the air.[31] Studies on riparian soils showed that long term flooding would lead to the loss the soil nitrogen.[32,33]

The flood–dry–flood cycle had increased the concentration of soil AP in RRZ indicating that the concentration of water phosphorus might be higher than the critical concentration of soil phosphorus for release during the flood period. Previous studies showed that, under the anaerobic condition, flooding could enhance the availability and solubility of soil phosphorus.[34,35] Mc Dowell[36] showed that sediment in a flood–dry–flood cycle condition would release more phosphorus compared to a continuous flooding condition. These might be the reason why RRZ had a high AP concentration.

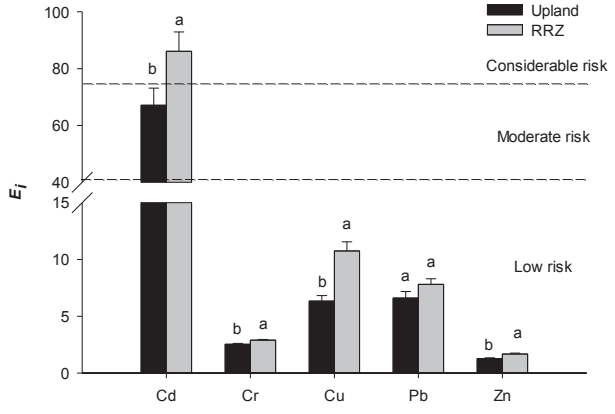

Fig. 5. Comparisons of mean values of E_i of potentially toxic metals in RRZ and Upland sites, tested by paired *t*-test. Errors bars represent ± SE. Different letters signify a significant difference at $p = 0.05$.

4.2. The Flood–Dry–Flood Cycle Has Increased the Potentially Toxic Metal Concentrations

The flood–dry–flood cycle caused by TGD had induced a significant increase in the concentrations of some potentially toxic metals (Cd, Cr, Cu, Pb, Zn) as well as their I_{geo} values (Cd, Cr, Cu, Pb, Zn), and E_i values (Cd, Cr, Cu, Zn). Moreover, correlation analysis showed that potentially toxic metals had significant positive correlation with each other (Table 4) suggesting that these potentially toxic metals might have a similar pollution source[15] and there was a cross-contamination risk of the soil in TGRA. Potentially toxic metals could deposit in soil and also react with other potentially toxic metals, which lead to cross-contamination. Considering RRZ is adjacent to farmland, fertilizer, which contains potentially toxic metal ions, could come into RRZ with leaching following precipitation events. Potentially toxic metal ions may, in this case, complex with soil particles.[37] Potentially toxic metals had a close correlation with TN and TP (Table 4), which are both thought of as non-point source inputs, suggesting that the potentially toxic metal pollution might be related to agricultural cultivation and fertilization.[38,39]

Cd had a very high concentration in both Upland and RRZ soils, higher than both the national standard and local back ground value. Based on Müller[40] and Hakanson,[28] among five tested potentially toxic metals Cd had the highest pollution level and ecological risk at RRZ soil, consistent with previous studies.[13,17,41] Cd exists in soil mainly in five forms: Exc-Cd (exchangeable fraction), Carb-Cd (carbonate-bound fraction), Oxider-Cd (oxide-bound fraction), Org-Cd (organic matter-bound), and Res-Cd (residual fraction).[42] Previous studies showed that flooding created an anaerobic reduction environment which would stimulate Cd transformed from least stable fraction Exc-Cd to more stable fraction Carb-Cd and Oxider-Cd.[43,44] Thus, during flooding period, after Cd from exogenous sources was absorbed by soil, the anaerobic reduction environment would help to make it deposit in RRZ soil.

Phytoremediation is a strategy for the removal of toxic metals from environment using plants,[45] and it has been widely applied in potentially toxic metal pollution renovation, such as the removal of arsenic by *Pteris vittata*.[46] As a hyperaccumulators, famous for its great accumulation capacity of potentially toxic metals, *Vetiveria zizanioides* was introduced in vegetation restoration practice in RRZ.[47] However, it failed to survive and adopt in the flood–dry–flood environment of the RRZ. Previous studies showed that *Salix variegate*, a shrub, one important species that applied to the vegetation restoration practice in RRZ, had a good Cd tolerance, Cd migration capability, and Cd accumulation ability.[48,49] As the most dominated species in RRZ, *Cynodon dactylon* has strong agamogenesis ability and well-developed stolon, which gives it a good accumulation ability of potentially toxic metals. Dai et al.[50] proved that the concentration of Cd in *C. dactylon* in the RRZ was under the limit of Chinese national standard feed hygiene ($0.5\ mg\ kg^{-1}$), which implies that it could be harvested as grazing. This represents a potential approach to reduce the Cd pollution of the water of Yangtze River, although the rate of Cd removal would likely be slow.

In summary, to avoid further deterioration it is necessary to enhance the protection of the RRZ soil from potentially toxic

metal pollution. There are three steps that might help effect this protection. First, the government should relocate companies which release potentially toxic metals to water and soil and manage the treatment of solid waste. Second, the government should enhance the management of land use in this RRZ, by regulating activities that contribute to non-point source pollution. Last but not least, the government could encourage people to plant hyper accumulators in the RRZ, such as *C. dactylon* and use them as grazing before flooding.

4.3. Suggestions for Future Studies

Due to the stage of development of the RRZ or/and the landscape context of the river, previous studies failed to reach agreements on dam effect on the concentrations of soil nutrients and potentially toxic metals in this novel RRZ of TGRA.[14–16] Nilsson et al.[51] investigated 88 RRZs in Sweden, ranging between one and 70 years in age, and found that the plant communities had not yet reached a stable stage even after 70 years since dam construction. As a newly formed RRZ, the RRZ of TGRA is in a very early stage, and the soil may still be changing.

Furthermore, studies were conducted at different elevations and different years.[14–18] At the RRZ, elevation corresponds directly to a winter flooding time and flooding depth (Figure 1), which may lead to differences in soil properties at different elevations. Given the potential role of flooding time on soil properties, future studies could investigate the role of different flooding times on soil chemistry.

Another difference across previous studies is soil type.[14–18] In the present study, TN showed significant differences between soil types both for the RRZ soil and Upland soil (Figure 3). Although TP and AP showed no significant difference between soil types, Shi et al.[29] found that yellow soil had a higher adsorption capacity of phosphorus than purple soil. In the present study, all five potentially toxic metals were significantly higher in purple soil than yellow soil in RRZ (Figure 3). Previous study showed that purple soil has a higher migration capability of colloid-absorbed Cd than yellow soil in RRZ.[52] However, the key role of purple soil and yellow soil in the sorption of specific potentially toxic metals in the RRZ merits further study.

5. Conclusion

The flood–dry–flood cycle caused by TGD has greatly changed soil chemistry including nutrient and potentially toxic metal concentrations. There are potentially important implications of this change: there is a cross-contamination risk of the soil in TGRA, which poses a risk to both the environment and human health. Cd is worthy of special attention: the concentrations are especially high and it had a considerable ecological risk in the RRZ. Following the operation of the TGD, soil potentially toxic metals have become a significant environment factor in the RRZ. As the last protective barrier for the Yangtze River, the largest freshwater river in China, soil in this newly created RRZ performs vital ecosystem services and should be monitored closely.

Abbreviations

AK, soil available potassium; AP, soil available phosphorus; Carb-Cd, carbonate-bound; Exc-Cd, exchangeable; Org-Cd, organic matter-bound; Oxider-Cd, oxide-bound; Res-Cd, residual; RRZ, reservoir riparian zone; SOC, soil organic carbon; TGD, Three Gorges Dam; TGRA, Three Gorges reservoir area; TK, soil total potassium; TN, soil total nitrogen; TP, soil total phosphorus; Upland, non-flooded upland.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

geoaccumulation index, nitrogen, potential ecological risk, potentially toxic metals, riparian zone

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