**Heavy metal concentrations in riparian soils along the Han River,
China: The importance of soil properties, topography and upland
land use**

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Abstract

Riparian zones can act as an important sink for various contaminants, including heavy metals. The retention and accumulation of heavy metals in riparian soils varies spatially and is related to many local factors, such as soil properties, topography and land use. However, the relative importance of such factors in determining the heavy metal contamination of riparian soils remains unclear. In this study, we investigated the concentrations of 10 heavy metals (i.e., Ba, Cd, Co, Cr, Cu, Mn, Ni, Pb, Sr and Zn) and their relationships to environmental features in 67 soil samples collected from 26 riparian sites along the Han River, China. Our results showed that there were significant and positive correlations among the concentrations of all heavy metals except for Ba, Mn and Sr. Heavy metal concentrations were, in general, positively associated with conductivity, fine substrate, carbon, nitrogen and phosphorus contents in soils but were negatively related to soil pH and density. Among the topographic conditions studied, elevation and distance from the river mouth were positively associated with the concentrations of Ba, Cd, Cr and Ni in riparian soils. Upland land use had a significant effect on the concentrations of Co, Cu and Zn. Generalized linear models revealed that soil properties, topography and land use together accounted for 11–69% of the variance in single metal concentrations, while redundancy analysis showed that such factors could explain 48% of the variance in overall metal levels. Our findings suggest that heavy metal concentrations in riparian soils are regulated not only by soil properties but also by physical characteristics such as topography and land use.

Keywords: Riparian zones; Sedimentation; Topographic factors; Trace metals; Yangtze River Basin

1. Introduction

Riparian zones, the **ecotones** between aquatic and terrestrial ecosystems, play a critical role in the maintenance of stream water quality, bank stability and aquatic biodiversity (Naiman and Decamps, 1997; Liu et al., 2014). Riparian zones are considered to act as an effective sink for heavy metals arriving via river flooding or moving from upland areas through the processes of sedimentation and adsorption (Bai et al., 2009; Ye et al., 2011; Zimmer et al., 2011; Pavlović et al., 2016). Some studies have further indicated that the capacity of riparian zones to accumulate heavy metals depends on the combined effects of soils, water and plants through a combination of physical, chemical and biological processes (e.g., Zhang et al., 2011; Tang et al., 2014). Heavy metals in riparian soils may be mobilized into adjacent water bodies via different hydrological processes such as surface runoff, leaching and transport of soil particles (Van Laer and Smolders, 2013).

Heavy metal concentrations in soils are related to a wide range of local environmental factors, including soil physical-chemical properties (Navas and Machín, 2002; Bartoli et al., 2012). A number of studies have examined the relationships between heavy metal concentrations and soil pH, but their results are not consistent (e.g., Du Laing et al., 2007). In general, low pH may weaken the strength of metal association and prevent the retention of metals by soils (Zhang et al., 2014). However, some studies have reported that soil pH is negatively correlated with the metal content of soils (Navas and Machín, 2002; Du Laing et al., 2007). Soil organic matter can directly affect metal concentrations and bioavailability through physical and chemical sorption, precipitation, complexation and chelation processes (Hall, 1998). Organic matter can also indirectly influence metal availability and mobility in soils by

70 acting as a food source for microorganisms which catalyze a variety of redox
71 reactions in the presence of electron acceptors (Du Laing et al., 2009).

72 Topography is a major factor controlling the variation of soil physical-chemical
73 properties due to its effect on runoff, drainage and soil erosion, which consequently
74 affect soil formation and development (Xiong et al., 2015). Therefore, content and
75 bioavailability of heavy metals in soils may be largely determined by topographic
76 conditions (Du Laing et al., 2009). Differences in the topography of riparian zones
77 often result in noticeable pedological and hydrological (e.g., flow pathways and
78 velocities) differences. Compared with steep areas, flat areas have a longer water
79 residence time and therefore may have a greater capacity to accumulate heavy
80 metals in soils. However, only a few studies have examined the effect of topography
81 on the soil heavy metal concentrations in river ecosystems (e.g., Du Laing et al., 2007;
82 Chen and Torres, 2012). One such study has demonstrated that metal abundances in
83 soils are strongly influenced by elevation and distance from the channel in an estuary
84 (Chen and Torres, 2012).

85 Several studies have reported that upland or adjacent land use characteristics
86 can influence the soil physical-chemical properties in riparian zones (Jha et al., 2010;
87 Xiong et al., 2015). Riparian areas may reduce the impact of upland land uses by
88 filtering and retaining soils, nutrients and dangerous chemicals (e.g., heavy metals) in
89 the surface soils. Until now, few studies have evaluated the effects of surrounding
90 land use on metal concentrations in riparian soils or river sediments (see Venne et al.,
91 2006; Smith and Owens, 2014). Venne et al. (2006) found that surrounding land use
92 types had no significant effect on metal accumulation in playa sediments in the
93 Southern High Plains, USA. However, Smith and Owens (2014) reported that

fine-grained sediments had consistently higher levels of several heavy metals (e.g., Mn) in agricultural sites than in forested areas.

To date, relatively few studies have focused on the distribution of heavy metals in riparian zones in China (e.g., Zhang et al., 2011; Xiao et al., 2015). The contributions of soil properties, topography and upland land use to metal contamination in riparian soils are also poorly understood. In the present study, we measured the concentrations of 10 heavy metals (i.e., Ba, Cd, Co, Cr, Cu, Mn, Ni, Pb, Sr, and Zn) in 67 surface soil samples collected from 26 riparian sites along the Han River in China. The objectives of this study were (1) to investigate the concentrations and spatial distribution of heavy metals in riparian soils; (2) to establish possible correlations between heavy metal concentrations and soil properties, topography and upland land use; and (3) to explore the relative contribution of such factors to the spatial variability of heavy metal concentrations in riparian soils using multivariate analyses.

2. Materials and methods

2.1. Study areas

The Han River, originating from the Ningqiang county of Shaanxi province, is the largest tributary of the Yangtze River, with a drainage area of approximately 159,000 km² and a total length of 1,577 km (Fig. 1). The Han River basin belongs to the north sub-tropic monsoon climatic region. The annual mean temperature is 12–16°C, with the highest and lowest temperatures of 43 °C and –13°C, respectively (Liu et al., 2013). The mean annual precipitation is approximately 804 mm, and 80% of the total rainfall is concentrated in the rainy season from May to October (Liu et al., 2011). The

main terrestrial vegetation in the Han River basin includes coniferous forest (e.g., *Pinus massoniana* and *Cunninghamia lanceolata*), deciduous forest, mixed coniferous and broad-leaved forest, shrub and herb (Liu et al., 2009).

The upper and lower reaches of the Han River are geographically divided by the Danjiangkou Reservoir, covering areas of 95,200 km² and 63,800 km², respectively (Fig. 1). Because the upper Han River basin is mainly located in the mountainous region, the riparian zones are generally restricted to a narrow band adjacent to the river channel approximately 2–10 m wide (Liu et al., 2013). In the lower Han River basin, the topography is relatively flat, and most of the riparian zones have a width over 10 m. Upland land use of riparian zones varies from source to mouth along the Han River. The most undisturbed portions of the Han River are the first 925 km, which are predominantly forested with some agricultural development. From 925 to 1577 km downstream, the upland land use is mostly agricultural, with urban and industrial land uses around some of the riparian zones. Coarse and fine sands were found to be dominant in most of the riparian zones with respect to silt and clay and this may be attributed to the continuous deposition of upstream eroded sediments on the riparian zones.

2.2. Field sampling

From May 9 to 16 of 2014, 26 riparian sites were non-randomly selected along the Han River based on ease of access (Fig. 1). Sites were chosen to represent a range of conditions on the Han River in terms of channel morphology, riparian width, and adjacent land use. The distance between neighboring sites was chosen to be at least 10 km. At each site, a sampling transect was randomly established perpendicular to

the direction of river flow and extended from the water's edge to the upper edge of the riparian zones. The length of the sampling transects depended on the riparian width and ranged from 2 m to over 30 m. One to three plots (1 m × 1 m) were selected along each transect in 10-m intervals based on the transect length. A total of 67 plots were established on the 26 riparian sites.

At each plot, five surface soil samples (i.e., 0–10 cm) were collected using a hand corer and the samples were well mixed to form a composite sample. We focused on surface soils because their heavy metal levels may reflect current environmental conditions (Bai et al., 2011). All of the soil samples were sealed in plastic bags and brought back to the laboratory for further analyses. At each site, longitude, latitude and elevation above sea level were recorded using a global positioning system (GPS; Model eTrex Summit, USA). The slope perpendicular to the contour lines was measured on each plot with a clinometer. For each plot, the distance to the river (i.e., lateral distance to the main channel) was measured using a tape measure. The distance to the river mouth was determined by measuring the distances between each sampling site and the mouth of Han River on a digital topographic map using ArcGIS version 10.0 (ESRI, Redlands, California, USA).

Upland land uses within approximately 100 m of each sampling site were noted and roughly assigned to forested, agricultural or residential categories (Xiong et al., 2015). The forest comprised coniferous, mixed and deciduous forests and shrublands. The agricultural lands included paddy field, dry farmland and fruit garden. Residential areas mainly covered urban, rural settlements and industrial lands. The 26 sampling sites were then separated into forested riparian (N=9), agricultural riparian (N=10) and residential riparian (N=7) according to their upland land uses.

2.3. Determination of metal concentrations and soil properties

Soil samples were air-dried at room temperature, coarse debris was removed, and then the soils were sieved through a 100-mesh nylon sieve. The concentrations of 10 heavy metals (i.e., Ba, Cd, Co, Cr, Cu, Mn, Ni, Pb, Sr and Zn) in the soils were determined using inductively coupled plasma atomic emission spectrometry (ICP-AES, Agilent ICP 720 OES). Approximately 0.2 g of each soil sample was accurately weighed and microwave-digested with a mixture of HNO₃, HCl, HF and H₂O₂ (Wang et al., 2014). Reagent blanks, standard reference materials and soil samples were synchronously analyzed. Average recoveries of standard reference metals ranged from 90-110%.

Soil pH and conductivity were measured in a soil to water ratio of 1:5 (v/v) using a probe (HI 991301, Hanna Instruments). To determine the percentage of fine substrates (silt and clay) in soils, approximately 50 g of air-dried soils were sieved through a 300-mesh (0.05-mm) sieve (Gomaa, 2014). The soil bulk density was measured by weighing soils of a known volume after 24 h drying at 105°C. The concentration of total carbon (TC) in riparian soils was measured with a TOC analyzer (Vario TOC cube, Elementar, Germany). After digesting soil samples with concentrated H₂SO₄ and HClO₄, soil total nitrogen (TN) and total phosphorus (TP) concentrations were analyzed using the Kjeldahl method and molybdate-blue colorimetric method, respectively.

2.4 Statistical analyses

Before statistical analyses, the data were tested with the Shapiro–Wilk test for

normality. Because most of the data were not normally distributed, non-parametric statistics were applied in the present study. Correlations among heavy metal concentrations, soil properties and topographic conditions were assessed by Spearman correlation analyses. We conducted a Kruskal-Wallis test to evaluate the effects of upland land use types (i.e., forested, agricultural and residential) on the heavy metal concentrations in riparian soils. Multiple comparisons were conducted with a Mann-Whitney test when the Kruskal-Wallis test indicated significant differences. The above-mentioned statistical analyses were performed using PASW Statistics 18.0 software (IBM SPSS Inc., Chicago, USA).

Multivariate methods, including generalized linear model (GLM) and redundancy analysis (RDA), were performed to explore the contribution of predictive variables (i.e., soil properties, topography and upland land use) to the spatial variability of heavy metal concentrations. The family quasi-Poisson distribution was used in the present study (Xiong et al., 2015) because there was over-dispersion when the GLM analyses were run using Poisson error distribution. The contribution of the significant explanatory variables to the final model was determined by the explained deviance: $D^2 = (\text{null deviance} - \text{residual deviance}) / (\text{null deviance})$. We used the R version 2.15.2 (R Core Team, 2012) for the GLM analyses.

Unlike GLM, RDA is an ordination technique that allows the examination of the influences of environmental factors on the overall metal levels in soils and not only on the concentration of a single metal (Lepš and Šmilauer, 2003). Gradient length of detrended correspondence analysis (DCA) was used to determine whether the RDA was the appropriate ordination form. RDA axes were statistically evaluated with a Monte Carlo permutation test. It should be noted that RDA can tolerate both

discontinuous and non-normally distributed data (Lepš and Šmilauer, 2003), although some studies used the square-root or log-transformed data when performing RDA. The software CANOCO (version 4.5, Ter Braak and Šmilauer, 2002) was used to perform the RDA.

3. Results

3.1 Metal concentrations in soils

The average concentrations of Ba (685 mg kg⁻¹), Cd (0.54 mg kg⁻¹) and Sr (168 mg kg⁻¹) in riparian soils were approximately 3.2, 6.8 and 2.2 times higher than corresponding background values, respectively (Table 1). The percentages of soil samples exceeding the background values for Ba, Cd, Cr, Cu, Sr and Zn were 100%, 100%, 80.6%, 82.1%, 98.5% and 89.6%, respectively.

The concentrations of Ba and Mn were not significantly correlated with most of the studied heavy metals (Table 2). However, the concentrations of Cd, Cr, Cu, Pb and Zn were significantly and positively correlated among each other. In general, Sr was negatively related to other metals (Table 2).

3.2 Correlation between metal concentrations and soil properties

All heavy metals assayed, except Cr and Mn, were significantly correlated to soil pH value (Table 3). Soil pH was positively associated with the contents of Ba and Sr, but was negatively related to the concentrations of Cd, Co, Cu, Ni, Pb and Zn. Soil conductivity showed positive relationships with Co, Cu, Pb and Zn contents. In general, heavy metal concentrations in riparian soils were positively affected by the percentage of fine substrates but were negatively related to soil bulk density (Table 3).

The negative correlations were observed between concentrations of four heavy metals (i.e., Ba, Cd, Cu and Zn) and soil TC (Table 3). Soil TN content had positive correlations with the concentrations of Cr, Pb and Zn, while TP content had positive relationships with the concentrations of Ba, Cd and Zn. No significant correlation was observed between Mn concentration and soil properties.

3.3 Correlation between metal concentrations and topography and land use

There was no significant correlation between heavy metal concentrations in soils and riparian slope and distance to river (Table 3). Riparian elevation was found to be positively related to Ba, Cd, Cr and Ni concentrations, but negatively correlated with the Sr content in soils. With increasing distance from the river mouth, the concentration of Ba, Cd, Cr and Ni increased gradually (Table 3). Upland land uses had a significant effect on the concentrations of Co, Cu and Zn in riparian soils (Fig. 2). The Zn content in residential riparian soils was significantly higher than that in agricultural and forested riparian soils.

3.4 Predicting metal concentrations using soil properties, topography and land use

GLM analysis demonstrated that soil properties, topography and land use together accounted for 11–69% of the variance in concentrations of heavy metals (except for Mn) in riparian soils (Table 4). Soil pH was the main indicator of Ba, Cd, Co, Cu and Ni concentrations, while distance from the river mouth was a good predictor of Ba, Cd and Cr contents. Moreover, soil density, percentage of fine substrate, TP content, elevation and upland land use could explain the spatial pattern of two or three metals (Table 4).

RDA showed that soil properties, topography and land use could explain 48% of the variance in overall metal levels (Table 5). Soil pH, bulk density, TP, elevation and distance from the river mouth alone could explain 5–9% of such variance. The eigenvalues of the four ordination axes were 0.348, 0.104, 0.013 and 0.008, respectively. The first axis with a correlation of 0.76 between metal concentrations and environmental factors contributed 34.8% of total variance. The second axis with a correlation of 0.57 between metal concentrations and environmental factors contributed 10.4% of total variance (Fig. 3).

4. Discussion

It has been frequently reported that heavy metal behavior (e.g., bioavailability, toxicity, mobility and transport) in soils is largely determined and constrained by a number of soil physicochemical properties such as pH, texture and organic matter (Taylor, 1996; Wang and Qin, 2006; Du Laing et al., 2007; Bartoli et al., 2012). Consistent with previous studies, the present study found that the heavy metal concentrations in riparian soils of the Han River were mainly influenced by soil pH, density and TC (Table 4 and 5). Soil pH value is generally acknowledged to be the principal factor governing the concentrations of heavy metals (Navas and Machín 2002). One may expect that a drop in soil pH value can cause the desorption of heavy metals from the soils or sediments, which will result in positive relationships between soil metal contents and pH values in riparian soils (Du Laing et al., 2009). However, these relationships were found to be negative in the present study (Table 3). This may be mainly attributed to the fact that soil pH value of the studied riparian zones fluctuates in a relatively narrow range (7.24 to 8.56).

It is well established that soil organic matter is positively correlated with available heavy metal contents and represents an important heavy metal sink (Ferraz et al., 2000; Bartoli et al., 2012; Yuan et al., 2015). Soil organic matter, a complex and heterogeneous component initially ascribing to the physical, chemical and biological evolution of biopolymeric materials, is further decomposed to fulvic and humic acids, kerogen and black carbonaceous materials via various degrees of diagenetic processes (Zhang et al., 2014). Soil organic matter in riparian zones is frequently quantified as TC or TOC (e.g., Bartoli et al., 2012). We found that soil TC had a positive effect on the heavy metal contents in riparian soils (Table 3). In the present study, we have not separately measured the TOC and total inorganic carbon (TIC) in riparian soils. Some studies have indicated that TIC has no significant correlation with heavy metal contents (e.g., Villares et al., 2003). The main mineralogical forms of TIC are carbonates which are commonly in neutral and basic environments and are more leachable than organic matter. It should be noted that the TC content of riparian soils in the Han River is relatively low, with an average of 0.68%. Soil organic matter originates from various sources such as plant residues, animal detritus, microbial biomass and other organic amendments applied to soils (Zhang et al., 2014). Therefore, wetland vegetation rehabilitation or organic matter amendments (e.g., the addition of biochar) can improve the soil properties and may increase the metal adsorption capacity of riparian soils (de Abreu et al., 2012).

Only a few studies have examined the relationships between soil density and heavy metal concentrations in soils (Onweremadu, 2008). Our data clearly showed that heavy metal concentrations in riparian soils were negatively affected by the soil bulk density (Table 3). This may be partly because the increase of soil bulk density is

typically associated with organic matter content reduction in riparian zones (Onweremadu, 2008; Xiong et al., 2015). Previous studies have reported that mineral silt and clay particles play a key role in the transport and storage of heavy metal in riparian soils (e.g., Zhang et al., 2014). In contrast, percentage of coarse substrate (e.g., sand and gravel) was generally found to be negatively correlated with the metal concentrations in soils (Bartoli et al., 2012). In the present study, the negative relationship between soil density and heavy metal contents may reflect the fact that the substrates in riparian soils of the Han River are dominated by sand and gravel, not silt and clay. In contrast to coarse substrates, silt and clay generally contain higher concentrations of heavy metals because of their larger surface area and higher cation exchange capability (Bartoli et al., 2012).

A large number of studies have addressed the impact of land use on heavy metal concentrations in soils (e.g., Venne et al., 2006; Bai et al., 2010; Alcalá-Jauregui et al., 2014). Riparian soils are mainly formed by the periodical deposition of suspended sediments from river water during flood events (Du Laing et al., 2009). However, metal accumulation in the riparian soils is not only controlled by upstream processes but also by the adjacent or upland land uses (Alcalá-Jauregui et al., 2014; Van Laer and Smolders, 2013). In the present study, upland land uses had a significant effect on the concentrations of Co, Cu and Zn in riparian soils (Fig. 2). Adjacent land-use was assumed to integrate many indirect ecological factors (Le Coeur et al., 1997). Riparian zones adjacent to agricultural fields can be influenced by mechanical operations, misplaced fertilizer or pesticide drift. Moreover, they are more often subject to trimming or direct herbicide spraying (Yu et al., 2014). Riparian zones adjacent to residential areas are strongly and frequently disturbed. Intensive

distribution of industrial and commercial regions can cause the discharge of pollutants such as household garbage and wastewater. Through atmospheric and water circulation, these pollutants may deposit in soils and ultimately lead to changes of chemical elements in riparian zones.

Topography is an important soil-forming factor (Xiong et al., 2015). Differences in the topography of riparian zones often result in important differences in hydrological and pedological processes (Du Laing et al., 2009). However, the effect of topography on the distribution and storage of heavy metals in soils has been little described in the literature (Chen and Torres, 2012; Rezapour et al., 2014; Yu et al., 2014). Our results indicated that topographic variables, including elevation and distance from the river mouth, were the main factors affecting the heavy metal concentrations in riparian soils in the Han River, China (Table 3 and 5). These findings are not consistent with Du Laing et al. (2007), who reported that heavy metal contamination did not reveal a clear trend as a function of the distance to the river mouth. In the present study, elevated metal pollution in upstream sites may be due to the long history of base and precious metal mining in high-elevation mountainous areas (Li and Zhang, 2010). Throughout the Upper Han River, China, mining and processing of metals have resulted in point-source release of contaminating metals into the local drainage network.

It has been reported that fine particle-related metals, such as Cd, Cr, Cu, Zn and Ni, will accumulate more at lower elevations (Chen and Torres, 2012). In general, low-elevation areas experience longer inundation times during flooding events than high-elevation areas. Hence, the longer deposition time likely stimulates the deposition of fine suspended particles. However, the present study reported a

positive relationship between elevation and concentration of several metals (Table 3).
The riparian zones sampled along the Han River have an elevation range from 42 to 553 m above sea level. The association of heavy metal concentrations with elevation is complicated by the fact that there were also significant relationships between soil physicochemical properties and elevation in riparian zones (data not shown). In other words, we infer that the indirect effect of elevation on metal abundance in riparian soils is primarily mediated through local soil properties.

5. Conclusions

The results of the present study indicate that heavy metal concentrations in riparian soils are regulated by several soil properties (e.g., pH, density and organic matter) and are also significantly influenced by both local topography and upland land uses. Therefore, land use and topography should be considered in addition to soil properties in modeling or predicting the heavy metal distribution in riparian zones. The results from the present study imply that vegetation restoration or soil organic matter amendments can improve the soil properties and increase the metal adsorption capacity of riparian soils.

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513 **Table 1** Summary statistics of heavy metal concentrations in riparian soils (mg kg⁻¹ dw)
514 collected from the Han River, China.

	Minimum	Maximum	Average	SD	Background value ^a	Over-limit ratio (%)	River sediment ^b
Ba	275	1352	685	254	212	100	nd
Cd	0.12	1.25	0.54	0.25	0.08	100	0.47
Co	10.4	46.6	15.4	6.52	13.8	46.3	15.5
Cr	38.6	377	84.6	45.8	66.8	80.6	81.4
Cu	18.6	128	37.7	20.9	25.5	82.1	24.3
Mn	472	1861	799	231	685	71.6	873
Ni	19	111	39	16.6	33.8	61.2	30.8
Pb	9.7	455	25.4	53.6	21.9	22.4	20.7
Sr	65	294	168	52	76.8	98.5	nd
Zn	41.6	155	95.5	24.1	69.6	89.6	75.2

515 nd, No data.
516 ^a Metal background values of soils in China (SEPAC, 1990);
517 ^b The average of heavy metals in Han River sediments (Yan and He, 1996).

518 **Table 2** Spearman correlations among heavy metal concentrations (mg kg⁻¹) in
 519 riparian soils (N= 67).

	Ba	Cd	Co	Cr	Cu	Mn	Ni	Pb	Sr	Zn
Ba	1.00	0.43**	-0.15	-0.01	0.16	-0.17	0.16	0.10	-0.02	0.52**
Cd		1.00	0.20	0.29*	0.42**	0.02	0.33**	0.33**	-0.20	0.63**
Co			1.00	0.63**	0.77**	0.21	0.68**	0.54**	-0.43**	0.40**
Cr				1.00	0.52**	0.24	0.68**	0.38**	-0.16	0.37**
Cu					1.00	0.20	0.76**	0.35**	-0.33**	0.62*
Mn						1.00	0.03	-0.09	0.45**	0.16
Ni							1.00	0.23	-0.46**	0.37**
Pb								1.00	-0.42**	0.53**
Sr									1.00	-0.15
Zn										1.00

520 *Significant at the 0.05 level; ** Significant at the 0.01 level.

521 **Table 3** Spearman correlations between heavy metal concentrations (mg kg⁻¹) and soil properties and topography in riparian soils.

	Ba	Cd	Co	Cr	Cu	Mn	Ni	Pb	Sr	Zn
Soil properties										
pH	0.28*	-0.24**	-0.34**	-0.23	-0.44**	0.03	-0.32**	-0.38**	0.31*	-0.28*
Conductivity (μS cm ⁻¹)	0.07	0.19	0.31*	0.07	0.50**	0.05	0.21	0.36**	-0.14	0.51**
Fine substrate (%)	0.37**	0.26**	0.10	0.02	0.29*	-0.13	0.35**	0.06	-0.38**	0.34**
Bulk density (g cm ⁻³)	-0.01	-0.40**	-0.24*	-0.04	-0.22	0.11	-0.14	-0.35**	0.29*	-0.31*
TC (g kg ⁻¹)	0.38**	0.43**	0.10	0.02	0.36**	-0.05	0.16	0.18	-0.03	0.68**
TN (g kg ⁻¹)	0.10	0.18	0.24	0.24*	0.16	-0.14	0.24	0.44**	-0.21	0.31*
TP (g kg ⁻¹)	0.47**	0.32**	-0.15	-0.18	0.17	-0.04	-0.22	0.09	0.16	0.51**
Topographic conditions										
Slope (degree)	-0.16	-0.04	0.21	0.13	0.01	-0.15	-0.06	0.13	0.09	-0.14
Elevation (m)	0.27*	0.37**	-0.02	0.25*	0.19	-0.24	0.52**	-0.09	-0.25*	0.12
Distance to river (m)	0.15	0.06	0.03	0.02	0.10	-0.03	0.15	0.01	-0.17	-0.04
Distance from the river mouth (km)	0.39**	0.42**	-0.06	0.26*	0.15	-0.20	0.50**	-0.06	-0.22	-0.20

522 *Significant at the 0.05 level; ** Significant at the 0.01 level.

Table 4 Effects of soil properties, topography and land use on the heavy metal contents in riparian soils analyzed using the generalized linear model.

Response variables	Independent variables	Estimate	Standard Error	t	P value
Ba (Null deviance = 5281.7; Residual deviance = 2564.6; $D^2 = 0.51$)					
	Intercept	-1.48	1.54	-0.95	0.35
	pH	0.81	0.18	4.39	<0.01
	TC	0.13	0.05	2.70	0.01
	TP	0.02	0.01	2.02	0.05
	Elevation	-0.003	0.001	-2.95	<0.01
	Distance from river mouth	0.002	0.001	3.66	<0.01
Cd (Null deviance = 6.82; Residual deviance = 3.13; $D^2 = 0.54$)					
	Intercept	-5.19	2.00	-2.60	0.01
	pH	0.56	0.25	2.26	0.03
	Fine substrate	0.01	0.003	2.79	<0.01
	Bulk density	-1.33	0.23	-5.85	<0.01
	TP	0.04	0.01	3.94	<0.01
	Distance from river mouth	0.002	0.001	2.29	0.03
Co (Null deviance = 139.11; Residual deviance = 94.01; $D^2 = 0.32$)					
	Intercept	9.29	1.64	5.67	<0.01
	pH	-0.77	-0.21	-3.71	<0.01
	Land use	-0.15	-0.06	-2.67	<0.01
Cr (Null deviance = 1052.03; Residual deviance = 938.97; $D^2 = 0.11$)					
	Intercept	5.44	0.45	11.98	<0.01
	Elevation	0.004	0.002	2.12	0.04
	Distance from river mouth	-0.002	0.001	-2.24	0.03
Cu (Null deviance = 402.46; Residual deviance = 231.13; $D^2 = 0.43$)					
	Intercept	12.07	1.80	6.72	<0.01
	pH	-1.02	0.22	-4.66	<0.01
	Land use	-0.16	0.06	-2.47	0.02
Ni (Null deviance = 282.66; Residual deviance = 195.61; $D^2 = 0.31$)					
	Intercept	9.96	1.46	6.81	<0.01
	pH	-0.78	0.18	-4.25	<0.01
Pb (Null deviance = 2016.79; Residual deviance = 631.79; $D^2 = 0.69$)					
	Intercept	5.01	3.81	1.31	0.19
	Conductivity	0.004	0.001	8.79	<0.01
	Bulk density	-1.04	0.42	-2.49	0.02
Sr (Null deviance = 944.00; Residual deviance = 678.64; $D^2 = 0.28$)					
	Intercept	3.19	1.36	2.35	0.02
	Fine substrate	-0.01	0.002	-2.75	<0.01
	Bulk density	0.46	0.16	2.72	<0.01
Zn (Null deviance = 371.46; Residual deviance = 149.19; $D^2 = 0.60$)					
	Intercept	4.45	1.07	4.14	<0.01
	Fine substrate	0.006	0.002	3.59	<0.01
	Bulk density	-0.29	0.12	-2.59	0.01
	TN	0.04	0.01	2.68	<0.01

D^2 = proportion of deviance explained by the model, which corresponds to the coefficient of determination R^2 . In this table, only significant explanatory variables are included in the final models. Mn is not listed because it cannot be explained by measured environmental factors.

528 **Table 5** RDA results showing the percentage variance of overall metal level in riparian
 529 soils explained by single and all explanatory variables.

Explanatory variables	% variance explained	<i>p</i> value	F ratio
Soil properties			
pH	8	0.004	6.03
Conductivity	1	0.722	0.38
Fine substrate	2	0.118	2.41
Bulk density	9	0.002	7.17
TC	3	0.064	3.04
TN	0	0.652	0.55
TP	5	0.014	5.03
Topography			
Slope	1	0.224	1.40
Elevation	6	0.002	5.80
Distance to river	2	0.214	1.57
Distance from the river mouth	8	0.008	5.76
Upland land use	3	0.092	2.35
All factors	48		

530 **Figure captions**

531 **Fig. 1** Locations of the 26 studied riparian sites along the Han River in central China.

532 **Fig. 2** Concentrations of heavy metals in soils collected from 67 riparian plots with
533 different upland land uses. Different letters indicate significant differences at $p < 0.05$.

534 **Fig. 3** RDA biplot of environmental factors and heavy metal concentrations in riparian
535 soils.

Fig. 1

Fig. 2

Fig. 3