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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.

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

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

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

Several studies have reported that upland or adjacent land use characteristics can influence the soil physical-chemical properties in riparian zones (Jha et al., 2010; Xiong et al., 2015). Riparian areas may reduce the impact of upland land uses by filtering and retaining soils, nutrients and dangerous chemicals (e.g., heavy metals) in the surface soils. Until now, few studies have evaluated the effects of surrounding land use on metal concentrations in riparian soils or river sediments (see Venne et al., 2006; Smith and Owens, 2014). Venne et al. (2006) found that surrounding land use types had no significant effect on metal accumulation in playa sediments in the 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 km^2 and a total length of 1577 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 km^2 and 63,800 km^2, 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,