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Geo-detection of factors controlling spatial patterns of heavy metals in urban topsoil using multi-source data

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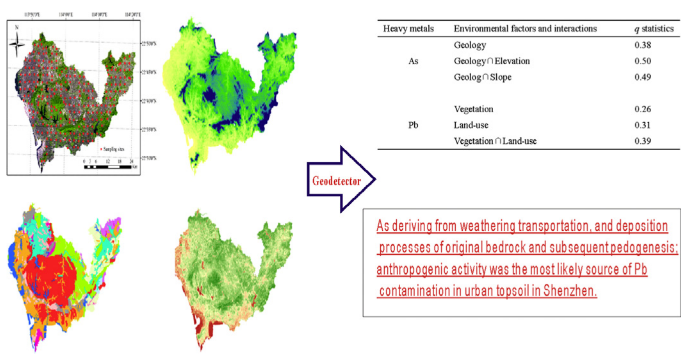
HIGHLIGHTS

- Heavy metals in topsoil are tracers of environmental contamination in urban area.
- Controlling factors of heavy metals reflect its pollution sources.
- Remote sensing provides convenient data to extract environmental factors.
- Geodetector explores factors controlling the spatial patterns of heavy metals.

GRAPHICAL ABSTRACT



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ABSTRACT

Heavy metal contamination has become a serious and widespread problem in urban environment. Understanding its controlling factors is vital for the identification, prevention, and remediation of pollution sources. This study aimed to identify the factors controlling heavy metal accumulation in urban topsoil using the geodetector method and multiple data sources. Environmental factors including geology, relief (elevation, slope, and aspect), and organism (land-use and vegetation) were extracted from a geological thematic map, digital elevation model, and time-series of Landsat images, respectively. Then, the power of determinant (q) was calculated using geodetector to measure the affinity between the environmental factors and arsenic (As) and lead (Pb). Geology was the dominant factor for As distribution in the this study area; it explained 38% of the spatial variation in As, and nonlinear enhancements were observed for the interactions between geology and elevation ($q = 0.50$) and slope ($q = 0.49$). Land-use and vegetation bi-enhanced each other and explained 39% of the spatial variation in Pb. These results indicated that geology and relief were the factors controlling the spatial distribution of As, and organism factors, especially anthropogenic activities, were the factors controlling the spatial distribution of Pb in the study area. As was derived from weathering transportation, and deposition processes of original bedrock and

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subsequent pedogenesis, and anthropogenic activity was the most likely source of Pb contamination in urban topsoil in Shenzhen. Moreover, geodetector provided evidence to explore the factors controlling spatial patterns of heavy metals in soils.

1. Introduction

Urban regions are one of the most important places for human society and economic activities. According to the projections of the United Nations Population Division, the number of urban inhabitants in the developing world is likely to increase to 3.90 billion by 2030 and to 5.26 billion by 2050 (Montgomery, 2008). The growing population will introduce extreme pressures on urban ecological environments because some intensive human activities which involve industrial wastes, vehicle emissions, and household garbage generate a large number of contaminants, including heavy metals, polycyclic aromatic hydrocarbons, and polychlorinated biphenyls (Luo et al., 2012; Tang et al., 2005). These contaminants are mainly concentrated in urban topsoil (0–20 cm), especially heavy metals (Wang, 2009). For example, mineral and energy consumption by industries and transportation is accompanied by the release of heavy metals in fossils; these heavy metals enter the atmosphere through engine exhaust and factory emissions and fall to the ground under the influence of gravity or rainfall, and finally accumulate in urban topsoil. Therefore, heavy metals in topsoil have been shown to be useful tracers of environmental contamination in urban area (Manta et al., 2002).

Urban soil, a type of anthrosol, is frequently characterized by strong spatiotemporal heterogeneity because it mixes various inputs of exogenous materials from human activities with original soil materials (Morel and Heinrich, 2008). Soil surveys and research have been focused on agricultural and forest regions in order to adapt to the increasing demands for food and fiber of the growing global population, and urban soil has been neglected (Lu et al., 2012). Since the 1990s, the important and complex influences of urban soil on the ecological environment have been gradually recognized, and strong interests in urban and suburban soils have appeared. In 1998, the working group of Soils in Urban, Industrial, Traffic and Mining Areas was launched at the 16th World Congress of Soil Science in Montpellier, France. It aimed to advance the study of functions, status and restoration of urban soil, as well as its role in the evolution of urban ecosystems (Dickinson et al., 2013). Recently, given its threats to urban ecosystems, heavy metal contamination in urban soil has received increasing attention from soil and environment scientists.

Heavy metals threaten the heath of humans and urban ecosystems through wind, water, or plant trajectories. For instance, heavy metals can be carried by dust under the impact of wind, and can further enter and pose risks to humans through inhalation (Wang, 2009). Furthermore, heavy metals in polluted soils tend to be more mobile than those in unpolluted soils, therefore, heavy metals in urban soil may cause surface- and ground-water contamination (Wilcke et al., 1998). Approximately 65% of all Chinese cities exhibit high or extremely high levels of heavy metal contamination (Wei and Yang, 2010). Thus, there is an urgent need to understand their spatial patterns and controlling factors, which are vital for the identification, prevention, and remediation of pollution sources.

The CLORPT model is widely employed to explore the spatial patterns and controlling factors of soil properties. It regards soil as the product of the joint action of multiple environmental factors, including climate (cl), organisms (o), relief (r), parent material (p), and time (t) (Jenny, 1941), namely $S = f(cl, o, r, p, t)$. Climate factors include rainfall, temperature, and solar radiation; organisms include vegetation cover and types, land-use, and anthropological activities; relief refers to topography, such as slope, aspect, elevation, and slop angle; parent material, like rock type, is the original supply of soil mineral elements; and time is often a theoretical or hypothetical span for soil development. Natural and anthropogenic factors all play important roles in the formation of topsoil; therefore, the spatial patterns of soil heavy metals in urban topsoil are affected by not only parent material and soil forming processes, but also anthropogenic activities (Zhang, 2006). Many studies have confirmed that heavy metal contamination in soil is closely linked with multiple environmental factors, such as parent material, relief, and organisms (Bou Kheir et al., 2014; Liu et al., 2016; Qiu et al., 2015; Wilford et al., 2016).

Historical surveying data are usually adopted to extract environmental factors for the spatial analysis of soil heavy metals. For example, Bagheri et al. (2015) derived relief factors, including slope, aspect, and elevation, from a digital elevation model (DEM) at 10 m spatial resolution. Bou Kheir et al. (2014) and Wilford et al. (2016) employed geological maps to extract parent material factors to further explore their spatial association with soil heavy metals. Moreover, remotely sensed data, such as MODIS (Moderate Resolution Imaging Spectroradiometer), SPOT (satellite for observation of Earth), and IKONOS satellite images, are frequently applied to obtain vegetation indexes, land-use, and other organism factors (Huo et al., 2010; Wilford et al., 2016). ASTER (Advanced Space-borne Thermal Emission and Reflectance Radiometer), with an adopted optical stereo-technique, offers DEM data with a spatial resolution of 30 m. Based on ASTER data, Wilford et al. (2016) obtained multiple relief factors using digital terrain analysis techniques. Compared with historical surveying data, remotely sensed data are easier to access, cheaper, and timelier.

Remotely sensed images are often used to generate vegetation indexes and land-use information (Huo et al., 2010; Wilford et al., 2016); however, the time-varying traits of these environmental factors are not considered. Moreover, land-use and vegetation indexes change over time, especially in rapidly changing urban environments. Using images from a specific time may not reflect the effects of temporal variation in these factors on the accumulation of soil heavy metals. The Landsat series provides image records of the Earth's surface for more than four decades, and these images are suitable for extracting long term vegetation indexes and land-use information.

Principal component analysis (PCA) and cluster analysis (CA) are applied to assist in the identification of environmental factors controlling heavy metal accumulation (Chen et al., 1997; Guo et al., 2012; Lee et al., 2006; Li et al., 2004; Ordonez et al., 2003; Sun et al., 2013). PCA and CA classify heavy metals into different categories, and the most likely pollutant sources, such as parent materials or anthropogenic activities, are concluded by experience for each category. Another method to analyze controlling factors is based on the statistical relationship between environmental factors and heavy metals (Lin et al., 2002; Navas and Machin, 2002). However, the relationships among the spatial patterns of heavy metals and environmental factors are not taken into consideration in PCA, CA, or correlation analysis.

A geographical detector method, namely geodetector, may be a better choice for exploring the factors controlling heavy metal accumulation in urban topsoil. Geodetector is based on the spatial stratified heterogeneity of geographical phenomena; its key underlying assumption is that if a geographical factor A is controlled by another geographical factor B, then B will exhibit a spatial distribution similar to that of A (Luo et al., 2015; Wang et al., 2010; Wang et al., 2016). Geodetector has been applied to analyze the factors controlling the spatial patterns of various geographical phenomena. For instance, Luo et al. (2015) employed geodetector to identify the dominant factors of dissection