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The spatial characteristics and pollution levels of metals in urban street dust of Beijing, China

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ABSTRACT

The components and concentrations of metals in street dust are indictors of environmental pollution. To explore the pollution levels of Cd, Cr, Cu, Mn, Ni and Pb in street dust and their spatial distribution characteristics, 220 dust samples were collected in a grid pattern from urban street surfaces in Beijing. Multivariate statistics and spatial analyses were adopted to investigate the associations between metals and to identify their pollution patterns. In comparison with the soil background values, elevated metal concentrations were found, except those for Mn and Ni. The results of the geo-accumulation index (I_{geo}) and the potential ecological risk index (Er^i) of the metals revealed the following orders: Cd > Cu > Cr > Pb > Ni > Mn and Cd > Cu > Pb > Cr > Ni. Levels of I_{geo} ranging from 0 to 5 were found and about 80% of the samples were below the moderately polluted level. The Er^i values of single elements were within the low ecological risk level in most sampling sites. Most of the metals in the street dust of Beijing were statistically significantly correlated. It is hard to clearly identify the sources of each metal in the street dust since local environments are very complex. Cadmium, Cu, Cr, Mn and Pb showed medium spatial autocorrelations within the sampling region. Similar spatial distribution patterns were observed for Cu, Cr and Pb, and these metals had relatively high spatial variabilities and were enriched in the center of the city with several peaks scattered in the suburbs. Metal pollution anomalies were identified by using cluster and outlier analyses. Locations identified as clusters with high values indicated non-point source pollution, while locations identified as outliers with high values indicated point source pollution. Traffic, construction, and other human activities influenced these high values. In addition, the locations identified as outliers with low values in urban areas might benefit from less transportation and better management.

1. Introduction

Cities are concentrated centers of production, consumption, and waste disposal. At present, nearly half of the world's population lives in urban agglomerations (Grimm et al., 2008), and this dense concentration leads to an increasing amount of pollutants being discharged into the urban environment. Street dust is one of the most common pollutants in cities and consists of particles deposited on roads that act as a "reservoir" for accumulating short-term environmental materials from the surrounding areas. The particles include materials worn off the pavement, vehicular-related deposition particles (vehicle exhaust particles, lubricating oil residues, tire wear particles, brake lining wear particles), particles from atmospheric deposition, plant matter, and materials produced by erosion of the adjacent soil (Li et al., 2001; Charlesworth et al., 2003; Lough et al., 2005; Hjortenkrans et al., 2006). The components and quantities of street dust are environmental pollution indicators (de Miguel et al., 1999). Contaminated street dust is an important issue that can potentially affect an urban environment. Dust particles can migrate via saltation, creep (diameters >100 μm), suspension (diameters <100 μm), or can become incorporated in the urban aerosol (<10 μm) (de Miguel et al., 1999). Street dust resuspension has proven to be one of the most important sources for airborne particulate trace metals in urban areas (Pereira et al., 2007). These polluted particles are easily deposited with a greater scope in dry and wet deposition after being spread broadly (Garnaud et al., 1999). The contaminants associated with street dust may harm the urban environment and endanger the ecosystem's health (Birch and McCready, 2009; Schafer et al., 2009). Trace metals adhering to or absorbed by dust particles can enter the human body though inhalation, ingestion, or directly through the skin (Ferreira-Baptista and de Miguel, 2005; Shi et al., 2011). They are toxic and non-biodegradable and can be easily accumulated in fatty tissues or deposited in the circulatory system, thus interfering with the normal functions of the internal organs or acting as auxiliary factors of other diseases (Ibanez et al., 2010).

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Indeed, concerns are growing over the pollution status and potential harm from street dust. The concentration of metals in street dust has proven to be extremely variable (Wei and Yang, 2010). The spatial distribution of metals in this dust is controlled both by the urban terrain and the emission source distribution (Meza-Figueroa et al., 2007). Pollutant load is usually reduced along the urban to suburban gradient (Krcmova et al., 2009). Higher metal concentrations are usually related to industrial activities, traffic and higher population density (Ahmed and Ishiga, 2006), and places where traffic is more likely to undergo stop–start maneuvers (such as at traffic lights) may result in higher metal concentrations in street dust (Charlesworth et al., 2003; Ewen et al., 2009).

The existing research on metals in street dust has mainly focused on the levels and source identification. Environmental and human health risk methods have been applied to explore the potential harm from the metals in the street dust (Faiz et al., 2009; Lu et al., 2009; Ghorbel et al., 2010). Contaminant levels between different functional areas or cities worldwide have also been compared (Banerjee, 2003; Herngren et al., 2006; Al-Khashman, 2007). Multivariate statistics and environmental magnetism methods have usually been taken to identify their sources. GIS mapping has been applied to describe the spatial distribution trends of metal concentrations in street dust (Charlesworth et al., 2003; Lopez et al., 2008; Shi et al., 2008; Li and Feng, 2012). However, quantitative spatial research, such as exploring the spatial autocorrelation intensity of metals in the street dust, identifying their ranges and distinguishing pollution hotspots statistically, is lacking, especially in metropolitan districts in developing countries. Therefore, spatial pattern identification is necessary. Street dust properties vary spatially at different scales and metal concentrations in street dust can be used to reveal the intensity and range of pollution.

As the capital of China, Beijing has experienced rapid urbanization over the past few decades in terms of its population, expansion patterns, and economic conditions, and unprecedented environmental changes have accompanied this development. With the aim of offering basic information for environmental monitoring and risk management, an extensive street dust survey was conducted in the urban areas of Beijing. The existence of Cd, Cr, Cu, Mn, Ni and Pb in the street dust was investigated.

The objectives of this study were to (1) investigate the degrees of concentration of Cd, Cr, Cu, Mn, Ni and Pb in the street dust of Beijing, (2) evaluate the degree of contamination compared to pre-industrial levels and assess the potential ecological risk of these metal pollutants, (3) determine the spatial distribution characteristics of the metals on a regional scale and discuss the factors that control their autocorrelation ranges and strength; and (4) find the clusters and outliers of metals on a local scale. Multivariate statistical methods and spatial analyses were used to achieve these goals. Geographic Information System (GIS) mapping was applied to evaluate the results by visualizing the spatial patterns.

2. Methods and materials

2.1. Study region

Beijing (115°24′–117°30′E, 39°28′–41°05′N), is located in the NE of the North China Plain. The city spreads over 16,410 km^2, and its altitude is approximately 20–60 m above sea level. Beijing has a sub-humid, warm, and temperate continental monsoon climate (hot and rainy summers and cold and dry winters). The mean temperature of Beijing is approximately 14.0 °C, and the average annual precipitation is approximately 500 mm. The main soil type in the investigated area is brown soil with a pH from 8 to 9. The population of Beijing has grown rapidly in the past 10 years and reached 17.6 million in 2009. As in a typical metropolis, industrial activities in Beijing have declined greatly and migrated to more sparsely populated areas. Transportation demands have increased rapidly as urban expansion and the development of a traffic network simultaneously occurred throughout the city. By the end of 2009, there were 23,200 vehicles for public transport and more than one million private cars registered in Beijing, and both of these numbers are still increasing.

2.2. Sampling sites and sampling methods

The sampling was carried out in September 2009. A total of 220 dust samples were obtained from the street surface within the boundary of the Sixth Ring Road in Beijing during the dry weather period (Fig. 1). Taking the spatial configuration of Beijing roads into consideration (grid-shaped main road system, six ring loops, and seven radiating highways in all directions), the following principles were followed. Within the Fifth Ring Road where the road network density is high, 1.5 km × 1.5 km grids were applied. Between the Fifth and Sixth rings, where the network is sparse and irregular, 6 km × 6 km grids were used. In addition, preset points were added from eight directions along an urban to suburb gradient. The road intersections located near the grids were chosen for sampling. Cleaners and generators were used to collect the street dust. At each intersection, a mixture of multi-point samples was collected within 10 m^2 to be representative of the site. More than 300 g of street dust was collected from each site. Dust was not obtained from areas adjacent to site-specific pollution sources, e.g., gasoline stations or construction sites. Road characteristics, land use near the sampling sites, and geographic coordinates of each plot were recorded.

2.3. Sample analysis

All samples were stored in sealed polyethylene bags, labeled, and then transported to the laboratory. Samples were air-dried for at least 1 week and then sieved through a 500 μm mesh nylon sieve. This mesh size ensured that all ranges of dust particles passed through and small stones and refuse were removed. Next, each sample was ground and fully mixed, and metals extracted according to USEPA method 3052 (USEPA, 1996) with a microwave laboratory unit. Concentrations of Cr, Cu, Ni, Pb and Mn were determined using inductively coupled plasma optical emission spectrometry (ICP-OES), and the Cd concentration was measured using inductively coupled plasma mass spectrometry (ICP-MS). Soil sample GSS–2 (geochemical standard reference sample soil in China) was analyzed to determine the accuracy of the procedure. The recovery of the total metals from the reference material was satisfactory and ranged between 90% and 105%. Throughout the experimental process, ultra-pure water was used for preparing the solutions, dilutions and blanks. All the glassware and plastic vessels were treated with 10% v/v HNO_3 for at least 12 h and then washed with distilled and deionized water before use. To avoid potential cross-contamination of the samples, contact with metals was avoided during all procedures.

2.4. Data processing and calculation methods

To quantify the metal contamination in the road dust, the geo-accumulation index (I_{geo}) and potential ecological risk index (Er^i) were used. Pearson correlation analysis and principal component analysis (PCA) were used to evaluate the relationship between metals in the street dust. The spatial distribution characteristics of metals in the street dust were then explored. The semivariogram functions were used to detect the autocorrelation distance of each metal and to provide basic parameters for spatial interpolation