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Spatial distribution of soil magnetic susceptibility and correlation with heavy metal pollution in Kaifeng City, China

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ABSTRACT

The characterization of heavy metal pollution is urgently needed in modern environmental studies. However, traditional geochemical methods for detecting soil heavy metals are rather time-consuming and expensive. In recent years, non-destructive and rapid magnetic techniques seem promising in monitoring soil pollution but it is questionable how this relates to heavy metal concentrations. Therefore, in order to understand the correlation of heavy metal pollution with environmental magnetism, magnetic susceptibility (χ_{LF}) and the concentrations of As, Cd, Cr, Cu, Ni, Pb and Zn were measured in the topsoil (0–15 cm) collected from Kaifeng City, China. In this study, the spatial distribution of heavy metals and χ_{LF}, as well as the correlation between pollution load index (*PLI*) and χ_{LF} were carried out. Results show that the contamination factor (*CF*) values of different heavy metals follow the order: Cd (10.48) > Zn (2.28) > Pb (1.68) > Cu (1.51) > Ni (0.81) > Cr (0.80) > As (0.65). The average pollution load index (*PLI*) of the metals is 2.53, representing a moderate pollution level as a whole of the city soil. In general, similar spatial distribution patterns of heavy metals and χ_{LF} were found in this research, which decrease progressively from the southeast/east to the northwest/west in the study area. High concentrations of heavy metals and high levels of χ_{LF} appears around the southeast, the north of the older city (within the ancient city wall), and along the Longxi–Haizhou Railway. Moreover, contents of As, Cd, Cr, Cu, Ni, Pb and Zn in soils and *PLI* are significantly positively correlated with their χ_{LF}. The results further attest that the measurement of χ_{LF} is a simple, rapid and quantitative method for the assessment of heavy metal contamination of soils. When $\chi_{LF} \leq 71 \times 10^{-8}$ m^3 kg^{-1}, the soil is considered to be non-polluted; $71 \times 10^{-8} < \chi_{LF} \leq 162 \times 10^{-8}$ m^3 kg^{-1} represents slightly polluted soils; $162 \times 10^{-8} < \chi_{LF} \leq 253 \times 10^{-8}$ m^3 kg^{-1} moderate pollution, and $\chi_{LF} \geq 253 \times 10^{-8}$ m^3 kg^{-1} corresponds to heavily polluted soils. However, the standard is exclusively valid for the study area and cannot be simply "transferred" to other polluted areas.

1. Introduction

Various environmental problems such as soil, air and water pollution are typical of many urban regions that followed rapid urbanization, with implications on urban ecosystems and human health. Pollutants generated by industrial production, fossil fuel combustion, and vehicle emissions are usually enriched in magnetic particles, and eventually enter urban soils through several ways, such as dry or wet precipitation and anthropogenic dumping. Moreover, these pollutants not only lead to the occurrence of heavy metal contamination of urban soils, but are also accompanied by a significant soil magnetic enhancement (Wang and Qin, 2005; Hu et al., 2007; Lu et al., 2008; Lu and Bai, 2008; Blundell et al., 2009; Wang, 2013a; Wang et al., 2013).

Numerous studies suggest that there is a strong correlation between heavy metal contents and magnetic parameters in soils (Spiteri et al., 2005; Lu and Bai, 2006; Lu et al., 2007; Yang et al., 2007; Jordanova et al., 2008; Morton-Bermea et al., 2009; Canbay et al., 2010; Karimi et al., 2011; El Baghdadi et al., 2012; Yang et al., 2012; Wang, 2013b), which provides the basis of the quantitative evaluation of heavy metal pollution levels using magnetic parameters. The environmental magnetism technology is increasingly applied as proxy methods for pollution screening and soil monitoring for its simple, sensitive, inexpensive and nondestructive characteristics (Schmidt et al., 2005; Wang and Qin, 2005; Lu and Bai, 2008; D'Emilio et al., 2010; Duan et al., 2010; Karimi et al., 2011).

Many studies on magnetic characteristics in urban soils have been conducted mainly in several industrially developed cities including Beijing (Zheng and Zhang, 2008), Shanghai (Hu et al., 2007), Nanjing (Duan et al., 2010), Hangzhou (Lu and Bai, 2006, 2008; Lu et al., 2008), Wuhan (Yang et al., 2007, 2012), Lanzhou (Xia et al., 2011;

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Wang et al., 2013), Xuzhou (Wang and Qin, 2005; Wang, 2013a, 2013b), Mexico (Morton-Bermea et al., 2009) and Isfahan (Karimi et al., 2011), but less in medium and small sized cities. Kaifeng is a medium-sized city in China, and a tourism developed city with a relatively weak industry. Some studies on heavy metal pollution of soils have been reported (Ma et al., 2011; Hou et al., 2011), however, little information is available regarding the magnetic characteristics and their relationship with heavy metals of soils in Kaifeng. In this paper, we studied the spatial distribution of magnetic susceptibility (χ_{LF}) in urban soils of Kaifeng City with the Kriging interpolation method and the correlation between pollution load indexes (*PLI*) of heavy metals (As, Cd, Cr, Cu, Ni, Pb and Zn) in urban soils and their magnetic susceptibilities (χ_{LF}). A new pollution level standard of soil heavy metal pollution using measurements of χ_{LF} was set up. The purpose of this study is to clarify the heavy metals and χ_{LF} spatial differentiation of urban soils and its relationship with human activities, to examine the relationship between soil magnetic susceptibility and heavy-metal contamination of Kaifeng City, and to develop a fast, quantitative and effective method for heavy metal pollution assessment of urban soils.

2. Materials and methods

2.1. Study area

Kaifeng City is one of the ancient capital cities of China in the middle east of Henan Province on the Huanghuai Plain, with geographic coordinates of 34°11′N–35°01′N and 113°52′E–115°15′E. Kaifeng City covers an urban area of 546 km^2 with a population of 898,900. The climate type of the city is the temperate continental monsoon climate with a mean annual temperature of 14 °C and mean annual precipitation of 636 mm. The urban soil of Kaifeng is formed on the parent material of the alluvial deposits of the Yellow River and superposed human activities. Kaifeng was the capital city of Henan Province with a relatively developed industry in the 1950s and 1960s. In 2014, the urban area of Kaifeng increased threefold through the adjustment of administrative divisions.

2.2. Sampling

Ninety nine topsoil (0–15 cm) samples were collected from the city (Fig. 1). Sampling sites were selected on green spaces and each of them was georeferenced with portable GPS. At each sampling site, the top 15-cm layer of the soil profile was collected with a stainless steel trowel and stored in a plastic bag. Each soil sample was a composite of 5 subsamples collected from the same sampling site. Foreign substances such as pieces of brick and tile, iron scraps, wood scraps, plastics and lime grains in soil samples were removed, and then the samples were air-dried, ground, and sieved through a 2-mm nylon sieve for the magnetic measurement. A subsample (5 g) of each well mixed soil sample was further ground to pass a 0.15-mm nylon sieve for heavy metal analysis.

2.3. Measurement of magnetic susceptibility and heavy metal contents of soils

Magnetic susceptibility of soils was measured at low (0.47 kHz; χ_{LF}) and high (4.7 kHz; χ_{HF}) frequencies respectively using a Bartington MS2 dual frequency sensor. Each data point was measured three times in order to check reproducibility and to avoid measurement errors. The error of the susceptibility measurements was found to be smaller than 3%, using triplicate measurements. Frequency-dependent susceptibility (χ_{FD}) of soils was then calculated and expressed as a percentage:

$$\chi_{FD}\% = (\chi_{LF} - \chi_{HF})/\chi_{LF} \times 100\%. \quad (1)$$

Soil samples were digested in a graphite digestion instrument with a mixture solution of concentrated HCl–HNO_3–HF–$HClO_4$. Concentrations of Cr, Cu, Ni and Zn in soils were measured using atomic absorption spectrometry (AA-6601F Model, Shimadzu Ltd., Japan), while Cd and

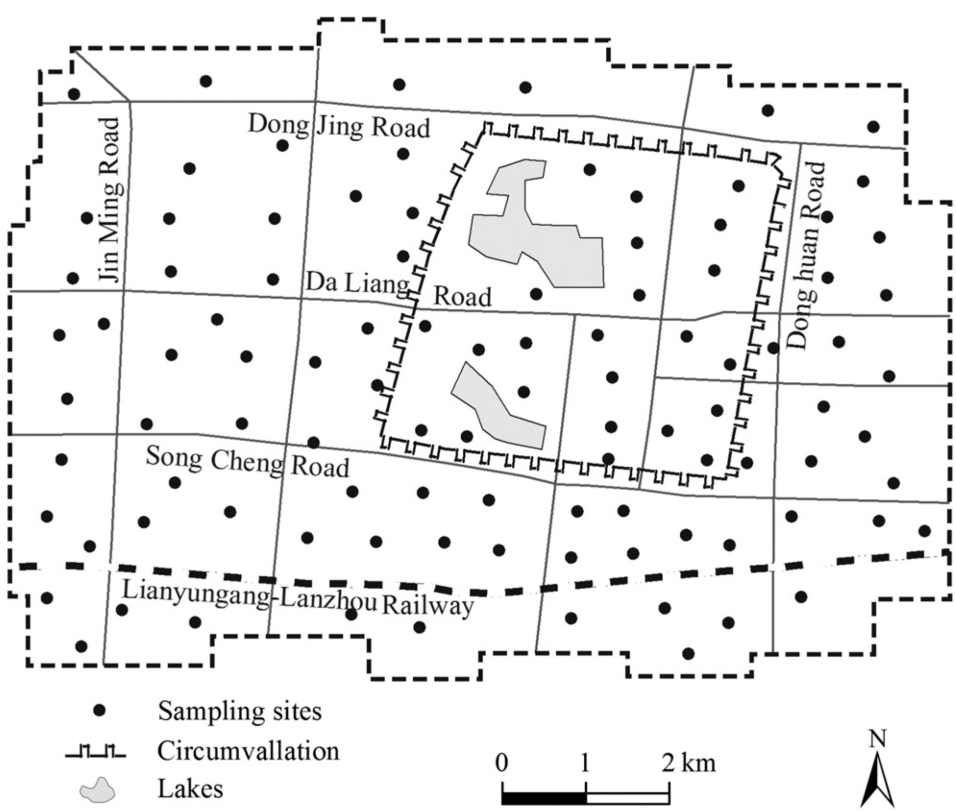

Fig. 1. Distribution of soil sample sites in Kaifeng City.