

# Heavy metals in urban ambient PM<sub>10</sub> and soil background in eight cities around China

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**Abstract** The ambient PM<sub>10</sub> and background soil samples were collected and analyzed with ICP-AES in eight cities around China to investigate the levels of ten heavy metals (Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, and Pb). The mean concentrations of ten heavy metals in PM<sub>10</sub> of the eight cities of China followed the order of Zn>Pb>Mn>Cu>Ni>Cr>Co>V. The metals in the ambient PM<sub>10</sub> and soil were compared in each city to evaluate the heavy metal mass fraction from anthropogenic sources in ambient air. The CD values in these cities were all above 0.2, indicating that the ingredients spectrums of PM<sub>10</sub> and soil vary markedly. Most heavy metals were enriched in PM<sub>10</sub>, except Fe and Ti. The results showed that almost all the cities suffer important heavy metal pollution from anthropogenic sources. The eight cities were also grouped according to their similarity in heavy metals of ambient PM<sub>10</sub> by cluster analysis to investigate the relationship between the heavy metals and the pollution sources of each city. The conclusion was that the eight cities were divided into three clusters which had similar industrial type and economy scale: the first cluster

consisted of Shenzhen, Wuxi, and Guiyang; followed by Jinan and Zhengzhou as the second grouping; and the third group had Taiyuan, Urumqi, and Luoyang.

**Keywords** Heavy metals · PM<sub>10</sub> · Soil · Cluster analysis · China

## Introduction

Heavy metals in ambient air could affect human health and cause many diseases, such as mental hypogenesis of children and cancer (Willers et al. 2005; Faruque and Hiroaki 2006; Liu et al. 2009). Atmospheric particulate matter (PM) is the major carrier of heavy metals in ambient air (Antonio et al. 2002; Sternbeck et al. 2002). Many studies on heavy metals in PM and their sources have been conducted in China and abroad. Research on levels of heavy metals in the atmospheric PM of Nanchang City (Liang et al. 2010) found that the order of heavy metals according levels in ambient air is Zn>Mn>Pb>Cd>Cu>Cr>Ni, and that industrial pollution is the main source of heavy metals in urban PM. The study of Xie et al. (2002) showed that the levels of atmospheric heavy metals were significantly higher in summer in Hengyang City, and hazardous heavy metals were enriched in fine PM (less than 2.0 μm). Furthermore, heavy metals were enriched by different sources, including soil and crustal dust, various industrial processes, vehicle emissions, and coal combustion (Huang et al. 2009). The source and

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origin of heavy elements in PM from regional background, urban and industrial sites of Spain were analyzed and researchers found that at industrial and traffic hot-spots, average heavy metal concentrations were at their highest, exceeding rural background levels by even one order of magnitude in the cases of Cr, Mn, Cu, Zn, As, Sn, W, V, Ni, Cs, and Pb (Querol et al. 2007). Furthermore, the Querol's study negotiated that steel production emissions were linked to high levels of Cr, Mn, Ni, Zn, Mo, Cd, Se, and Sn (and probably Pb). Copper metallurgy areas showed high levels of As, Bi, Ga, and Cu. High levels of Ni and V (in association) were tracers of petrochemical plants and/or fuel–oil combustion.

Urban populations are exposed to metals in suspended particles, and these are often well above natural background levels owing to anthropogenic processes (Antonio et al. 2002). A great deal of research has focused on the metal composition of soil background primarily. Zhou and Xia (2010) defined and modeled the geochemical background of Cu, Zn, Pb, and Cd contents in mineralization-influenced soil from the Hengshi River watershed, Guangdong Province, China. Based on an extensive investigation conducted in the whole area of Beijing, the background concentrations of soil heavy metals were investigated (Chen et al. 2004). The revised background concentrations of the soils in Beijing were proposed to be 7.1 mg/kg for As, 0.1 mg/kg for Cd, 29.8 mg/kg for Cr, 18.7 mg/kg for Cu, 26.8 mg/kg for Ni, 24.6 mg/kg for Pb, and 57.5 mg/kg for Zn, respectively. Background concentration of trace elements were determined for soil in the southern part of the Grand Duchy of Luxembourg (Horckmansa et al. 2005) and a clear distinction was seen between the trace element content of the soil developed on the Minette sandstone and shales. The total content of Ba, Cr, Cu, Ni, Pb, V, and Zn determined by means of X-ray fluorescence was studied in soil of an agro-industrial area near Barcelona (NE Spain) in order to establish their background levels (Tobías et al. 1997). The upper limits of the established background ranges were: Cr, 275 mg/kg; Cu, 145 mg/kg; Ni, 83 mg/kg; Pb, 91 mg/kg; V, 183 mg/kg; and Zn, 326 mg/kg.

In the last 30 years, the economy of China had made a rather high growth and the heavy metal pollution might become more serious according to this growth in cities around China. In this article, we focused on the characteristics of spatial distribution of the heavy metal compositions of urban ambient PM<sub>10</sub> in eight cities around China and its relation to

soil dust as background were also examined in order to research on identifying emission sources of heavy metals in urban ambient air of China. Our results could serve as a fundamental data set for the health risk assessment in the future. What's more, we were trying to relate the heavy metal pollution in ambient air to the city's economy type based on the cluster analysis method.

## Experimental method

### Area description

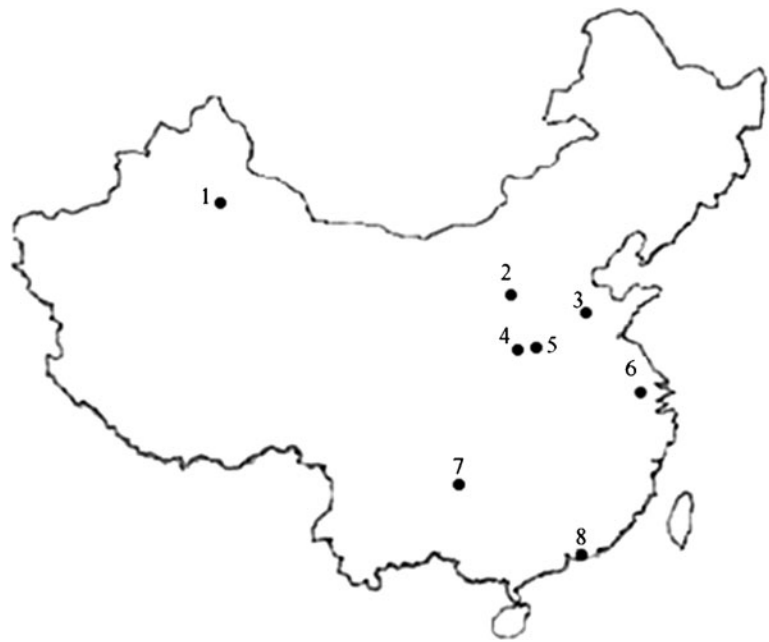
The eight cities examined in this study were: Urumqi (86°37'E, 42°45'N), Taiyuan (111°30'E, 37°27'N), Jinan (117°00'E, 36°40'N), Guiyang (106°27'E, 26°44'N), Luoyang (111°08'E, 33°35'N), Shenzhen (113°46'E, 22°27'N), Wuxi (119°33'E, 31°07'N), and Zhengzhou (112°42'E, 34°16'N). These are located in different regions of China with different climate, economic structure, and soil background. The locations of the cities are provided in Fig. 1.

Several data on these eight Chinese cities were shown in Table 1. Different economic structures are developed in these cities. Taiyuan, Urumqi, and Luoyang have high-developed coal mining and metal smelting industry, so-called mining industry city and are the important heavy industry cities of China. The gross domestic product (GDP) of the three cities were respectively 35.0 (2002), 32.9 (2001), and 51.8 (2006) billion. The major industries of these cities are metallurgy industries. Shenzhen, Wuxi, Guiyang, Jinan, and Zhengzhou mainly developed light industry, such as electronic industry, textile industry, and tourism. There are few coal mining and metal smelting industry in these five cities, so-called non-mining industry city or semi-mining industry city. Machinery and textile industries are the major industries in Jinan, Guiyang, and Zhengzhou, as well as biological and microelectronics industries in Shenzhen and Wuxi. The GDP of these five cities were respectively 495.1 (2004), 161.8 (2005), 41.5 (2005), 66.1 (2000), and 53.0 (2003).

### Sample collection

Ambient and soil samples were collected in the eight cities as follows (Table 2):

**Fig. 1** The locations of the eight cities in China (in the map: 1 Urumqi, 2 Taiyuan, 3 Jinan, 4 Luoyang, 5 Zhengzhou, 6 Wuxi, 7 Guiyang, and 8 Shenzhen)



Ambient PM<sub>10</sub> samples were collected in 3 weeks (a winter week, a spring week, and a summer or fall week) in each city, that represent different seasons (winter, spring, and summer or fall, respectively) at sites that represent different functional areas, such as city

downtown areas, industrial areas, educational or residential areas, and heavy traffic areas. All the sites were established with the criterion of Environmental Monitoring Station of China. The establishment of the functional areas complies with “Principle and technical

**Table 1** City overview

Name	Population, ten thousand	Built-up areas, km <sup>2</sup>	Climate type	GDP, billion	Major industry	Major mineral resources
Urumqi	175.7 (2002)	167.1 (2002)	Temperate continental climate	35.0 (2002)	Petrochemicals, metallurgy industry	Coal
Taiyuan	239.2 (2001)	177 (2001)	Monsoon climate of medium latitudes	32.9 (2001)	Metallurgy, machinery, chemical and coal industry	Coal, iron ore, gyps
Jinan	264.5 (2000)	120 (2000)	Warm and semi-humid continental monsoon climate	66.1 (2000)	Machinery, textile and steel industry	Iron ore, coal, limestone mine, granite and others
Luoyang	151.0 (2006)	144 (2006)	Warm and semi-humid continental monsoon climate	51.8 (2006)	Machinery, petrochemical and metallurgy industry	Molybdenum ore
Zhengzhou	239.8 (2003)	170 (2003)	Monsoon climate of medium latitudes	53.0 (2003)	Textile, metallurgy and building materials industry	Fire clay mineral, bauxite, natural oil stone
Wuxi	228.5 (2005)	181 (2005)	Subtropical monsoon climate	161.8 (2005)	Microelectronics, biological industry	Limestone mine, marble mine and others
Guiyang	206.3 (2005)	495 (2005)	Subtropical moist climate	41.5 (2005)	Metallurgy, machinery, chemical and construction industry	Bauxite
Shenzhen	181.93 (2004)	703 (2004)	Subtropical marine climate	495.1 (2004)	Finance, biological and microelectronics industry	–

**Table 2** The sampling information of the eight cities

	Sampling duration	Number of ambient PM <sub>10</sub> samples	Number of soil samples
Urumqi	Jan 2002–July 2002	105	37
Taiyuan	Apr 2001–Jan 2002	254	35
Jinan	Dec 1999–Sep 2000	224	16
Luoyang	Dec 2005–May 2006	105	10
Zhengzhou	Nov 2002–Apr 2003	270	9
Wuxi	Jan 2005–Sep 2005	153	30
Guiyang	Jul 2005–Nov 2005	180	8
Shenzhen	Jun 2004–Dec 2004	234	8
Total	–	1,525	153

methods for regionalizing ambient air quality function of China”, 1996. Samples were collected for 20 h every day from 8:00 AM to 4:00 AM of the next day during the sampling period using medium-volume PM<sub>10</sub> samplers (Wuhan Tianhong Intelligence Instrumentation Facility, TH-150 Medium Volume Sampler). One sampler was used to collect airborne particles on polypropylene-fiber filters (90-mm diameter, Beijing Synthetic Fiber Research Institute, China) for elemental analysis. Gravimetric values of PM<sub>10</sub> were determined based on quartz filters. Loaded and unloaded filters were conditioned for 48 h in darkened desiccators before gravimetric determination. The filter was air-proofed in a tinfoil pouch after sampling. A total of 1,525 available ambient samples were collected in the eight cities. Further details about sampling of ambient PM<sub>10</sub> had been previously described (Feng et al. 2005; Watson and Chow 1993; Bi et al. 2007).

Soil dust was collected from bare croplands, hilly country, dry riverbeds in the vicinity of the eight cities, or exposed land within urban areas (Han et al. 2009). After collection, the samples of soil dust were air dried, and a 150-mesh nylon, the YFJ classifier, was used to separate out the source samples of which sizes were less than 10  $\mu\text{m}$  (Feng et al. 2005). A total of 153 available soil dust samples were collected in the eight cities.

### Analysis

The determination of levels of heavy metals (Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, and Pb) was carried out by inductively coupled plasma atomic emission

spectroscopy (ICP-AES, ICP-9000N+M, Jarrell-Ash Corporation, USA). Each polypropylene filter was cut into pieces and placed at 25-ml polyfluortetraethylene beaker with 7 ml HNO<sub>3</sub> and 3 ml HClO<sub>4</sub>. After covering, the solution was heated on a galvanothermy board at 100°C for about 24 h. The measurement was increased to 260°C until smoke appeared. When the solution was only 3 ml left, the galvanothermy board was shut off. After cooling, we filtered it into a 15-ml test tube and diluted to 15 ml with deionized water. The analysis process of soil sample was the same with 0.1 g (Xu 2011).

Blanks (including filters) and duplicate sample analyses were performed for approximately 10 % of all the samples, and most of the relative average deviation of the duplicate samples was less than 5 %. Certified reference materials (CRM) were used to ensure accuracy and precision (National research center of CRM, China).

### Data treatment

*Concentration diagrams* The concentration diagram is a log–log plot of the concentration or mass fraction of the chemical components at one site against those at another (Zhang and Friedlander 2000). The log–log diagram is used because of the large concentration ranges for the various heavy metal components. The diagonal line of unit slope represents the hypothetical case in which the mass fractions of the heavy metal components for the ambient PM<sub>10</sub> ( $x$ -axis) and soil dust are equal. The diagonal divides the diagram into regions of comparative enhancement (above the line) or depletion (below the line) for individual heavy metal components.

*Hierarchical clustering methods* Collections of chemical measurements made at different sampling sites can be grouped according to their similarity by a mathematical procedure known as cluster analysis (Johnson and Wichern 1992; Hopke et al. 1976). For this purpose, a measure of closeness or similarity is needed. Similarity measures for aerosols have been evaluated by Wongphatarakul (Wongphatarakul 1997). The wide variation in chemical component concentrations in the aerosol databases requires some type of normalization procedure. It is convenient to introduce the coefficient of divergence (CD) used earlier in biological applications (Clark 1952; Rhodes et al. 1969), and defined as follows (Wongphatarakul et al. 1998; Zhang and Friedlander 2000):

$$CD_{jk} = \sqrt{\frac{1}{p} \sum_{i=1}^p \left( \frac{x_{ij} - x_{ik}}{x_{ij} + x_{ik}} \right)^2} \quad (1)$$

where  $x_{ij}$  represents the average mass fraction for a heavy metal component  $i$  of  $PM_{10}$  or soil dust,  $j$  and  $k$  represent  $PM_{10}$  and soil dust, respectively, and  $p$  is the number of heavy metal components. The CD value is shown on the concentration diagrams. The most similar sampling sites are grouped first. Clusters are merged using one of the three commonly applied linkage methods: single linkage (minimum distance), complete linkage (maximum distance), and average linkage (average distance) (Anderberg 1973). In this study, the average linkage was calculated. Average linkage clustering uses the average similarity of observations between two groups as the measure between the two groups. As the similarities between clusters decrease, all subgroups are fused into a single cluster. Finally, a dendrogram (tree diagram) is drawn to show the groupings and the linkage distances, which are proportional to the degree of dissimilarity between the clusters.

## Results and discussion

### Heavy metals in urban ambient $PM_{10}$

The levels of  $PM_{10}$  and heavy metal contents (mean± standard and deviation (SD)) determined in this study were presented in Table 3. As shown in Table 3,  $PM_{10}$  average concentrations in the eight cities were all higher

than the Scottish Environment Protection Agency (SEPA) secondary annual standards ( $100 \mu\text{g}/\text{m}^3$ , China, SEPA 1996), as well as for Europe ( $40 \mu\text{g}/\text{m}^3$   $PM_{10}$ , annual limit value, Directive 2008/50/EC).

The heavy elements (in micrograms per cubic meter) obtained from the different cities around China were presented with the aim to establish the average levels of each heavy element in  $PM_{10}$ . The mean concentrations of ten heavy metals in the eight cities of China followed the order of  $Zn > Pb > Mn > Cu > Ni > Cr > Co > V$ , which was consistent with the conclusion found by Huang et al. (2009). The highest level was observed for Zn, with a mean concentration in the range of  $0.21\text{--}1.29 \mu\text{g}/\text{m}^3$ , followed by Pb in the range of  $0.03\text{--}0.85 \mu\text{g}/\text{m}^3$ . The lowest level was measured for V with a range of  $0.0017\text{--}0.0344 \mu\text{g}/\text{m}^3$ . In the cities of China except the eight, such as Beijing ( $0.78 \mu\text{g}/\text{m}^3$ , Sun et al. 2004) and Wuhan ( $0.68 \mu\text{g}/\text{m}^3$ , Zhu et al. 2009), Zn was also found to be the highest. Meanwhile, the mean concentrations of heavy metals in eight cities were all higher than those reported in Tokyo (Iijima 2001), Seoul (Kim et al. 2005), and Costa Rica (Murillo and Marín 2010)

In Taiyuan, the concentration of heavy metals was highest than other cities, while in Jinan was lowest. Meanwhile, the orders of mean concentrations of the heavy metals were different from cities. For example, the heavy metals in ambient particles of Urumqi were in the order of Cu, Zn, Pb, Mn, Ni, Cr, Co, and V, while in Jinan was Cr, Zn, Mn, Pb, Cu, V, and Ni. The mean Cr concentrations in eight cities were all above the annual limit set by the World Health Organization ( $0.0025 \mu\text{g}/\text{m}^3$ , WHO 2000). Mean Pb concentrations were all below the Environmental Protection Agency (EPA) ambient air quality standards ( $1.50 \mu\text{g}/\text{m}^3$ ) (EPA 1997).

### Relationship between heavy metals in urban ambient $PM_{10}$ and soil dust

Background soil represents the original levels of chemical elements in the soil that less affected by human activities. The CDs can conveniently determine the similarity of component spectrum between the background soil and  $PM_{10}$ , furthermore, we can explain the reason that lead to the difference. If the element components in  $PM_{10}$  and soil are exactly similar, the CD is almost 0. Otherwise, if the components vary considerably, the CD will go to 1 (Hu and

**Table 3** Heavy metals in urban ambient PM<sub>10</sub> (micrograms per cubic meter)

City		Total	V	Cr	Mn	Co	Ni	Cu	Zn	Pb
Urumqi	C	302.61	0.0300	0.0400	0.2600	0.0400	0.0500	1.0100	0.5500	0.3400
	SD	116.69	0.0100	0.0200	0.0700	0.0200	0.0200	0.3700	0.1400	0.2100
Taiyuan	C	260.01	0.0344	0.1843	0.6422	0.0444	0.0673	0.5276	1.2939	0.7894
	SD	114.78	0.0113	0.2289	0.2888	0.0129	0.0788	0.7130	0.9533	0.4969
Jinan	C	156.69	0.0245	0.2938	0.1288	–	0.0066	0.0286	0.2124	0.0289
	SD	72.19	0.0268	0.1846	0.1241	–	0.0046	0.0167	0.2114	0.0116
Guiyang	C	103.71	0.0024	0.0783	0.4738	0.0157	0.0131	0.0274	0.3370	0.1024
	SD	49.31	0.0016	0.0899	0.7161	0.0354	0.0203	0.0343	0.2781	0.7061
Luoyang	C	283.37	0.0100	0.1100	0.2300	0.0200	0.8400	0.1500	0.8800	0.1100
	SD	130.13	0.0001	0.0800	0.2000	0.0100	2.4200	0.2400	0.8900	0.0600
Shenzhen	C	114.48	0.0158	0.0843	0.0632	0.0068	0.0301	0.0527	0.4938	0.0615
	SD	41.72	0.0091	0.1214	0.0361	0.0045	0.0235	0.0310	0.3676	0.0511
Wuxi	C	112.33	0.0017	0.0501	0.1052	0.0039	0.0161	0.0366	0.6923	0.0632
	SD	29.42	0.0002	0.0187	0.0223	0.0023	0.0223	0.0070	0.0957	0.0190
Zhengzhou	C	184.12	0.0200	0.0300	0.2600	0.0300	0.0400	0.2600	0.9100	0.8500
	SD	67.58	0.0001	0.0001	0.0300	0.0001	0.0001	0.0600	0.2000	0.2100
Beijing <sup>a</sup> , China	C	–	0.0130	0.0400	0.1160	0.0050	0.075	0.0800	0.5050	0.4090
Wuhan <sup>b</sup> , China	C	–	0.0070	0.0110	0.1100	0.0010	0.0040	0.0400	0.6760	0.2400
Tokyo <sup>c</sup> , Japan	C	–	0.0060	0.0060	0.0700	0.0010	0.0050	0.0270	0.2330	0.0640
Seoul <sup>d</sup> , Korea	C	–	0.0030	0.0736	0.0376	0.0025	0.0463	0.0282	0.4280	0.2000
Costa Rica <sup>e</sup> , America		42.00	0.0080	0.0034	0.0410	–	0.0029	0.1030	–	0.0078
SEPA		100 (Annual)								1.0 (Annual)
EPA		150 (24 h)								1.5 (Quarterly)
WHO		50 (24 h)		0.0025 (Annual)						0.5 (Annual)

<sup>a</sup>Sun et al. 2004<sup>b</sup>Zhu et al. 2009<sup>c</sup>Iijima 2001<sup>d</sup>Kim et al. 2005<sup>e</sup>Murillo and Marín 2010

Wei 2002). However, there are no explicit dividing standards for the similarity of the two ingredients spectrum. Ji (2006) compared the chemical composition of some cities, and found that if the CD is below 0.2, the result of source apportionment for the two karaburan spectrum is the same. Therefore, in this paper, we defined the demarcation point was 0.2.

Concentration diagrams comparing heavy metal components in PM<sub>10</sub> and soil dust in eight cities were shown in Fig. 2. Almost all the heavy metals were enriched in PM<sub>10</sub>, except Fe and Ti, which were mainly concentrated at soil. This showed that the heavy metals were mainly introduced into atmospheric environment by various anthropogenic activities in these cities. Main

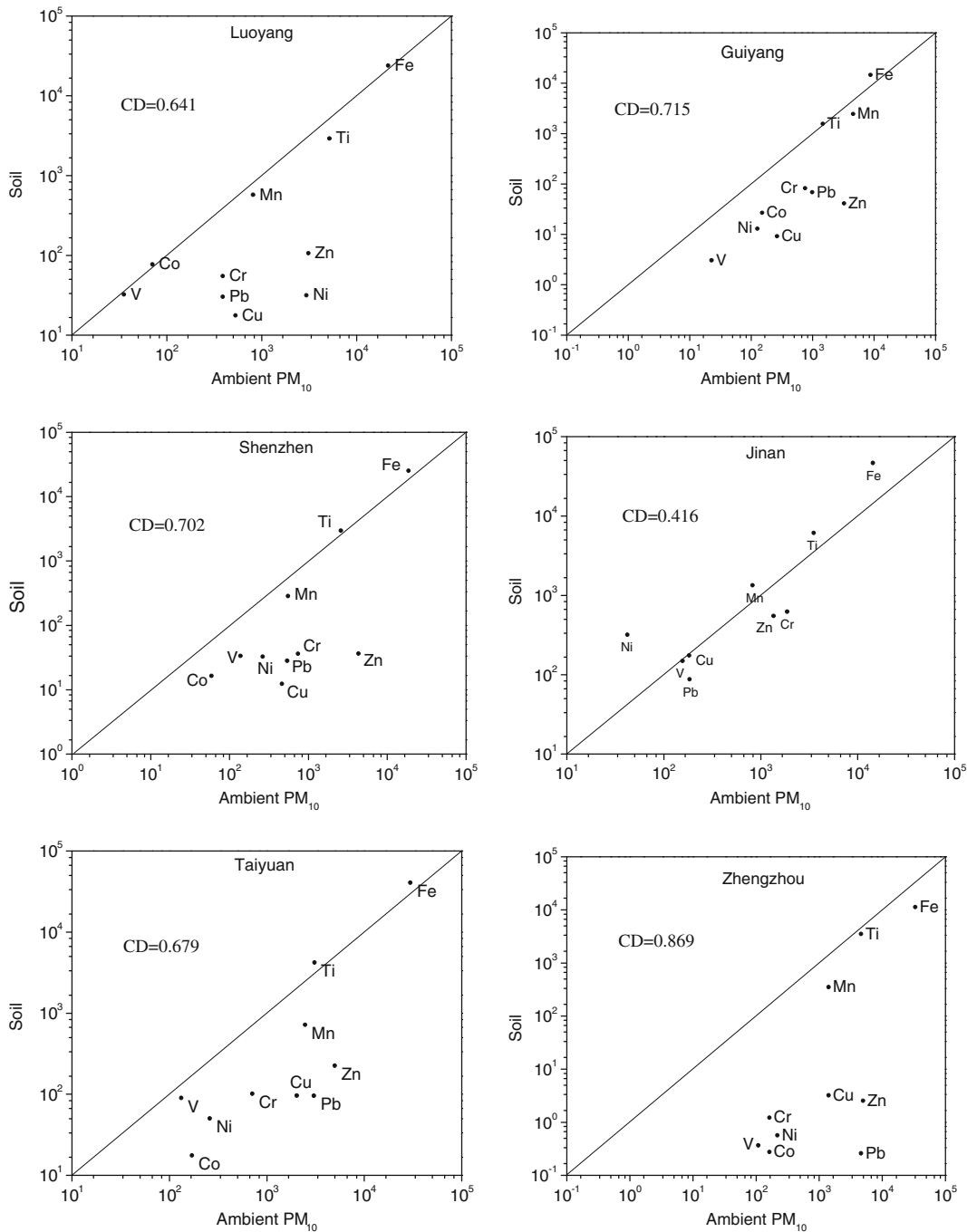
anthropogenic sources of heavy metals exist in various industrial point sources, e.g., present and former mining activities, foundries, smelters, and diffuse sources such as piping, constituents of products, combustion by-products, traffic, industrial, and human activities (Al-Khashman 2004). The CD values in these cities were all above 0.2, indicating that the ingredients spectrums of PM<sub>10</sub> and soil vary markedly. The result was in good agreement with the conclusions of previous studies of the eight cities (Tursun et al. 2010; Showan 2005; Wang et al. 2011)

However, the heavy metals concentrated at PM<sub>10</sub> were different from cities. For example, in Urumqi, the highest values were observed for Cu and Zn. In Jinan

and Luoyang, the highest levels were Cr and Zn, as well as Zn and Ni, respectively. Zn and Pb were the highest levels in both Taiyuan and Zhengzhou. In the other cities, such as Guiyang, Zhengzhou, and Wuxi, the concentration of Zn was much higher than other

metals. The studies of Showan (2005) and Wang et al. (2011) had proved the results.

Element enrichment may be concerned with industrial type of the city. Ni is used to produce stainless steel, high nickel alloy steel, and alloy steel which was



**Fig. 2** Concentrations of chemical composition in PM<sub>10</sub> and soil dust

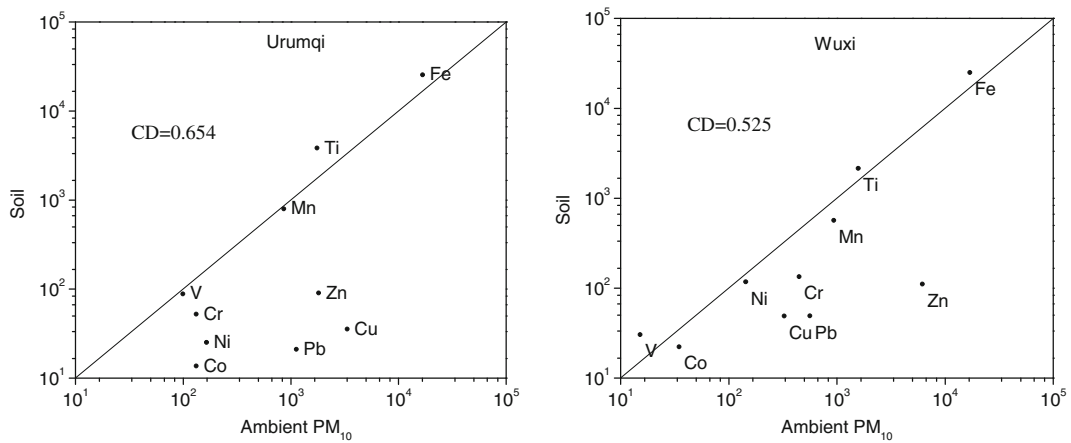


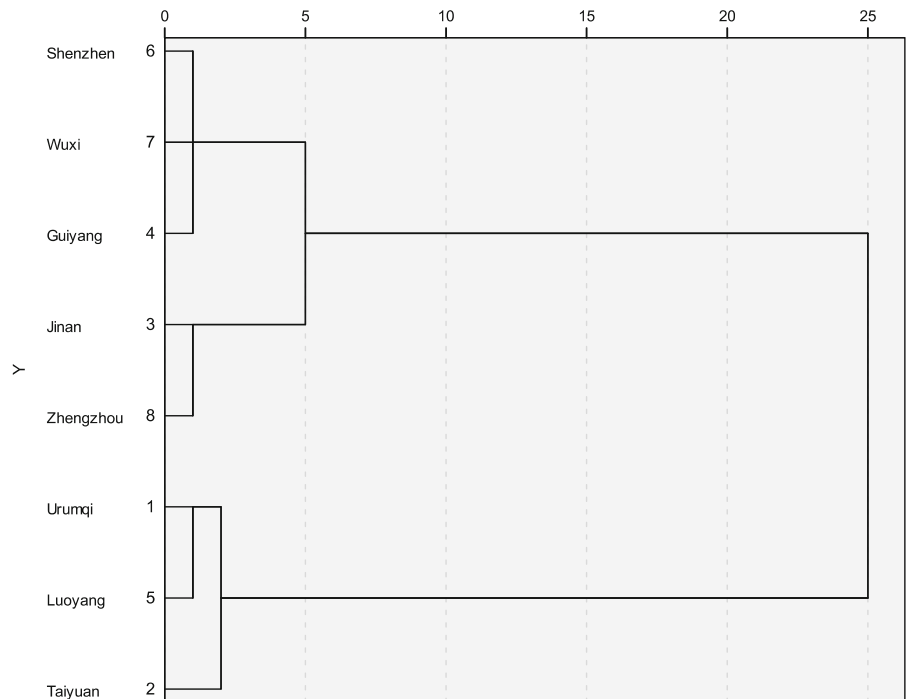
Fig. 2 (continued)

widely used in kinds of manufacturing. That may be the reason that Ni is abundant in Luoyang, where there are many machinery and metallurgy industries. Zn is mainly used in steel, metallurgy, machinery, electrical, chemical, medicine, and light industry. In Wuxi and Shenzhen, the pillar industry is high-tech industry, such as microelectronics industry, biomedical industry, and so on. In Guiyang, machinery industry and chemical industry are the major industry. As a result, Zn was most enriched in PM<sub>10</sub> in the three cities.

Cluster analysis

Cluster analysis was performed on the concentrations of heavy metal elements in ambient PM<sub>10</sub> to classify the eight cities into different groups. The result was illustrated in the dendrogram (Fig. 3). The distance cluster represents the degree of association between cities. The lower the value on the distance cluster, the more similar is the association. We divided these cities into three clusters.

Fig. 3 Cluster analysis





The first cluster consisted of Shenzhen, Wuxi, and Guiyang. The PM<sub>10</sub> and heavy metal pollution in this group was the lowest. Shenzhen and Wuxi are economically developed areas of China and the GDP are relatively high, thus there is more concern about environment. Meanwhile, the main industrial types in Shenzhen and Wuxi are high and new technology industries, such as precision machinery and automobile accessories industry, finance industry, tourism, and so on. As a result, the heavy metal pollution in Shenzhen and Wuxi is less severe. Guiyang belongs to the energy-deficient area and GDP is almost at the lowest in the eight cities. There is less coal mining and metal smelting industry than other cities, except aluminum industry. According the results, Shenzhen, Wuxi, and Guiyang are all non-mining industry cities.

Jinan and Zhengzhou were the second grouping. They both have light industry and some metal smelting industry (not so much like mining industry cities), so-called semi-mining industry city. The PM<sub>10</sub> and heavy metal pollution are heavier than the first grouping.

The third grouping had Taiyuan, Urumqi, and Luoyang. These cities are all the important heavy industry cities of China and have quite a few coal mining and metal smelting industries. In addition, the structures of light industry and heavy industry are imbalance in the three cities (Huang 2009; Lu and Hu 2007; Zhang 2009). Cr, Ni, Cu, Zn, and Pb are mainly enriched in this cluster. The heavy metal pollution of this grouping is the most serious.

In summary, the heavy metal component profile of each city was grouped into three clusters and the cities in the same cluster have similar industrial type and economy scale. So, the heavy metal pollution was suggested to have great relation with the industrial type and its economy scale of each city in China.

## Conclusions

PM<sub>10</sub> average concentrations of eight industrial or urban areas were all higher than the SEPA secondary annual standards, as well as for Europe (40 µg/m<sup>3</sup> PM<sub>10</sub>, annual limit value). The mean concentrations of ten heavy metals in China were in the following order: Zn>Pb>Mn>Cu>Ni>Cr>Co>V. However, the orders of mean concentrations of these heavy metals were different for each city. Maximum mass

concentration of chemical elements was found in Taiyuan, while the minimum mass concentration existed in Jinan.

Almost all the heavy metals were enriched in PM<sub>10</sub>, except Fe and Ti, which were concentrated in the soil. This showed that the heavy metals were mainly introduced into aquatic environments by various anthropogenic activities in these cities. The CD values between the heavy metal components of PM<sub>10</sub> and soil in these cities were all above 0.2, indicating that the ingredients spectrums of PM<sub>10</sub> and soil vary markedly. Anthropogenic activities were suggested to be the primary sources of the ambient heavy metal pollution in these Chinese cities.

Cluster analysis of the heavy metal components was performed to divide these eight cities into three clusters, which had similar industrial type and economy scale: the first cluster consisted of Shenzhen, Wuxi, and Guiyang; followed by Jinan and Zhengzhou as the second grouping; and the third group had Taiyuan, Urumqi, and Luoyang. The heavy metal pollution was suggested to have great relations with the level of economic development and industrial type of each city.

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