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Spatial distribution, environmental risk and source of heavy metals in street dust from an industrial city in semi-arid area of China

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Abstract: Environmental risks associated with Co, Cr, Cu, Mn, Ni, Pb, V and Zn in street dust collected from Baotou, a medium-sized industrial city in a semi-arid area of northwest China, were assessed by using enrichment factor and the potential ecological index. Their spatial distributions and sources in the dust were analyzed on the basis of geostatistical methods and multivariate statistical analysis, respectively. The results indicate that street dust in Baotou has elevated heavy metal concentrations, especially of Co, Cr, Cu, Pb and Zn. Co in the dust was significantly enriched. Cr and Pb were from moderate to significant enrichment. Cu and Zn were from minimal to moderate enrichment, whereas Mn, Ni and V in the dust were from deficient to minimal enrichment. The ecological risk levels of Co and Pb in the dust were moderate to considerable and low to moderate, respectively, whereas those of other heavy metals studied in the dust presented low ecological risk. Different distribution patterns were found among the analyzed heavy metals. Three main sources of these heavy metals were identified. Cr, Mn, Ni and V originated from nature and industrial activities. Cu, Pb and Zn derived mainly from traffic sources, and Co was mainly from construction sources.

Introduction

Environmental deterioration and contamination have become serious in urban areas due to rapid, continuous and unorganized industrialization and urbanization (Kumar 2013, Holnicki et al. 2017). Among urban environmental issues and types of contamination, atmospheric pollution is one of the major environmental issues. Particulate matter, originating from natural sources and anthropogenic emissions, is the primary atmospheric pollutant in addition to sulfur dioxide (SO_2) and nitrogen oxides (NO_x) (Lu et al. 2010, Holnicki et al. 2017). Atmospheric particulates can be deposited on the Earth's surface, forming dust. Dust can be re-suspended into the atmosphere by wind, affecting the atmospheric environment quality and human health (Khairy et al. 2011). As one type of urban environmental medium, dust is an important bond linking atmosphere, soil and water. It is a sink and source of contaminants in urban environments. Urban dust often contains high levels of toxic heavy metals and organic contaminants (Langer et al. 2010, Lu et al. 2010, Chłopek et al. 2016) owing to various anthropogenic sources such as industrial emissions, traffic emissions, coal and fuel combustion, waste disposal, municipal activities, construction, and residential heating (Thorpe and Harrison 2008, Lu et al. 2014). Due to their toxicity, persistence, bioaccumulation, and biomagnifications, heavy metals in dust pose a potential threat to ecological systems and human health (Shi et al. 2011). Heavy metals concentrated in dust can be easily transferred into the human body by inhalation, ingestion and dermal contact absorption (Glorennec et al. 2012). They accumulate in the tissues and internal organs of the human body (Zheng et al. 2010), affecting the central nervous system and acting as cofactors, initiators, or promoters of other diseases (Faiz et al. 2009). Therefore, research on heavy metal contamination in dust is essential to understanding the possible change of urban environmental quality caused by intensive anthropogenic activities.

Concentrations, distributions, source identification, contamination levels and risk assessment of heavy metals in street dust have been investigated internationally in recent decades (Charlesworth et al. 2003, Ahmed and Ishiga 2006, Faiz et al. 2009, Lu et al. 2010, Atiemo et al. 2011). Although most of the existing studies were carried out in developed countries or the megacities of developing countries (Banerjee 2003, Han et al. 2006, Shi et al. 2011, Nazzal et al. 2013, Tang et al. 2013), limited information is available on heavy metal contamination of street dust in rapidly industrializing and urbanizing medium and small cities (Lu et al. 2014). Differences among cities, including population density and industrial activities, could have a large impact on the findings of individual studies (Lu et al. 2014). The environmental issues are even more serious in the medium and small industrial cities, compared with megacities, due to the neglect of environmental protection or the lack of pollution treatment technology (Lu et al. 2014).

Source identification of heavy metals is a very complex problem. GIS spatial analysis may have strong applicability in the discrimination of local pollution. The element tracing technique is used to identify the source of a certain element. Multivariate statistical methods (correlation analysis, principal component analysis and cluster analysis) reflect the overall pollution of the whole study area, and the discrimination ability of the local pollution is limited. Therefore, the use of comprehensive methods for source identification of heavy metals is necessary. In this paper, we have combined multivariate statistical analysis with GIS spatial analysis, the change of time series and the characteristics of the surrounding environment to identify sources of heavy metals in street dust from Baotou city.

Baotou is a medium-sized industrial city in a semi-arid area of northwest China. Like other metropolises of China, Baotou city faces many environmental problems caused by its hostile environment, poor urban planning, and rapid development. Especially, since the implementation of the Chinese Great Western Development policy in the 1990s was carried out, the problems became serious. With large centralized anthropogenic activities, there is a need to evaluate the urban environmental quality. In our previous work, we reported heavy metal concentrations and a contamination assessment for different--sized particles of street dust from Baotou and found that Cr, Cu, Mn, Ni, Pb, V and Zn were mainly accumulated in the < 50 μm particles, whereas Co was primarily accumulated in 300–1000 μm dust particles, and Ba was mostly present in 100–300 μm particles (Han et al. 2016). To the best of our knowledge, the literature on the spatial distribution, the environmental risk and source identification of heavy metals in street dust from Baotou city is still non-existent. The objectives of the present study focus on determining the concentrations of heavy metals in the street dust of Baotou, mapping the spatial distribution of heavy metals through geostatistical analysis and GIS for the purpose of identifying the spatial patterns and possible hot spots of the concentrations of heavy metals, and identifying the potential sources or influencing factors of heavy metals in the dusts using correlation analysis, principal component analysis and cluster analysis. The contamination level and the potential ecological risk of heavy metals in the street dust were also assessed. The results could offer the basic information for regulators and engineering in environmental monitoring, protection and risk management.

Materials and methods

Background of study area

Baotou (109°15'–110°26'E, 40°15'–42°43'N), the largest city in the Inner Mongolia autonomous region and an important industrial base of China, is located in the Tumochuan and Hetao Plains, with the Yellow River to the south and Mongolia to the north (Fig. 1). The climate of Baotou city is a typical semi-arid temperate continental monsoon climate, with an annual average temperature of 6.5°C, an annual average precipitation of 240–400 mm and an annual evaporation capacity of 1940–2340 mm. The local soil type is mainly chestnut soil. The prevailing wind direction is northwest. The total area and urban area of Baotou are 27,768 and 1,051 km^2, respectively, and its resident population was 2,692,900 in 2013. Baotou is the railway and highway transportation hub linking the north and northwest of China. The number of motor vehicles was 458,000 in 2013. Baotou has abundant iron, rare earth, niobium, titanium, manganese, gold, copper and other mineral resources. It is an important industrial base and rare earth industrial center of China. The main industries are the rare earth industry, iron and steel manufacturing, coal-fired power generation, aluminum smelting, dairy, heavy duty vehicles, metallurgy, and machinery manufacturing. The gross domestic product (GDP) of Baotou was 350,300 million RMB in 2013, with a 9.3 percent growth rate, and the industrial output value accounted for ~52 percent of the GDP. Aluminum, iron and steel, trace earth elements, electric power and equipment manufacturing account for ~50 percent of the industrial output.

Sampling and analytical procedures

A total of 83 street dust sampling sites were selected in the Baotou urban area (Fig. 1). At every sampling site, a dust composite sample of 300–500 g composed of 5–8 sub-dust samples was collected by sweeping using a clean plastic brush and dustpan during the cold and dry season in October 2012. The actual latitude and longitude coordinate of each sampling site was recorded by a global positioning system (GPS). All dust samples were stored in self-sealed polyethylene bags, labeled, and transported to the laboratory. After being air-dried at room temperature for two weeks, all samples were sieved through a 1.0 mm nylon mesh to remove large particles such as tree leaves, refuse and small stones before halving. One half was stored prior to analysis of physiochemical characteristics. Approximately 50 g of each sample was separated by halving, ground with an agate mortar and pestle, and then carefully homogenized and sieved through a 75 μm nylon mesh (Lu et al. 2010). To avoid potential cross-contamination of the samples, all handling procedures were carried out without contact with metals.

To measure metal concentrations, 4.0 g of milled dust samples and 2.0 g of boric acid were weighed out, placed in the mold (JJW-60, Changchun machine factory production) and pressed into a 32 mm diameter pellet under 30 t of pressure (Lu et al. 2010). Then, the concentrations of Co, Cr, Cu, Mn, Ni, Pb, V and Zn in the street dust samples were measured by wavelength dispersive X-ray fluorescence spectrometry (XRF, PANalytical PW-2403 apparatus), with a detection limit of 0.1 mg kg^{-1} for trace metals (Zhang et al. 2015). Standard samples (GSD12, GSS10) and 15% repeat samples were used for quality control in the experiment. The precision, calculated as the relative standard deviation of duplicate samples, was routinely 3–5%. The analyzed accuracy, calculated from the relative error of the standard reference materials, was less than 5%.

Environmental risk assessment of heavy metals in street dust

A number of different calculation methods have been applied to quantify the degree of heavy metal pollution or enrichment of heavy metals in street dust (Shi and Wang 2013). Examples of these methods include the enrichment factor, the potential

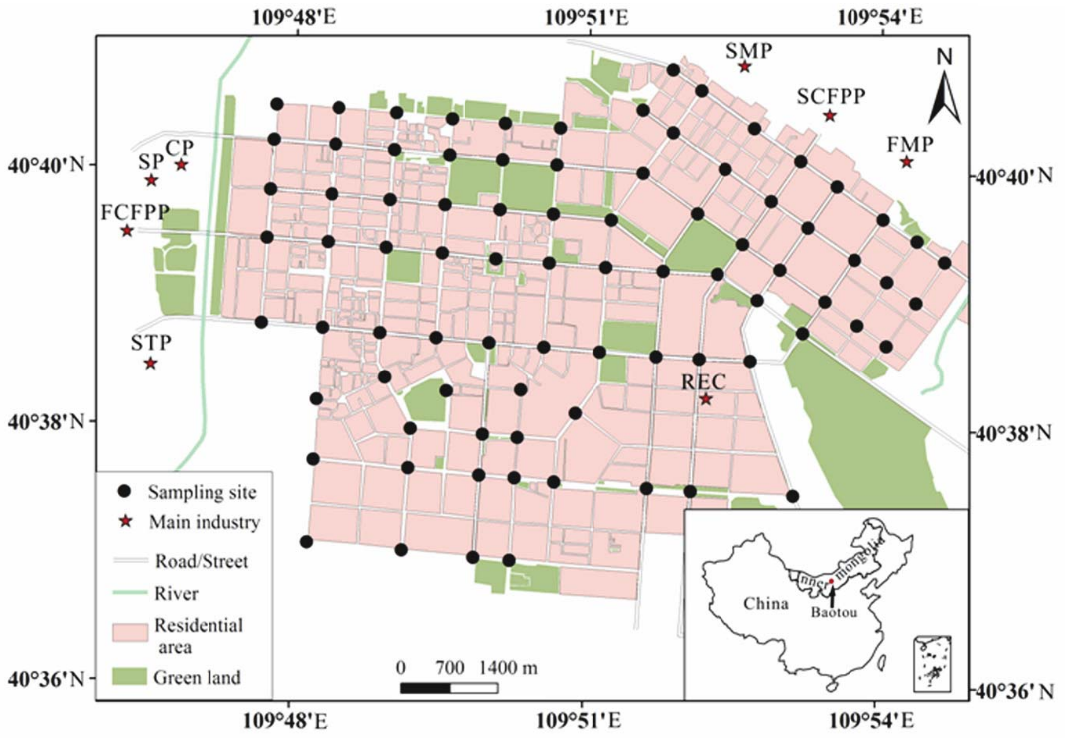

Fig. 1. Study area and sampling sites in Baotou, China. CP: cement plant; SP: steel plant; FCFPP: first coal-fired power plant; STP: steel tube plant; SMP: second machinery plant; SCFPP: second coal-fired power plant; FMP: first machinery plant; REC: Rare earth company

ecological risk index, the geo-accumulation index, the Nemerow pollution index, and the pollution index. Each method has its own advantages and disadvantages. The pollution index can provide a quantitative judgment for heavy metals; however, the method does not consider the variation of the background values caused by different contaminations and cannot reflect the ecological risk caused by heavy metals. The geo-accumulation index method can reveal the pollution level of heavy metals, but the method cannot reflect the toxic effects of heavy metals. The potential ecological risk index can partially overcome the shortcomings of the pollution index and the geo-accumulation index methods. The enrichment factor can also differentiate whether the metals originate from anthropogenic activities or from natural processes. Therefore, the enrichment factor can also assess the degree of anthropogenic influence (Han et al. 2006). Due to these characteristics, the enrichment factor and potential ecological risk index were used in the study to assess the accumulation level and degree of potential ecological risk of heavy metals in the dusts. The enrichment factor (*EF*) of an element, an important parameter for evaluating the degree of impact of human activities on its enrichment, was calculated by (Buat-Menard and Chesselet 1979, Han et al. 2006, Turner and Simmonds 2006)

$$EF = (C_i/C_{ref})_{\text{sample}}/(C_i/C_{ref})_{\text{background}} \tag{1}$$

where C_i is the concentration of heavy metal i, and C_{ref} is the concentration of the reference element for normalization. In the *EF* calculation, the elements with low variability of occurrence, such as Al, Fe, Ti, Si, Sr and K, (Han et al. 2006, Turner and Simmonds 2006, Lu et al. 2010), can often be used as reference elements. *EF* analysis can assist in differentiating anthropogenic sources from natural sources. A value of *EF* close to 1 indicates a natural origin, where values >10 are considered to originate mainly from an anthropogenic source (Han et al. 2006; Turner and Simmonds 2006). *EF* can also assist in determining the degree of metal enrichment and contamination. $EF \leq 2$ means deficiency to minimal enrichment, $2 < EF \leq 5$ means moderate enrichment, $5 < EF \leq 20$ indicates significant enrichment, $20 < EF \leq 40$ signifies very high enrichment, and $40 < EF$ means extremely high enrichment (Han et al. 2006).

The potential ecological risk index (*RI*) of heavy metals was defined as (Håkanson 1980)

$$RI = \sum_{i=1}^{n} E_i = \sum_{i=1}^{n} T_i \times C_f^i = \sum_{i=1}^{n} T_i \times \frac{C_s^i}{C_b^i} \tag{2}$$

where *RI* is the potential ecological risk index of heavy metals in the analyzed sample, E_i is the potential ecological risk factor of heavy metal i, and T_i is the toxic-response factor of heavy metal i as calculated by Håkanson (1980) and Xu et al. (2008), i.e., Co (5) = Pb (5) = Cu (5) = Ni (5) > Cr (2) = V(2) > Zn(1) = Mn(1). C_f^i, which is the pollution index of heavy metal i, is equal to the concentration of heavy metal i in the sample (C_s^i) divided by its background value (C_b^i). In this work, C_b^i is the background value of local soil (Wang et al. 2007). The evaluation index classification presented by Hakanson (1980) was based on eight pollutants (Hg, Cd, As, Pb, Cu, Cr, Zn and PCB) in sediments, whereas the pollutants considered in this study are Co, Cr, Cu, Mn, Ni, Pb, V and Zn. Thus, the original evaluation index classification was adjusted according to the number of pollutants and the ratio of the toxicity coefficient of each element. The degree of ecological risk was classified as low ecological risk ($E_i < 15$, $RI < 50$), moderate ecological risk ($15 \leq E_i < 30$, $50 \leq RI < 100$), considerable ecological risk ($30 \leq E_i < 60$, $100 \leq RI < 200$), high ecological risk ($60 \leq E_i < 120$, $RI \geq 200$) and very high ecological risk ($E_i \geq 120$) (Lu et al. 2014; Zhu et al. 2008; Zhao and Li, 2013).

Multivariate statistical analysis

Correlation analysis, principal component analysis and cluster analysis have been widely used in the source identification of heavy metals in sediment (Kartal and Tokalıoğlu 2006, Yalcin et al. 2010), soil (Lee et al. 2006) and dust (Han et al. 2006; Lu et al. 2010; Tang et al. 2013). Correlation analysis can reveal the inter-relationship between pairs of the studied heavy metals. Principal component analysis (PCA) is used to reduce a large number of variable parameters and to extract a small number of principal components (Lu et al. 2010, Nazzal et al. 2013). Cluster analysis (CA) can classify elements of different sources on the basis of the similarities of their chemical properties. These three methods are complementary. Cluster analysis is used to verify the results of principal component analysis, and principal component analysis can quantitatively explain the results of cluster analysis. Correlation analysis can also improve and support the results of cluster analysis or principal component analysis. In this work, Correlation analysis, PCA and CA were conducted using the commercial statistics software package SPSS version 19.0 for Windows (SPSS Inc., USA) to identify the relationships among heavy metals in the street dusts and their possible sources.

Results and discussion

Heavy metal concentrations in street dust

Statistics of heavy metal concentrations in the street dust of Baotou, as well as background values of local soil (Wang et al. 2007), are shown in Table 1. Table 1 reveals that the concentrations of Co, Cr and Pb in all of the dust samples, V, Cu and Zn in 90% of the samples, and Mn in of the 50% samples are higher than their corresponding background values, whereas the concentrations of Ni in most samples (95%) are lower than its background value in local soil. The measurement results indicate that the dusts of Baotou have elevated concentrations of heavy metals, especially Co, Cr, Cu, Pb and Zn, which are 4.0–10.7, 1.8–5.8, 0.9–4.0, 1.5–8.7 and 0.8–2.4 times the background values of local soil (Wang et al. 2007), respectively. The mean concentrations of heavy metals in street dust from Baotou divided by the corresponding background value of local soil decrease in the order Co > Pb > Cr > Zn > Cu > V ≈ Mn > Ni. Co, Cr, Cu, Pb, and Zn in the dusts have larger coefficients of variation (CV > 20%) than Mn, Ni, and V, demonstrating that the concentration differences of Co, Cr, Cu, Pb, and Zn in all dust samples are appreciable and that the effects of anthropogenic activities on the concentrations of these metals are striking.

Kurtosis values of all analyzed heavy metals in the samples except for Cr and Zn are larger than zero, which indicates that the distributions of these metals are steeper than normal. The skewness values of Cu, Ni, and Pb are higher than unity, which demonstrates that these three elements positively skew towards lower concentrations (Lu et al. 2010), as can be confirmed by the fact that their arithmetic mean concentrations are greater than their medium concentrations. As a result, the geometric means of Cu, Ni, and Pb provide more valid data than their arithmetic means (Lu et al. 2010).

The concentrations of heavy metals in Baotou street dust are compared with data reported for other cities in the world in Table 1. The mean concentrations of Co in Baotou street dust are appreciably higher than in other cities, whereas the mean concentrations of Cu, Pb and Zn in street dust from Baotou are lower than those of other cities. The other trace metal concentrations in Baotou street dust are within the range of those of the compared cities. The street dust is a complex mixture of particulates and contaminants derived from an extensive range of urban and industrial sources and processes (Han et al. 2006). The deposition of atmospheric particulates is one type of important source of ground dust (Zhang et al. 2015). Dusts of different cities have various concentration levels of metals, which may be related to the local natural environment, economic development, urbanization level, industrial type, traffic, environmental protection and pollution control technologies, etc. Baotou is an important center of the iron and steel industry and the rare earth industry city in China. The higher concentrations of Co and Cr in Baotou are probably related to the urban construction and these two types of industrial activities. In contrast, the lower concentrations of other heavy metals in Baotou compared with Baoji and Tongchuan, particularly Cu, Pb, and Zn, may be related to the heavy traffic in the other cities.

Spatial distribution of heavy metals in street dust

The spatial distributions of Co, Cr, Cu, Mn, Ni, Pb, V and Zn in the street dust of Baotou city were determined using the Kriging interpolation method with ArcGIS software, and the results are shown in Fig. 2. Fig. 2a shows that there are two high-value zones of Co concentration (>6 times the background value) in the study area, i.e., the north high-value zone and the middle-south high-value zone. The north high-value zone of Co concentration is located in the vicinities of a machinery plant and residential areas, whereas the middle-south high-value zone is situated near commercial areas and residential areas, with many construction sites and a building and decorative materials market. The spatial distribution characteristics of Cr concentrations in the dusts revealed that the west is higher than the east (Fig. 2b). The west high-value zone of Cr concentration is located in the vicinity of a steel plant, a coal-fired power plant, a machinery plant and a cement plant, and the sporadic hot-spots of Cr concentration are located near garages. As for the concentration of Cu in the dust, one hot-spot is found in the middle of the western study area (Fig. 2c). The street dust samples collected from the middle of the western study area, the area where the machinery plant, the building materials market and the commercial center are located (with heavy traffic), has higher Cu concentrations (>1.5 times the background value). Cu concentrations in the dusts decrease radially from that hot-spot to the surroundings. The spatial distribution of Mn in the dusts (Fig. 2d) is similar to that of V (Fig. 2g), i.e., the concentrations of Mn and V decrease from west to east, and the dust samples collected from the southeastern part of the study area, the vicinity of a big Ecological Park, have lower Mn and V concentrations. The concentrations of Ni in most dust samples are close to or lower than its corresponding background value in local soil (24.5 mg kg^{-1}) (Wang et al. 2007). Moreover, the hot-spots of Ni concentration (>1.5 times background value)

Table 1. Descriptive statistics of heavy metals in street dust of Baotou and reference value as well as the reported data for other cities (mg kg^{-1})

Heavy metal	Co	Cr	Cu	Mn	Ni	Pb	V	Zn
Min	39.7	103.0	16.3	408.9	16.1	28.6	58.6	47.2
5%	41.8	124.9	19.2	439.9	17.7	31.4	63.1	57.4
10%	45.7	132.0	20.5	472.8	18.5	33.9	66.3	62.7
25%	51.2	146.7	22.8	502.4	19.7	42.7	68.8	73.2
Median	59.4	176.6	27.9	553.5	21.5	58.8	73.7	90.3
Mean	60.2	189.6	29.4	572.1	21.6	64.9	75.5	89.5
GM	59.1	182.6	28.2	565.5	21.4	59.6	75.0	87.3
75%	64.6	225.8	32.5	627.0	22.7	81.0	80.6	106.1
90%	78.5	272.5	38.0	686.6	24.1	104.6	87.2	113.4
95%	82.6	291.3	46.6	717.7	24.9	120.5	90.2	122.0
Max	105.8	327.7	77.1	894.3	43.5	162.7	103.2	136.4
SD	12.3	53.8	9.8	89.2	3.2	28.4	8.7	19.6
CV(%)	20.4	28.4	33.4	15.6	14.9	43.8	11.5	21.9
Skewness	0.9	0.7	2.5	0.7	3.9	1.2	0.9	0.0
Kurtosis	1.2	-0.3	9.2	1.1	26.3	1.5	1.0	-0.8
Reference value[a]	9.93	56.4	19.17	508.6	24.5	18.76	65.5	55.68
Baoji[b]	15.9	126.7	123.2	804.2	48.8	433.2	88.9	715.3
Tongchuan[c]	34.0	106.4	32.6	369.1	25.3	75.2	55.7	141.8
Xi'an[d]		167.28	94.98	687		230.52		421.46
Guangzhou[e]	13.0	78.8	176	481	23.0	120	23.0	586
Ottawa[f]	8.31	43.3	65.84	431.5	15.2	39.05	34.0	112.5
Madrid[g]	3	61	188	362	44	1927	17	467
Luanda[h]	2.9	26	42	258	10	351	20	317
Avilés[i]	7.03	41.6	183	1661	27.5	514	28.1	4892

GM: geometric mean, SD: standard deviation, CV: coefficient of variation.

[a] Wang et al. 2007; [b] Lu et al. 2010; [c] Lu et al. 2014; [d] Han et al. 2006; [e] Duzgoren-Aydin et al. 2006; [f] Rasmussen et al. 2001; [g] De Miguel et al. 1997; [h] Ferreira-Baptista and De Miguel 2005; [i] Ordóñez et al. 2003

are very limited and mainly distributed in the center of the study area (Fig. 2e): the neighborhoods of the steel plant, the coal-fired power plant, the machinery plant and the garages.

With regard to the spatial distribution of Pb, one hot-spot was found in the center of the study area, which is the commercial center of Baotou city and has the busiest traffic. The concentrations of Pb in street dusts decline gradually from the center hot-spot to the surroundings (Fig. 2f). The concentration of Zn in the dusts has a similar spatial distribution to that of Cu, i.e., the dust samples collected from the west industrial area and the commercial area with heavy traffic have higher Zn concentrations, whereas the dust samples from the southeastern part of the study area, which is the largest park in Baotou city, have lower Zn concentrations (Fig. 2h). The spatial distribution characteristics of all analyzed heavy metals in the street dust of Baotou may be related to their sources and the influence of anthropogenic activities.

Contamination and environmental risk of heavy metals in street dust

Enrichment factors (*EF*s) of all analyzed metals were calculated for each dust sample relative to the background value of the local soil. In this study, Al is used as a reference element. The box-plots of *EF* for metals in street dust from Baotou city are provided in Fig. 3. The order of mean *EF* values is Co (6.8) > Cr (3.8)>Pb (3.5) > Zn (1.8) > Cu (1.7) > Mn (1.3)=V (1.3) > Ni (1.0). The mean *EF* values of Co, Cr and Pb were > 2, indicating that the street dusts were contaminated by these metals. In particular, the maximum *EF* values of Co and Pb were higher or close to 10, showing that the sources of Co and Pb in the dust were related to human activities. The *EF* values of Mn, Ni and V in all dust samples were < 2, showing deficiency to minimal enrichment. The *EF* values of Co in 95% of the samples were between 5 and 20, and those in 5% of the samples were between 2 and 5, indicating significant enrichment and moderate enrichment, respectively. The mean *EF* values of Cr (3.8) and Pb (3.5), as well as 84% of the *EF* values of Cr and 69% of the *EF* values of Pb, were between 2 and 5, indicating moderate enrichment, whereas 16% of the *EF* values of Cr and 23% of the *EF* values of Pb were in the 5–20 range, demonstrating significant enrichment. The mean *EF* values of Cu (1.7) and Zn (1.8), as well as 83% of the *EF* values of Cu and 67% of the *EF* values of Zn were <2, revealing deficiency in minimal enrichment, whereas 17% of

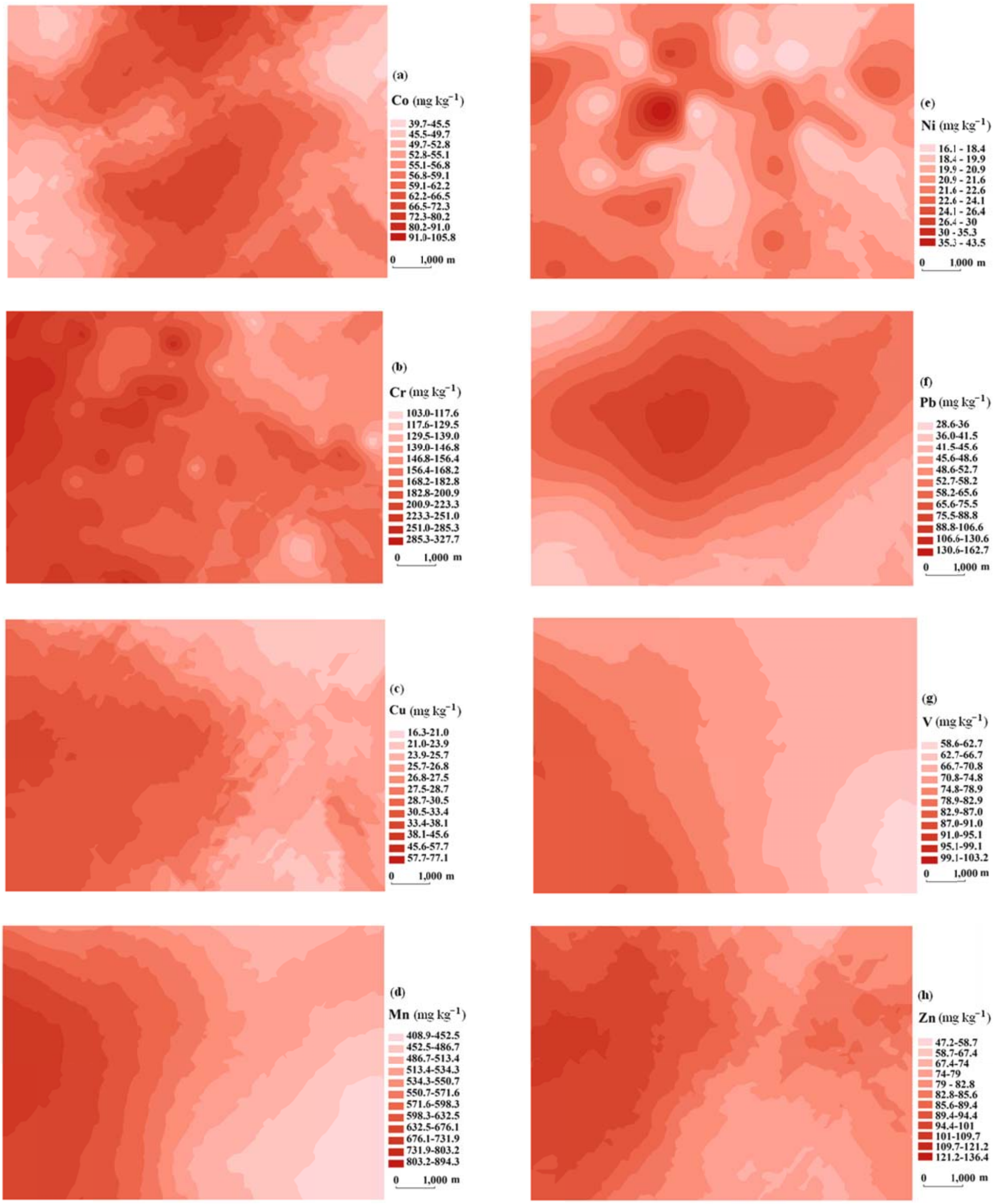

Fig. 2. Spatial distribution of heavy metal concentration in street dust of Baotou

the *EF* values of Cu and 33% of the *EF* values of Zn were in the range of 2–5, indicating moderate enrichment.

The E_i values of all analyzed metals in street dust collected from Baotou are summarized in Fig. 4. The mean E_i value decreases in the order Co (30.3) > Pb (17.3) > Cu (7.7) > Cr (6.7) > Ni (4.4) > V (2.3) > Zn (1.6) > Mn (1.1), which is different from their order of enrichment factors. The reason for this phenomenon is due to the difference in their toxic-response factors. The E_i values of Cr, Mn, Ni, V and Zn in all of the dust samples and those of Cu in 96% of the samples were <15, indicating low ecological risk. The E_i values of Pb in 43% of the samples were <15, those in 49% of the samples

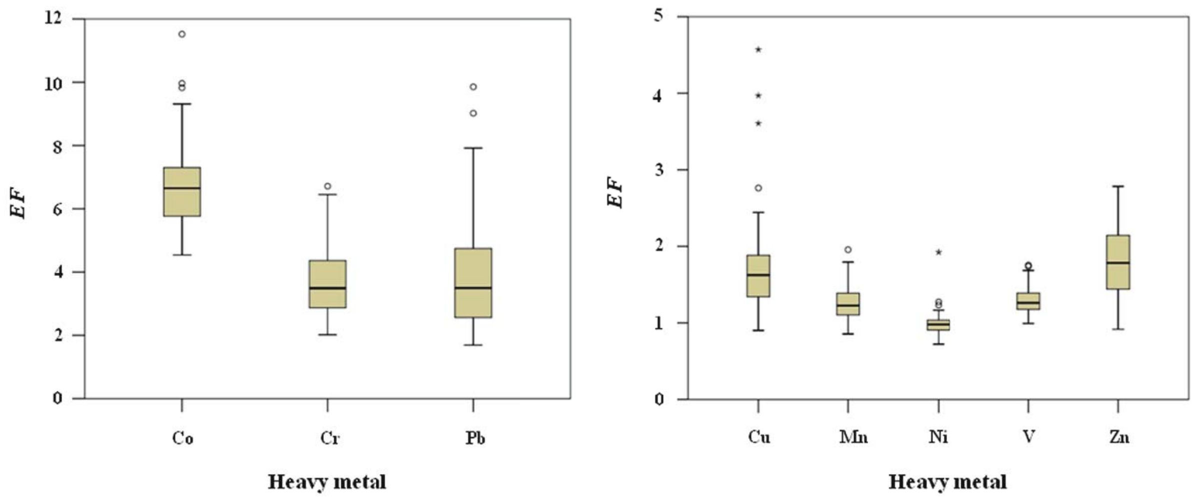

Fig. 3. Box-plot of EF for heavy metals in street dust of Baotou

were between 15 and 30, and those in 8% of the samples were between 30 and 60, indicating that Pb in the dusts was mainly associated with low to moderate ecological risk, whereas some samples presented considerable ecological risk. The E_i values of Co in 51% of the samples were between 15 and 30, and those in 49% of the samples were between 30 and 60, showing that Co in street dust of Baotou presented moderate to considerable ecological risk. The potential ecological risk index (*RI*) of heavy metals in street dust of Baotou ranged from 49.7 to 101.1 with a mean of 71.5, revealing that the comprehensive ecological risk of heavy metals in the dust was moderate, which was mainly due to the contributions of Co (42.4%) and Pb (24.2%).

Source identification of heavy metals in street dust

Sources of heavy metals in street dust collected from Baotou were identified using multivariate statistical analysis methods by combined use of their concentrations, spatial distributions and enrichment levels. Principle component analysis (PCA) results show that there are three eigenvalues >1 and that these three principle components explain 72.47% of the total variance (Table 2). The first principle component explains 33.38% of the total variance, and it is loaded heavily on Cr, Mn, Ni and V. They are significantly positively correlated with each other at $P<0.01$ (Table 3) and are classified into one cluster by the cluster analysis (Fig. 5). These results indicate that Cr, Mn, Ni and V have the same sources in the dusts. Cr, Mn, Ni and V are extensively used to produce stainless steel and alloys (Yeung et al. 2003), which can be confirmed by the spatial distributions of Cr, Mn, Ni and V in the dusts. The high--value zones of Cr, Mn, Ni and V in street dust from Baotou are located in the neighborhoods of the steel plant, the coal-fired power plant and the machinery plant. Cr in all dust samples presents elevated concentrations compared to the local soil and its enrichment factors are higher (*EF*=2.0–6.7), showing Cr in the dusts mainly originated from anthropogenic sources, i.e. industrial sources. Mn, Ni and V in the dusts are deficiency to minimal enrichment, indicating that they mainly came from natural sources, partly came from anthropogenic sources.

The second principle component is loaded primarily by Cu, Pb and Zn, accounting for 23.34% of the total variance (Table 2). Cu, Pb and Zn have significantly positive correlations in correlation analysis (Table 3) and are classified together in CA (Fig. 5). These results indicate that Cu, Pb and Zn have similar sources in the street dust of Baotou. The concentrations of Cu, Pb and Zn in the most dust samples are significantly higher than their background values in local soil. Pb presents moderate to significant enrichment in the dusts, and Cu and Zn display minimal to moderate enrichment in the dusts. These show that the sources of Pb, Cu and Zn in the dusts are related to the local anthropogenic activities. Cu is a component of alloys used in mechanical parts due to its desirable qualities such as corrosive resistance and strength (Lu et al. 2010). Cu is also present in brass automotive radiators due to its high corrosive resistance and high thermal conductivity (Yang et al. 2011), and it is often used in car lubricants (Lu et al. 2010). Zinc alloy and galvanized board are widely used in motor vehicles. Zinc compounds have also been employed extensively as antioxidants and as detergent/dispersant improvers for lubricating oils (De Miguel et al. 1997). Zn, added to tires during the vulcanizing process, comprises from 0.4% to 4.3% of the resulting tire tread (Lu et al. 2010). The wear and tear of vulcanized vehicle tires and corrosion of galvanized automobile parts are the main sources of Zn in the urban environment (Han et al. 2006; Lu et al. 2010). Deterioration of the mechanical parts in vehicles over time results in Cu and Zn being emitted to the surrounding environment (Li et al. 2004). Oxidation of lubricating oils upon exposure to air at high temperature results in the formation of organic compounds that are corrosive to metals (Lu et al. 2010). Cu and Zn can be released to the urban environment as a result of wear of automobile oil pumps or corrosion of metal parts that come into contact with the oil (Lu et al. 2010). The spatial distribution patterns of Cu, Pb and Zn in the street dust of Baotou show that the higher-value zones for Cu, Pb and Zn are distributed in a similar manner, i.e., centered in the west-middle industrial area and commercial center, which have heavy traffic, suggesting that Cu, Pb and Zn in the street dust of Baotou mainly originated from vehicular traffic.

The third principle component is dominated by Co, accounting for 15.75% of the total variance (Table 2). The coefficient of variation of Co is relatively large, and its concentrations in the street dusts are clearly higher than its

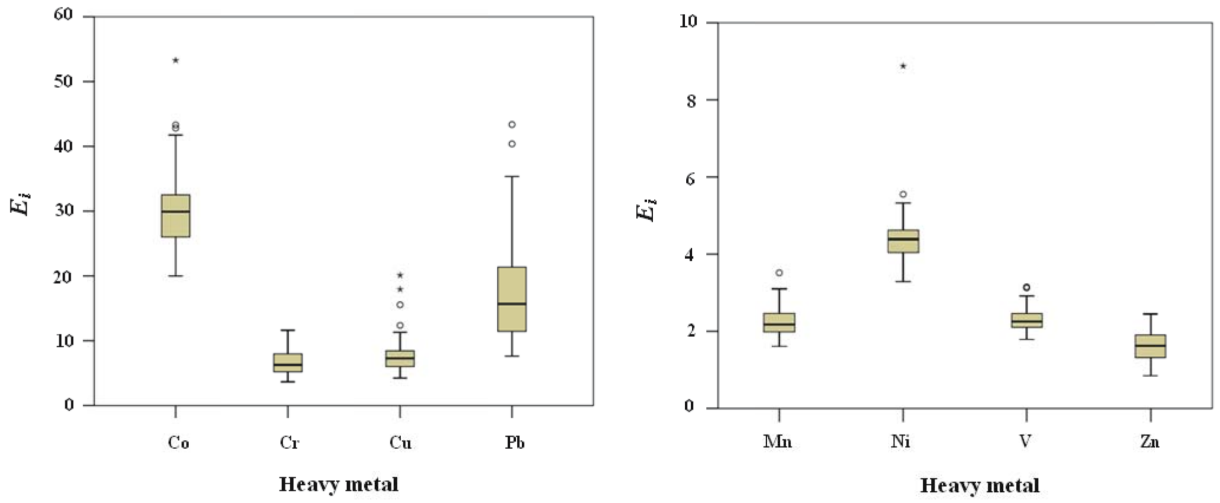

Fig. 4. Box-plot of EF for heavy metals in street dust of Baotou

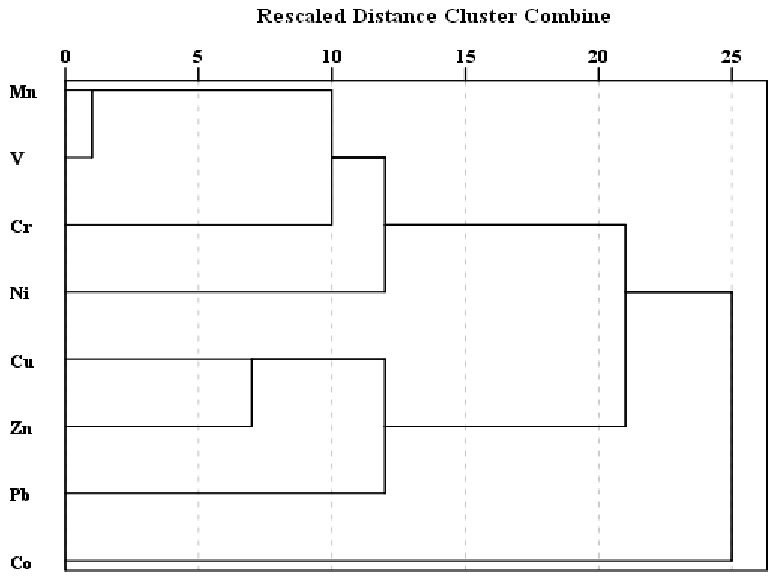

Fig. 5. Dendrogram results of cluster analysis based on Ward's method of hierarchical cluster analysis for eight elements

Table 2. Rotated component matrix for data of urban dusts

Element	Component			Communalities
	1	2	3	
Co	0.027	0.042	0.962	0.928
Cr	0.798	-0.067	0.078	0.647
Cu	0.341	0.665	0.022	0.559
Mn	0.813	0.345	-0.236	0.836
Ni	0.621	0.260	0.100	0.463
Pb	-0.020	0.825	0.092	0.689
V	0.876	0.183	-0.128	0.817
Zn	0.322	0.720	-0.487	0.859
Eigenvalue	2.67	1.87	1.26	
% of variance explained	33.38	23.34	15.75	
% of cumulative	33.38	56.72	72.47	

Rotation method: varimax with Kaiser normalization. Extraction method: principal component analysis, after 4 times of iteration convergence in rotation. PCA loadings>0.5 are shown in bold.

Table 3. Pearson's correlations matrix for the heavy metal concentrations

	Co	Cr	Cu	Mn	Ni	Pb	V	Zn
Co		0.907	0.648	0.219	0.591	0.653	0.663	0.001
Cr	0.013		0.024	0.000	0.000	0.507	0.000	0.163
Cu	0.051	0.247*		0.000	0.014	0.010	0.000	0.000
Mn	-0.136	0.523**	0.414**		0.000	0.007	0.000	0.000
Ni	0.060	0.374**	0.269*	0.422**		0.124	0.000	0.000
Pb	0.050	0.074	0.283**	0.295**	0.170		0.238	0.000
V	-0.049	0.516**	0.394**	0.880**	0.465**	0.131		0.000
Zn	-0.365**	0.155	0.561**	0.595**	0.394**	0.434**	0.430**	

The left lower part is correlation coefficient; the right upper part is significant level.
* Correlation is significant at the 0.05 level (two-tailed).
** Correlation is significant at the 0.01 level (two-tailed).

corresponding background value in local soil. Co presents significant enrichment in the dusts. These indicate that Co in the street dust is mainly governed by human activities. Co is not correlated with the other heavy metals considered, except for Zn (Table 3), and it is separated from other principal components in the PCA (Table 2) and clusters in the CA (Fig. 5), showing that Co has a different source than other heavy metals. Co is extensively used in alloys, coating materials, paints and pigments. These Co-containing materials are widely used in modern buildings due to their gloss, faultless color and visual impact. This is true for the reconstruction of the middle-south commercial area and the construction of the north residential area in Baotou city, which correspond precisely to the areas of high Co concentration in the dust. This suggests that Co in the street dust of Baotou predominantly originated from building construction or renovation, as well as weathering and corrosion of building materials.

Conclusions

Street dusts of Baotou have elevated Co, Cr, Cu, Pb, V and Zn concentrations compared to the background values of local soil. Mn, Ni and V in the dusts exhibited deficiency to minimal enrichment. Cu and Zn exhibited minimal to moderate enrichment, whereas Cr and Pb exhibited moderate to significant enrichment, and Co exhibited significant enrichment in the dusts. The ecological risks of Cr, Mn, Ni, V, Zn and Cu in the dusts are low, whereas the ecological risk of Pb is low to moderate, and Co in the street dust of Baotou shows moderate to considerable ecological risk. The comprehensive ecological risks of all heavy metals analyzed in the dust are moderate. Different distribution patterns were found among the analyzed heavy metals. Mn and V, Cu and Zn had similar distribution patterns. The middle of the western study area is the high-value area for most heavy metals. The zones of high Co concentration were located in the north and middle-south of the study area, where many construction sites are located. The dust samples collected from the industrial area and commercial area with heavy traffic have high Cu, Pb and Zn concentration. Hot-spot areas of Cr, Mn, Ni and V are mainly associated with industrial activities. The source of Cr, Mn, Ni and V is a mixture of natural sources and industrial emissions of iron and steel plant and coal-fired power plan. Cu, Pb and Zn mainly originated from traffic emissions. Co was primarily derived from construction sources.

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