Contamination and health risk assessment of heavy metals in road dust in Bayan Obo Mining Region in Inner Mongolia, North China

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Abstract: The objective of this study was to investigate the concentration and spatial distribution patterns of 9 potentially toxic heavy metal elements (As, Cd, Co, Cr, Pb, Cu, Zn, Mn, and Ni) in road dust in the Bayan Obo Mining Region in Inner Mongolia, China. Contamination levels were evaluated using the geoaccumulation index and the enrichment factor. Human health risks for each heavy metal element were assessed using a human exposure model. Results showed that the dust contained significantly elevated heavy metal elements concentrations compared with the background soil. The spatial distribution pattern of all tested metals except for As coincided with the locations of industrial areas while the spatial distribution of As was associated with domestic sources. The contamination evaluation indicated that Cd, Pb, and Mn in road dust mainly originated from anthropogenic sources with a rating of "heavily polluted" to "extremely polluted," whereas the remaining metals originated from both natural and anthropogenic sources with a level of "moderately polluted". The non-cancer health risk assessment showed that ingestion was the primary exposure route for all metals in the road dust and that Mn, Cr, Pb, and As were the main contributors to non-cancer risks in both children and adults. Higher HI values were calculated for children (HI=1.89), indicating that children will likely experience higher health risks compared with adults (HI=0.23). The cancer risk assessment showed that Cr was the main contributor, with cancer risks which were 2–3 orders of magnitude higher than those for other metals. Taken in concert, the non-cancer risks posed by all studied heavy metal elements and the cancer risks posed by As, Co, Cr, Cd, and Ni to both children and adults in Bayan Obo Mining Region fell within the acceptable range.

Keywords: road dust; heavy metal elements; contamination assessment; health risk assessment; Bayan Obo Mining Region

1   Introduction

Road dust is comprised of solid particles which accumulate on impervious, hard road surfaces, such as cement and sidewalks in urban areas (Liu *et al*., 2014). Road dust plays an

active role as a "sink and source" of pollutants due to enhanced levels of metals and other pollutants and frequent interactions of dust with the atmosphere and other mediums through resuspension and deposition of dust particles (Moreno *et al*., 2013). Therefore, road dust can contribute significantly to environmental pollution in urban areas and is considered an indicator of heavy metal contamination from atmospheric deposition (Zheng *et al*., 2010a). Moreover, heavy metal elements in road dust are known to easily enter the human body through ingestion, inhalation, and dermal contact (Cook *et al*., 2005). The adverse effects on human health from exposure to heavy metal elements have been well-documented (Valko *et al*., 2006; Zheng *et al*., 2006; Sun *et al*., 2010), necessitating a thorough determination of the health risks of road dust containing to local residents (Shi *et al*., 2008).

Several prior studies have evaluated the concentration, distribution, pollution potential, and health risks of heavy metals in road dust (Zheng *et al*., 2010a; Apeagyei *et al*., 2011). However, most previous research focused on road dust in capital cities or mega-cities which were characterized by dense traffic and overpopulation. Small regions affected mainly by mining activities have received relatively limited attention. Mining activities are notorious for their adverse impacts on the environment (Wang *et al*., 2008). Large quantities of dust laden with high levels of heavy metals can be released into the air and deposited as road dust as a result of mining operations including crushing, grinding, excavating, smelting, and refining (Csavina *et al*., 2012). Thus, in comparison with mega-cities or capital cities, the environmental and human health risks associated with road dust metals in mining regions requires further investigation.

Bayan Obo is a mining town in western Inner Mongolia. Mining activities were in operation for 80 years before the discovery of iron minerals in 1927 and rare earth elements (REE) minerals in 1936. Larger-scale mining has led to soil pollution with heavy metals in Bayan Obo (Guo *et al*., 2011; Si *et al*., 2015). However, the contamination characteristics of heavy metals in road dust in Bayan Obo, as well as the association between dust-borne metallic elements and their adverse human health impacts, are not well understood.

In an effort to supplement previous research and obtain more information regarding road dust pollution in Bayan Obo, the objectives of this study were to 1) investigate the mass concentration of heavy metal components of road dust collected in Bayan Obo and analyze their spatial variation; 2) evaluate the contamination levels of these metals using the geo-accumulation index (I_{geo}) and enrichment factor (EF); and 3) develop a quantitative estimation of the non-carcinogenic and carcinogenic risks of heavy metals in road dust to local residents.

2 Materials and methods

2.1 Site description

Bayan Obo Mining Region (hereafter Bayan Obo for short) (41°46′58″N, 109°58′25″E) is considered the largest known (REE)-Fe-Nb deposit. Located in the west of Inner Mongolia, Bayan Obo contains large reserves on iron, niobium, and REE. Containing 1.4 billion tons of iron, 1 million tons of Nb_2O_5, and more than 40 million tons of REE minerals (70% of global REE storage) (Wu, 2008), Bayan Obo contributes 45% of worldwide REE production (Drew *et al*., 1990). The main minerals present are bastnasite, monazite, and RE-Nb miner-

als such as aeschynite, felgusonite, and columbite. The mining region is comprised of 3 ore zones: the Main Orebody, the East Orebody, and the West Orebody. The region is 48 km² in area, 18 km in length from east to west, and 3 km in width from north to south. The Main Orebody and the East Orebody contain 5.41% and 5.18% rare earth oxides (REOs), respectively, while the West Orebody is still in the exploitation process. Iron and REE minerals are currently extracted at a rate of 15,000 tons per day from the Main and East Orebodies. The raw minerals are transported through railways to Baotou city for reprocessing, while the 8 tons of tailing products produced each year are disposed of freely in open pits (Wang *et al*., 2014).

Bayan Obo is characterized by a cold semi-arid climate with a mean annual temperature of 7.2°C. Prevailing winds are southeast towards the residential area with an average wind speed of 1.2 m·sec^{-1}. Nearly 30,000 people live in the residential area located in the south of the ore body, most of them work for the mining industry. The dry climate and strong winds allow for extensive dispersal of the dust in mining sites, especially in the downwind direction towards the residential areas. The vast grasslands in the areas cannot effectively block dust dispersion due to intense winds.

2.2   Sample collection

A total of 23 points distributed in the main residential area were selected as road dust sampling sites in Bayan Obo Mining Region (Figure 1), including sites near the mine. There are no commercial activities in the Bayan Obo region. At each sampling site, approximately 200g of composite road dust from 3–5 sub-sampling sites were collected in April 2014 from impervious surfaces (road, pavement and gutter) using a clean polyethylene brush and tray. The exact location of each sampling site was measured by global positioning system (GPS). All road dust samples were stored in self-sealed polyethylene bags, labeled, and transported to the laboratory for analysis.
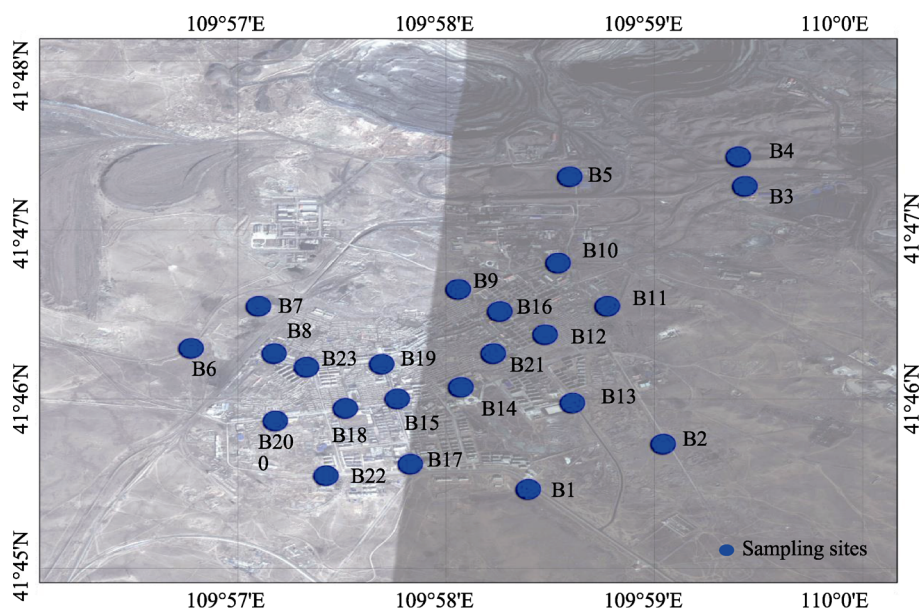

Figure 1   Map of the study area and sampling sites in Bayan Obo Mining Region (April 2014)

2.3   Sample processing

All samples were air-dried naturally for approximately 15 days, sieved through a 2.0 mm mesh nylon sieve to remove small stones and debris, and then carefully resieved through a 0.1 mm sieve. Prior to determination of heavy metals concentrations, sieved dust samples were ground and then a 0.5g milled dust sample was digested in a mixture of HNO_3, $HClO_4$ and HF solution by heating to obtain ca. 0.5 ml of colorless solution. After cooling, the solution was transferred to a test tube and then diluted to 25 mL with deionized water. Concentrations of Cr, Cu, Zn, Pb, and Ni were determined by inductively coupled plasma optical emission spectroscopy (ICP-OES, Optima 5300 DV, Perkin Elmer) and concentrations of Cd and Co were analyzed by inductively coupled plasma mass spectrometry (ICP-MS, ELAN DRC-e, Perkin Elmer SCIEX). Each measurement was conducted in duplicate. National reference samples, replicates, and blanks were used to ensure accuracy of the results. The relative errors of all measurements were less than 5% on average. To prevent potential contamination of the samples, all chemical treatments were performed in an ultra-clean laboratory, and all reagents were at high purity grade.

2.4   Contamination assessment methodology

2.4.1   Geoaccumulation index

The geoaccumulation index (I_{geo}) developed by Müller (1969) was previously adopted to assess metal pollution (Wei et al., 2009; Lu et al., 2009; Fu et al., 2012). In this study, I_{geo} was used to identify whether the road dust in Bayan Obo were polluted by heavy metals and quantify the degree of the contamination. I_{geo} was calculated by:

$$I_{geo} = \log_2 (C_n/1.5B_n) \tag{1}$$

where C_n is the concentration of the metal in the road dust, B_n is the background level of metals in soils of Inner Mongolia (Gao et al., 2007; Xu and Tao, 2004), and the factor 1.5 is a constant value to account for possible variations in background values (Wei et al., 2009). Based on I_{geo} values, the sites were categorized into seven classes (Table 1) (Müller, 1969).

Table 1   The classification of contamination levels based on the I_{geo} values

I_{geo} value	Class
$I_{geo} \leqslant 0$	Unpolluted
$0 < I_{geo} \leqslant 1$	Unpolluted/Moderately polluted
$1 < I_{geo} \leqslant 2$	Moderately polluted
$2 < I_{geo} \leqslant 3$	Moderately polluted/Strongly polluted
$3 < I_{geo} \leqslant 4$	Strongly polluted
$4 < I_{geo} \leqslant 5$	Strongly polluted/Extremely polluted
$I_{geo} > 5$	Extremely polluted

2.4.2   Enrichment factor

Enrichment factor (EF) has been widely used to differentiate anthropogenic and natural sources of trace elements in soils (Lu et al., 2009). EF is defined as:

$$EF=\left(\frac{C_n}{R}\right)_{dust} \bigg/ \left(\frac{C_n}{R}\right)_{background} \tag{2}$$

where C_n and R are concentrations of the metal and reference element, respectively, in the road dust or the background soil. In this study, Al was selected as the reference material. A value of EF close to 1 indicates a crustal origin, whereas those EF values >10 indicates a non-crustal source (Wang et al., 2014).

2.5 Health risk assessment model

2.5.1 Exposed dose

In this study, the risk assessment model developed by the Environmental Protection Agency of the United States (US EPA) was used to evaluate the health risks posed by heavy metals in road dust. Local residents were divided into adults and children and the following exposure categories were used: (1) adults and children through mouth and nose; 2) ingestion of dust particles through mouth; and 3) dermal contact with dust through exposed skin. According to the human health evaluation manual (Part A) and supplemental guidance for dermal risk assessment (Part E) (EPA, 1989; 2004), the daily intake dose (D) of a pollutant through each pathway can be evaluated:

$$D_{ing} = \frac{C \times IngR \times EF \times ED \times CF}{BW \times AT} \tag{3}$$

$$D_{inh} = \frac{C \times InhR \times EF \times ED}{BW \times AT \times PEF} \tag{4}$$

$$D_{dermal} = \frac{C \times SA \times SL \times ABS \times EF \times ED \times CF}{BW \times AT} \tag{5}$$

According to the classification list developed by the International Agency for Research on Cancer (IARC), four carcinogenic metals (As, Cd, Cr and Ni), and one possible carcinogen Co (Group 2B) were investigated for their carcinogenic risks (IARC, 2014). The life time average daily dose for these five metals was calculated by:

$$LADD = \frac{C \times EF}{AT \times PEF} \times \left(\frac{InhRchild \times EDchild}{BWchild} + \frac{InhRadult \times EDadult}{BWadult} \right) \tag{6}$$

where C is the upper limit of the 95% confidence interval for the mean (95% UCL), which is considered as a conservative estimate of the "reasonable maximum exposure" (EPA, 1992). Since the concentrations of most metals in the road dust samples followed an approximate log-normal distribution, the 95% UCL in this study was calculated using previously described methods (Zheng *et al.*, 2010a; Zheng *et al.*, 2010b). The other exposure factors for these models are shown in Table 2.

2.5.2 Risk characterization

For non-carcinogenic risks, Hazard quotient (HQ) was used to assess the non-carcinogenic risks posed by metals in road dust.

$$HQ=D/RfD \tag{7}$$

where RfD is the corresponding reference dose. An HQ<1 indicates no adverse health effects, while HQ>1 indicates that adverse health effects are likely to occur.

The hazard index (HI) is equal to the sum of HQs and is used to represent the total potential non-carcinogenic risks of different pollutants via three exposure routes described previously. An HI<1 indicates that there is no significant risk of non-carcinogenic effects. If HI>1, then a noncarcinogenic effect is likely to exist (EPA, 1989).

In the case of carcinogenic risks, the life time cancer risk can be estimated by:

$$R=LADD/SF \tag{8}$$

where SF is the corresponding slope factor. Any cancer risk in the range of 10^{-6}–10^{-4} is considered acceptable by the US EPA (1989). The RfD and SF values of all investigated metals

(Ferreira-Baptista and De Miguel, 2005; Zheng *et al.*, 2010) are presented in Tables 7 and 8.

Table 2   Exposure factors

Factor	Definition	Value Adults	Value Children	Unit	Reference
BW	Average body weight	70	15	kg	EPA, 1989
IngR	Ingestion rate	100	200	mg·day^{-1}	EPA, 1989
InhR	Inhalation rate	20	7.6	m^3·day^{-1}	Zheng *et al.*, 2010a
PEF	Particle emission factor	1.36×10^9		m^3·kg^{-1}	EPA, 2001
SA	Surface areas of the skin that contacts the airborne particulates	5700	2800	cm^{-2}	EPA, 2004
SL	Skin adherence factor	0.07	0.2	mg·m^{-3}	
EF	Exposure frequency	180	180	days·year^{-1}	Zheng *et al.*, 2010a
ED	Exposure duration	24	6	years	
ET	Exposure time	24		hours·day^{-1}	EPA,2001
AT (non-cancer risk)	Averaging time	ED×365		days	
AT (cancer risk)	Averaging time	70×365		days	
ABS	Dermal absorption factor	0.03 for As, 0.001 for other metals		–	EPA,2004
CF	Conversion factor	1×10^{-6}		kg·mg^{-1}	

Table 3   The concentrations of heavy metals in road dust collected in Bayan Obo (April 2014, mg·kg^{-1})

Concentration	Maximum	Minimum	Mean	Geometric mean	Median	S.D.	Inner Mongolia B.
Cd	4.63	1.21	2.20	2.05	1.83	0.90	0.037
Co	41.27	20.65	26.94	26.62	25.74	4.49	9.0
Cr	260.80	85.09	141.24	136.76	139.60	38.46	35.7
Cu	51.09	20.49	36.39	35.75	36.36	6.79	12.7
Pb	526.70	88.04	183.93	167.51	160.50	95.41	13.5
Zn	729.00	192.00	299.37	283.92	261.80	117.51	47.5
As	19.46	8.01	12.02	11.78	11.49	2.57	6.1
Ni	49.82	24.96	31.25	30.85	29.41	5.52	16.6
Mn	7956.00	1575.00	3407.30	3206.43	3172.00	1349.94	434.3

3   Results

3.1   Heavy metals contents in road dust

The descriptive statistics related to heavy metal content of dust in the Bayan Obo region are listed in Table 3. The background values of the metals in soils of Inner Mongolia are also shown in Table 3. The concentrations of 9 metals varied widely in this region and followed the order of Mn>Zn>>Pb>Cr>Cu>Ni>Co>As>Cd. All road dust showed contained elevated concentrations of heavy metals in comparison with those of Inner Mongolia background

average concentrations (Xu and Tao, 2004; Gao *et al.*, 2007). This was particularly true for Cd, which exceeded the background value 60-fold.

The mean heavy metal content was compared to the data collected from other cities or regions reported in previous studies (Table 4). These results indicated that the road dust in residential areas of Bayan Obo contains considerably higher concentrations of Cd, Co, and Mn, and lower levels of in Cu, Zn and Ni compared with other cities, except for Ni in Hangzhou (Zhang and Wang, 2009). The concentration of Cr was close to that measured in Shanghai (Shi *et al.*, 2008), Nanjing (Liu *et al.*, 2014), and Baoji (Lu *et al.*, 2009), where urban environments were heavily affected by human activities. Additionally, the Pb content in Bayan Obo, which exceeded that measured in Urumqi (Wei *et al.*, 2009) and Nanjing (Liu *et al.*, 2014), was still detected at a relatively low level compared with other industrial and developed cities.

Table 4 The average concentrations of heavy metals in road dust in different areas (mg·kg^{-1})

Concentration	Cd	Co	Cr	Cu	Pb	Zn	As	Ni	Mn	Reference
Bayan Obo	2.20	26.94	141.24	36.39	183.93	299.37	12.02	31.25	3407.30	This study
Hangzhou	1.59	19.96	51.29	116.04	202.16	321.40		25.88	509.56	Zhang and Wang, 2009
Urumqi	1.17	10.97	54.28	94.54	53.53	294.47		43.28	926.60	Wei *et al.*, 2009
Shanghai	1.23		159.30	196.80	294.90	733.80		83.98		Shi *et al.*, 2008
Baoji		15.90	126.70	123.17	433.20	715.30	19.80	48.80	804.20	Lu *et al.*, 2009
Nanjing			139.0	238.0	113.0	307.0		47.0	786.0	Liu *et al.*, 2014
Inner Mongolia B.	0.037	9.0	35.7	12.7	13.5	47.5	6.1	16.6	434.3	Xu *et al.*, 2004 Gao *et al.*, 2007
China B.	0.07	11.2	53.9	20.0	23.6	67.7	11.2	23.4	482.0	Xu *et al.*, 2004

3.2 Spatial distributions of heavy metals in road dust

The spatial distribution pattern of 9 potentially toxic metals (As, Cd, Co, Cr, Pb, Cu, Zn, Mn and Ni) in road dust in Bayan Obo is presented in Figure 2. Cd, Cr, Co, Pb, Cu, Mn, Ni, and Zn show spatial distribution patterns which coincide with the locations of industrial areas. The concentrations of those eight metals were higher near tailing ponds and ore bodies in the west and north, and in good agreement with the predominated wind direction. These results indicated that heavy metals (except for As) likely originate from industrial sources in the study region. The spatial distribution pattern of As was very different from those of the other tested metals. The hot-spot areas of As were mainly associated with residential areas located in the south of the study region, suggesting that As contamination may be primarily associated with domestic pollution sources. Several restaurants in these areas were used by residents for ceremonies and celebrations which often included the use of large amounts of fireworks. Additionally, residents in Bayan Obo region still cook by the coal-fired style, which can result in significant arsenic emissions (Zhang *et al.*, 2002).

3.3 Contamination assessment results

High "absolute" values of metals are not necessarily positively correlated to higher metal contamination levels due to variations in geochemical background levels, land use patterns,
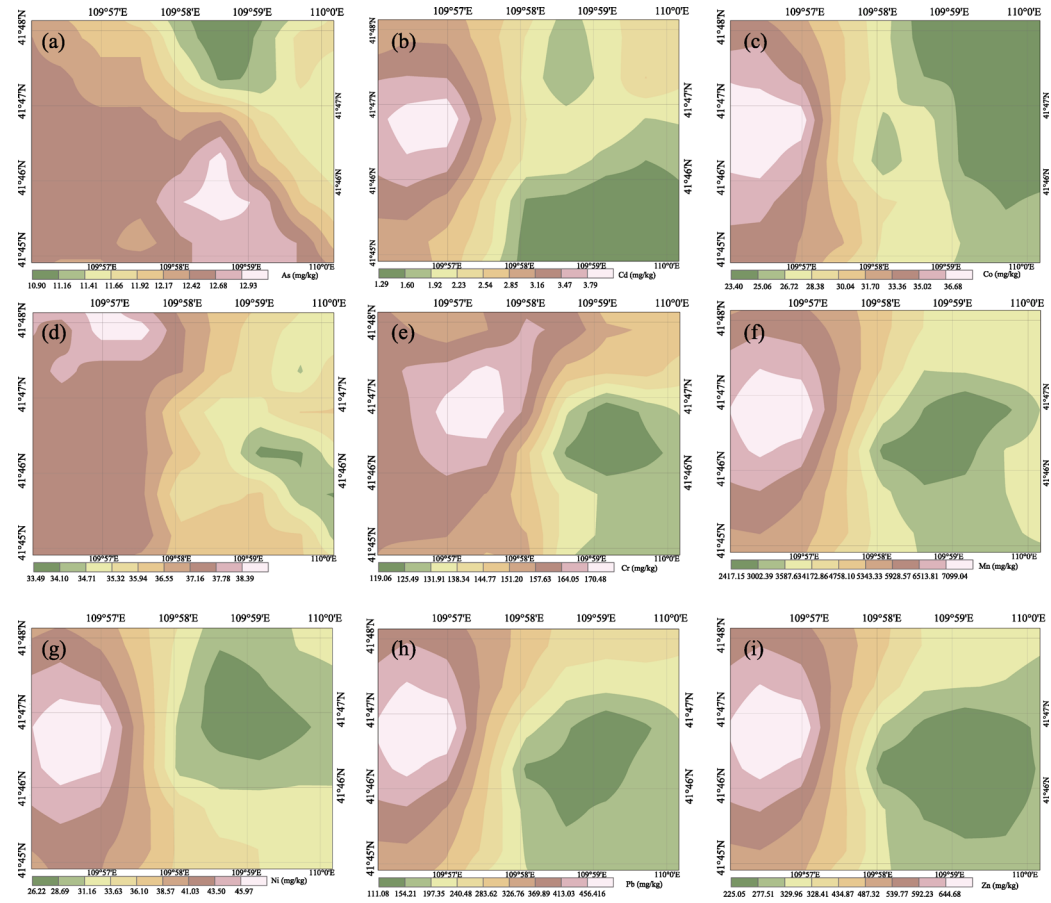
Figure 2 The spatial distribution of heavy metal elements (As, Cd, Co, Cr, Pb, Cu, Zn, Mn and Ni) in road dust in Bayan Obo (April 2014)

and human activities among different cities. Therefore, the geoaccumulation index was used to assess the contamination extent. The average I_{geo} values of As, Ni, Cu, and Co fell in the range of 0–1 (Figure 3), indicating that the road dust in Bayan Obo residential areas were polluted or moderately polluted by these four metals. The average I_{geo} value of Cr and Zn were 1.35 and 1.99, respectively, placing those two metals into the class of moderately polluted. The average I_{geo} value for Mn (2.30) resulted in a moderately to heavily polluted determination, while the average index of Pb (slightly higher
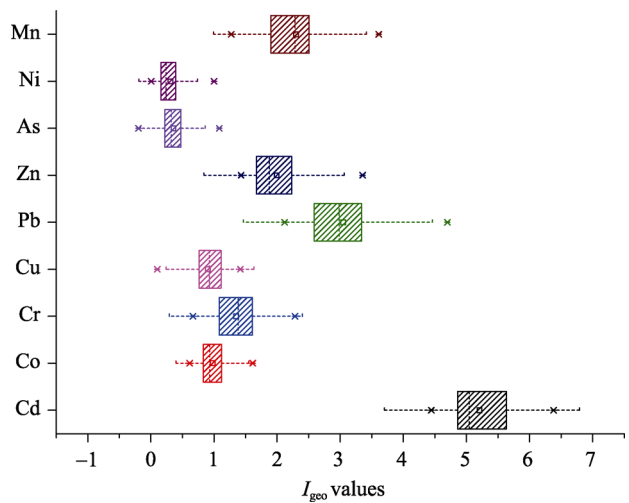

Figure 3 The I_{geo} value of heavy metals in road dust in Bayan Obo (April 2014)

than 3), pointed to a heavy contamination. Cd contamination resulted in the highest I_{geo} value (5.21), suggesting that the road dust was extremely polluted by Cd in Bayan Obo residential areas. Take in concert, the contamination levels of the 9 studied heavy metals were in the order of Cd>Pb>Mn>Zn>Cr>Co>Cu>As>Ni.

The I_{geo} values of heavy metals in this study were also compared to results from other cities reported in previous studies. As shown in Table 5, the road dust in residential areas of Bayan Obo was contaminated by Cr, Cd, Pb, Mn, and Co at higher levels, whereas by Cu, As, and Ni was relatively low compared to other cities. Contamination by Zn was higher compared with cities without industry and overpopulation, such as Hangzhou(Zhang and Wang, 2009) and Urumqi (Wei *et al*., 2009), but lower than that measured in the heavy industrial city of Baoji (Lu *et al*., 2009) and developed city of Shanghai (Shi *et al*., 2008). Despite the low absolute Pb concentrations, levels of Pb pollution were still higher than those in other cities and similar with that measured in Baoji (Lu *et al*., 2009), in which the absolute Pb concentration was 2.36 times higher than that in Bayan Obo.

Table 5 The average I_{geo} values of heavy metals in road dust in different areas

I_{geo}	Cd	Co	Cr	Cu	Pb	Zn	As	Ni	Mn	Reference
Bayan Obo	5.21	0.98	1.35	0.90	3.05	1.99	0.36	0.31	2.30	This study
Hangzhou	3.14	0.10	−1.10	1.70	2.42	1.51		−0.88	−0.98	Zhang and Wang, 2009
Urumqi	0.80	−0.30	−0.10	0.40	0.30	0.50		0.00	0.00	Wei *et al*., 2009
Shanghai	2.65		0.50	2.19	2.94	2.54		0.84		Shi *et al*., 2008
Baoji				1.79	3.19	2.58	3.04	0.17	−0.21	Lu *et al*., 2009

EFs were used to identify whether the heavy metals originated from non-crustal sources or crustal sources. The EF values for nine studied metals in road dust of Bayan Obo are listed in Table 6. The average values of EF for Cd, Pb, and Mn were greater than 10, indicating that enrichment of these three metals, particularly Cd, was caused by anthropogenic sources, whereas the average values of EF for Cr, Cu, Co, As and Ni ranged between 2.6–5.5, implying mixed influence of both crustal and non-crustal sources. Although the EF value for Zn (8.82) was slightly lower than the threshold value (=10), it is reasonable that anthropogenic sources heavily contributed to Zn contamination.

Table 6 The average EFs values of heavy metals in road dust collected in Bayan Obo (April 2014)

	Cd	Cr	Cu	Pb	Zn	Co	As	Ni	Mn
EF	81.37	5.31	3.74	19.51	8.82	3.98	2.57	2.53	11.0

3.4 Health risk assessment results

3.4.1 Non-carcinogenic risk assessment

The HQ and HI for Cr, Ni, Pb, Cd, Cu, Mn, As, Co and Zn in road dust samples of Bayan Obo residential areas were calculated (Table 7). The integrated HI values were 1.89 for children and 0.23 for adults living in Bayan Obo region, indicating children are likely to experience significantly higher non-cancer risks.

Among three different exposure pathways, the HQ_{ing} values were the highest and contributed the most to HIs for both children and adults, indicating that ingestion of road dust ap-

pears to be the most threatening exposure way to human health in Bayan Obo (Figure 4). The inhalation of road dust had the lowest contribution to health risks for children and the HQ_{inh} values were 2–4 orders of magnitude lower compared with the other two pathways for children, indicating that the non-cancer risks posed by the inhalation of resuspended road dust might be negligible compared with ingestion and dermal
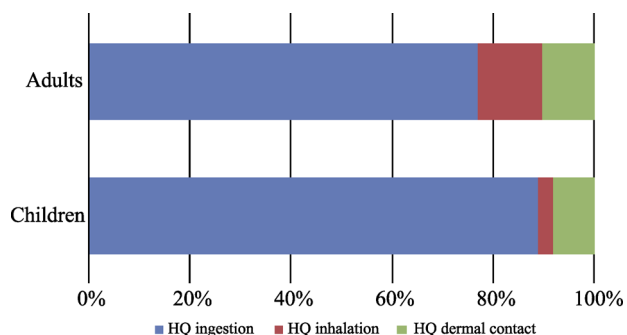

Figure 4 Non-carcinogenic risk distribution of different exposure ways for children and adults in Bayan Obo (April 2014)

contact. Similar results were obtained by previous studies (Ferreira-Baptista and De Miguel, 2005; Zheng *et al*., 2010a).

Table 7 HIs for each non-carcinogenic metal in road dust collected in Bayan Obo (April 2014)

	C (95%UCL)	Oral RfD	Inhal RfD	Dermal RfD	HQ ingestion	
					Adult	Children
Cd	2.59	1.00E-03	1.00E-03	5.00E-05	1.82E-03	1.70E-02
Cr	157.87	3.00E-03	2.86E-05	6.00E-05	3.71E-02	3.46E-01
Cu	39.33	4.00E-02	4.02E-02	1.20E-02	6.93E-04	6.47E-03
Pb	225.19	3.50E-03	3.52E-03	5.25E-04	4.53E-02	4.23E-01
Zn	350.18	3.00E-01	3.00E-01	6.00E-02	8.22E-04	7.68E-03
Ni	33.63	2.00E-02	2.06E-02	5.40E-03	1.18E-03	1.11E-02
Co	28.88	2.00E-02	5.71E-06	1.60E-02	1.02E-03	9.49E-03
As	13.13	3.00E-04	3.01E-04	1.23E-04	3.08E-02	2.88E-01
Mn	3991.06	4.60E-02	1.43E-05	1.84E-03	6.11E-02	5.70E-01
Sum					1.80E-01	1.68E+00

	HQ inhalation		HQ dermal		HI	
	Adult	Children	Adult	Children	Adult	Children
Cd	2.81E-07	4.98E-07	1.52E-04	9.98E-04	1.98E-03	1.80E-02
Cr	5.71E-04	1.01E-03	7.39E-03	4.84E-02	4.50E-02	3.95E-01
Cu	1.01E-07	1.80E-07	1.00E-05	6.55E-05	7.03E-04	6.53E-03
Pb	6.98E-06	1.24E-05	1.27E-03	8.32E-03	4.66E-02	4.31E-01
Zn	1.34E-07	2.38E-07	1.82E-05	1.19E-04	8.41E-04	7.79E-03
Ni	1.65E-07	2.93E-07	1.71E-05	1.12E-04	1.20E-03	1.12E-02
Co	5.23E-04	9.27E-04	5.06E-06	3.32E-05	1.55E-03	1.05E-02
As	4.57E-06	8.11E-06	9.00E-03	5.90E-02	3.98E-02	3.47E-01
Mn	2.89E-02	5.13E-02	6.10E-03	3.99E-02	9.61E-02	6.62E-01
Sum	3.00E-02	5.32E-02	2.40E-02	1.57E-01	2.34E-01	1.89E+00

Additionally, children were found to experience higher health risks through ingestion compared with adults. The values of HQ_{ing} for children were 9.33 times higher than those for adults and accounted for larger proportions (88.9% for children, 76.9% for adults) in inte-

grated HI values. This result may be partially attributed to the special behavior patterns of children, particularly frequent hand-to-mouth contact.

The HIs for all studied metals were ranked in the order: Mn>Pb>Cr>As>Cd>Co> Ni>Zn>Cu for adults, and Mn>Pb>Cr>As>Cd>Ni>Co>Zn>Cu for children (Table 7 and Figure 5). Mn, Cr, Pb, and As were the main contributors to health risks posed by road dust metals exposure for both children and adults, and Cu had the smaller contribution. The HQ_{inh} of Mn and the HQ_{derm} of Cr and As were 2–5 orders of magnitude higher than those of other metals for both children and adults, suggesting that exposure to Cr and As via dermal contact, and for Mn through inhalation, may produce the most serious health effects.

The HI values for all metals tested in this study were within the safe level (=1), suggesting minimal non-carcinogenic risk to children and adults from exposure to road dust metals. However, the integrated HI for children (HI=1.89) slightly exceeded the safe level (=1), indicating that the potential health risk to children should be addressed and studied in more detail.
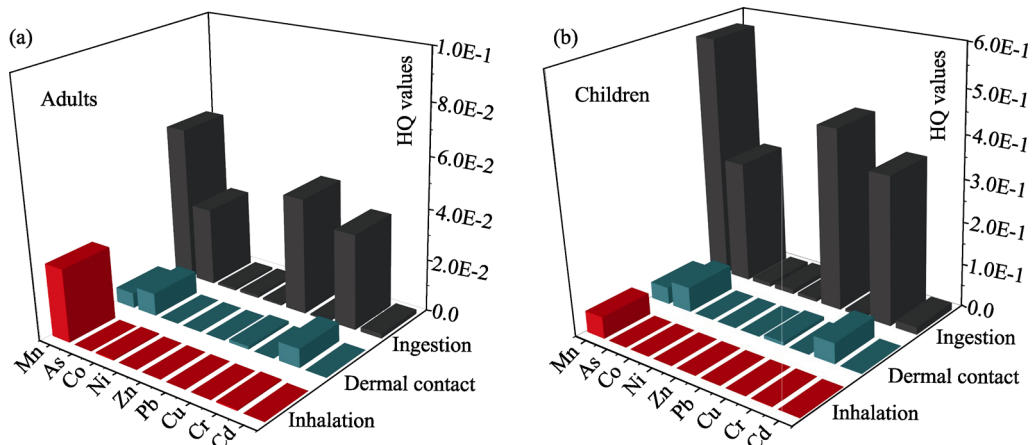

Figure 5   The HQs of each heavy metal in road dust in Bayan Obo for adults (a) and children (b) (April 2014)

3.4.2   Carcinogenic risk assessment

The cancer risks according to inhalation exposure to Cd, Cr, Ni, Co, and As are presented in Table 8. Results showed that the overall risk of cancer decreased in the order Cr>Co>As> Ni>Cd. The leading heavy metal was Cr for which cancer risks were 1–3 orders of magnitude higher than those for other metals. Overall, cancer risk values for all heavy metals in this study were within the acceptable range, implying negligible carcinogenic risk.

Table 8   Cancer risks for each carcinogenic metal in road dust collected in Bayan Obo (April 2014)

	Cd	Cr	Ni	Co	As
Inhal SF	6.30E+00	4.20E+01	8.40E-01	9.80E+00	1.51E+01
R	8.37E-10	3.40E-07	1.45E-09	1.45E-08	1.02E-08

4   Conclusions

A total of 23 road dust samples were collected from Bayan Obo Mining Region in the spring of 2014. The concentration and spatial distribution patterns of 9 potentially toxic heavy

metal elements (As, Cd, Co, Cr, Pb, Cu, Zn, Mn, and Ni) in road dust were analyzed. Contamination levels were evaluated using the geoaccumulation index and the enrichment factor. Human health risks for each heavy metal element were assessed using a human exposure model.

Results showed: (1) Concentrations of Cd, Co, Zn, Pb, Ni, As, Cu, Mn, and Cr were significantly higher compared with background values. (2)The spatial distribution of Cd, Co, Zn, Pb, Ni, Cu, Mn, and Cr were all in accordance with the locations of industrial areas and the predominant wind direction, indicating that these eight metals likely originated from industrial sources. The spatial distribution of As showed a different pattern and was instead primarily associated with domestic pollution sources, including firework use and coal combustion. (3) Contamination assessments showed that the road dust in Bayan Obo was contaminated by all investigated metals to varying extents. Cd, with an average I_{geo} value of 5.21, presented the highest pollution risk. Moreover, the road dust was categorized as heavily polluted by Mn and Pb and moderately polluted by Zn and Cr, whereas Cu, As, Ni and Co in the dust were rated as "moderately polluted" to "polluted" based on average I_{geo} values. (4) EF values indicated that accumulation of Cd, Pb, and Mn in road dust was caused mainly by human activities, whereas the enrichment of other metals derived from a combination of crustal and anthropogenic sources. The EF value of Zn (8.82) was close to the threshold value 10, implying a greater influence from human activities. (5) The health risks analysis showed that ingestion was the dominant exposure pathway for both children and adults. The sum of HI values for Mn, Cr, Pb, and As accounted for nearly 98% of the integrated HI values, indicating that these four metals were the greatest contributors to non-cancer risks. (6) Among the 5 carcinogenic metals, Cr was the leading contributor to cancer risks, followed by Co, As, Ni, and Cd. (7) Although both non-carcinogenic and carcinogenic risk for each metal fell within acceptable values, children were more susceptible than adults and experienced higher non-carcinogenic risk from exposure to metals in road dust. The risks to children living in the mining region of Bayan Obo from exposure to mining-related activities should receive greater attention.

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