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Heavy metal concentrations in roadside soils and correlation with urban traffic in Beijing, China

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ABSTRACT

A detailed investigation was conducted to study the heavy metal concentrations in roadside soils of Beijing. The concentrations of Cd, Cu, Pb and Zn showed a decreasing trend with increasing distance from the road while such trend was not identified in As, Cr and Ni. In addition, the concentrations of Cd, Cu, Pb and Zn significantly positively correlated with black carbon (BC) and TOC ($p < 0.01$). The soil samples from West 2nd Ring Road with the highest traffic volume had the highest heavy metal concentrations of the 10 roads, and Pb concentration was significantly positively correlated with traffic volumes ($p < 0.05$). According to the soil guideline values of China, Cd was considered to have considerable contamination in roadside soils, while Cu, Pb and Zn less, but As, Ni, Cr none. The concentrations of heavy metals in roadside soils of Beijing were considered medium or low in comparison with those in other cities; this may be due to the windy and dry climate in Beijing. The heavy metals could move with wind along the wind direction and the soil samples had higher heavy metal concentrations at the downwind direction.

1. Introduction

As the urban area has high population density and intensive anthropogenic activities, there are a great number of sources of heavy metals in cities, placing a considerable influence on human health. Emissions of heavy metals may come from domestic waste, chemical industry and transportation. These emissions have been continuously adding heavy metals to urban soils and they will remain present for many years even after the pollution sources have been removed. Therefore, it is indisputable that heavy metal concentrations in urban soils are significant environmental issue, and a large number of researches have been conducted all over the world [1–5]. Urban traffic is one of the major sources for urban soil pollution. Roadside soils are important reservoir for the pollution directly from vehicle sources, which could come easily in contact with pedestrians and people residing within the vicinity of the roads either by suspended dust or by direct contact.

In recent years, many studies have focused on the concentration, distribution and source identification of heavy metals in roadside dust [6–11]. For instance, Pb, Cu, Mn, Zn, Cd and Ni were significant environmental pollutants in roadside dust in Istanbul, Turkey [12]. High concentrations of heavy metal in roadside dust were identified in association with junctions controlled by traffic lights where vehicles were likely to stop regularly in Birminghan, UK [13]. Pb, Zn and Cu in roadside dust presented serious pollution in Baoji, China [7]. However, as regards heavy metal levels in roadside soils, little work has been done [14,15]. Due to the fact that soil could be a main source for the dust and could be a reservoir for the deposition of dust, it is important to assess the effects of traffic on the distribution and levels of heavy metals in roadside soils.

Beijing, as the political, economic and cultural centre of China, has experienced rapid urbanization and industrialization in the last decades. The fast development has exerted a lot of pressure on its urban environment, particularly the roadside area caused by more and more urban traffic. Although leaded gasoline has not been used in Beijing since 1997, soils could act as a reservoir for lead pollution over the years [16]. The objectives of this study were to determine the concentrations of heavy metals in roadside soils in Beijing, and analyze the correlation between the heavy metals and urban traffic. The relationship between heavy metals and distance from the road and link between heavy metal pollution and climate were discussed in detail. Assessment was also made to identify the heavy metal contamination levels.

2. Materials and methods

2.1. Study area

Beijing, the capital of China, is situated at the northern tip of the roughly triangular North China Plain, with its center located at 39.9N and 116.4E. The urban area of Beijing spreads out of the concentric ring roads, of which the 5th Ring Road passes through

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several satellite towns. The city has a typical monsoon-influenced climate, characterized by hot, humid summers due to the East Asian monsoon, and generally cold, windy, dry winters due to the vast Siberian anticyclone. Its annual average temperature is about 11.5 °C and the annual precipitation is about 500 mm. In the last three decades, Beijing has been undergoing a fast economic development and urban construction, during which the urban population has reached over 15 million.

2.2. Sample collection

A total of 80 topsoil samples (0–20 cm) were carefully collected from the roadside soils of 10 main roads in Beijing with a stainless steel shovel in April 2008. The coordinates of the sample locations were recorded with a GPS. For Chang'an Avenue, West 2nd Ring Road, Yongdingmen Inner Street, Jingtong Expressway and East 5th Ring Road which were expressed by double lines in Fig. 1, each line represented 2 sampling sites, all the sampling sites were 1m away from the road and the 2 sampling sites in each line were 100m away from each other. Therefore 4 samples were collected from each road. Moreover, in order to find the relationship between heavy metal concentrations and the distance from the road, additional roadside soil samples were collected from Badaling Expressway, Jingshi Expressway, South 4th Ring Road, North 3rd Ring Road and Airport Expressway, which were expressed by 6 lines in Fig. 1. The 3 lines on the same side of the road were 1m, 10m and 30m away from the road, respectively. Each line also represented 2 sampling sites and the 2 sampling sites in each line were also 100m away from each other. Therefore 12 samples were collected from each road. Each topsoil samples were composed of 5 sub-samples paralleled to the road with a 4 m distance from each other.

2.3. Sample preparation and analysis

The soil samples were dried indoors at room temperature, the impurities such as stones and tree leaves were removed from them; the samples were then ground to pass through a 0.15 mm nylon sieve for analysis. A small portion of each sample (0.25 g) was transferred into a Teflon beaker (50 ml) containing 5.0 ml HNO_3 (GR, 65%), 10.0 ml HF (AR, 40%), and 2.0 ml $HClO_4$ (AR, 60%). The solution was heated for 3 min at 200 °C; the beaker was then removed from the heat and allowed to cool. 5.0 ml HNO_3 (GR, 65%), 10.0 ml HF (AR, 40%), and 2.0 ml $HClO_4$ (AR, 60%) were added to the beaker again, and the solution was heated at 200 °C for 10 min. After that, the beaker was covered and allowed to stand for 12 h, and then heated until the fume of $HClO_4$ disappeared. Immediately 8 ml aqua regia was added to the beaker, the solution was heated until the residual volume was 2–3 ml, and the wall of the beaker was washed with 10 ml Milli-Q water (18.2 MΩ.cm). The solution was then transferred from the beaker to a volumetric polypropylene tube (25 ml) and the solution was made up to the mark with dilute nitric acid. The concentrations of Cd, Cr, Cu, Ni and Pb were determined with ICP-MS (X Series II, Thermo Fisher Scientific), and the concentration of Zn was determined with ICP-OES (IRIS Intrepid II, Thermo Fisher Scientific). Another small portion of each sample (0.25 g) was placed into a volumetric polypropylene tube (25 ml), to which 10 ml aqua regia was added. The tube was then placed in a boiling water bath for 1 h and shaken one time. After the tube was removed and allowed to cool, 1.0 ml $KMnO_4$ (AR, 1%) was added and the mixture was shaken. The tube was allowed to stand for 30 min. the solution was diluted to 25 ml with oxalic acid (AR, 1%), shaken and allowed to stand for 1 day to determine the As concentration. The concentration of As was determined by HG-AFS (XGY-1011A, National Engineering Center Analytical Instrument, China).

BC content in soil samples was determined with the chemo-thermal oxidation method [17]. The soil samples were acidified in the silver capsules with 1 M HCl (stop adding until gas evolution was no longer observed) to remove inorganic carbon and dried overnight at 40 °C, the organic carbon was then removed during a thermal oxidation procedure at 375 °C in a tube furnace for 24 h in the presence of excess oxygen. Finally, BC content in soil samples was determined by an elemental analyzer (Vario EI, Elementar Analysensysteme GmbH, Germany).

The quality assurance and quality control (QA/QC) procedures were conducted by using standard reference materials; GSS-1, GSS-2, GSS-3 and GSS-8 (Geochemical Standard Soil). Recoveries of the 7 observed heavy metals were between 96–110% for As, 95–103% for Cd, 94–107% for Cr, 92–106% for Cu, 97–102% for Ni, 95–105% for Pb and 96–108% for Zn, respectively. Duplicated samples were performed simultaneously for 20% of the soil samples, the standard deviation ranged within 5%, and blank samples were also performed throughout all the experiments.

Descriptive analysis was carried out with Excel 2003 (Microsoft Inc., Redmond, USA) and SPSS v.16.0 (SPSS Inc., Chicago, USA). In addition, correlation and cluster analysis (CA) were also performed. The cluster analysis was performed according to Lee et al. [2], the

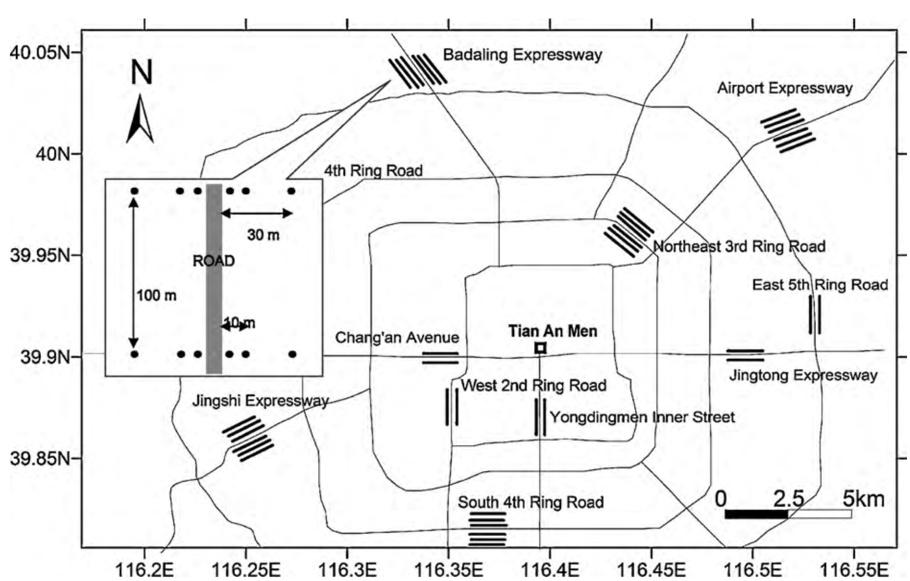

Fig. 1. Sampling sites of roadside soils in urban area of Beijing (each line represents 2 sampling sites).

Table 1
Heavy metal concentrations (mg/kg) in roadside soils in urban area of Beijing.

Road	As	Cd	Cr	Cu	Ni	Pb	Zn
Chang'an Avenue (*N* = 4)	6.9 ± 0.9	0.209 ± 0.062	61.2 ± 2.0	30.3 ± 5.8	26.0 ± 3.0	42.6 ± 15.4	65.9 ± 19.0
West 2nd Ring Road (*N* = 4)	7.0 ± 1.4	0.353 ± 0.077	62.1 ± 0.5	42.2 ± 7.2	22.9 ± 1.1	81.3 ± 22.6	138.9 ± 35.3
Yongdingmen Inner Street (*N* = 4)	8.6 ± 0.5	0.214 ± 0.053	59.0 ± 0.9	24.9 ± 4.7	26.3 ± 1.9	26.3 ± 9.0	92.0 ± 13.7
Jingtong Expressway (*N* = 4)	8.7 ± 1.2	0.243 ± 0.023	65.5 ± 0.9	34.0 ± 1.9	29.4 ± 4.6	35.4 ± 11.9	100.7 ± 19.0
East 5th Ring Road (*N* = 4)	7.9 ± 0.9	0.213 ± 0.461	60.8 ± 1.9	29.1 ± 5.9	29.7 ± 3.2	29.7 ± 6.9	72.4 ± 22.8
Badaling Expressway (*N* = 12)	9.2 ± 0.7	0.173 ± 0.009	61.3 ± 1.2	26.5 ± 5.5	28.4 ± 1.1	36.1 ± 11.0	100.3 ± 19.4
Northeast 3rd Ring Road (*N* = 12)	7.5 ± 0.8	0.224 ± 0.098	59.4 ± 3.3	28.7 ± 5.2	26.1 ± 2.2	33.4 ± 13.0	92.6 ± 15.3
Airport Expressway (*N* = 12)	7.7 ± 0.5	0.293 ± 0.111	63.0 ± 1.1	32.4 ± 2.3	30.0 ± 2.2	32.5 ± 8.9	84.0 ± 20.0
South 4th Ring Road (*N* = 12)	7.6 ± 0.8	0.211 ± 0.070	60.1 ± 0.9	28.1 ± 2.9	24.5 ± 2.0	28.0 ± 19.9	91.5 ± 16.7
Jingshi Expressway (*N* = 12)	7.4 ± 0.9	0.228 ± 0.052	57.5 ± 3.1	25.8 ± 3.3	23.3 ± 3.1	37.4 ± 14.6	87.4 ± 19.0
Mean (*N* = 80)	8.1	0.215	61.9	29.7	26.7	35.4	92.1
Background values of Beijing [28,34]	7.1	0.119	66.7	18.7	26.8	24.6	57.5
SD (*N* = 80)	0.9	0.070	2.3	5.7	2.4	13.5	18.7
Skewness (*N* = 80)	−0.080	0.585	−0.138	1.293	0.116	2.984	1.107

raw data were standardized before execution of clustering in CA. The data were firstly standardized to Z score (with a mean of 0 and a standard variation of 1) and then classified with the Ward's method. The distance measure was the Squared Euclidean distance.

3. Results and Discussion

3.1. Heavy metal concentrations in roadside soils

Analytical results of the heavy metal concentrations of the investigated soil samples were summarized in Table 1. The arithmetic means of As, Cd, Cr, Cu, Ni, Pb and Zn were 8.1 ± 0.9, 0.215 ± 0.070, 61.9 ± 2.3, 29.7 ± 5.7, 26.7 ± 2.4, 35.4 ± 13.5 and 92.1 ± 18.7 mg/kg, respectively. The coefficients of skewness of Cd, Cu, Pb and Zn were much higher than zero, revealing the positively skewed distribution. It indicated that some relatively high values of Cd, Cu, Pb and Zn existed in the samples. In contrast, the coefficients of skewness of As, Cr and Ni were close to zero, indicating that they followed normal distributions. The mean concentrations of Cd, Cu, Pb and Zn in roadside soils in Beijing were obviously higher than the corresponding background values, indicating the pollution from the traffic. The maximum concentrations of Cd, Cu, Pb and Zn simultaneously existed in the samples collected from the West 2nd Ring Road. As the earliest built Ring Road, the 2nd Ring Road is closest to the heart of the city; traffic jams on this ring road have become part of everyday life. Some parts of the 2nd Ring Road would be like a temporary parking lot during rush hours. Therefore, we may attribute the high concentrations of Cd, Cu, Pb and Zn in the samples from the West 2nd Ring Road to the heavy traffic there.

Detailed information of physicochemical properties of these roadside soil samples, such as particle size distribution, pH, TOC and cation exchange capacity (CEC), can be found elsewhere [18]. The BC contents in roadside soil samples varied from 0.03 to 0.75%, with the mean of 0.25%. Being produced by incomplete combustion of biomass and/or fossil fuel, BC has been found in urban soils [19,20], it can reflect the pollution history of a city during urbanization. BC in soil profiles of different layers can be used as a record of historical activities, and BC in the surface layer of soils was mainly from traffic emission [21]. In this study, Pearson's correlation analysis indicated that Cd, Cu, Pb and Zn were significantly positively correlated with BC/TOC. The correlation coefficients between heavy metals and BC were 0.570, 0.347, 0.525 and 0.586 for Cd, Cu, Pb and Zn, respectively ($p < 0.01$); and the correlation coefficients between heavy metals and TOC were 0.499, 0.386, 0.410 and 0.462 for Cd, Cu, Pb and Zn, respectively ($p < 0.01$). This was in agreement with the research results reported by He et al. [21], who also found significant correlations of BC with Cu, Pb and Zn in Nanjing. As no significant correlation of BC/TOC with As, Cr and Ni was found, we may attribute the correlations of BC/TOC with Cd, Cu, Pb and Zn to (i) the coexistence of BC/TOC with Cd, Cu, Pb and Zn as a result of mechanical abrasion and fuel burning of vehicles and (ii) the adsorption capacity of BC/TOC, and further research needs to be conducted. The particle size distribution in roadside soils was divided into 3 parts: 1–0.01 mm, 0.01–0.001 mm, <0.001 mm. Percentage of 1–0.01 mm particles ranged from 57.6% to 79.8%; percentage of 0.01–0.001 mm particles ranged from 7.1% to 18.6%; and percentage of <0.001 mm ranged from 10.0% to 24.3%. The pH of soil samples ranged from 7.79 to 8.80, with a mean of 8.39, suggesting a slightly alkaline condition of the roadside soils in Beijing. The CEC of soil samples ranged from 6.17 to 20.29 cmol/kg. In the present study we found significant correlations of each part of the particles with As, Cr and Ni, and we also found significant correlations of CEC with As, Cr and Ni (Table 2), which inferred that As, Cr and Ni may have the same sources.

3.2. Relationships between the heavy metals and the traffic

Relationships between the concentrations of heavy metals and the distance from the traffic lane were analyzed in 5 roads in Beijing. The concentrations of Cd, Cu, Pb and Zn showed a decreasing trend with increasing distance from the road on both sides in Badaling Expressway, Airport Expressway, South 4th Ring Road and Jingshi

Table 2
Pearson correlation of particle size distribution with heavy metals in roadside soil samples.

Particle size	As	Cd	Cr	Cu	Ni	Pb	Zn
1–0.01 mm	−0.708**		−0.365**		−0.693**		
0.01–0.001 mm	0.592**		0.453**	0.280*	0.643**		
<0.001 mm	0.660**	−0.332**	0.380**		0.590**	−0.282*	−0.312**
pH							
CEC	0.507**		0.310**		0.527**		

**Correlation is significant at the 0.01 level (two-tailed).
* Correlation is significant at the 0.05 level (two-tailed).

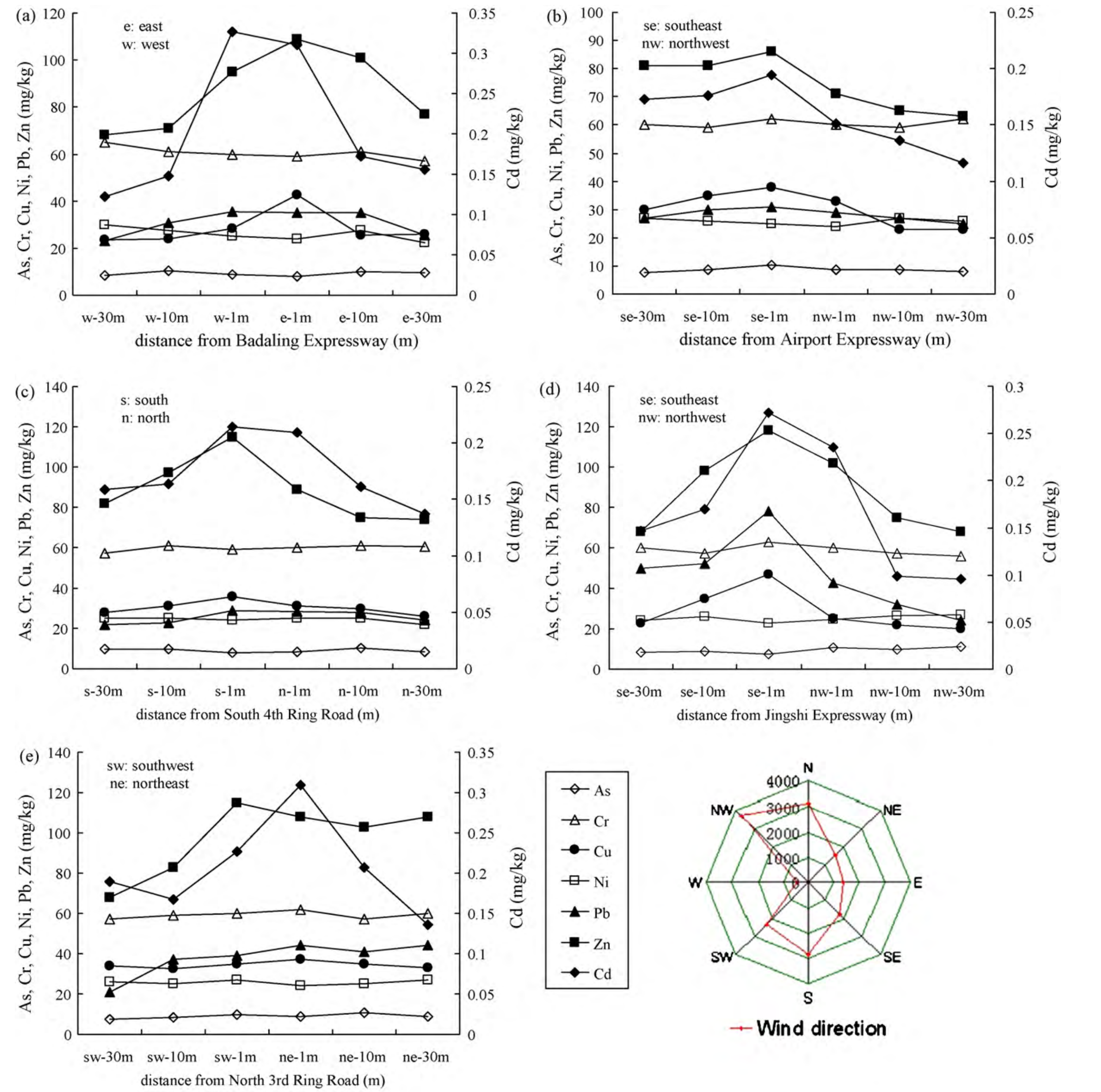

Fig. 2. Heavy metal distribution patterns in both sides of the road in (a) Badaling Expressway, (b) Airport Expressway, (c) South 4th Ring Road, (d) Jingshi Expressway and (e) Northeast 3rd Ring Road.

Expressway (Fig. 2 a-d). The curves were smooth, showing that Cd, Cu, Pb and Zn reached farther distances from the road. Take Badaling Expressway for example, the concentrations of Cd, Cu, Pb and Zn on west side decreased from 0.323, 29.1, 36.3 and 94.0 mg/kg (1 m from the road) to 0.125, 25.3, 23.4 and 67.7 mg/kg (30 m from the road), respectively; the concentrations of Cd, Cu, Pb and Zn on east side decreased from 0.311, 43.1, 36.5 and 109.3 mg/kg (1 m from the road) to 0.156, 28.5, 28.1 and 77.7 mg/kg (30 m from the road), respectively. In the Northeast 3rd Ring Road, Cd and Cu showed a decreasing trend in north side of the road, Pb and Zn showed a decreasing trend on southwest side of the road, while the concentrations of Cd, Cu, Pb and Zn on the other side did not show a decreasing trend with increasing distance from the road. This may be due to the fact that Northeast 3rd Ring Road is close to the center of the city, other factors such as domestic disposal or building construction would also affect the distribution patterns of heavy metals. As, Cr and Ni didn't show the decreasing trend with the increasing distance from the 5 main roads studied, indicating the independence of As, Cr and Ni on traffic.

The total automobile number of Beijing has reached 3,900,000 in 2009. Road traffic data from Beijing transport department showed that the overall traffic flows ranged from 24,000 vehicles per day for East 5th Ring Road to 246,000 vehicles per day for West 2nd Ring Road. As mentioned in section 3.1, the maximum concentrations of Cd, Cu, Pb and Zn simultaneously existed in the samples collected from the West 2nd Ring Road; this could be explicable in terms of the highest traffic volume of this Road. In addition, Pearson's correlation analysis indicated that Pb concentration was signifi-

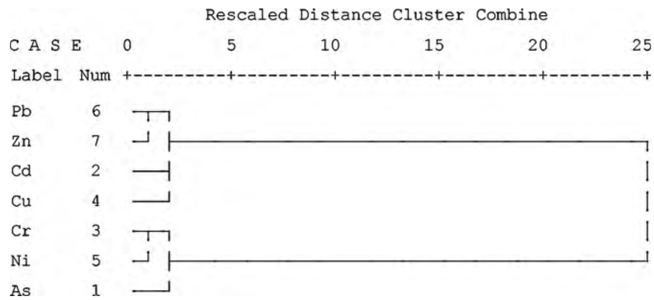

Fig. 3. Hierarchical dendrogram for 7 elements obtained by Ward's method.

cantly positively correlated with traffic volumes ($p < 0.05$) of the 10 roads investigated. It inferred that the heavy metal concentrations in roadside soils were affected by traffic volume.

Cluster analysis (CA) was also performed on the seven investigated heavy metals in roadside soil samples. The results were illustrated in a hierarchical dendrogram. The lower the value on the distance cluster, the more significant the association was [2]. Two distinct clusters can be identified from Fig. 3. The first cluster contained Cd, Cu, Pb and Zn, and the second cluster contained As, Cr and Ni. Clustering of the heavy metals was formed at a low distance criterion less than 5, indicating the close relationship of the heavy metals in each cluster.

The results of descriptive statistic, distribution patterns, cluster analysis and correlation analysis agreed well with each other. All the results divided the heavy metals into two groups: the first included Cd, Cu, Pb and Zn, and the second As, Cr and Ni. The former group was significantly influenced by the urban traffic. Cu and Pb could be emitted from the normal activity and deterioration of vehicles on roads [22,23]. However, the concentration of Pb in the roadside soils in Beijing was the lowest in Table 3, indicating the improvement of the urban environment since the use of the unleaded gasoline in Beijing in 1997. Zn may come from tire abrasion and lubricating oil of vehicles [14,24,25]. In addition, rainfall runoff from roads and pavements also made a small but significant contribution to the Cd concentration in roadside soils, which could be explained mainly by the use of Cd in vehicle tires and fall-out from burning vehicle fuels [26,27].

3.3. Comparison of heavy metal concentrations in roadside soils of Beijing with those in other cities

Heavy metal concentrations in roadside soils in Beijing were compared with those in other cities around the world, and the soil background values of the world were used as the reference values (Table 3). Even after considering the geographical differences, the Pb concentration in Ibadan was almost 10 times as much as the world background. The Zn concentration in Jeddah and Kampala and the Cu concentration in West Bank were much higher than the world background values. These indicated the severe pollution from the local traffic.

The mean value of Cr in Beijing was higher than those in other cities, which was due to the high background concentration of Cr (68.1 ± 15.9 mg/kg) in Beijing [28]. The level of Ni in Beijing was comparable to that reported in other cities. As shown in Table 3, the mean concentrations of Cu and Zn in roadside soils in Beijing were considered middle compared with those in other cities, and the mean concentrations of Cd and Pb were considered low compared with those in other cities. From the city size and the population, the other cities mentioned in this study cannot compare with Beijing. The population in Beijing is 17,000,000, and the total automobile number has reached 3,900,000 in 2009. For the other 5 cities, the population ranged from 80,000 in Galway to 3,400,000 in Jeddah, less than the automobile number in Beijing. Therefore the traffic volume in Beijing is higher than the other cities mentioned here. According to Fakayode and Olu-Owolabi [29], the traffic is divided into 3 levels: heavy traffic (>1500 vehicles per hour), medium traffic (250–1500 vehicles per hour) and low traffic (<250 vehicles per hour). The average traffic volume of the ten studied roads in Beijing was 6,000 vehicles per hour. Based on this classification, the traffic in Beijing is heavy. In addition, the average speed during morning/evening peak hours in Beijing is 18.5 km/h, lower than the internationally recognized traffic jam level (20 km/h). The middle and low concentrations of Cd, Cu, Pb, and Zn may be due to the dry and windy climate in Beijing. Rainfall runoff from urban roadways often contains heavy metals in both particulate and dissolved forms. Because heavy metals do not degrade naturally, high concentrations of them in runoff can result in accumulation in roadside soils [27]. However, the annual precipitation is about 500 mm in Beijing, and 80% of the precipitation occurs in June, July and August, it is dry and windy for most part of the year. In addition, the previous studies showed that the heavy metals were lost from the roadside soils based on the mass balance calculations, and the wind may be the most likely reason for this lost [27,30,31].

As shown in Fig. 2, the prevailing wind direction in Beijing is northwest, especially in winter and spring. In order to analyze the effects of wind on heavy metal distribution in roadside soils, the heavy metal concentrations on the downwind direction side were compared with those on the upwind direction side. In Jingshi Expressway and Airport Expressway with southwest-northeast direction and South 4th Ring Road with east-west direction, the concentrations of Cd, Cu, Pb and Zn on side of downwind direction were higher than those on side of upwind direction, which suggested that the wind could affect the heavy metal distribution in roadside soils. For example, in Airport Expressway, the mean concentrations of Cd, Cu, Pb and Zn in the upwind direction were 0.134, 26, 27 and 66 mg/kg, respectively, and the mean concentrations of Cd, Cu, Pb and Zn in the downwind direction were 0.181, 34, 29 and 83 mg/kg, respectively. In addition, besides the roadside soils, we simultaneously collected another 50 urban soil samples in Beijing (Fig. S1, supplementary material). To understand whether the wind could affect the distribution of heavy metals, the soil samples from site 1–9 along the northwest wind direction in Fig. S1 were analyzed. It can be seen from Fig. S2 (supplementary material) that the concentrations of Cd, Cu, Pb and Zn showed an increasing trend

Table 3
Comparison of mean concentrations of heavy metals (mg/kg) in roadside soils in Beijing and other cities.

Location	As	Cd	Cr	Cu	Ni	Pb	Zn	Reference
Galway, Ireland	–	–	–	16.6	22.1	40.8	81.8	[35]
Jeddah, Saudi Arabia	13.85	–	53.3	–	46.7	47.5	222.2	[14]
Ibadan, Nigeria	–	1.36	51.6	31.4	38.9	307	86.1	[15]
Kampala, Uganda	–	1.12	–	–	–	45.3	140.9	[36]
West Bank, Palestine	–	0.27	42.4	60.4	18.9	87.4	82.2	[37]
Beijing, China	8.1	0.215	61.9	29.7	26.7	35.4	92.1	This study
Background values of the world	6	0.35	70	30	50	35	90	[28]

Table 4
Pollution index (P_i) of the heavy metals of all the roadside soil samples.

		As	Cd	Cr	Cu	Ni	Pb	Zn
Chang'an Avenue ($N=4$)	Mean	0.53	1.11	0.67	0.86	0.66	1.00	0.92
	Range	0.49–0.59	0.95–1.34	0.66–0.69	0.77–0.97	0.65–0.68	0.89–1.08	0.82–1.04
West 2nd Ring Road ($N=4$)	Mean	0.48	1.55	0.67	1.09	0.55	1.17	1.24
	Range	0.44–0.51	0.83–2.42	0.59–0.74	0.94–1.18	0.53–0.60	1.08–1.23	0.77–1.69
Yongdingmen Inner Street ($N=4$)	Mean	0.51	0.57	0.64	0.69	0.64	0.73	0.65
	Range	0.46–0.53	0.45–0.63	0.57–0.72	0.63–0.77	0.53–0.75	0.60–0.74	0.60–0.73
Jingtong Expressway ($N=4$)	Mean	0.65	1.43	0.65	0.81	0.73	0.93	0.99
	Range	0.59–0.74	1.19–1.79	0.55–0.75	0.56–1.15	0.63–0.85	0.77–1.03	0.94–1.02
East 5th Ring Road ($N=4$)	Mean	0.59	1.15	0.70	0.84	0.72	0.83	0.72
	Range	0.44–0.71	0.93–1.54	0.63–0.76	0.66–0.97	0.60–0.80	0.71–0.94	0.62–0.78
Badaling Expressway ($N=12$)	Mean	0.59	1.17	0.66	0.80	0.65	0.87	0.84
	Range	0.44–0.72	0.66–2.07	0.53–0.78	0.66–1.26	0.53–0.73	0.66–1.03	0.64–1.21
Northeast 3rd Ring Road ($N=12$)	Mean	0.62	1.10	0.72	0.87	0.72	0.90	0.92
	Range	0.51–0.71	0.89–2.00	0.60–1.11	0.65–1.18	0.60–1.00	0.63–1.03	0.70–1.20
Airport Expressway ($N=12$)	Mean	0.60	0.95	0.65	0.87	0.69	0.85	0.77
	Range	0.44–0.85	0.63–1.95	0.43–0.80	0.66–1.05	0.55–0.85	0.68–1.02	0.61–0.96
South 4th Ring Road ($N=12$)	Mean	0.44	0.90	0.65	0.80	0.61	0.85	0.81
	Range	0.38–0.51	0.57–1.48	0.60–0.70	0.57–1.04	0.55–0.65	0.71–1.01	0.56–1.10
Jingshi Expressway ($N=12$)	Mean	0.45	1.11	0.68	0.76	0.61	0.90	0.83
	Range	0.30–0.56	0.48–2.23	0.60–0.82	0.49–1.18	0.45–0.78	0.63–1.16	0.60–1.60

from site 1 to site 9, indicating that the heavy metals could move with wind along the wind direction. So we may infer that heavy metals will move away with wind and it is difficult for them to accumulate in dry roadside soils, which leads to the lower levels of Cd, Cu, Pb, and Zn in roadside soils of Beijing. On the other hand, the samples on the side of downwind direction of a road had higher concentrations.

3.4. Assessment of heavy metal contamination levels in roadside soils

Assessment of roadside soil quality for heavy metals was performed by pollution index (P_i), which was suggested by Huang [32]:

$$P_i = C_i/X_a \quad (C_i \le X_a)$$
$$P_i = 1 + (C_i - X_a)/(X_b - X_a) \quad (X_a < C_i \le X_b)$$
$$P_i = 2 + (C_i - X_b)/(X_c - X_b) \quad (X_b < Ci \le X_c)$$
$$P_i = 3 + (C_i - X_c)/(X_c - X_b)(C_i > X_c)$$

In the above formulas, C_i was the observed concentration of specific heavy metal in roadside soils; X_a was the no-polluted threshold value; X_b was the lowly polluted threshold value and X_c was the highly polluted threshold value. The P_i was classified into no contamination ($P_i \le 1$), low contamination ($1 < P_i \le 2$), moderate contamination ($2 < P_i \le 3$) and high contamination ($P_i \ge 3$). According to Soil Environmental Quality Standards in China [33], Grade I is the threshold of natural background value, Grade II is threshold of human health and Grade III is the threshold value for plant growth. So X_a, X_b and X_c could be defined according to Grade I, Grade II and Grade III criteria. They were 15, 30, 40 mg/kg for As; 0.2, 0.3, 1.0 mg/kg for Cd; 90, 200, 300 mg/kg for Cr; 35, 100, 400 mg/kg for Cu; 40, 50, 200 mg/kg for Ni; 35, 300, 500 mg/kg for Pb and 100, 250, 500 mg/kg for Zn, respectively.

The proportions of heavy metal contamination levels for the roadside soil samples close to roads (1 m away from the road) were shown in Fig. 4, none of the roadside soil samples was contaminated with As Cr and Ni, revealing no contamination of As, Ni and Cr. 15.8% of the samples for Cu, 39.4% of the samples for Pb and 28.9% of the samples for Zn were lowly contaminated. For Cd, 42.1% of the samples were lowly contaminated and 13.2% of the samples were moderately contaminated according to Soil Environmental Quality Standards in China, and the mean concentration of Cd of each road in Table 1 was about 2 times as much as the background value of

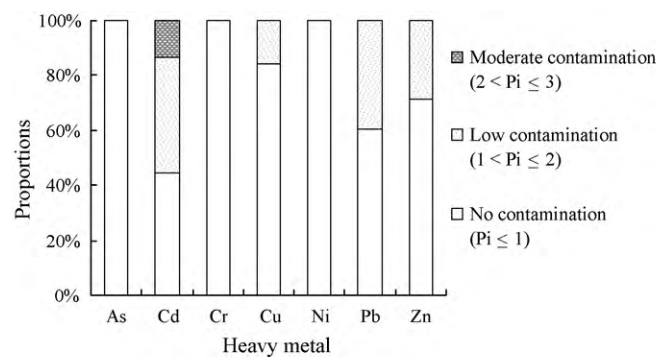

Fig. 4. Proportions of various contamination levels of heavy metals in roadside soil samples (1 m away from the road).

Cd (0.119 mg/kg) in Beijing. In addition, as shown in Table 4, 7 of 10 roads in this study had high mean values of Pi for Cd (over than 1), so it inferred that Cd contamination in roadside soils in Beijing was apparent and noteworthy.

4. Conclusion

The heavy metal concentrations in roadside soils in Beijing were investigated in this work. The concentrations of Cd, Cu, Pb and Zn showed a decreasing trend with increasing distance from the road on both sides in Badaling Expressway, Airport Expressway, South 4th Ring Road and Jingshi Expressway. In addition, the heavy metal concentrations in roadside soils were affected by traffic volume, Pearson's correlation analysis indicated that Pb concentration was significantly positively correlated with traffic volumes ($p < 0.05$) of the 10 roads investigated. The concentrations of heavy metals in roadside soils in Beijing were considered medium or low compared with those in other cities around the world, which may be due to the windy and dry climate in Beijing. The heavy metals could move with wind along the wind direction and the soil samples had higher heavy metal concentrations at the downwind direction.

The calculated values of P_i of heavy metals in roadside soils showed that some roadside soil samples were lowly contaminated with Cu, Pb and Zn. Over 50% of the soil samples were lowly and moderately contaminated with Cd, indicating that Cd contamination in roadside soils in Beijing was apparent and noteworthy. In addition, the roadside soil samples in Beijing were not contaminated with As, Cr and Ni. These findings indicated that more attention should be paid to Cd contamination in roadside soils in Beijing.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jhazmat.2010.05.060.

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