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Evaluation and source identification of trace element contamination of soils in the Qixia lead-zinc mining area, Jiangsu, China

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Abstract
Purpose The Qixia mine is one of the largest lead-zinc mines in Eastern China and has been operational for approximately 60 years. Source identification for trace element contamination of soils in the Qixia mining area has been lacking. This report details the evaluation and source identification of trace element contamination (including Cu, Zn, Pb, Cd, Hg, Cr, As, and Ni) of soils in this area.
Materials and methods Thirty-three soil samples from roadsides and fields in the study area were collected and analyzed. The index of geo-accumulation (I_{geo}) was employed to evaluate contamination. Methods of multivariate statistical analysis were used to determine the probable sources of the pollutants.
Results and discussion The analysis showed that the levels of contamination ranked in the following order: Cd > Pb/Zn> > As/Cu> > Hg > Cr/Ni. In the sampling area nearest the mine, soil samples collected from roadsides showed much higher levels of contamination than those collected from fields away from the roadways. Trace element contamination decreased as the distance from the mine increased. Contamination extended to a distance of approximately 700 m from mineral transportation routes, with the area of greatest impact at 200 m or less. Multivariate statistical analysis and ore composition data suggest that the Cu, Zn, Pb, Cd, and As found in the soil samples originate from anthropogenic sources. Ni and Cr are considered to be at natural background concentrations.
Conclusions This study distinguished between natural and anthropogenic sources of trace element contamination in the soils of the Qixia mining area. The contamination of Cu, Zn, Pb, Cd, and As is linked to the mining activities and is likely due to the transportation of ore concentrates and tailings.

Keywords Geo-accumulation index · Multivariate statistical analysis · Qixia lead-zinc mine · Soil contamination · Source identification · Trace elements

1 Introduction

As China's recent rapid economic development has progressed, environmental degradation has increased. Today, trace element contamination of soils is a major environmental problem in China (Cheng 2003; Wang et al. 2001). Trace elements are usually inert contaminants and can accumulate in soil and threaten human health through direct or indirect pathways (Hough et al. 2004; Pruvot et al. 2006). Ore mining and processing activities are widely believed to be the main source of trace element contamination in China today (Forstner 1995; Moreno-Jiménez et al. 2011). A wide variety of mineral resources in sizeable quantities occur in China, and the country's expanding industrial sector demands rapid access to these resources in useable form (Hu et al. 2010; Shen et al. 2005). However, a lack of oversight in environmental management has led to many instances of improper utilization of mineral resources and consequent environmental disruption (Hu et al. 2010).

Recent environmental research has studied the trace element contamination in China's mining areas. Previous studies have evaluated the levels and extent of such contamination

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and assessed the risk of exposure to human health. Sources of trace element contamination have also been identified through environmental research (Li et al. 2007; Liu et al. 2005; Wang et al. 2010; Zhang et al. 2009; Zhuang et al. 2009). Such studies have supported the belief that soils in many mining areas in China are polluted with trace elements.

China's lead-zinc mineral reserves are some of the largest in the world (Wu 2008), and many regions of China where extraction of these resources is going on have experienced significant soil pollution (Zhang et al. 2012). The study of soil contamination due to the mining and processing of lead-zinc ores has now become an important topic of discussion in China.

The Qixia lead-zinc mine is located in the Qixia District of Nanjing City, Jiangsu Province, China (Fig. 1). The area's climate is classified as subtropical monsoon. Nanjing's mean

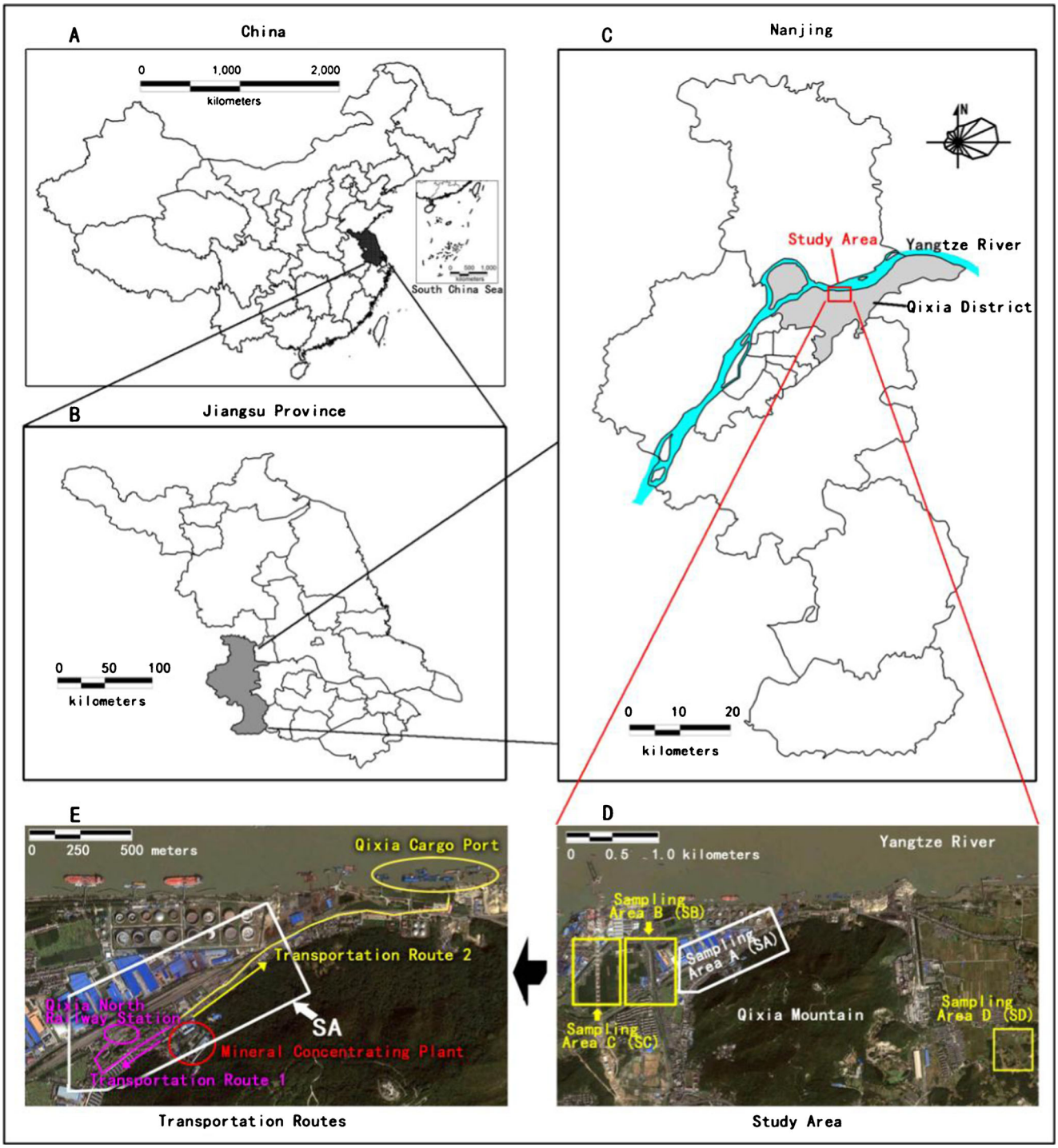

Fig. 1 Location of the study area and sampling areas

annual temperature is 16.7 °C and varies from 2.3 °C in January to 29.5 °C in July. The mean annual precipitation is 1,239 mm, with rainfall occurring mostly in summer. The region's annual prevailing wind directions are east (E), southeast (SE), and northeast (NE) (Fig. 1(C)), with east and southeast winds prevailing in the summer and east and northeast winds prevailing in the winter.

The Qixia mine has been operational for approximately 60 years and is one of the largest lead-zinc mines in Eastern China, with an estimated 4 million tons of lead and zinc reserves. The area surrounding the Qixia mine has suffered serious environmental deterioration, including soil contamination by trace elements. Previous environmental research in the Qixia mining area has evaluated the extent of trace element contamination in soils (Chen et al. 2006; Chu and Luo 2010) and studied the risk of such pollution on human health (Qu et al. 2012). Proper environmental management for the future will require an accurate understanding of the sources of the pollution and whether the contamination is the result of natural or anthropogenic (man-made) origins (Baize et al. 2010; Desaules 2012). Source identification for trace element contamination of soils in the Qixia mining area has been lacking; thus, the relationship between the regional contamination and the mining activities in this area has not been firmly established. Additionally, previous research has evaluated only Cu, Zn, Pb, Cd, Cr, and As, while only a few studies in the area have assessed levels of Ni and Hg.

The present study aims to (1) evaluate trace element contamination of soils near the Qixia mine by Cu, Zn, Pb, Cd, Hg, Cr, As, and Ni; (2) identify the natural and/or anthropogenic sources of each of the trace elements in soils; (3) understand the relationship between trace element concentrations in soils and the Qixia lead-zinc mine; and (4) provide a scientific basis for proper environmental management measures within the Qixia mining area.

Table 2 Seven classes of I_{geo} index

Class	Value	Soil quality
0	$I_{geo} \leq 0$	Practically uncontaminated
1	$0 < I_{geo} \leq 1$	Uncontaminated to moderately contaminated
2	$1 < I_{geo} \leq 2$	Moderately contaminated
3	$2 < I_{geo} \leq 3$	Moderately to heavily contaminated
4	$3 < I_{geo} \leq 4$	Heavily contaminated
5	$4 < I_{geo} \leq 5$	Heavily to extremely contaminated
6	$I_{geo} > 5$	Extremely contaminated

2 Materials and methods

2.1 Description of sampling areas

The ore body of the Qixia lead-zinc mine is located under Qixia Mountain; hence, mining activities are conducted underground. Raw ores mined at Qixia are transported to a mineral concentration plant located on the northwest side of Qixia Mountain (Fig. 1(E)). There are two transportation routes in the Qixia mining area (Fig. 1(E)). One is for transportation of ore concentrates and tailings to the Qixia North Railway Station, and the other is for transportation to the Qixia Cargo Port via truck. The treated wastewater from the ore concentrate is not used in local irrigation, but is discharged into the Yangtze River, located to the north of the mining area, through a discharge channel.

Table 1 Mean values and standard deviations for trace element concentrations (mg/kg) in soils

Sampling area	Soil types	Mean value (standard deviation)							
		Cu	Zn	Pb	Cd	Hg	Cr	As	Ni
A (*N*=21)	Roadside soils (*N*=9)	238 (188)	10,858 (8,482)	2,589 (1,928)	67.4 (50.2)	0.36 (0.29)	30.1 (16.6)	110 (83)	20.1 (4.6)
	Field soils (*N*=12)	59.6 (40.4)	1,065 (738)	468 (443)	5.61 (4.04)	0.19 (0.20)	17.6 (5.1)	42.1 (33.6)	18.4 (4.4)
	Total	136 (153)	5,262 (7,331)	1,377 (1,659)	32.1 (44.7)	0.26 (0.25)	23.0 (12.9)	71.4 (67.6)	19.2 (4.4)
B (*N*=5)	Roadside soils (*N*=2)	69.7 (23.5)	1,256 (1,078)	573 (447)	5.35 (5.04)	0.17 (0)	24.3 (3.0)	43.4 (23.5)	23.8 (1.3)
	Field soils (*N*=3)	33.1 (1.2)	244 (73)	118 (23)	0.72 (0.26)	0.13 (0.05)	22.8 (2.5)	26.3 (15.9)	22.3 (1.8)
	Total	47.7 (23.2)	649 (776)	300 (335)	2.57 (3.58)	0.15 (0.04)	23.4 (2.5)	33.1 (18.8)	22.9 (1.6)
C (*N*=5)	Roadside soils (*N*=2)	27.3 (3.0)	82.0 (6.6)	58.9 (21.2)	0.11 (0.05)	0.08 (0.04)	23.7 (0.1)	9.30 (0.71)	22.8 (1.2)
	Field soils (*N*=3)	24.4 (2.1)	77.5 (7.3)	65.4 (5.7)	0.13 (0.02)	0.13 (0.03)	20.0 (1.4)	8.27 (0.65)	18.1 (1.1)
	Total	25.5 (2.7)	79.3 (6.6)	62.8 (11.9)	0.12 (0.03)	0.11 (0.04)	21.4 (2.2)	8.68 (0.81)	20.0 (2.7)
D (*N*=2)	Field soils	13.1 (0.07)	45.3 (13.3)	24.2 (0.35)	0.20 (0.05)	0.03 (0.01)	16.2 (3.2)	5.80 (1.27)	13.7 (1.9)
Detection limit		0.1	0.5	0.1	0.01	0.01	0.1	0.5	0.1
Background value	Jiangsu (CNEMC 1990)	22.3	62.6	26.2	0.13	0.29	77.8	10	26.7
	Nanjing (GNBVS 1979)	32.2	76.8	24.8	0.19	0.12	59.0	10.6	35

In order to accurately assess the environmental impact of the mining and ore-concentrating activities at Qixia, four sampling areas were selected (Fig. 1(D)). The area within approximately 200 m of the transportation routes, including the mineral concentration plant, was designated as sampling area A (SA) (Fig. 1(E)). Due to the large local residential population and the E and NE prevailing wind directions, the sampling in SA focused on the surrounding area of transportation route 1 (Fig. 1(E)). Sampling areas B (SB) and C (SC) were also selected based on prevailing wind directions and were located downwind of the Qixia mine. SB and SC were located approximately 200~700 and 700~1,200 m away from the transportation routes, respectively. Soil samples in SA, SB, and SC were collected in March 2011. Sampling area D (SD) was selected for additional sampling as a reference area which is not affected by mining activities. SD is located approximately 3 km from the mining areas on the opposite side of Qixia Mountain and is generally upwind of the mining area. Samples in SD were collected in January 2012.

2.2 Sampling

For the study, 33 soil samples were collected from vegetable fields and along roadsides. Figure 3 shows the spatial distribution of the sampling sites. The soil samples collected from the roadsides were collected along the transportation routes within SA and at the edges of residential streets within SB and SC. The roadside soils have been compacted by vehicles or humans, and only the topsoil can pose a health impact to local people. For the soils in the fields in this area, they are always plowed at a depth of over 20 cm for vegetable cultivations. Therefore, soil samples were taken at a depth of 5 cm. For each soil sample (1 kg), three to five subsamples of topsoil were collected and blended. The samples were air-dried, and stones and coarse plant roots or residues were removed. The samples were then thoroughly mixed, crushed, and passed through a 2-mm and 0.149-mm mesh sieve. Finally, the soil samples were stored in polyethylene bottles at ambient temperature prior to chemical analysis.

2.3 Sample analysis

The presence of Hg in the soil samples was detected using thermal decomposition, amalgamation, and atomic absorption spectrophotometry (TDA/AAS) (AMA254, LECO Co., Ltd., USA) according to the USEPA method 7473 (USEPA 1998). The concentrations of other trace elements, including Cu, Zn, Pb, Cd, Cr, As, and Ni, were measured with inductively coupled plasma-mass spectrometry (ICP-MS) (Agilent 7500i, Agilent Scientific Technology Ltd., USA) using the USEPA method 200.8 (USEPA 1994). The detection limit of each measurement was defined as the concentration value, which is numerically equal to three times the standard deviation of ten replicate blank measurements. The detection limits of all measured trace elements are shown in Table 1. Reagent blanks and standard reference materials were used for quality assurance of the trace element analysis. The recoveries of the elements ranged from 90 to 110 %.

2.4 Evaluation of trace element contamination in soils

Trace element contamination in the soil samples was evaluated via the index of geo-accumulation (I_{geo}) proposed by Muller for bottom sediments (Muller 1969) and adapted for use in soil contamination assessments (Ji et al. 2008; Loska et al. 2004; Wei and Yang 2010). The I_{geo} assesses contamination by comparing current

Table 3 Mean I_{geo} values of trace elements in soils in the Qixia mining area

Sampling areas		I_{geo}							
		Cu	Zn	Pb	Cd	Hg	Cr	As	Ni
A	Roadside soils	2.30	6.56	6.12	7.89	1.00	−1.56	2.79	−1.39
	Field soils	0.30	3.21	3.65	4.30	0.08	−2.33	1.40	−1.51
	Total	1.49	5.51	5.21	6.82	0.53	−1.94	2.17	−1.45
B	Roadside soils	0.53	3.45	3.95	4.23	−0.08	−1.86	1.45	−1.14
	Field soils	−0.55	1.08	1.67	1.34	−0.47	−1.96	0.73	−1.24
	Total	−0.02	2.49	3.01	3.17	−0.26	−1.92	1.06	−1.20
C	Roadside soils	−0.82	−0.49	0.66	−1.37	−1.17	−1.90	−0.77	−1.20
	Field soils	−0.99	−0.57	0.81	−1.13	−0.47	−2.15	−0.94	−1.54
	Total	−0.92	−0.54	0.76	−1.25	−0.71	−2.05	−0.87	−1.39
D	Field soils	−1.88	−1.35	−0.62	−0.51	−2.58	−2.45	−1.45	−1.94

and preindustrial concentrations in soils. The I_{geo} index is calculated using following equation:

$$I_{geo} = \log_2\left(\frac{C_i}{1.5B_i}\right) \quad (1)$$

C_i is the measured concentration of the element i in soil, and B_i is the geochemical background value of the element. The constant 1.5 allows analysis of both natural fluctuations in the content of a given substance in the environment and very small anthropogenic influences. Muller (1969) has defined seven classes of I_{geo} as shown in Table 2.

2.5 Statistical analysis

Multivariate statistical analytical methods, including correlation analysis and principal component analysis (PCA), were applied to identify the potential sources of pollution

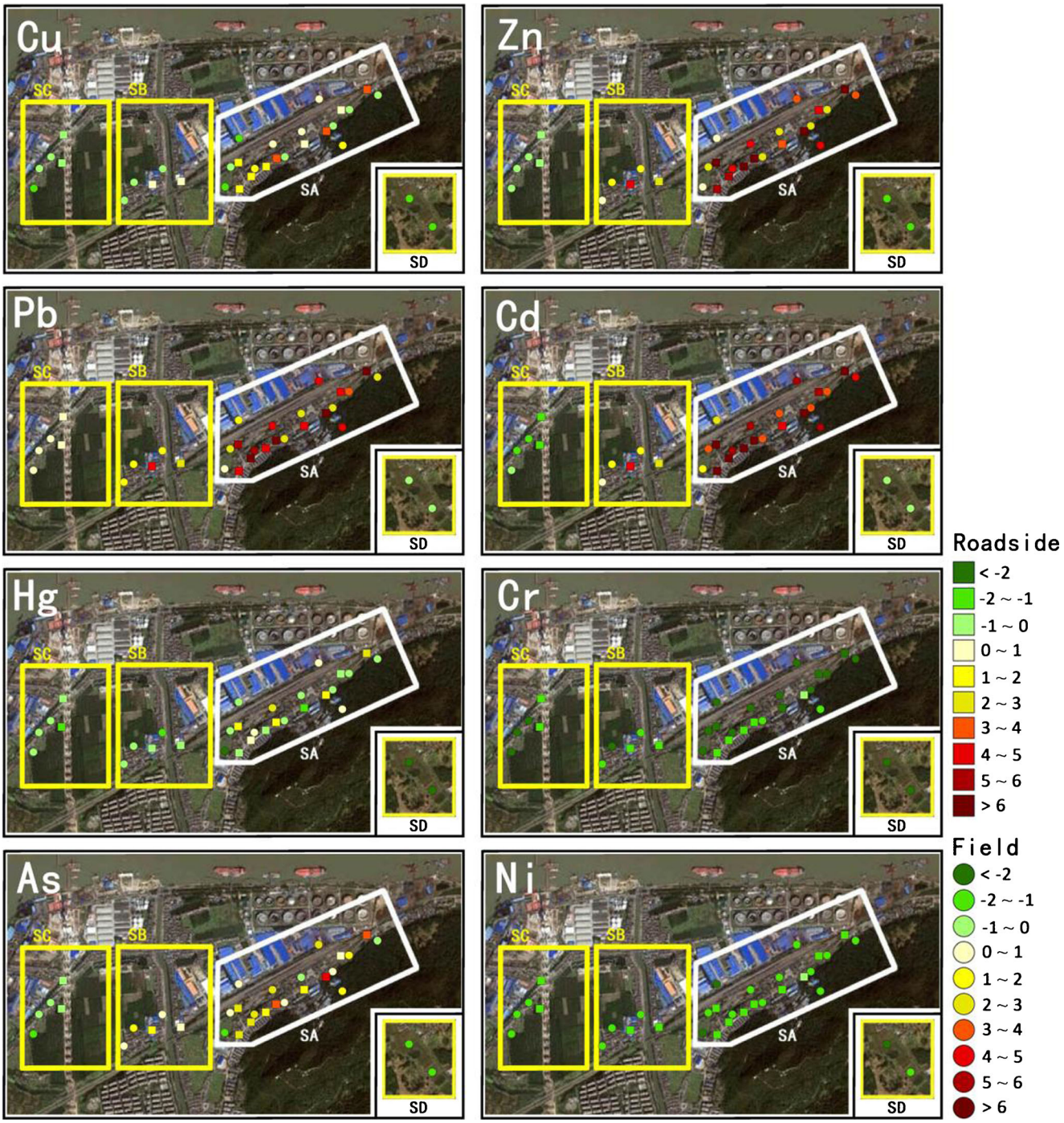

Fig. 2 Spatial distribution of I_{geo} values of roadside and field soils

(Filgueiras et al. 2004; Fu and Wei 2013). All statistical analyses were performed using SPSS 16 for windows.

3 Results

3.1 Trace element concentrations in soils

A total of 33 topsoil samples were collected, including 13 roadside soil and 20 field soil samples. The numbers of samples, detection limits, mean values, and standard deviations of each element found in the four sampling areas are shown in Table 1.

Trace element concentrations in soils varied greatly among the four sampling areas (Table 1). With the exception of Cr and Ni, trace element concentrations decreased as the distance from the mine increased. Concentrations of Cu, Zn, Pb, Cd, and As in soils decreased according to sampling area in the following order: SA>>SB>>SC>SD. Concentrations of Hg were found in the following pattern: SA>SB/SC>SD. Concentrations of Cr and Ni in soils were found to be statistically the same in all four sampling areas.

Varying concentrations of trace elements were found in different soil types. In SA and SB, concentrations of Cu, Zn, Pb, Cd, and As in the roadside soils were significantly higher than those in the field soils. However, differences between roadside soils and field soils within SB were much less than the differences found within SA. In SC, concentrations of Cu, Zn, Pb, Cd, and As found in roadside soils and field soils were consistent with one another. In SA, Hg and Cr contaminations in roadside soils were roughly twice as high as the respective concentrations found in field soils. In SB and SC, no differences were found in Hg or Cr concentration between the different types of soil. Differences in concentrations were found to be smaller as the distance from the mine increased. Because trace element contamination in the roadside and field soils of SC was nearly equal, only field soil samples were collected in the background sampling area (SD). Concentrations of Ni in roadside and field soils were found to be at the same levels in SA, SB, and SC.

3.2 Evaluation of the contamination of trace elements in soils

To evaluate trace element contamination of soils in the Qixia mining area, the background values for soils in Nanjing and the surrounding Jiangsu Province were obtained from existing literature and are shown in Table 1. The background levels for the assessed trace elements in soils in Jiangsu and Nanjing were essentially identical, with the exception of Hg. The background value of Hg in soils in Nanjing (0.12 mg/kg) was lower than that of Jiangsu Province (0.29 mg/kg). The I_{geo} method was applied to evaluate the levels and overall range of contamination. The background values for Nanjing were chosen as the geochemical background values (B_i), as indicated in Eq. (1). The mean I_{geo} values are shown in Table 3. The spatial distribution of I_{geo} values is shown in Fig. 2.

As shown in Table 3, soil contamination by each of the eight trace elements studied occurs in the following order: Cd > Pb/Zn> > As/Cu> > Hg > Cr/Ni. Cadmium was the most prevalent pollutant. The I_{geo} values of Cd in SA and SB were 6.82 and 3.17, respectively. In SC and SD, Cr contamination was virtually nonexistent. Levels of Pb and Zn were slightly lower than the levels of Cd. The I_{geo} values of Pb were 5.21 and 3.01 in SA and SB, respectively, and the values of Zn were 5.51 and 2.49 in SA and SB, respectively. The pollution levels of As and Cu were found to be much lower than the levels of Pb and Zn, but were greater than the level of Hg. The I_{geo} values of As were 2.17 and 1.06 in SA and SB, respectively. In SA, the I_{geo} value of Cu was 1.49, and in SB, only the I_{geo} value of roadside soils was found to be greater than 0 (0.53).

I_{geo} values for Cr and Ni found in the four sampling areas and I_{geo} values of Hg in SB, SC, and SD were all found to be less than 0, indicating that the soils are practically uncontaminated by these elements. The I_{geo} value of Hg in SA was 0.53 and classified as class 1, indicating slight mercury pollution in the Qixia mining area, limited to areas near the transportation routes (SA).

As shown in Table 3 and Fig. 2, the I_{geo} values in different sampling areas indicate that contamination decreases with increasing distance from the mine. The most heavily contaminated area is SA, located approximately 200 m from the mining transportation routes, followed by SB. The I_{geo} values of trace elements were less than 0 in SC, with the exception of Pb, which had the widest contamination range of all the assessed elements. In SC, the downwind sampling area farthest from the mine, the I_{geo} value of lead was 0.76 (class 1), indicating the I_{geo} level of uncontaminated to moderately contaminated. The I_{geo} values of all elements in SD were less than 0.

Table 4 Coefficients of Pearson correlation between the trace elements in soils (n=33)

	Cu	Zn	Pb	Cd	Hg	Cr	As	Ni
Cu	1							
Zn	0.968[a]	1						
Pb	0.961[a]	0.951[a]	1					
Cd	0.919[a]	0.984[a]	0.923[a]	1				
Hg	0.766[a]	0.777[a]	0.773[a]	0.785[a]	1			
Cr	0.765[a]	0.671[a]	0.674[a]	0.574[a]	0.367[b]	1		
As	0.953[a]	0.887[a]	0.958[a]	0.839[a]	0.756[a]	0.708[a]	1	
Ni	0.352[b]	0.262	0.241	0.190	0.161	0.709[a]	0.303	1

[a] Correlation is significant at the 0.01 level (two-tailed)

[b] Correlation is significant at the 0.05 level (two-tailed)

Table 5 Total variance explained for trace elements

Component	Initial eigenvalues			Extraction sums of squared loadings			Rotation sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	6.032	75.396	75.396	6.032	75.396	75.396	5.349	66.865	66.865
2	1.261	15.757	91.152	1.261	15.757	91.152	1.943	24.287	91.152
3	0.380	4.744	95.897						
4	0.194	2.419	98.316						
5	0.089	1.119	99.435						
6	0.029	0.356	99.791						
7	0.015	0.184	99.975						
8	0.002	0.025	100.00						

3.3 Source identification by multivariate statistical analysis

Evaluation of trace element concentrations shows that the soils in Qixia mining areas are contaminated by Cu, Zn, Pb, Cd, As, and Hg. However, the evaluation of contamination alone does not prove that pollution was caused by the mining and processing activities in the area. To address this issue, multivariate statistical analysis was used to identify the probable sources of the trace elements found in the soil samples.

Table 4 shows Pearson's correlation coefficients for all of the elements assessed. The coefficients for combinations of Cu, Zn, Pb, Cd, Hg, and As were >0.7 ($p<0.01$), indicating that these elements may come from the same source. Additionally, Ni was shown to be significantly correlated with Cr ($r=0.709$, $p<0.01$), indicating that these two contaminants may originate from the same source. However, Cr is also highly correlated with Cu ($r=0.765$, $p<0.01$), As ($r=0.708$, $p<0.01$), Zn ($r=0.671$, $p<0.01$), and Pb ($r=0.674$, $p<0.01$). Thus, the origins of Cr may or may not be the same as those of Cu, Zn, Pb, Cd, Hg, and As.

To further identify the sources of contamination, PCA was applied. The total variance explained for the eight trace elements assessed is shown in Table 5. The KMO value is 0.758, indicating a good fit for the PCA. Two principal components were extracted with eigenvalues greater than 0.9 and explained 91.2 % of the total variance. The loading plot of the rotated component of trace elements is shown in Fig. 3(A).

PC1, which contains Cu, Zn, Pb, Cd, Hg, and As, explained 66.9 % of the total variance. Therefore, the elements in PC1 are considered to have originated from the same source. When the results of the soil sampling were factored in, it was determined that the elements in PC1 originated primarily from anthropogenic sources (i.e., mining and processing activities). PC2 contains Ni and Cr and explains 24.3 % of the total variance. Because Ni and Cr contamination was practically nonexistent, these elements are considered to be at natural background concentrations.

4 Discussion

The sources of the trace element contamination in the soils of the Qixia mining area were identified through PCA. To further validate these results, the mineral compositions of raw ores

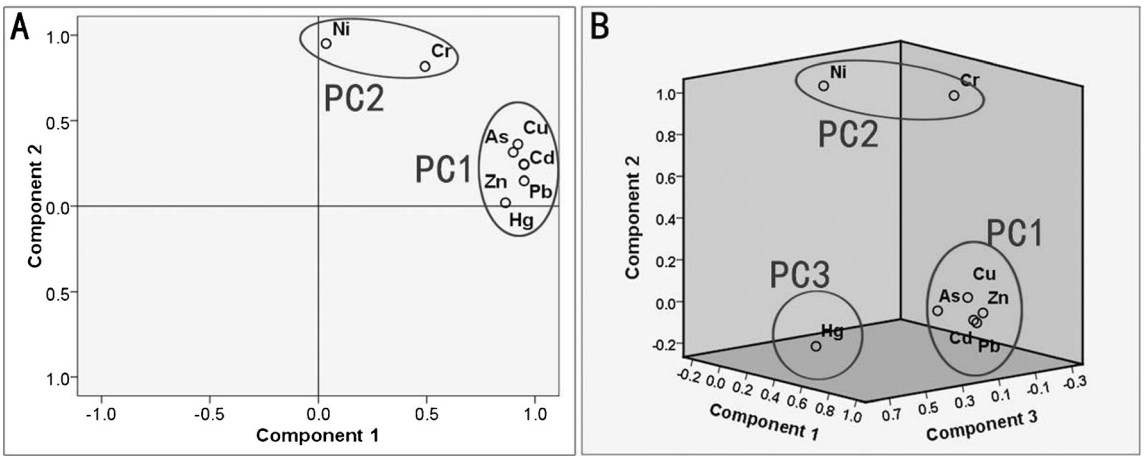

Fig. 3 The loading plots of rotated components. **A** For all samples without constraining to extract three components; **B** excluding two Cr outliers and constraining to extract three components

obtained from the Qixia mine were obtained from published literature (Table 6). Since the Qixia mine is a lead-zinc mine, the concentrations of Pb and Zn in the ores as expected are very high. Copper, Cd, and As are typically associated with Pb and Zn; thus, their concentrations in the ores were very high. A lack of effective pollution control at the Qixia mine is believed to contribute to the Cu, Zn, Pb, Cd, and As contamination found near the mine. Concentrations of Cr and Ni found in the raw ore are less than 50 mg/kg. The mineral compositions of the ores further prove that Cu, Zn, Pb, Cd, and As pollution in the soils predominately originate from the mine.

In the initial correlation analysis, Cr was found to be strongly correlated with Cu, As, Zn, and Pb. However, in the soils analyzed, Cr appears to be at natural background concentrations. An in-depth analysis of the concentration data shows that two roadside soil samples in SA had high Cr concentrations of 65.4 and 42.1 mg/kg, while the concentrations in the other samples were lower than 36 mg/kg. These Cr concentrations are not considered to be abnormal, however, because they are lower than the background value for Jiangsu (77.8 mg/kg) and only slightly higher than the background value for Nanjing (59 mg/kg). The I_{geo} values of Cr within the two samples noted above are less than 0. When these two samples were removed from consideration, correlation analysis showed Cr to only be significantly correlated with Ni (r= 0.738, p<0.01), but not with other elements (r<0.4, p>0.05). The results of correlations among the elements of Cu, Zn, Pb, Cd, Hg, As, and Ni are unchanged following the removal of these outliers. And, the loading plot of the reanalysis of PCA is the same as Fig. 3(A).

With regard to Hg, the I_{geo} and PCA results showed Hg to be a minor contaminant in SA and to be included in PC1. However, since the Hg concentrations in soils and raw ores are both very low, a relationship between Hg contamination in the Qixia soils and mining activities remains poorly established. To address this issue, an additional PCA was constrained to extract three factors. The results of this analysis showed Hg to be included in PC3 (Fig. 3(B)), indicating that the contamination pattern of Hg is not the same as those of the other elements in PC1 or PC2. Due to the low levels of Hg in soils and raw ores, further study to determine its source appears to be unnecessary.

Table 7 Mortality rate from lung cancer and bronchiolar carcinoma in the study area and Nanjing City

Area	Population (2010)	Average annual mortality rate from lung cancer and bronchiolar carcinoma (per 10^5)
SA + SB + SC	6,200	21.5[a]
SA	420	238.1[a]
SB + SC	5,780	5.8[a]
Qixia District	395,400	31.9[b]
Nanjing	8,004,680	42.6[b]

[a] Data of the years 2008–2010

[b] Data of the year 2010

Wastewater from the ore concentrate at Qixia is discharged directly into the Yangtze River through a discharge channel and is not used for local vegetable production. Soils in the area, therefore, are not directly polluted by wastewater. Also, since mining activities at Qixia are conducted underground, their impact on surface soil is limited. Figure 1(e) shows the two transportation routes used at the mine. The on-site investigation revealed that no effective environmental measures are in place to diminish pollution during the transportation phase. Ore concentrates and tailings often fall onto the road during transport to the railway station or cargo port. Results of this study show roadside soils to be more contaminated by trace elements than field soils in the sampling area nearest the Qixia mine (SA). These differences diminish outside SA, as distance from the mining area increases. These findings suggest that transportation may be the primary means of distribution for the contaminants.

Cancer mortality data (2008–2010) for the study area and Nanjing City were collected from the Chinese Center for Disease Control and Prevention. Population data were obtained from local government statistics. These data show the annual mortality rate from lung cancer and bronchiolar carcinoma in SA to be much higher than that of the study area as a whole (Table 7). Four deaths were attributed to lung cancer and bronchiolar carcinoma in the study area during this

Table 6 Multi-element analysis of ores in Qixia lead-zinc mine from literature (unit: mg/kg)

Samples	Cu	Zn	Pb	Cd	Hg	Cr	As	Ni	References
Raw ore sample 1	440	45,100	19,800	260	N.D.	N.D.	920	N.D.	(Cai 2007)
Raw ore sample 2	560	57,400	54,800	62	N.D.	N.D.	5,700	N.D.	
Raw ore sample	2,600	70,600	41,400	490	N.D.	<50	1,000	<50	(Wei et al. 2008)
The upper part of the ore body	N.D.	N.D.	N.D.	N.D.	0.6–4.5	N.D.	N.D.	N.D.	(Hu 1985)
The middle part of the ore body	N.D.	N.D.	N.D.	N.D.	0.26–3.5	N.D.	N.D.	N.D.	
The lower part of the ore body	N.D.	N.D.	N.D.	N.D.	0.4–1.8	N.D.	N.D.	N.D.	

N.D. no data

period. Overall, the death rate was $21.5/10^5$, which was lower than the death rates of Qixia District and Nanjing City. However, three of these deaths occurred in SA. Since the population of SA is only 420, the death rate from lung cancer and bronchiolar carcinoma in SA was $238.1/10^5$. The high concentrations of trace elements and raised dust due to the transportations are likely affecting the health of the population in SA. However, due to the small population base in the study area, uncertainties about this relationship persist. To confirm the likelihood of adverse health effects on the local population by trace element-laden dust pollution along mining transportation routes, future epidemiological studies are needed.

5 Conclusions

The Qixia lead-zinc mine, which is one of the largest lead-zinc mines in Eastern China, has been operational for 60 years and has generated a serious trace element pollution problem in the area. The I_{geo} values of the eight trace elements assessed in soils show that the area in the vicinity of the Qixia mine was heavily polluted by Cd, Zn, and Pb and to a lesser extent by Cu and As. Mercury contamination was slight. Nickel and chromium levels found in study soils are believed to reflect natural background concentrations.

This study is the first to distinguish between natural and anthropogenic sources of trace element contamination in the soils of the Qixia mining area. Multivariate statistical analysis and ore composition data show that contamination of soils by Cu, Zn, Pb, Cd, and As is due to mining and ore processing activities. Further investigation indicates that transportation of ore concentrates and tailings may be the main means of dispersal of trace elements from the mining operations. The findings in the present study suggest that rigid control and management measures for trace element pollution from the mining activities are urgently needed at the Qixia lead-zinc mine.

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