



Spatial distribution, source, and risk assessment of soil toxic metals in the coal-mining region of northwestern China

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Abstract

Soil toxic metal pollution is one of the most prominent environmental problems in the rapid industrialization of societies because of the considerable harm caused to human existence and the surrounding environments. Soil samples from 80 sampling sites around the coal-mining region of northwestern China were collected, and the geo-accumulation index (I_{geo}), pollution index (PI), and potential ecological risk index (PRI) were calculated, with the objective of assessing the soil toxic metal pollution level. The results showed that the average concentrations of Cr, Hg, and As exceeded the regional background values and the national soil environmental quality standards of China, while those of Zn, Cu, and Pb were below both soil-quality standards. The I_{geo} of toxic metals was ranked as $Hg > As > Cr > Pb > Cu > Zn$. The I_{geo} of Zn, Cu, and Pb indicated low pollution; the soils were moderately polluted by Hg and slightly moderately polluted by As, while other elements presented low pollution levels. The PI values of both As and Hg were higher than 3, indicating heavy pollution of these two metals. Zn and Cu originated from parent material, while Cr, As, and Hg originated from human activities such as coal burning, chemical industry, and traffic. Pb was influenced by both natural factors and human activities. The results of ecological risk assessment in the region showed that Zn, Cu, Cr, and Pb in all sample sites presented a low ecological risk, while Hg presented a high ecological risk. Therefore, Hg is the most hazardous toxic metals in the region. The spatial distribution trends revealed that the high-risk regions were found to be the industrial region of the study area. The research results provide a scientific basis and technical support for monitoring and early warning of soil pollution in arid regions.

Keywords Coal mining · Toxic metal pollution · Pollution index (PI) · Risk assessment · Spatial distribution

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Introduction

Toxic metal pollution in soil is a serious environmental problem due to the threat that it poses to natural ecosystems, agricultural land, and human health (Begum et al. 2009; Qiu et al. 2011; Marrugo-Negrete et al. 2017; Sawut et al. 2018a; Yang et al. 2018; Eziz et al. 2018). Therefore, it has become an issue of great concern to international researchers (Morton-Bermea et al. 2009; Sun et al. 2010; Hu et al. 2014; Qing et al. 2015; Lazo et al. 2017; Spahić et al. 2018; Lü et al. 2018). Toxic metals include the 11 most environmentally important metal(-loid)s, i.e., Zn, Cu, Cr, Pb, Hg, and As (Alloway 2013; Peng et al. 2018). The process of monitoring and evaluating the soil quality of regional environments involves categorizing the toxic metals that are present. Toxic metal pollution is mainly caused by natural geologic background and human activity, which is believed to be the main source of pollution

(Facchinelli et al. 2001; Wei and Yang 2010; Desaulles 2012; Li et al. 2014; Islam et al. 2015; Sawut et al. 2018b). There are numerous examples of soil-polluting human activities (Li et al. 2011; Zhao et al. 2014). Mining activities are a major anthropogenic source of toxic metal pollution and are associated with fatal diseases (Lăcătușu et al. 2009). Some diseases such as endemic arsenosis, fluorosis, selenosis, and lung cancer are caused by mining combustion (Finkelman et al. 2002; Dai et al. 2004, 2007, 2012; Belkin et al. 2008). Mineral excavation, transportation, smelting, refining, disposal of tailings, and wastewater can also inhibit soil microbial activity (Nabulo et al. 2010; Jiao et al. 2012; Biljana et al. 2018).

Geographic information systems (GISs) are widely used to map the spatial variation of soil toxic metal pollution in unsampled areas (Gong et al. 2010; Kharroubi et al. 2012; Mamat et al. 2014; Li et al. 2015, 2016; Krishnakumar et al. 2017; Zhang et al. 2018). Li et al. (2004) used the GIS method to analyze the spatial relationships of Ni, Cu, Pb, and Zn in the soil and to evaluate the severity of pollution; Pekey (2006) mapped the distribution of the concentrations and enrichment factors for toxic metals; Carr et al. (2008) created elemental spatial distribution maps for Galway City; Davis et al. (2009) determined the potential sources of nine metals in surface soils; and Zhang et al. (2009) combined multivariate statistical and geostatistical analysis to categorize the source of toxic metals (Cu, Zn, and Pb; Cd; and Ni). Mamat et al. (2014) analyzed the spatial distribution of toxic metals and determine the relationship between land use types and soil source materials in Yanqi basin in northwest China. Zhang et al. (2018) mapped the spatial distribution of soil metal concentrations in Chinese soils presented.

China is one of the largest consumer and producer of coal in the world. The high volume of coal use in China has focused attention on the amounts of toxic trace elements released from coal mining and combustions (Dai et al. 2012; Zhang et al. 2012; Li et al. 2014; Dai et al. 2015; Sawut et al. 2018b). The Eastern Junggar open coal mine is one of the biggest open coal mines in China; its coalfield has large coal reserves, thick coal seams, good coal quality, and good storage conditions. The predicted reserves are 390 billion tons and account for 7.2% of China's coal reserves (Xia 2014). Along with the development of the regional economy and increasing demands for energy sources, exploitation of coal resources has increased since 2006 in this region. Although surface mining has greatly enhanced social and economic development, it has caused several environmental problems, especially open-pit coal mining, which has damaged the soil and vegetation and has changed the hierarchical structure of natural soils. The toxic metals that occur naturally in the soil environment are relatively stable and resistant to biodegradation (Gergen and Harmanescu 2012). To manage contaminated areas and to control further pollution of the soil, it is essential to understand the extent of the toxic metals within this

area (Markus and McBratney 2001; Morton-Bermea et al. 2009). Toxic metal pollution in arid regions has become a problem, which should be tackled by identifying spatial distributions of pollution and by carrying out risk assessments. These investigations can play an important role in restoring damaged ecosystems, protecting soil environmental quality, and developing a scientific basis for conducting sustainable coal-mining activities.

The main objectives of the present study are the following: (1) the determination of spatial variation of Zn, Cu, Cr, Pb, Hg, and As in the Junggar coal mine area; (2) the identification of pollution sources of toxic metals; and (3) the characterization of their spatial variability for risk assessment in the study area.

Data sources and methods

Study area

The study area was located to the north of Tianshan Mountain, east of the Junggar Basin (44° 20'–45° 10' N, 88° 36'–89° 50' E) in the Xinjiang Uyghur Autonomous Region of northwestern China (Fig. 1). The region is approximately 90 km from the east to west and has a width of 60 km from the north to south, totaling an area of approximately 5400 km². The region is east of the Gurbantonggut desert and has an elevation that increases from 450 to 800 m as one travels from the south to north. The region is in a continental desert climate temperate zone with a mean annual temperature of 7.0 °C, mean annual precipitation of 183.5 mm, mean annual potential evaporation rate of 2042.5 mm, and an average annual wind speed of 2.0 m/s (Xia et al. 2016).

The main soil type's attributes in the study area are shown in Table 1. The soil types in this area mainly consist of saline soil, eolian sandy soil, gray-brown desert soil, gypsum brown desert soil, and desert alkali soil. Soil organic matter (SOM) is the most important adsorbent for metals; thus, it was considered to be an important factor to determining the species and bio-availability of soil toxic metals (Shi et al. 2012; Rennert and Rinklebe 2017). The descriptive statistics of the SOM and pH are shown in Table 2. In this study, the mean soil organic matter (SOM) content ranged from 0.26 to 95.9 mg/kg, mean value of SOM is 6.35 g/kg, and the coefficient of variation (CV) is 160%, belonging to a large variation; it was explained that SOM is unstable and there exist large differences of SOM between the different sample sites in this region. Soil pH was found to play the most important role in determining metal speciation, solubility from mineral surfaces, and movement (Zhao et al. 2010; Zeng et al. 2011; Rennert et al. 2018). From Table 2, it can be seen that pH value ranged from 7.16 to 8.86; the mean value of pH is 8.31; and the coefficient of variation (CV) is 55.45, belonging to middle variation, and the

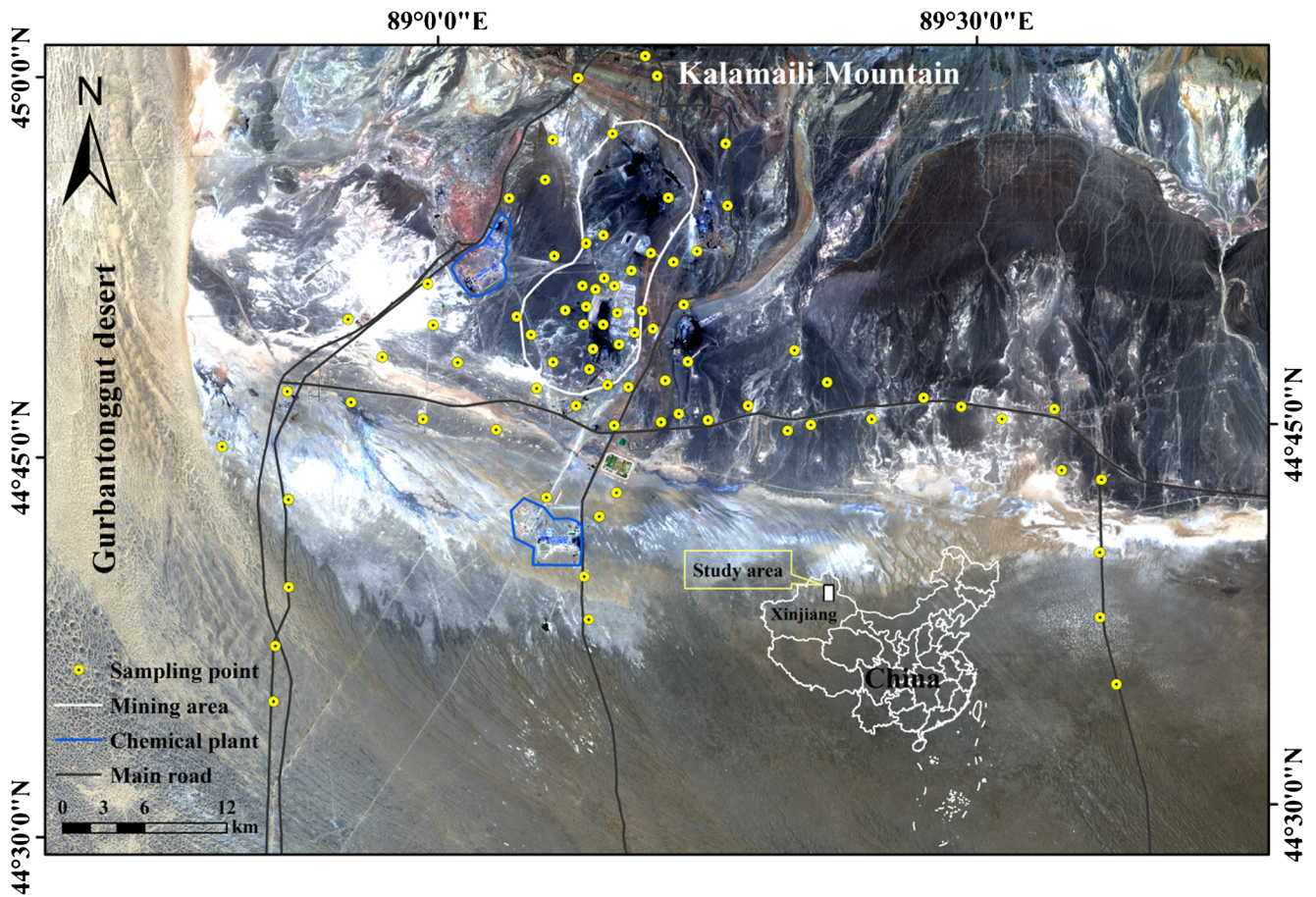


Fig. 1 Sketch map of the study area

soil presents alkalinity. These results explain that the sampled soils covered a wide arrange of SOM and pH, being suitable for studying the toxic metal contamination in this region. In the past 10 years, coal-mining factories and chemical plants have been established in this area and have formed an industrial belt. Open-pit coal mines, chemical plants, vehicles, and other industries have led to soil toxic metal pollution in this region (Liu et al. 2015).

Soil sampling and chemical analysis

In this study, a total of 80 soil samples were collected in July 2015. The geographical coordinates of sampling stations are plotted in Fig. 1. The soil sampling depth was 0–20 cm. A hard plastic shovel was used to collect 1 kg of soil for each sample. Each soil sample was mixed in a sampling bag, numbered, and sealed. The positions of soil sampling sites and

Table 1 Main soil type attributes in the study area (depth, 0–20 cm) (Xia 2014)

Soil types	Saline soil	Eolian sandy soil	Gray-brown desert soil	Gypsum brown desert soil	Desert alkali soil
Sand grains (%)	48.00	89.00	89.00	34.00	40.00
Powder particle (%)	36.00	6.00	6.00	44.00	30.00
Clay (%)	16.00	5.00	5.00	22.00	30.00
Compactness (kg/dm ³)	1.30	1.40	1.40	1.45	1.48
Gravel (%)	7.00	10.00	10.00	2.00	5.00
Calcium carbonate (%)	29.50	0.00	0.00	16.40	3.00
Gypsum (%)	15.10	0.00	0.00	1.50	0.00
Alkali (%)	31.00	2.00	2.00	3.00	13.00
Salt (dS/m)	42.80	0.10	0.10	3.50	0.10

Table 2 Descriptive statistics of the SOM and pH value

Element	Sampling points, <i>n</i>	Maximum	Minimum	Mean	Standard deviation	Coefficient of variation (%)
SOM (g/kg)	80	95.9	0.26	6.35	10.15	160
pH value	80	7.16	8.86	8.31	0.46	55.45

sampling dates were recorded using a GPS. The soil samples were taken to the laboratory; air dried; pushed through a 2-mm nylon sieve, purged of plant roots, stones, and other substances; and finally passed through a 0.25-mm nylon sieve for complete dissolution.

Digestion with a mixture of concentrated HCl–HNO₃–HF–HClO₄ acid was performed on 0.5 g of each soil sample (CEPA 1995). After preparing the soil samples, atomic fluorescence spectrometry (AFS) was used to measure the contents of Hg and As, and inductively coupled plasma atomic emission spectrometry was used to measure the concentrations of Zn, Cu, Cr, and Pb (Qing et al. 2015; Liang et al. 2017). Quality assurance and quality control (QA/QC) were followed in accordance with the National Reference Materials of China. To guarantee the accuracy of each measurement, blank sample measurements were carried out. The recovery of each toxic metal in each sample was between 97.4 and 101.3%.

Data analyses

Descriptive statistical analyses

Descriptive statistics, Pearson's correlation coefficient analysis, and principal component analysis (PCA) were performed using the SPSS20.0 software package (IBM, Armonk, NY, USA). The geo-accumulation index and potential ecological risk index were processed using Microsoft Excel 2007. Spatial variation of the heavy metals in soil was performed using Arc GIS 10.2 (ESRI, NY Str., Redlands, USA).

Inverse distance-weighted interpolation

Spatial interpolation was achieved using the inverse distance weighting (IDW) interpolation method with Arc GIS10.2. The IDW interpolation method is a common method used in soil-quality surveys in which GIS is integrated with multivariate statistical analysis (Lee et al. 2006; Iñigo et al. 2011; Huang et al. 2015; Bower et al. 2017). The IDW interpolation method is frequently used to perform spatial interpolation due to its fast implementation, ease of use, and precise prediction of unknown data (Lu and Wong 2008; Hou et al. 2017); it makes the fundamental assumption that the interpolating surface should be influenced more so by nearby points than by distant

points. The interpolating surface is a weighted average of the scatter points, and the weight assigned to each scatter point diminishes as the distance from the interpolation point to the scatter point increases. The values of unknown points are calculated with a weighted average of the values available from the known points (Shahbeik et al. 2014). The IDW method employs a deterministic estimation method that is based on the weighted inverse distance of points (Eq. 1). Factors that affect the model accuracy include the distance power, the minimum and maximum number of adjacent points, and the search radius (Ghazanfari et al. 2017). The IDW interpolation method can be formulated as follows:

$$Z_0 = \frac{\sum_{i=1}^n Z_i d_i^{-m}}{\sum_{i=1}^n d_i^{-m}}, \quad (1)$$

Where Z_0 is the estimated value for an interpolated point, Z_i is a known value, d is the distance from points without sampling to the estimation point, n is the total number of samples, and m is the distance power.

Geo-accumulation index

The geo-accumulation index (I_{geo}) is a quantitative standard for evaluating heavy metal pollution in deposit substances. It was proposed by Müller (1969); therefore, it is also called the Müller index. The geo-accumulation index is classified into seven classes, each of which represents the heterogeneous pollution degree (Förstner and Müller 1981). The geo-accumulation index is widely used for evaluating soil toxic metal pollution (Wei et al. 2009; Li et al. 2014):

$$I_{geo} = \log_2[C_n / (1.5 \times B_n)], \quad (2)$$

Where I_{geo} is the geo-accumulation index, C_n is the measured value of the toxic metals in soil, and B_n is the background value of the soil. In this study, we used the soil background value of Xinjiang (CEPA 1995, CNEMC 1990). The classification of toxic metal pollution is shown in Table 3.

Pollution index

The pollution index (PI) is defined as the ratio of the element contents in a soil sample to the background contents of the corresponding element in Xinjiang soil (CNEMC 1990). The

Table 3 Classification of soil toxic metal pollution

I_{geo}	Grade	Pollution level
< 0	1	Not polluted
0–1	2	Slight-moderate pollution
1–2	3	Moderate pollution
2–3	4	Moderate-strong pollution
3–4	5	Strong pollution
4–5	6	Strong-extreme pollution
> 5	7	Extreme pollution

PI of each element was calculated and classified as either low ($PI \leq 1$), medium ($1 < PI \leq 3$), or high ($PI > 3$) (Wu et al. 2015).

Potential ecological risk index

The use of the potential ecological risk index (PRI) to assess the ecological risk of soil toxic metals was proposed by the Swedish scientist Hakanson in 1980 (Hakanson 1980). The PRI method is used to show the pollution degree of a single toxic metal and to evaluate the environmental risk of several elements (Cai et al. 2015; Qing et al. 2015). The PRI is calculated using the following equations:

$$PRI = \sum_i^n E_r^i \tag{3}$$

$$E_r^i = T_n^i \times C_r^i \tag{4}$$

$$C_r^i = \frac{C^i}{C_n^i}, \tag{5}$$

Where PRI is the sum of the potential ecological risk index of the toxic metals in soil, E_r^i is the potential ecological risk coefficient of a certain toxic metal, T_n^i is the toxicity coefficient, C_r^i is the pollution factor of a toxic metal, C^i is the measured value of the toxic metals in soil, and C_n^i is the background value of the toxic metals. In this study, the toxicity coefficients of Zn, Cu, Cr, Pb, Hg, and As are 5, 10, 2, 5, 40, and 10, respectively (Hakanson 1980; Pejman et al.

2015). Hakanson (1980) defined five categories for E_r^i and four categories for PRI, as shown in Table 4.

Results and discussion

Toxic metal contents in soil

Table 5 shows that the average contents of Zn, Cu, Cr, Pb, Hg, and As were 47.84, 19.28, 68.51, 16.69, 0.28, and 33.48 mg/kg, respectively. Among the toxic metals, Cr, Hg, and As exceeded the background value of Xinjiang (CEPA 1995, CNEMC 1990) by 1.4, 16.4, and 2.9 times, respectively, and exceeded the second grade of national soil quality standards (GB15618-1998) by 1.1, 4.3, and 2.9 times, respectively. The toxic metals Zn and Cu were lower than the soil background value of Xinjiang and the national standard, but the maximum toxic metal contents exceeded both standards. The toxic metal content was ranked as $Cr > Zn > As > Cu > Pb > Hg$. The CV of Zn, Cu, Cr, Pb, and As was 22.44%, 30.51%, 52.08%, 33.28%, and 14.45%, respectively, indicating moderate variation ($10\% < CV < 100\%$). The CV of Hg was 228.67%, indicating high variation ($CV > 100\%$). The content of Hg was higher than that of other metals, and this element was distributed randomly, indicating that Hg is readily affected by external factors and possibly originates from man-made sources.

Table 6 depicts the correlation results between different toxic metals and shows a moderate positive correlation between Zn and Cu ($R^2 = 0.67, P < 0.01$), indicating that Zn and Cu possibly originate from the same pollutant source (Li et al. 2015). There were weak correlations between Zn-As, Cu-Cr, Cu-As, Pb-Hg, and Pb-As, with correlation coefficients of 0.35, 0.40, 0.41, 0.33, and 0.33, respectively. The correlations of the other toxic metals were lower than 0.30 ($P < 0.01$), demonstrating weak correlations.

To further understand the relationship between toxic metals and their sources, principal component analysis (PCA) was performed (Wu et al. 2014). The PCA results of six toxic metals are shown in Table 7; there were two principal components: the loading capacities of Zn and Cu were 0.88 and 0.84, respectively, on PCA1. The average contents of these two elements

Table 4 Classification of the ecological risk coefficient (E_r^i) and potential ecological risk index (PRI) of toxic metals

E_r^i value	Ecological risk levels	PRI value	Grades of potential ecological environmental risk
$40 \leq E_r^i < 80$	Moderate risk	$150 \leq RI < 300$	Moderate risk
$80 \leq E_r^i < 160$	Considerable risk	$300 \leq RI < 600$	Considerable risk
$160 \leq E_r^i < 320$	High risk	$RI \geq 600$	Very high risk
$E_r^i \geq 320$	Very high risk		

Table 5 Descriptive statistics of toxic metals in soil

Elements	Ranges (mg/kg)	Median (mg/kg)	Average (mg/kg)	Standard deviation (mg/kg)	Coefficient of variation (%)	Kurtosis	Skewness	Background values in Xinjiang (mg/kg)	National standard (mg/kg)
Zn	25.47–81.20	48.33	47.84	10.74	22.44	1.17	0.63	68.80	74.20
Cu	9.05–42.35	19.02	19.28	5.88	30.51	2.32	1.01	26.70	22.60
Cr	18.0–158.69	53.46	68.51	35.68	52.08	0.29	1.22	49.30	61.00
Pb	7.22–33.00	16.03	16.69	5.55	33.28	0.20	0.62	19.40	26.00
Hg	0.05–3.56	0.07	0.28	0.65	228.67	14.44	3.81	0.017	0.065
As	2.87–68.70	35.77	33.48	10.07	14.45	2.14	−0.18	11.20	11.20

were close to the soil background value of Xinjiang, and relatively low CV values were observed. In addition, there was a strong correlation between these elements. Therefore, it was surmised that the two metals originated from the soil parent material. On PCA 2, the loading capacities of Cr, Hg, and As were 0.67, 0.84, and 0.63, respectively. The average contents of these elements in soil exceeded the background value of Xinjiang and the national standards value and were sensitive to external factors. Open-pit coal mining and other human activities greatly increase the contents of toxic metals in soil. The loading capacity of Pb was 0.55 and 0.48 on PCA1 and PCA 2, respectively, indicating that the element was affected by both natural and human factors.

Spatial distribution of toxic metals

The spatial distribution of six toxic metals in soil is shown in Fig. 2. The red color represents higher contents whereas the blue color represents lower contents. The spatial distributions of Zn and Cu were similar. The peak values of the two elements appeared around the coal-mining area and near the industrial area, indicating that these metals have the same pollution sources. The two metals primarily originated from soil parent materials, due to the fact that they were both affected by the natural factors of topography and landforms (Liu et al. 2015). Higher Cr contents were presented along the road and in the mining area, where human activities are the most frequent. This explains that Cr accumulation in soil was due to

Table 6 Correlation matrix of soil toxic metals

	Zn	Cu	Cr	Pb	Hg	As
Zn	1					
Cu	0.67**	1				
Cr	0.29**	0.40**	1			
Pb	0.17	0.16	0.28**	1		
Hg	−0.01	0.06	−0.08	0.33**	1	
As	0.35**	0.41**	0.05	0.33**	0.16	1

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

open mining and other industrial activities (Yao et al. 2013; Liu et al. 2016).

High contents of Pb were mainly distributed around the coal-mining area, chemical plant, and along the road, and uniform distributions were observed in other parts of the study area. Human activities such as automobile emissions play a dominant role in the enrichment of Pb in surface soil (Huang et al. 2007; Soltani et al. 2015). Automobile activity on the road to transport coal results in waste gas emissions and Pb accumulation in soil. The uniform distribution of lead in the study area indicated that huge amounts of Pb exist in soil parent material. Liu et al. (2011) study showed that Pb is readily affected by geogenic and anthropogenic factor influences. Therefore, geogenic and anthropogenic factors are considered to be the main influential factors of Pb distributions.

Relatively higher contents of As were distributed around the coal mine, chemical plant, and roadside, likely due to traffic and coal combustion sources (Lu et al. 2009). Anthropogenic emissions of As to the atmosphere are approximately three or four times higher than those from natural sources (Sanchez-Rodas et al. 2007). Therefore, it was assumed that As was primarily affected by anthropogenic activities such as industrial atmospheric emissions, metal smelting, and coal burning.

Table 7 Factor matrix of soil toxic metals

Elements	Principal component	
	PCA1	PCA2
Zn	0.88	0.065
Cu	0.84	0.072
Cr	0.38	0.67
Pb	0.55	0.48
Hg	0.12	0.84
As	0.06	0.63
Percentage of variance (%)	35.90	27.08
Percentage of cumulative variance (%)	35.90	62.98

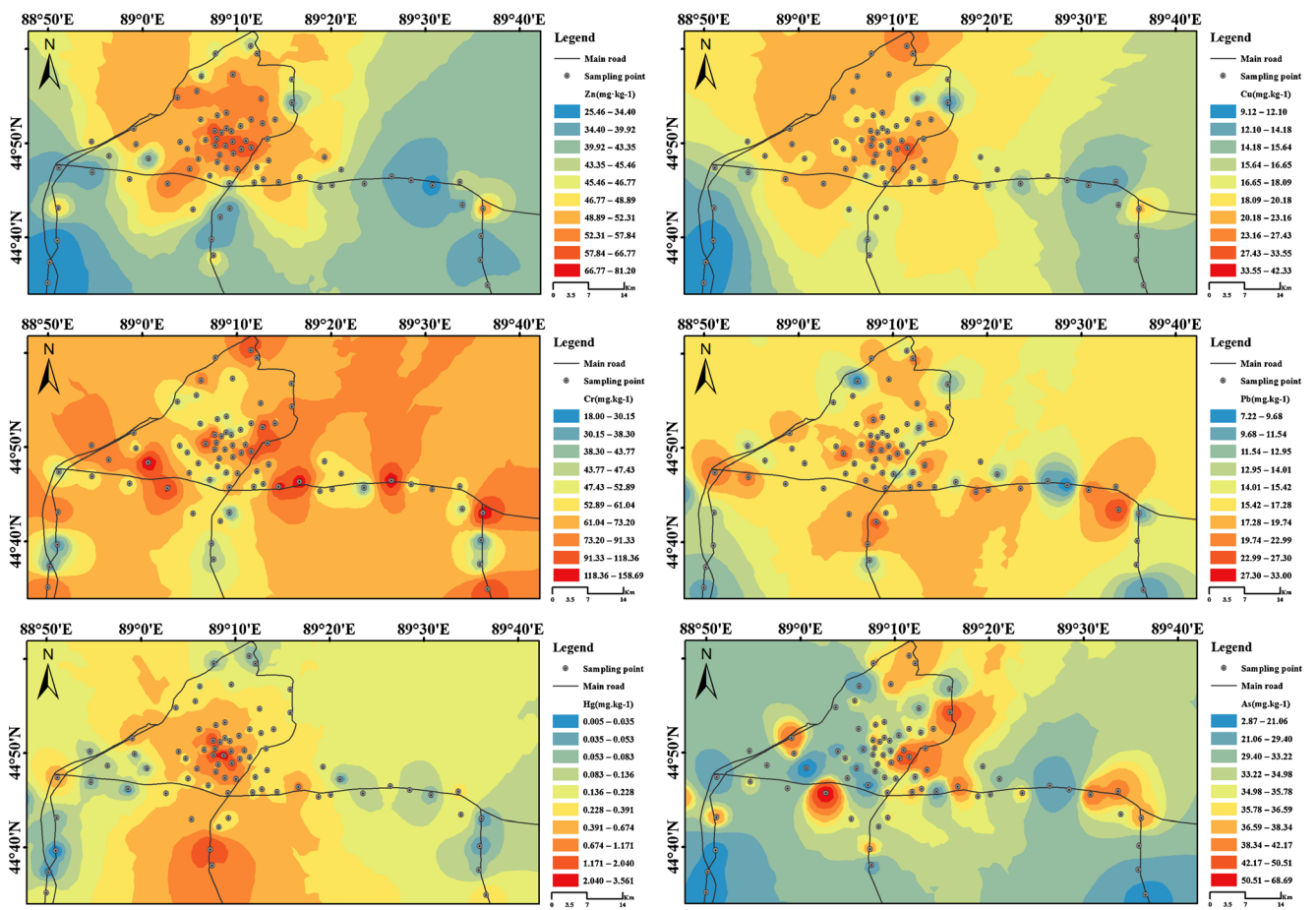


Fig. 2 Spatial distribution of soil toxic metals

In the present study, Hg exhibited significant accumulation in the soil, which was quite different from other metals. The contents of Hg along the boundary between the coal mine and chemical plant were much higher compared to other areas, which indicated that the increasing contents of Hg could be

attributed to the emissions from steel industry (Qing et al. 2015), coal burning, and subsequent atmospheric deposition (Nakagawa and Hiromoto 1997; Kuo et al. 2006). The Wucaiwan coal power and the coal chemical industry belt, the Huoshaoshan high-load energy industrial parks, and the

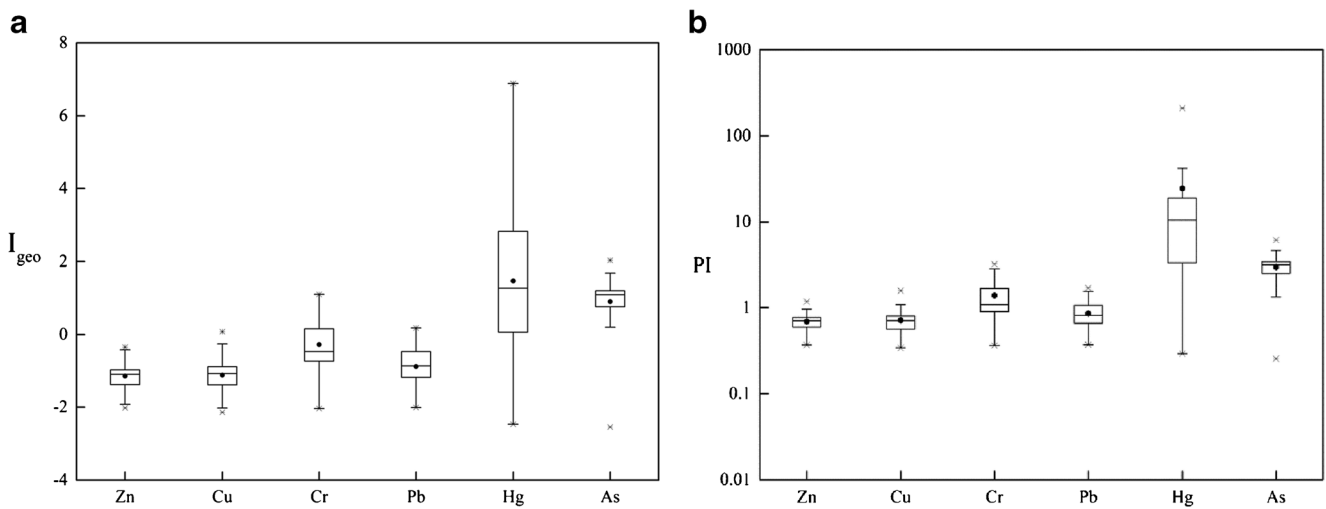


Fig. 3 Box plots of the geo-accumulation index (I_{geo}) of soil toxic metals (a); box plots of the pollution index (PI) of soil toxic metals (b). Boxes depict the 25th, 50th (median), and 75th percentiles, and whiskers depict the minimum and maximum values. Mean values (O); outliers (*)

Table 8 Distribution frequency of the potential ecological risk coefficient (E_r^i) of single toxic metals

Elements	Minimum	Maximum	Mean	Standard deviation	Distribution frequency of samples				
					$E_r^i < 40$ Low risk	$40 \leq E_r^i < 80$ Moderate risk	$80 \leq E_r^i < 160$ Considerable risk	$160 \leq E_r^i < 320$ High risk	$E_r^i \geq 320$ Very high risk
Zn	1.85	5.90	3.48	0.78	80				
Cu	1.70	7.93	3.61	1.10	80				
Cr	0.73	6.44	2.78	1.45	80				
Pb	1.86	8.51	4.30	1.43	80				
Hg	12.72	925.48	282.2	260.83	12	9	17	13	29
As	2.57	61.33	29.9	8.99	75	5			

Jiangjunmiao coalification industrial parks are the main metal smelting manufacturing industries and the main sources of the toxic metal pollution in this region. Previous studies showed that emissions from the chemical plant were the primary reason for Hg pollution (Gong et al. 2010; Xia 2014).

Based on above analyses, in comparison with the mining areas of other countries, toxic metal pollution levels were lower than in the Barapukuria coal basin in the Dinajpur district of the northern part of Bangladesh (Bhuiyan et al. 2010) and the Rodalquilar mining area in SE Spain (Choe et al. 2008). The pollution levels of the study area were lower than those in the eastern part of China such as Liaoning Province (Qing et al. 2015), northwestern Xi'an, China (Chen et al. 2016), and northeastern Shenyang, China (Li et al. 2013). A comparison of our results with similar studies carried out in different parts of Xinjiang, northwestern China, indicated that the average contents of Zn, Cu, Cr, and Pb in the present study were relatively lower than in the area of Urumqi City, northeastern Tianshan, the Midong district, Yanqi Basin, and the Boston Lake Basin of Xinjiang (Liu et al. 2007; Qian et al. 2013; Mamat et al. 2014; Eziz et al. 2017). The average contents of Hg and As were higher in the study area than in other areas of Xinjiang.

Toxic metal pollution in soil

Assessment of the I_{geo} and PI

The I_{geo} values of the six toxic metals in soil are shown in Fig. 3a. The I_{geo} ranged from -2.01 to -0.34 (mean, 1.14) for

Zn, -2.14 to 0.079 (mean, 1.11) for Cu, -2.04 to 1.10 (mean, 0.28) for Cr, -2.01 to 0.18 (mean, 0.88) for Pb, -2.47 to 6.89 (mean, 1.47) for Hg, and -2.55 to 2.03 (mean, 0.90) for As. The mean values of I_{geo} were in the order of $Hg > As > Cr > Pb > Cu > Zn$. The mean I_{geo} of Hg indicated that there was moderate Hg pollution, while the mean I_{geo} of As indicated slight-to-moderate pollution. The mean values of Zn, Cu, Cr, and Pb indicated no pollution. The mean I_{geo} values of Zn, Cu, Cr, and Pb were lower than those in the other industrial regions such as Beijing, Inner Mongolia, Shandong, Yunnan, Tibet, and China (Li et al. 2014; Chen et al. 2015). Except for mean I_{geo} of Hg being lower than that in Beijing, Hg and As were higher than in other regions.

The PI was calculated according to the background value of soil toxic metals in Xinjiang and was found to be different for each of the six toxic metals (Fig. 3b). The range of PI for the different metals was $0.37-1.18$ (Zn), $0.34-1.59$ (Cu), $0.37-3.22$ (Cr), $0.37-1.70$ (Pb), $0.29-210$ (Hg), and $0.25-6.13$ (As). According to the results, the average PI for all metals followed the decreasing order of $Hg (10.5) > As (3.16) > Cr (1.09) > Pb (0.81) > Cu (0.71) > Zn (0.71)$. The Zn, Cu, and Pb values indicated no pollution ($PI \leq 1$); Cr presented moderate pollution ($1 < PI \leq 3$), and the mean PI values of As and Hg were higher than 3 ($PI > 3$), indicating heavy pollution. The mean PI values of Zn, Cu, Cr, and Pb in this region were lower than those in Anshan City, China; Yanqi Basin, Xinjiang, China; and Bangladesh (Bhuiyan et al. 2010; Qing et al. 2015; Eziz et al. 2017), while the mean PI of Hg was higher than in these regions. This finding concurs with a previous study (Liu et al. 2015).

Table 9 Statistical analysis of the potential ecological risk index (PRI) of heavy metals in soil

Potential ecological risk level	$PRI < 150$	$150 \leq PRI < 300$	$300 \leq PRI < 600$	$PRI \geq 600$
Level	Low risk	Moderate risk	Considerable risk	Very high risk
Frequency	28	22	14	16
Percentage	35.00	27.50	17.50	20.00

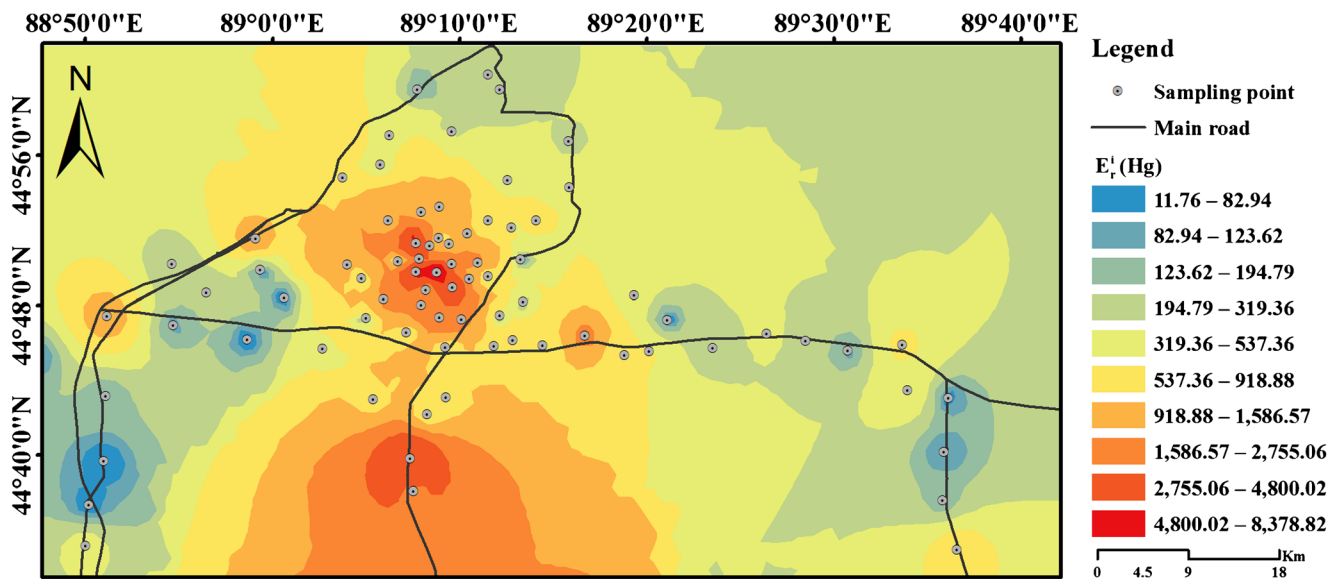


Fig. 4 Spatial distribution of the potential ecological risk coefficient (E_r^i) for Hg in soil

Potential ecological risk of soil toxic metals

The mean value of E_r^i for Zn, Cu, Cr, and Pb was below 40 for all the sample sites, indicating a low risk (Table 8). However, at several sites, As presented moderate risk. The percentages of Hg in different samples were 15.00%, 11.25%, 21.25%, 16.25%, and 36.25%, and the mean value of Hg was 282.2, indicating that Hg presented a major risk to the soil environment. The contribution of the toxic metals to the potential ecological hazard followed the order of Hg > As > Pb > Cu > Zn > Cr.

Based on the analysis of PRI of toxic metals in soil (Table 9), certain levels of ecological risk occurred in the soil of the study area. Approximately 35% of the

study area had a low-risk status, 27.5% had a moderate-risk status, 17.50% had a considerable risk status, and 20.0% had a very high-risk status.

The toxic metal Hg exceeded the soil background value several times, posing a danger to the surrounding environment. Therefore, Hg presented the greatest environmental risk to the area. To further assess the risk that Hg posed in the study area, we analyzed the spatial distribution of E_r^i for Hg in soil (Fig. 4). Areas that presented the greatest environmental risk were concentrated in regions with intensive human activities, such as the Wucaiwan coal-mining area, the Huoshaoshan high-load energy industrial park, the Jiangjunmiao coalification industrial park, and the Dongfangxiwang chemical plant.

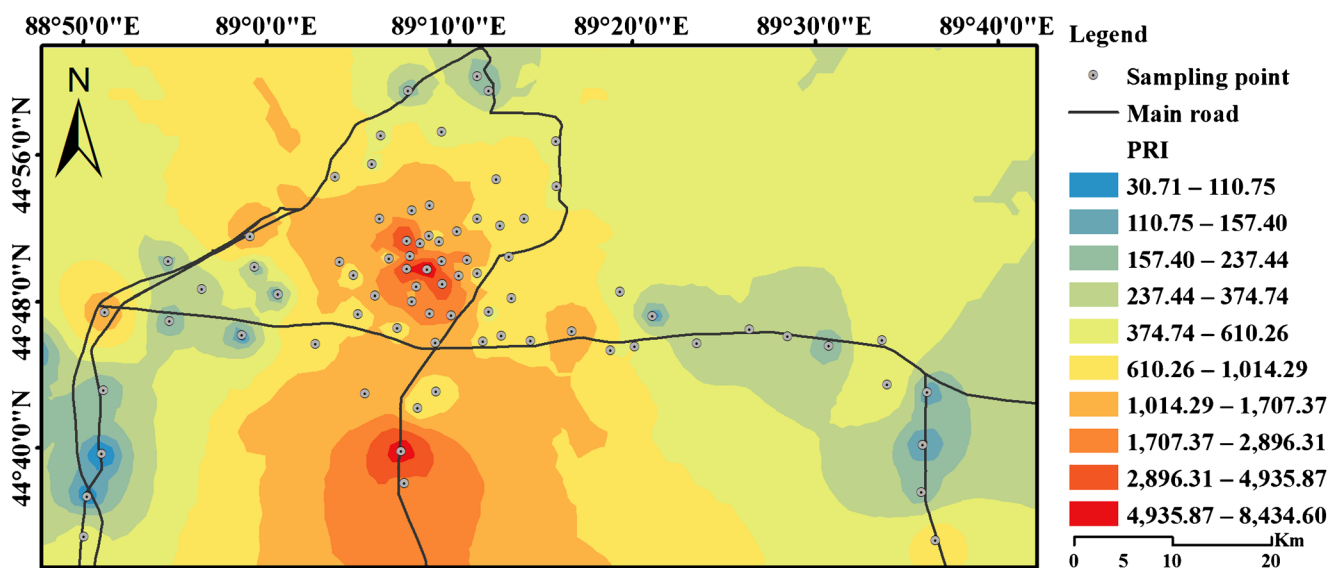


Fig. 5 Spatial distribution of potential ecological risk index (PRI) for all toxic metals in soil

As shown in Fig. 5, the spatial distribution of the PRI exhibited the same trends as those of E_r^i . High PRI values were observed in the regions surrounding the coal-mining area, industrial area, living area, and the southern portion of Kalamaili Mountain. The potential ecological risk in these areas was comparatively high. The spatial variation pattern map showed that most of the regions had a moderate risk status.

Conclusions

In the present work, the spatial distribution, source, and potential ecological risk of toxic metals were determined in the coal-mining region of northwestern China. The main conclusions are as follows:

1. The contents of toxic metals in the soil were ranked as follows: $Cr > Zn > As > Cu > Pb > Hg$; the soil toxic metal contents of Cr, Hg, and As exceeded the regional background values by 1.4, 16.4, and 2.9 times and exceeded the national soil environmental quality standards of China (GB15618-1995) by 1.1, 4.3, and 2.9 times, respectively. The toxic metals Zn, Cu, and Pb were lower than the limits of both soil standards.
2. A relatively strong correlation was observed between Zn and Cu, both of which primarily originated from the parent material. The toxic metals Cr, As, and Hg originated from human activities such as coal burning, chemical industries, and traffic. The toxic metal Pb originated from a combination of both natural factors and human activities. The spatial distribution trends reveal that the high contents of toxic metals are associated with the middle parts of the study area, which are probably more impacted by atmospheric deposition from coal mining, chemical plants, and other industrial activities. Our research concluded that coal mining and chemical plants were the primary causes of soil toxic metal pollution in the study area.
3. The I_{geo} and PI of toxic metals were ranked in the following order: $Hg > As > Cr > Pb > Cu > Zn$. The I_{geo} of Hg indicated moderate pollution, while the I_{geo} of As indicated slight-to-moderate pollution. The I_{geo} of other toxic metals indicated low pollution levels. The PI values of Zn, Cu, and Pb indicated no pollution ($PI \leq 1$), while Cr presented moderate pollution ($1 < PI \leq 3$), and the mean values of As and Hg were higher than 3 ($PI > 3$), indicating heavy pollution. The results of the potential ecological risk in the study area showed that Zn, Cu, Cr, and Pb across all sample sites presented low risk, while most of the soil samples had a low to very high ecological risk of Hg. Hg is the most hazardous toxic metal in this region; to

avoid further pollution in the region, it is necessary to control Hg emissions from nearby industrial areas.

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