REVIEW ARTICLE

Heavy metal pollution of soils from coal mines in China

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Abstract

Mining activities are among the main sources of heavy metal contamination in the environment. To analyze heavy metal pollution of soils from coal mines in China, we assessed pollution and potential ecological risk, compared heavy metal concentrations between soils from coal mines and soils from metal mines and identified the relationship between heavy metals on the nationwide scale. The data of heavy metal concentrations for 50 coal mines and 35 metal mines were collected from the published literature. Coal mines referred in this paper are distributed in 18 provinces and 4 climatic zones in China. Methods including Index of geoaccumulation (I_{geo}), Nemerow pollution index (P), potential ecological risk index and other statistics (Pearson correlation method and ANOVA variance analysis) were utilized. Compared with soils influenced by metal mining, heavy metal concentrations in soils from coal mines were much lower. For heavy metals, higher I_{geo} for Cd, Pb and Ni was observed. Soils were contaminated or slightly contaminated when calculated based on Chinese soil guidelines (grade I and grade II) but slightly contaminated or severely contaminated when calculated based on province backgrounds. Most heavy metals (i.e., As, Cr, Cu, Ni and Zn) showed a low potential ecological risk, whereas Cd, Pb and Hg showed slightly higher ecological risk potential. Statistically significant and positive correlations were found in pairs of As/Cr, As/Ni, As/Pb, As/Hg, Ni/Cr and Ni/Cu ($P < 0.01$) and Cu/Pb ($P < 0.05$).

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1 Introduction

Soil pollution caused by heavy metals due to human activities is an important issue in many parts of the world (Solgi et al. 2012), and China is not an exception. With the acceleration of industrialization and consequential food toxicity accidents, such as arsenic (As) poisoning in Guizhou province and children with excessive lead (Pb) blood levels in Guangdong province, heavy metal pollution in soils has threatened the public health and attracted public attention in China (Romkens et al. 2009; He et al. 2013). Mining exploitation, ore concentrating and transportation emit dust and create wastewater. In the process, a large amount of pollutants, including trace elements, are emitted into the environment (Yenilmez et al. 2011; Kronbauer et al. 2013), threatening production security, ecological security and habitat security in the mining area (Bai et al. 2006; Loupasakis et al. 2014; Zhang et al. 2015). Heavy metals such as As, Cd, Cr, Cu, Ni, Pb, Zn and Hg are considered as environmentally hazardous elements and are among the most covert, persistent and irreversible of pollutants in the ecosystem (Wang et al. 2001; Belkin et al. 2008; Saikia et al. 2014). Moreover, this kind of pollution also threatens health and well-being of human beings and animals along the food chain through bioaccumulation (Cardwell et al. 2002; Pruvot et al. 2006; Nabulo et al. 2010).

It is essential to identify pollution sources and assess pollution levels before control actions are taken. Index of geoaccumulation and Nemerow pollution index have been widely applied to evaluate the pollution condition of soils (Yang et al. 2013; Hu et al. 2014). However, these methods ignore the toxicity differences between different heavy metals (Ali et al. 2015; Yan et al. 2015a, b). Potential ecological risk index, which totally considered issues of the toxicity and combined effect of heavy metals, was widely used in the quality evaluation of soils (Fan et al. 2011). Multivariate statistics and geostatistical analysis have been used to identify the sources and map the spatial distributions of heavy metals in soils (Micó et al. 2006; Saby et al. 2009; Maas et al. 2010; Yan et al. 2015a, b; Tóth et al. 2016). Because the advantages of considerable cost savings and time savings, techniques of remote sensing and field spectroscopy combined with spectral analysis were also applied to investigate the distribution of heavy metals in mining areas (Kemper and Sommer 2002; Choe et al. 2008; Liu et al. 2012). Heavy metals are involved in the biogeochemical cycles, and heavy metals at elevated concentrations are also responsible for the degradation of soil quality. Relationships among heavy metals and soil physicochemical properties, and effects of heavy metals on plants were also studied by many researchers (Dragovic et al. 2008; Perlatti et al. 2015; He et al. 2016; Sun et al. 2016). Numerous researchers have concentrated on the assessment of potential health risks for inhabitants in the mine-affected areas (Sipter et al. 2008; Cai et al. 2015; Chen et al. 2015; Liao et al. 2016).

In spite of a large amount of previous research on heavy metals in soils, only a few studies have been undertaken to discover heavy metal pollution from coal mines on the national scale in China. The objectives of this paper were to (1) analyze heavy metal pollution caused by coal mining in China; (2) assess the potential ecological risk of coal mines in China; (3) compare the differences of heavy metal pollutions in coal mines and metal mines; (4) study the relationships between different heavy metal elements on the national scale.

2 Materials and methods

2.1 Data collection and processing

Making use of the main literature databases, including CNKI in full Database, Wangfang Database and Web of Science, heavy metal concentrations of soil samples from 50 coal mining areas and 35 metal mining areas were collected from a host of studies related to soil heavy metal pollution from mines in China. Distribution of coal mines is shown in Fig. 1. Basic description and heavy metal concentration data of the coal mines and metal mines were summarized in Supplementary Tables S1, S2, S3 and S4. The basic statistical information of heavy metal concentration in coal mines of the different provinces was displayed in Supplementary Table S5.

Coal provides more than 70% of total energy in China. During the period of "the Tenth Five-Year Plan" (2001–2005), China has planned and constructed 14 coal bases nationwide (Fig. 1). They include about 40 coal mines, and the total area is 103.4 thousand km². Coal reserves total 690.8 billion tons, more than 78% of total reserves of China (Liu et al. 2014). Most coal mines referred in this paper belong to the aforementioned coal bases and have become research hot-spots in China, such as Pingshuo coal mine, Huainan coal mine, Huaibei coal mine, Heidaigou coal mine, Shengli coal mine and Yanzhou coal mine. Therefore, these coal mines are representative to a great extent.

Sampling and soil analysis methods employed in the referred studies are conventional and all widely accepted by soil researchers in the world. In general, samples were randomly collected within the top 30-cm soil layer in the coal mining area. The locations of sampling sites were recorded using a hand-held Global Positioning System (GPS). Afterward, samples were naturally air-dried at room temperature and sieved through a 2-mm nylon sieve to remove
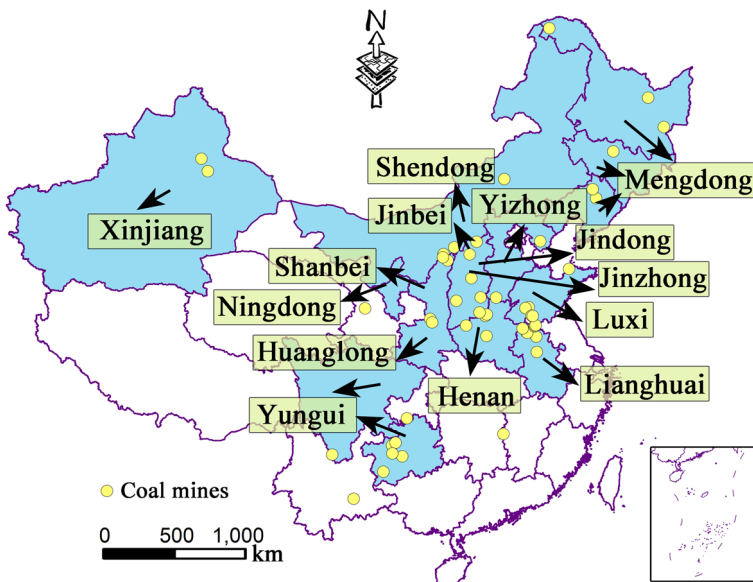

Fig. 1 Distribution of coal bases in China and coal mines referred in the study

stones and other coarse debris. Heavy metal concentrations of soil samples were processed by a variety of analytical methods, such as atomic fluorescence spectrophotometry (Han et al. 2007; Guo et al. 2012), flame atomic spectrophotography (Wang et al. 2009; Shi et al. 2012) and inductively coupled plasma atomic emission spectrometry (ICP-AES) (Cui et al. 2004; Shi and Wang 2013; Wang et al. 2014; Liu et al. 2016a, b).

2.2 Methods

2.2.1 Index of geoaccumulation (I_{geo})

The index of geoaccumulation was proposed by Muller (1969) and became one of the most widely used quantitative indexes in evaluating the contamination degree, since it takes the effects of the human activities into consideration (Liu et al. 2016a, b). Its formula is as follows (Wang et al. 2016):

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

where I_{geo} is the index of geoaccumulation (Table 1); C_n is the heavy metal concentration measured in coal mine soils; B_n is the geochemical background value of the corresponding toxic element in the soil.

2.2.2 Nemerow pollution index (P)

The overall pollution of heavy metal in soil was calculated by Nemerow pollution index (P). It was originally introduced by Nemerow (1974). Since heavy metal pollution in soils is usually caused by many contaminants at the same time, Nemerow pollution index is widely adopted to reflect the overall pollution condition of heavy metals and environmental quality. It is defined as follows:

$$P_{ij} = C_{ij}/S_i \tag{2}$$

$$P_{ave} = \frac{1}{6}\sum_{i=1}^{n} P_i \tag{3}$$

$$P = \sqrt{\frac{1}{2}(P^2_{max} + P^2_{ave})} \tag{4}$$

Table 1 Evaluation standard of indexes of geoaccumulation

Class	I_{geo}	Pollution level
0	<0	Practically uncontaminated
1	0–1	Uncontaminated to moderately contaminated
2	1–2	Moderately contaminated
3	2–3	Moderately to heavily contaminated
4	3–4	Heavily contaminated
5	4–5	Heavily to extremely contaminated
6	>5	Extremely contaminated

where P_{ij} is the pollution index of some single heavy metal, C_{ij} is the measured concentration of the given heavy metal, S_i is its corresponding background concentration. P_{ave} and P_{max} are the average value and maximum value of all the heavy metals concentration, respectively. P is the Nemerow pollution index and is interpreted as: not contaminated ($P \leq 1$), slightly contaminated ($1 < P < 2$), moderately contaminated ($2 < P < 3$), severely contaminated ($P > 3$).

2.2.3 Potential ecological risk index (RI)

The potential ecological risk index was firstly proposed by Hakanson from a sedimentological perspective to study heavy metal contaminants in coastal sediments (Hakanson 1980). It has been widely adopted to assess heavy metal pollution of soils (Maanan et al. 2015).

$$P_i = C_d^i / C_r^i, \; P = \sum_{i=1}^{m} P_i \tag{5}$$

$$E_f^i = T_f^i P_i, \; RI = \sum_{i=1}^{m} E_f^i \tag{6}$$

where C_d^i is the measured heavy metal concentration of mine soils and C_r^i is the geochemical background value; E_f^i is the toxic coefficient of heavy metals and RI is the potential ecological risk of the heavy metals (Table 2).

According to earlier research (Li et al. 2008; Xu et al. 2008; Li et al. 2011), the toxic coefficients were set as follows: $Zn = 1 < Cr = 2 < Ni = Cu = Pb = 5 < As = 10 < Cd = 30 < Pb = 40 < Hg = 80$. The values are all calculated based on the method that Hakanson presented in 1980 (Hakanson 1980).

2.2.4 Other statistical methods

The Pearson correlation method (Shinar et al. 1985) was applied to analyze the correlations between different toxic elements at 1% and 5% levels of probabilities. In order to determine the significance of differences among the mean heavy metal concentrations of coal mine soils and other metal mine soils, the ANOVA was used. The statistical analyses were performed using SPSS 19.0 (SPSS Inc. Chicago, USA).

Table 2 Ecological risk assessment of heavy metals

E	RI	Pollution level
< 40	< 150	Practically uncontaminated
40–80	150–300	Moderately contaminated
80–160	300–600	Heavily contaminated
160–320	> 600	Extremely contaminated

3 Results and discussion

3.1 Overview of heavy metal concentrations in coal mine soils of China

The average heavy metal concentrations of soil samples in each coal mine were viewed as the values that represent the corresponding coal mine. The statistics and pollution assessment of each coal mine were all based on these average concentrations in this study. Meanwhile, based on the data of coal mines, basic descriptive statistics of soil metal concentrations in the 50 coal mines are derived as Table 1. The percentile, mean, skewness and kurtosis values of heavy metal concentrations were calculated. Meanwhile, in order to assess the heavy metal pollution of soils in the coal mines, Chinese soil guidelines (grade I and grade II) (GB15618-1995) and province backgrounds (listed in Table 1 and Supplementary Table S6, respectively) in the first national soil pollution survey were used in the evaluation process. They represent the average natural levels for uncontaminated soil, the threshold values for protecting human health and the provincial average values, respectively.

From Table 3, it can be seen that median concentrations for As (10.466), Cr (66.370), Cu (28.618), Ni (34.510), Pb (26.700), Zn (67.160) and Hg (0.056) were lower than their corresponding Chinese soil guidelines (grade I), and the median concentrations for all the heavy metal elements were all below their corresponding Chinese soil guidelines (grade II), indicating that heavy metal concentrations in soils of most coal mines were relatively low and did little harm to the environment. It was in agreement with Fang et al. (2015). However, the comparison between table S3 and S5 shows that the median concentrations for most heavy metal elements surpassed their corresponding province backgrounds in the first national soil pollution survey: 63.16% of Cd samples, 58.54% of Cu samples, 66.67% of Ni samples, 58.70% of Pb samples and 61.11% of Hg samples exceeded their corresponding province backgrounds, indicating heavy metal concentrations of coal mine soils were higher than the average levels of provincial wide soils. The mean concentrations for

Table 3 Basic statistical information about average heavy metal concentration in Chinese coal mine soils (heavy metal concentration unit: mg kg^{-1})

	As	Cd	Cr	Cu	Ni	Pb	Zn	Hg
10th	4.785	0.111	29.455	11.363	8.895	16.078	46.848	0.029
25th	7.834	0.144	39.255	18.824	21.841	22.340	54.865	0.036
50th	10.466	0.268	66.370	28.618	34.510	26.700	67.160	0.056
75th	22.032	0.443	83.476	37.054	48.243	39.181	84.577	0.096
90th	25.821	1.473	105.849	66.369	134.050	58.673	119.056	0.289
Mean	29.283	0.518	92.890	33.180	47.101	41.012	79.404	0.090
Skewness	4.415	2.676	4.399	2.245	2.733	4.050	2.423	2.428
Kurtosis	19.637	7.674	19.602	6.550	8.235	16.619	6.582	5.689
Chinese soil guidelines (grade I)	15	0.20	90	35	40	35	100	0.15
Chinese soil guidelines (grade II)								
pH < 6.5	40	0.30	150	50	40	250	200	0.30
6.5 < pH < 7.5	30	0.60	200	100	50	300	250	0.50
pH > 7.5	25	1.0	250	100	60	350	300	1.0

all the heavy metals surpassed their median values, and the average concentrations for As (29.283), Cd (0.518), Cr (92.890), Ni (47.101) and Pb (41.012) exceeded the corresponding Chinese soil guidelines (grade I). This was particularly true for As and Cd, whose concentrations were about 1.95 and 2.59 times greater than their corresponding Chinese soil guidelines (grade I), respectively. The result agrees with the report by Zheng et al. (2013).

Although the heavy metal concentrations of most soil samples in the coal mines were relatively lower than Chinese soil guidelines (grade I and grade II), they exceeded corresponding province backgrounds. This means that heavy metal concentrations of coal mine soils were below the threshold values for protecting human health while they exceeded province background. The elevated heavy metal concentrations of coal mine soils mainly arise from all kinds of mining activities. Compared with natural soils, the elevated concentrations of heavy metals in the mining-affected soils were also reported elsewhere, e.g., China (Gu 2011), Bangladesh (Bhuiyan et al. 2010) and India (Mishra et al. 2008). In comparison with the global average values for Cu (30 mg kg^{-1}) and Zn (80–120 mg kg^{-1}) (Adriano 2001), and the global baselines for Pb (20 mg kg^{-1}) and Ni (100 mg kg^{-1}) in uncontaminated soils (Kabata-Pendias and Pendias 1992; Ross 1994), higher average concentrations of Cu and Pb, and lower concentrations of Zn and Ni can be found in Chinese coal mine soils.

3.2 Metal pollution assessment with different indexes and toxicological reference values

In order to predict heavy metal pollution of coal mine soils, comparative assessments were made using Index of geoaccumulation and Nemerow pollution index based on Chinese soil guidelines (grade I and grade II) and province backgrounds. Geoaccumulation indexes calculated using grade I and grade II indicate the national pollution level. Comparative results are summarized in Figs. 2 and 3.

It can be seen from Fig. 2a–c that Geoaccumulation indexes showed much fluctuation. It ranged from −8.07 to 3.98 with an average −0.89 when calculated based on Chinese soil guidelines (grade I) and ranged from −9.59 to 2.98 with an average −2.47 when calculated based on Chinese soil guidelines (grade II). Geoaccumulation indexes also varied between samples when calculated based on province backgrounds, in a range from −7.83 to 4.70 with an average −0.44. The medium concentrations for all the heavy metal elements in soils of the 50 coal mines were not higher than their corresponding reference values. However, the nationwide coal mine soils were polluted by heavy metals in slightly varying degrees. Geoaccumulation indexes calculated based on Chinese soil guidelines (grade I) showed that 25.00% of soil samples for As, 44.74% of soil samples for Cd, 4.74% of soil samples for Cr, 14.63% of soil samples for Cu, 11.11% of soil samples for both Ni and Hg, 13.04% of soil samples for Pb and 7.32% of soil samples for Zn surpassed 0, indicating a certain extent of soil contamination. When calculated based on Chinese soil guidelines (grade II), Geoaccumulation indexes for 5.00% of As samples, 21.05% of Cd samples, 4.76% of Cr samples, 4.88% of Cu samples, 11.11% of Ni samples surpassed 0, while Geoaccumulation indexes for all the Pb, Zn and Hg samples were below 0, implying the different accumulation levels among these heavy metal elements. Similarly, Li et al. (2014) and Chen et al. (2012) also found that Cd appeared to cause the greatest contamination in mine soils compared with other metal elements. When calculated based on province backgrounds, pollution assessment showed that 25.00% of As samples, 50.00% of Cd samples, 11.90% of Cr samples, 19.51% of Cu samples, 27.78% of Ni samples, 19.57% of
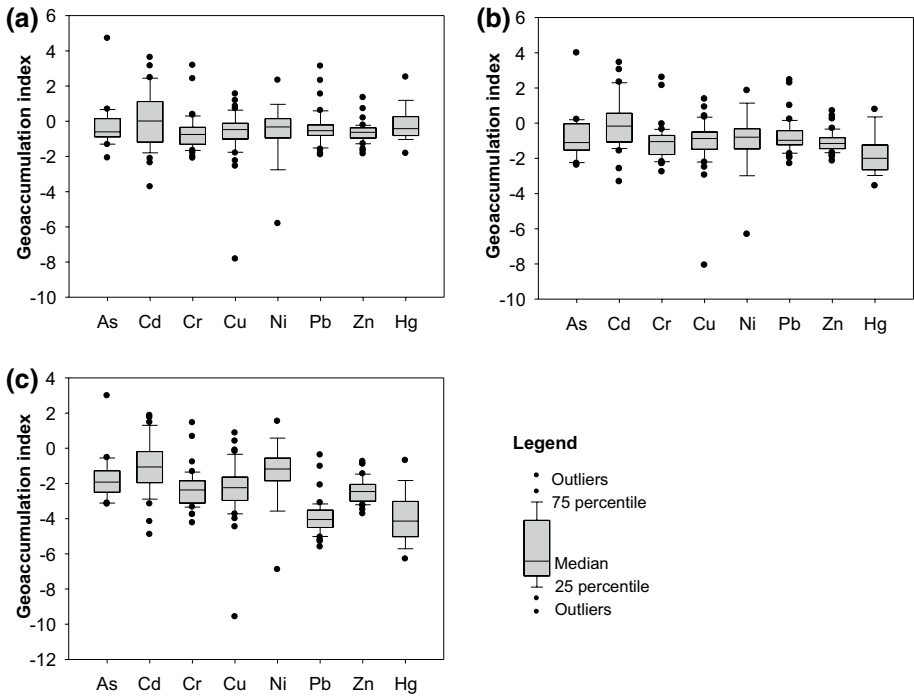
Fig. 2 Box-plots of Geoaccumulation indexes calculated based the average concentrations of heavy metals in the coal mines and the corresponding background values of different criterions. **a** Calculated with the corresponding province backgrounds in the first national soil pollution survey; **b** calculated with Chinese soil guidelines (grade I); **c** calculated with Chinese soil guidelines (grade II)
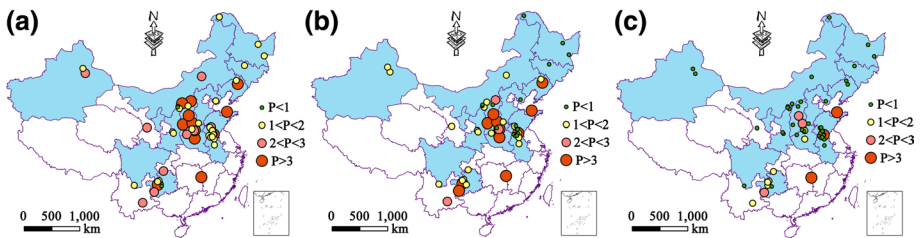

Fig. 3 Results of pollution assessment using Nemerow pollution index based the average concentrations of heavy metals in the coal mines and the corresponding background values of different criterions. **a** Calculated with the corresponding province backgrounds in the first national soil pollution survey; **b** calculated with Chinese soil guidelines (grade I); **c** calculated with Chinese soil guidelines (grade II)

Pb samples, 7.32% of Zn samples and 27.78% of Hg samples range from uncontaminated to moderately contaminated. Our results, however, were basically in agreement with many previous studies (Wei and Yang 2010; Wang et al. 2011).

Figure 3 shows pollution assessment using Nemerow pollution index with different background values. The details of Nemerow pollution index analysis are shown in Table S7. It can be observed that pollution degrees varied between different coal mines nationwide. It is particularly true when assessed based on province backgrounds, with

Nemerow pollution index ranging from 0.71 to 142.29 with an average 6.13. If we take into account the limits of Chinese soil guidelines, Nemerow pollution indexes range from 0.50 to 130.24 with an average 5.12 for Chinese soil guideline (grade I) and 0.14–19.02 with an average 1.41 for Chinese soil guideline (grade II). The top 5 most polluted sites in the referred coal mines were distributed in Jiangsu province ($n = 1$), Shandong province ($n = 1$), Jiangxi province ($n = 2$) and Shanxi province ($n = 1$) according to the assessment based on the province backgrounds, with the Nemerow pollution indexes exceeding 9. Cd in Jiangsu province and Jiangxi province, As in Shandong province, and Pb in Shanxi province were the main metal elements that led to the elevated Nemerow pollution indexes. However, Nemerow pollution indexes for most sites in the coal mines were less than 1 or ranged from 1 to 2 when calculated based on Chinese soil guidelines (grade I) (72.00% of samples were below 1 and 14.00% of samples ranged from 1 to 2) and Chinese soil guidelines (grade II) (32.00% of samples were below 1 and 38.00% of samples ranged from 1 to 2). It was evident that soils in most coal mines on the nationwide scale were not contaminated or slightly contaminated by heavy metals. Compared with the previous research on agriculture soils in China (Song et al. 2013), with Nemerow pollution index for 16.67% of samples surpassed 1, heavy metal pollution for coal mine soils were much heavier. However, when calculated based on province backgrounds, results showed that 50.00% and 26.00% of coal mine soil were classified as slightly contaminated ($1 < P < 2$) and severely contaminated ($P > 3$). Heavy metals released into the environment from various anthropogenic activities are toxic to soil organisms and affect the abundance, diversity and distribution of the soil organisms (Uwizeyimana et al. 2017). The severely contaminated soil in some coal mines revealed in our study may have exerted harmful effects on the organisms and should be paid attention to.

3.3 Potential ecological risk

The potential risk to the environment and population due to soil heavy metals arising from coal mining has been well described (Sun and Li 2015). However, the research of coal mine soils on the nationwide scale is rare. Potential ecological risks of heavy metals in the coal mine soils are presented in Fig. 4. According to Fig. 4, the median risk indexes of the
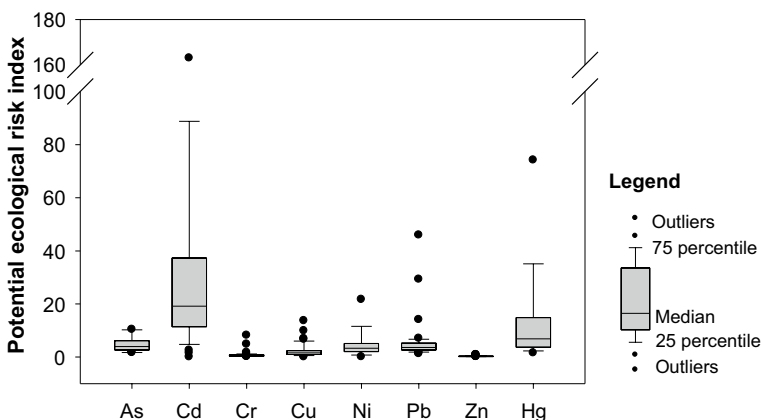

Fig. 4 Potential ecological risk index calculated with Chinese soil guidelines (grade II)

heavy metals were of the order: Cd $(21.30) > Hg(6.84) > As(3.96) > Pb(3.61) > Ni(3.31) > Cu(1.59) > Cr(0.58) > Zn(0.27)$. Potential ecological risk indexes for As, Cr, Cu, Ni and Zn sampling sites were relatively concentrated, with most values below 40. Their variation ranges were 1.66–118.63, 0.16–8.17, 0.01–13.60, 0.06–21.60 and 0.11–0.89, respectively, indicating soils were practically uncontaminated by these five metal elements. However, Cd, Pb and Hg showed the slightly higher potential ecological risk, with ranges of potential ecological risk indexes 1.50–163.00, 1.23–45.92 and 1.52–30.72. The referred coal mine soils were most contaminated by Cd: 10.81% of sampling sites were moderately contaminated; 8.11% of sampling sites were heavily contaminated and 2.70% of sampling sites were extremely contaminated. Among the provinces, Shanxi province and Jiangxi Province showed the higher potential ecological risk when just considering Cd. Cao et al. (2009) also found that Cd contamination had high potential ecological risk, and the sampling sites were mainly distributed near coal mines in Jilin Province, China; Jiang et al. (2014) found that Cd was the key influence factor to cause the potential ecological risk, whereas other heavy metals only showed slight potential ecological risk to the environment in soils around the coal gangue dump. Overall, it can be concluded that the heavy metals in nationwide coal mine soils have a low potential ecological risk.

3.4 Comparison with metal mines in China

In China, there are a large number of metal mines and the metal mining process has caused severe heavy metal pollution (Wong 2003). Metal concentrations collected in this study were compared with those from metal mines in China (Fig. 5). The data of heavy metal concentrations for metal mines were collected from earlier studies (Supplementary Table S4). The results in this comparison showed that the difference of As, Cr and Ni concentrations between coal mine soils and metal mine soils were not significant according to the analysis of variance. However, Cd concentration of coal mine soils (0.52 mg kg^{-1}) was significantly lower than that of lead and zinc mine soils (14.22 mg kg^{-1}), tungsten mine soil (25.59 mg kg^{-1}) and molybdenum mine soils (29.85 mg kg^{-1}) ($P < 0.05$). The average concentration of Cu in copper mine soils was about 18.77 times as high as coal mine soils. Meanwhile, it exceeded other metal mine soils. Lead and zinc mine soils were rich in Pb and Zn. The Pb and Zn concentration of lead–zinc mine soils was significantly higher than that of coal mine soils and other metal mine soils ($P < 0.05$). Lead and zinc mine soils, along with gold mine soils, also rich in Zn and Hg at these sampling sites were significantly higher than coal mine soils and other metal mines ($P < 0.05$). Overall, the concentrations of the referred heavy metal element of coal mine soils were relatively lower compared with metal mine soils. These results corroborate several findings that much more elevated concentrations for many heavy metal elements were ubiquitous in heavy metal mine soils in China (Zhuang et al. 2009), Spain (Rodriguez et al. 2009) and Turkey (Koz et al. 2012).

3.5 Correlation relationship between different heavy metals

Inter-element relationships provide information on heavy metal sources and pathways (Dragovic et al. 2008; Rodriguez et al. 2008). To further investigate the interrelationships of the heavy metals in coal mine soils nationwide, correlation analysis was employed and the results are presented in Table 4.

It can be seen from Table 4 that the statistically significant ($P < 0.01$) and positive correlation relationships existed among some heavy metals, indicating some important common
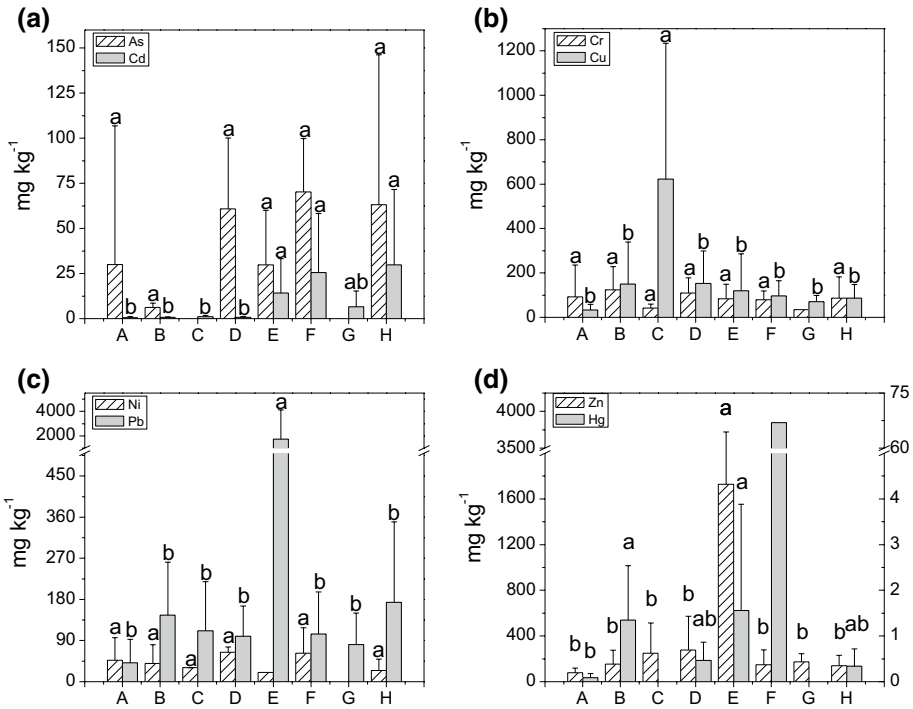
Fig. 5 Comparison of heavy metal concentration between coal mines and metal mines of China. A: Coal mine; B: Gold mine; C: copper mine; D: Iron mine; E: Lead and zinc mine; F: Tungsten mine; G: Manganese mine; H: Molybdenum mine

Table 4 Correlation relationship between different heavy metals

	As	Cd	Cr	Cu	Ni	Pb	Zn	Hg
As	1							
Cd	0.306	1						
Cr	0.997**	0.180	1					
Cu	0.533	0.029	0.224	1				
Ni	0.983**	0.260	0.733**	0.680**	1			
Pb	0.884**	0.028	0.269	0.376*	0.223	1		
Zn	0.279	− 0.028	− 0.157	0.257	0.239	0.280	1	
Hg	0.640**	0.010	0.331	0.127	− 0.121	0.004	− 0.016	1

*Indicate the statistical significance at probability level of $p < 0.05$

**Indicate the statistical significance at probability level of $p < 0.01$

factors may determine their concentrations. As–Cr, As–Ni, As–Pb, As–Hg, Ni–Cr and Ni–Cu were pairs that significantly and positively correlated at $P < 0.01$, and Cu–Pb was the pair that significantly and positively correlated at $P < 0.05$, implying their similarities in the prevalence and sources. This was especially true for the correlated pairs of As/Cr and As/Ni, with the Pearson correlation coefficients reaching 0.997 and 0.983, respectively.

These results are consistent with those obtained by Navas and Machin (2002), Bhuiyan et al. (2010), who found significant correlations between them as well.

3.6 Limitations and future study

Statistics showed that there are 10.8 thousands of coal mines in the end year of 2015 in China. Limited by data availability of heavy metal concentrations in coal mine soils, the coal mine sites referred in our study may not fully represent the nationwide pollution condition of coal mine soils. Furthermore, types and qualities of heavy metal elements may differ among different studies, which may exert a slight effect on the consistency of the obtained data. However, these slight discrepancies were not large enough to alter the general results of our study because processing and test methods for coal mine soils are alike in the selected studies and are widely accepted by the scientific community.

Environmental protection of soils requires a good knowledge of the present conditions and the spatial distribution of contaminants of concern (Ghanbarpour et al. 2013). Heavy metals are widely viewed as variables distributed in the geographical space. Spatial structure analysis and spatial distribution analysis for heavy metal concentration are also important to comprehensively understand pollution sources, identify critical and contaminated areas of coal mine soils. This may be what we should continue to study.

4 Conclusion

This paper reviews heavy metal pollution in soils from Chinese coal mines on the nationwide scale. We found that many heavy metals exhibited statistically significant and positive correlations, i.e., As/Cr, As/Ni, As/Pb, As/Hg, Ni/Cr, Ni/Cu and Cu/Pb. Although lower heavy metal concentrations compared with metal mine areas were found in soils near coal mines, some heavy metals (i.e., Cd, Pb and Ni) for parts of coal mines exceed their corresponding province backgrounds and Chinese soil guidelines (grade I). Meanwhile, parts of sampling sites showed contaminated and potential risk to some extent. In the future coal mining activity, environmental protection continues to be an arduous task.

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