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Soil heavy metal pollution source analysis based on the land use type in Fengdong District of Xi'an, China

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Abstract The soil environment imposes a great influence on human health. Soil heavy metal pollution caused by human activities is an important part of environmental problems in urban areas. Due to an inadequate infrastructure, imperfect management, and intensive human activities, the sources of heavy metals in urban fringe areas are often more complicated than those in other areas, such as mining areas and agricultural irrigation areas. To solve this problem, the first step is to locate the source of pollution. However, the traditional methods of source analysis, such as principal component analysis and positive matrix factorization, always require correlations between elements. This study examined the Hg, Cd, Pb, and Cu contents in the Fengdong District of Xi'an, China, and found that these elements are not correlated in this area. Hence, traditional source analysis methods are not applicable in the study area. In response to this problem, this research proposed a new source analysis method based on Pearson's correlation analysis. The Nemerow index, geoaccumulation index, and ecological risk index were adopted to evaluate soil heavy metal pollution in the study area. Via comparison to the actual situation, it was concluded that the geoaccumulation index is more suitable for source analysis in this area. Through Pearson's correlation analysis, it was found that the geoaccumulation index is significantly correlated with the various land use types. Among them, transportation land exerted a greater impact on Pb pollution, and industrial land exerted a significant impact on the Hg distribution. The Cu distribution was related to construction land, while the Cd distribution was mainly related to urban land and cultivated land. In addition, the demolition of residential areas and abandoned farmlands imposed significant effects on Pb and Cd pollution, respectively.

Keywords Soil heavy metals · Pollution assessment · Source analysis · Land use types · Urban fringe area

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Introduction

Research on soil heavy metal pollution has become a topic of heightened interest worldwide (Liu et al., 2016a, 2016b; Zhuang & Lu, 2020). Intensive traffic, agricultural sewage irrigation, industrial pollution, and mining activities are usually the main causes of heavy metal pollution in soil (Fei et al., 2020; Li et al., 2013; Sun et al., 2019; Yang et al., 2013). Most current studies have focused on source analysis of heavy metal pollution in mining and industrial areas, but the pollution sources in these areas are relatively singular (Mehr et al., 2017). Due to complex and frequent human activities and poor infrastructure, urban fringe areas have become some of the most seriously impacted areas with complex pollution sources (Dmitri & Maria, 2009; Wang et al., 2018; Zhang et al., 2018; Zhao et al., 2014). Understanding the sources of heavy metal pollution in urban fringe soil exhibits a great significance to the sustainable development of cities (Ajah et al., 2015; Fei et al., 2020; Huang et al., 2018; Shiliang et al., 2019).

At present, there are many methods to identify the sources of heavy metal pollution in soil (Davis et al., 2009; Dong et al., 2018; Fei et al., 2020; Gu et al., 2012; Lv, 2019; Sungur et al., 2014). Among these methods, principal component analysis (PCA) and positive matrix factorization (PMF) models are the most commonly employed methods, and they have been applied successfully by many scholars (Dong et al., 2018; Huang et al., 2018; Wen et al., 2017; Zheng et al., 2013). PCA can only define fuzzy principal components by simplifying high-dimensional variables and calculating the contribution of pollution sources (Gu et al., 2012; Huang et al., 2018; Lv, 2019; Wen et al., 2017), which needs to be explained through experience (Fei et al., 2020). In addition, PCA requires a certain correlation among the considered elements. The PMF method is more suitable for the detection of more elements. If only two or three independent heavy metals occur in a region, how can we analyze the source of these heavy metals?

Studies have reported that soil exhibits different physical and chemical properties under various land use patterns (Ali et al., 2014; Li et al., 2020; Qishlaqi et al., 2009). The current research has mainly focused on the relationship between one type of land use and heavy metal accumulation or the evolution of the accumulation of a single element under different land use types

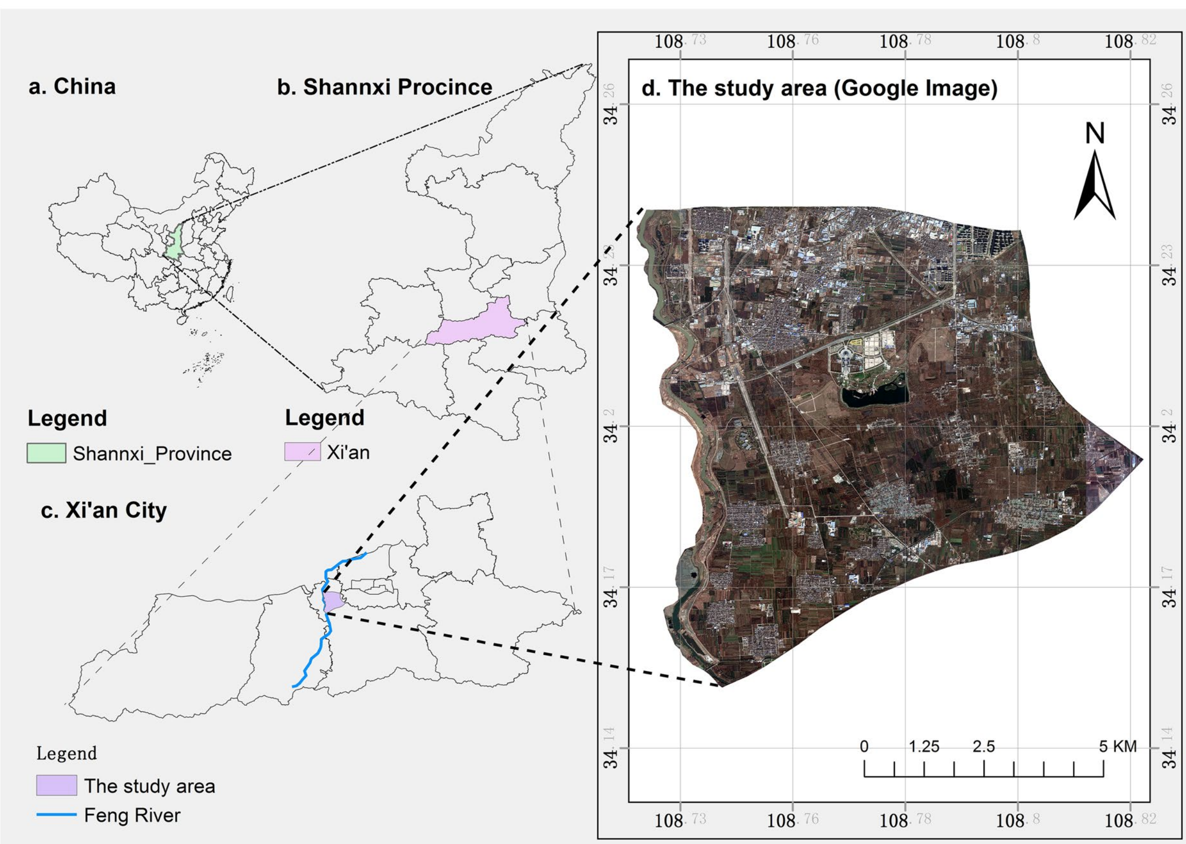

Fig. 1 Location of the study area

(Shang et al., 2015; Sungur et al., 2015; Zheng et al., 2013). Few studies have linked heavy metal pollution to land use patterns (Agata et al., 2017; Fernández & Carballeira, 2001; Li et al., 2020). The relationship between land use types and soil heavy metal pollution requires further research.

This study chooses a typical urban fringe area of the Fengdong District in Xi'an, China, as the study area. Hg, Cu, Pb, and Cd were detected and analyzed based on the Nemerow index, geoaccumulation index, and Hakanson ecological risk index. Pearson's correlation analysis was conducted to analyze the relationship between the land use pattern and soil pollution distribution in the study area. This study can provide a new idea for source analysis of soil heavy metal pollution under the condition of independent elements.

Materials and methods

Study area

The study area is located in Fengdong District, a new suburb of Xi'an city in Central China (Fig. 1). As the largest developing country worldwide, China has undergone rapid urbanization in recent years. The manifestation of urbanization is the expansion of the cities, thus disrupting the ecological pattern of suburbs, and causing a certain degree of environmental pollution and destruction. Xi'an, as the gate to the development of Western China, because of its unique geographical location and economic and social conditions, is also experiencing rapid expansion and urbanization. Fengdong is located on the east bank of Fenghe River and in the western part of Xi'an city, which is only 12 km away from the center of the city. The study area is surrounded by the traffic arteries of Xi'an city, and high traffic flows occur. With an altitude of 388 m, the flat terrain contains many villages and cultivated land. The average annual precipitation is approximately 600–700 mm, the average annual temperature is 13.4 °C, and the soil types mainly include collapsible loess and Lou soils, which are suitable for a variety of crops. Therefore, the area has a long history of agricultural cultivation, and the primary crops in the area are wheat, corn, and fruit trees such as apple, pear, peach, and cherry trees. Because of the superior agricultural irrigation conditions and geographical location, this area exhibits a long history of population concentration and agriculture. However, with the acceleration of the integration of Xi'an and the construction of an international metropolis, a part of the rural areas in the study area has been demolished, and a part of the cultivated land has been abandoned. Due to the location of the urban fringe, industrial development has also caused regional environmental pollution and damage. As a transition zone connecting urban and rural areas, the study area contains a dense population and exhibits long-term agricultural irrigation conditions. Industry and transportation are well developed here, but the level of environmental protection is insufficient. With complex land use patterns and serious soil pollution, this area is very typical of other developing city fringe areas globally.

Table 1 Classified standard of Nemerow index

Class	Value range	Pollution level
Class 0	$0.0 < NI_i \leq 0.5$	Uncontaminated
Class 1	$0.5 < NI_i \leq 1.0$	Uncontaminated to moderate contamination
Class 2	$1.0 < NI_i \leq 2.0$	Moderate contamination
Class 3	$2.0 < NI_i \leq 3.0$	Moderate to high contamination
Class 4	$3.0 < NI_i \leq 4.0$	High contamination
Class 5	$4.0 < NI_i \leq 5.0$	High to extremely high contamination
Class 6	$NI_i > 5.0$	Extremely high contamination

Sampling and analysis

To avoid the influence of human factors on the research results, a square grid was set up, and each center point of the grid was adopted as a sampling point. At each sampling point, soil at a depth of approximately 20 cm was collected, and each sample weighted approximately 0.5 kg. Finally, 451 effective samples were collected in this study area. The samples were dried, sieved, mixed, and analyzed according to China national standard HJ/

Table 2 Classified standard of comprehensive pollution index

Class	Value range	Pollution level
Class 0	$NI_c < 0.7$	Uncontaminated
Class 1	$0.7 \leq NI_c < 1.0$	Uncontaminated to moderate contamination
Class 2	$1.0 \leq NI_c < 2.0$	Moderate contamination
Class 3	$2.0 \leq NI_c < 3.0$	High contamination
Class 4	$NI_c < 3.0$	Extremely high contamination

Table 4 Biological toxicity coefficients of heavy metals

Pollution factor	Pb	Cu	Cd	Hg
Toxicity index	5	5	30	40

T166-2004 at the Nonferrous Metal Northwest Geological Test Center, Xi'an, China (Unsal et al., 2014; Wang et al., 2018; Yoon et al., 2006). The data of each sampling were analyzed and mapped in Excel 2016, MATLAB R2014a, and SPSS version 23. To obtain the land use types in the study area, Google images with a 0.95-m resolution were downloaded, and ENVI5.3 and ArcGIS version 10.3 were employed for supervised classification of the study area.

Assessment of heavy metal pollution

Kriging interpolation, as a commonly applied spatial interpolation method in geostatistics and soil pollution assessment because of its unbiasedness (Hu & Cheng, 2016; Li et al., 2013; Liu et al., 2016a, 2016b), was adopted to interpolate the 471 sampling points in the study area.

At present, there are many effective methods for soil metal pollution evaluation, such as the Nemerow index (Morton-Bermea et al., 2009), geoaccumulation index, ecological risk assessment (Hakanson, 1980), enrichment factor (Karim et al., 2015), and pollution load index. Among these, the first three methods were selected to evaluate the pollution level in the study area.

1. Nemerow index

The Nemerow index method is an environmental quality index based on the background value of a given soil element (Jian et al., 2011; Pascual & Abollo, 2005). This method can effectively evaluate the soil pollution (Morton-Bermea et al., 2009). The Nemerow index expresses the pollution degree caused by a single element, and it is expressed as the ratio of the measured value to the background value (Hakanson, 1980; Swab et al., 2019; Zhang et al., 2018). The equation is as follows:

$$NI_i = AC_i/BV_i \tag{1}$$

$$NI_C = \sqrt{\frac{\left(\overline{NI}\right)^2 + \left(NI_{imax}\right)^2}{2}} \tag{2}$$

where NI_i is the pollution index of element i, AC_i is the measured value of pollutant metal i, BV_i is the upper limit of the background value of the soil environment in Shanxi Province (Hakanson, 1980; Swab et al., 2019; Zhang et al., 2018), NI_c is the comprehensive pollution index of the detected elements, NI_{imax} is the maximum value of the Nemerow index of each heavy metal, and $\overline{NI}$ is the arithmetic mean of NI_i. The evaluation results of the Nemerow index are classified into 7 classes, as listed in Table 1, and the comprehensive pollution evaluation results are classified into 5 domains (Cheng et al., 2007) (Table 2).

2. Geoaccumulation index

The geoaccumulation index (Igeo), also referred to as the Muller index, not only reflects the natural

Table 3 Classified standard of geo-accumulation index

Class	Value range	Pollution level
Class 0	Igeo ≤ 0	Uncontaminated
Class 1	0 < Igeo ≤ 1	Uncontaminated to moderate contamination
Class 2	1 < Igeo ≤ 2	Moderate contamination
Class 3	2 < Igeo ≤ 3	Moderately to high contamination
Class 4	3 < Igeo ≤ 4	High contamination
Class 5	4 < Igeo ≤ 5	High to extremely high contamination
Class 6	Igeo > 5	Extremely high contamination

Table 5 Classified standard of the potential ecological risk index

Class	Value range	Pollution level
Class 0	Eir < 40	Low potential risk
Class 1	40 ≤ Eir < 80	Moderate potential risk
Class 2	80 ≤ Eir < 160	Considerable potential risk
Class 3	160 ≤ Eir < 320	High potential risk
Class 4	Eir ≥ 320	Significant potential risk

Table 6 Classified standard of RI

Class	Value range	Pollution level
Class 0	RI < 110	Low potential ecological risk
Class 1	110 ≤ RI < 220	Moderate potential ecological risk
Class 2	220 ≤ RI < 440	Strong potential ecological risk
Class 3	440 ≤ RI < 880	Very strong potential
Class 4	RI > 880	Highly-strong potential

Table 7 Statistical results of soil heavy metal concentrations in the study area

Elements	Minimum /mg·kg^{-1}	Maximum /mg·kg^{-1}	Average /mg·kg^{-1}	Standard deviation	Variance	CV	Skewness	Kurtosis
Pb	17.50	830.00	41.75	42.86	1837.33	102.70%	14.49	258.37
Cu	12.80	475.70	30.53	22.00	483.81	72.10%	18.67	377.51
Cd	0.07	4.19	0.30	0.35	0.12	116.80%	6.83	58.79
Hg	0.01	3.50	0.10	0.18	0.03	193.50%	14.88	264.61

variation in the heavy metal distribution but also reflects the impact of human activities (Sekabira et al., 2010; Zhang et al., 2018; Zhao et al., 2014). Compared to the Nemerow index, this method emphasizes the influence of human factors and is more suitable for the analysis of human pollution sources (Krzysztof et al., 2003; Shi et al., 2014; Zhao et al., 2016). The equation is:

$$GeoI_i = \log_2 \left\{ \frac{AC_i}{M * BV_i} \right\} \quad (3)$$

where $GeoI_i$ is the geoaccumulation index of heavy metal i, AC_i is the measured value of element i, BV_i is the upper limit of the background value in Shannxi Province, and M is a modification coefficient, which is applied to adjust the difference in the environmental background value caused by different rocks and is generally set to 1.5 (Wei et al., 2014). The pollution level is classified into seven grades (Muller, 1969), as listed in Table 3.

3. Ecological risk assessment

The potential harm of different heavy metals to ecosystems varies. The ecological risk index proposed by Swedish researcher Lars Hakanson (Hakanson, 1980) considers the toxicity coefficient of heavy metals to evaluate the potential impact on the ecological environment (Sun et al., 2019; Zou et al., 2018). The equation is

$$ER_i = \mathrm{BT}_i \frac{AC_i}{BV_i} \quad (4)$$

$$RI = \sum_{i=1}^{n} ER_i \quad (5)$$

where ER_i is the ecological risk index for element i, AC_i is the actual measured value of heavy metal i, BT_i is the biological toxicity coefficient of heavy metal element i, BV_i is the upper limit of the background value, and RI is the comprehensive potential ecological risk index for the evaluated heavy metals, which is related to the type and quantity of the pollutants, and is positively correlated with the toxicity (Ajah et al., 2015; Hakanson, 1980; Sun et al., 2019). The biological toxicity coefficients of the considered heavy metals are listed in Table 4. According to the classification criteria proposed by Hakanson (Hakanson, 1980), the pollution level can be divided into five categories according to the E_R^i value and into five categories according to the RI value (X. Li et al., 2013). The classification criteria are summarized in Tables 5 and 6, respectively.

Source analysis of heavy metal pollution

Studies have verified that land use patterns exert an important impact on the accumulation of heavy metals in soil (Agata et al., 2017; Fernández & Carballeira, 2001; Li et al., 2020; Shang et al., 2015; Tang et al., 2017). Via comparison of the pollution distribution and land use

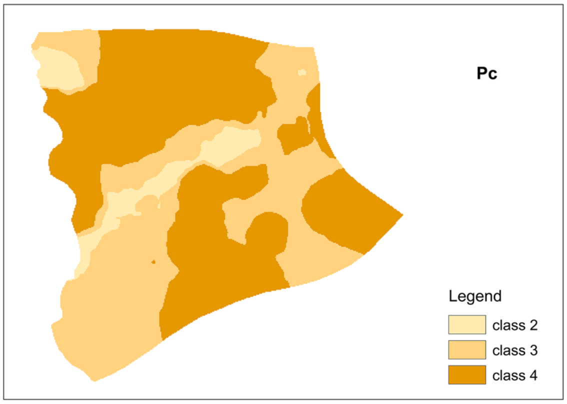

Fig. 2 Comprehensive evaluation results of Nemerow index

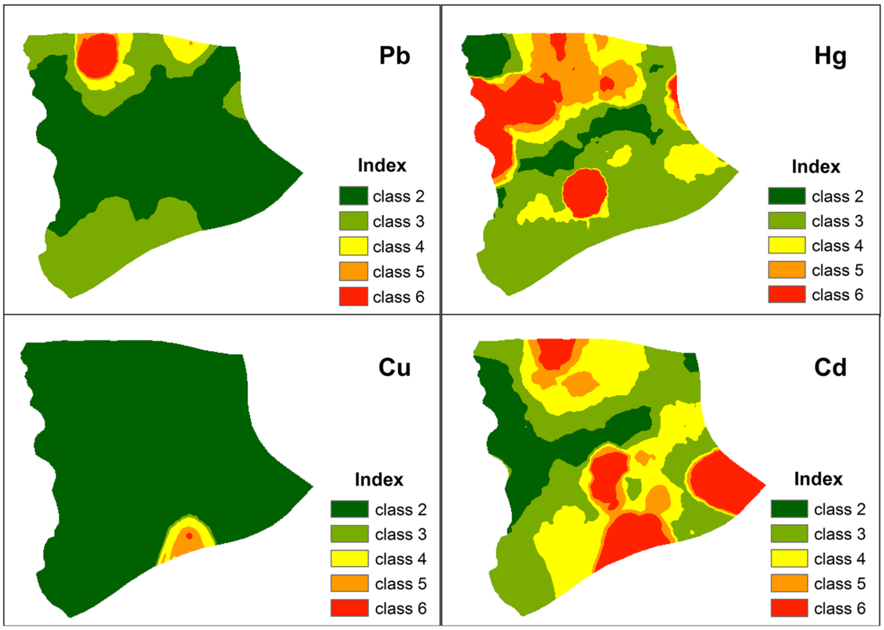

Fig. 3 Nemerow index of each soil heavy metals

pattern, it was found that the distributions of land use and soil pollution in the study area are similar to a certain extent. Therefore, this study analyzed the possible sources of heavy metal pollution based on the relationship between the pollution distribution and land use pattern.

The grid data of the heavy metal pollution assessment grade were recorded as P, for $P=\{P1, P2, \cdots, Pn\}$, where $P1$, $P2$, ··, Pn indicate the evaluation grade. The land use type at each grid data point was recorded as L, for $L=\{L1, L2, \cdots, Ln\}$, where $L1$, $L2$, ··, Ln denote the land use types. Pearson's correlation analysis between heavy metal pollution and land use types can reveal the relationship between the land use distribution and the spatial distribution of soil pollution, and the calculation equation is

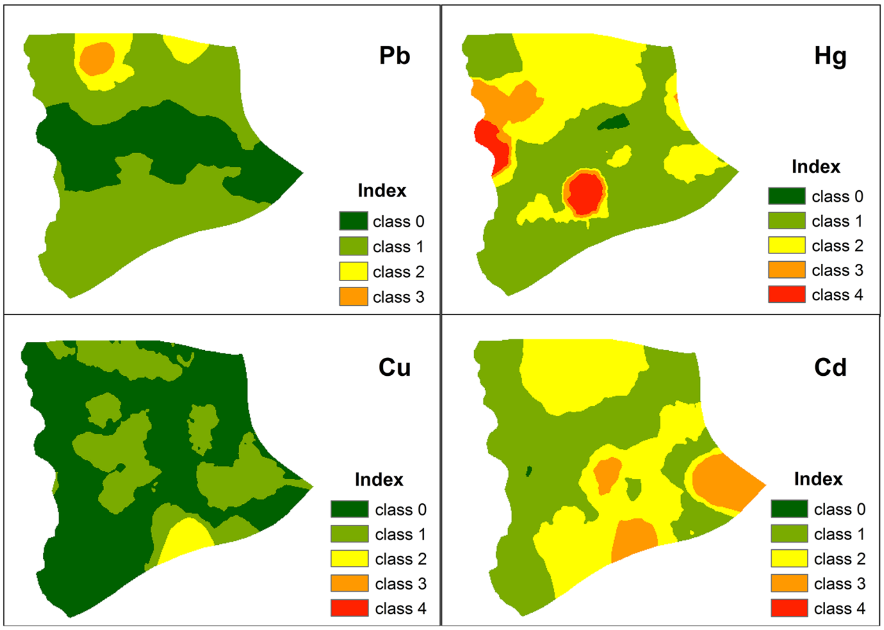

Fig. 4 Results of geo-accumulation index assessment of soil heavy metals

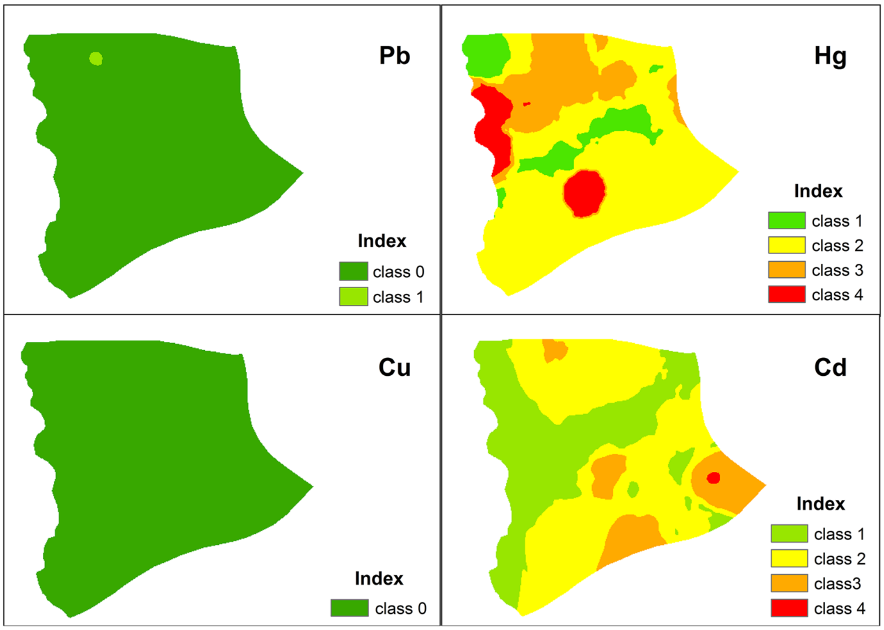

Fig. 5 Interpolated maps of the potential ecological risk of each element

$$\rho_{P,L} = \frac{\text{cov(P, L)}}{\sigma_P \sigma_L} = \frac{E((P-\mu_P)(L-\mu_L))}{\sigma_P \sigma_L} = \frac{E(PL) - E(P)E(L)}{\sqrt{E(P^2) - E^2(L)}\sqrt{E(P^2) - E^2(L)}} \quad (6)$$

where P is the pollution index of the heavy metals in soil, and L denotes the land use type.

Results and discussion

Statistical analysis

First, the contents of the four heavy metals were statistically analyzed, and the analysis results are listed in Table 7. The skewness and kurtosis of the Cu, Pb, and Hg contents in the study area are much higher than normal values, indicating that certain parts of the study area exhibit high accumulation rates (Zhang et al., 2018). Moreover, the coefficients of variation (CVs) of Hg, Cd, and Pb were 193.50%, 116.80%, 102.70%, and 72.10%, respectively, suggesting high variability (CV > 35%), which indicate that the spatial distribution of these elements may be seriously affected by human activities (Jing et al., 2018; Xu et al., 2014). The K-S normality test also verified that the distribution of the heavy metals in the study area is seriously affected by human activities (Hu & Cheng, 2013).

Analysis of the Nemerow index

Kriging-interpolated maps of the Nemerow index are shown in Figs. 2 and 3. Figure 2 shows the comprehensive evaluation results of the Nemerow index, and Fig. 3 shows the Nemerow index of each soil heavy metal. The comprehensive Nemerow index of the whole study area is 3.82, and the Nemerow

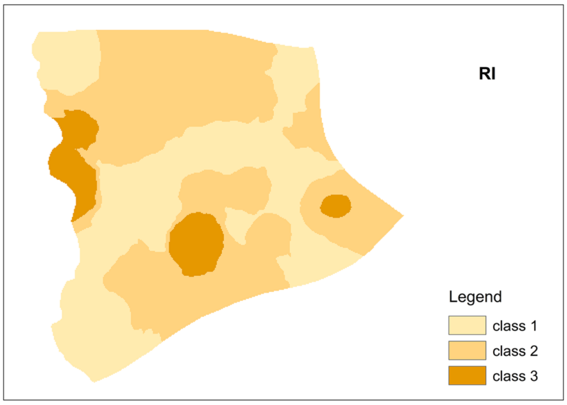

Fig. 6 Comprehensive index of the potential risk in the study area

Table 8 Results of the Pearson's correlation analysis

Pearson's correlation	Pb	Cu	Cd	Hg
Pb	1.00	0.11*	0.11*	0.04
Cu	0.17*	1.00	0.14**	0.03
Cd	0.11*	0.14**	1	0.10*
Hg	0.05	0.03	0.10*	1.00

*Significant at the 0.05 level; **Significant at the 0.01 level.

index of Cd, Pb, Cu, and Hg is 3.41, 1.98, 1.52, and 3.76, respectively. This result indicates that the study area is seriously heavy metal polluted. Pb and Cu reveal moderate to high contamination, while Hg and Cd reveal high contamination. The pollution is more serious in the northern and southern parts of the study area. Pollution in the north mainly involves Pb and Hg pollution, and the pollution in the south largely encompasses Cu and Cd pollution. In addition, Hg pollution is observed in the western part of the research area and Cd pollution in the middle part. In general, the spatial distributions of these four elements are not related.

Analysis of the geoaccumulation index

Kriging-interpolated maps of the geoaccumulation index are shown in Fig. 4. The degrees of cumulative pollution of Hg, Cd, Pb, and Cu were 1.11, 1.04, 0.31, and -0.01, respectively, indicating that Cd and Hg occurred at moderate contamination levels, Pb occurred at the uncontaminated to moderately contaminated level, and there was no Cu pollution. In contrast to Nemerow analysis, the geoaccumulation index indicates relatively low Hg and Cd pollution levels but relatively high Pb and Cu pollution levels. The geoaccumulation index clearly distinguished the moderate to high pollution levels of Hg and Cd, respectively.

Ecological risk assessment of soil heavy metal pollution

The potential ecological risk indexes of Hg, Cd, Pb, and Cu in the study area are 150.57, 102.46, 9.93, and 7.62, respectively. Kriging-interpolated maps of the potential ecological risk of each element are shown in Fig. 5. Because the Cu and Pb pollution levels are relatively low and the biological toxicity coefficients of these two elements are low, there is no significant spatial difference in the evaluation results across the study area, and the potential pollution levels are considerable. In contrast, the biological toxicity coefficients of Cd and Hg are higher, and the pollution degree is also higher, resulting in potential ecological risk values of Cd and Hg that are more than ten times higher than those of Cu and Pb. A high potential risk of Cd pollution was mainly distributed in the southwestern part of the study area, while a considerable potential risk was distributed in the northern and southern parts of the study area. A considerable potential risk of Hg pollution occurred throughout the whole study area, and the west was evaluated as exhibiting a significant potential risk. The distribution of the potential ecological risk levels was similar to that of the Nemerow index in appearance, but the ecological risk index overamplified the pollution level of highly toxic elements and reduced the pollution level of low-toxicity elements. The comprehensive index of the potential risk in the study area (Fig. 6) reached 271.30, and the distribution was similar to that of the comprehensive Nemerow index, but the evaluation level was relatively lower.

Table 9 Results of principal component analysis of heavy metals

Components	Total variance explained			Heavy metals	Component matrixes
	Initial eigenvalues	% of variance	Cumulative		1
1	1.28	32.00	32.00	Pb	0.55
2	0.98	24.51	56.51	Cu	0.60
3	0.90	22.56	79.08	Cd	0.67
4	0.83	20.92	100.00	Hg	0.40

Comparative analysis of the three methods

The Nemerow index is the ratio of the actual value of the heavy metals in soil to the background value. This method can simply reflect the extent of pollution, but it cannot distinguish whether the detected pollution is man-made. The geoaccumulation index increases the variation coefficient K, which considers the influence of man-made pollution and environmental geochemical and natural diagenesis on the background value. This approach can more directly reveal the pollution degree of the considered heavy metals and can effectively reflect the enrichment degree of heavy metals in sediments. The ecological risk assessment method not only considers the pollution degree of the heavy metals but also considers the ecological impact of their toxicity. However, in source analysis, the pollution degree of heavy metals with a high biological toxicity is exaggerated, resulting in a deviation in

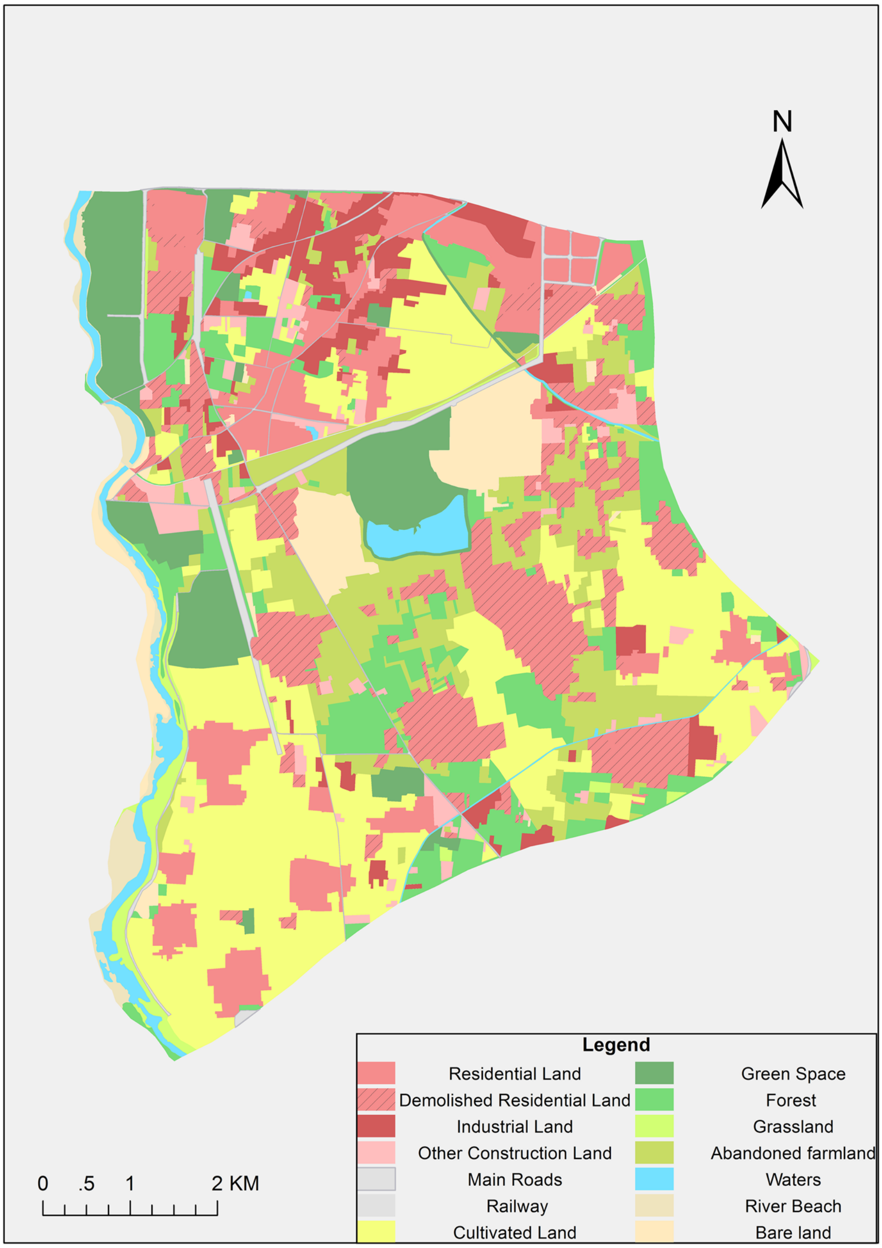

Fig. 7 Land use classification of the study area

the comprehensive pollution degree. Through comparative analysis of these three evaluation methods, the geoaccumulation index can clearly distinguish the degree of pollution, so it is more suitable for source analysis of heavy metal pollution in this study area.

Analysis of the heavy metal pollution sources

A commonly employed method to explore the sources of heavy metal pollution is PCA. Its basic principle is to reduce the dimension of the original indicators with a certain correlation to establish a few principal components to reveal the possible sources of pollution (Hu & Cheng, 2013; Yoon et al., 2006). A large number of studies has demonstrated that PCA is an effective tool for the identification of the sources of heavy metals (Bai et al., 2011; Han et al., 2006; Karim et al., 2015). However, the correlation between the heavy metal elements in this study area is significant at the 0.05 level but not strong (<0.30) (Table 8), resulting in a KMO value of only 0.56, which renders PCA unsuitable (Table 9).

PMF is another quantitative source analysis method recommended by the U.S. Environmental Protection Agency. PMF can be applied in the analysis of heavy metal pollution sources in soil and can better address missing and inaccurate data. However, this method requires a large number of receptor samples. Because the study area is small and the sample data are insufficient, the PMF method is not applicable in this area.

In view of the poor feasibility of traditional methods in this study, we analyzed the possible sources of pollution through the relationship between the land use and pollution via Pearson's correlation analysis. According to the land use status of the study area, the area was divided into 6 major categories and 14 subclasses: construction land (divided into residential land, demolished residential land, industrial land, and other construction land (used for commercial and social services)), transport land (divided into main roads and railways), arable land (cultivated land and abandoned farmland), green space (parks, forests and grasslands), water system (waters, rivers and beach), and bare land. The classification results were verified during sampling, and the classification accuracy was higher than 98%. The land use classification is shown in Fig. 7, and the Pearson's correlation analysis results of the land use types and heavy metal pollution are listed in Table 10.

Table 10 The Pearson correlation analysis between land use types and heavy metal pollution

Land use type	Pb	Cu	Cd	Hg
Green space	−0.02	0.06*	−0.11**	0.19**
construction land	0.23**	0.21**	0.22**	0.26**
Arable land	−0.12*	−0.03	0.28**	−0.12**
Traffic land	0.20**	−0.03	−0.07**	0.03**
Water system	−0.06*	−0.07*	−0.16**	−0.03**
Bare land	−0.02	0.02	−0.26**	−0.03**

**Significant at 0.01 levels (double tail); *Significant at 0.01 levels (double tail).

Table 10 indicates that the Pb distribution was significantly correlated with transport land and construction land at the 0.01 level, the Cu and Hg distributions were significantly correlated with construction land, and the Cd distribution was significantly correlated with the distribution of arable land. The distribution of comprehensive pollution based on Nemerow index and ecological risk assessment was positively correlated with construction land and significantly negatively correlated with bare land.

To further verify the impact of the land use types on heavy metal pollution, 100-m-wide buffer zones of residential land, demolished residential land, industrial land, other construction land, main roads, cultivated land, and abandoned farmland were established. The Pearson correlation results between the various buffer zones and heavy metal pollution is listed in Table 11.

Table 11 reveals that industrial land significantly influenced the distribution of the four elements, especially Pb and Hg, which indicates that industrial pollution is the main source of Pb and Hg pollution. Pb and Hg pollution was more serious along highways, which is typically caused by automobile exhaust and tire friction (Zhang et al., 2018). In general, traffic exerted a greater impact on the Pb content, while industrial pollution exerted a greater impact on the Hg content. The Cu distribution was correlated with construction land except residential land. This indicated that the impact of industrial and commercial

Table 11 Correlation between buffer zones and heavy metal pollution

Buffer zone	Pb	Cu	Cd	Hg	Pc	RI
Demolished residential land	−0.18**	0.11**	0.07*	0.10**	0.01	0.04
Cultivated land	0.05	−0.07*	0.28**	−0.08*	−0.03	0.01
Industrial land	0. 31**	0.13**	0.12**	0.28**	0.26**	0.29**
Main roads	0. 44**	−0.04	−0.13**	0.22**	0.09**	0.12**
Abandoned farmland	−0.21**	−0.10**	0.02	−0.06*	−0.01	−0.04
Residential land	0. 15**	0.08*	0.11**	0.07*	0.06*	0.11**
Other construction land	0.14**	0.15**	0.11**	0.17**	0.24**	0.23**

**Significant at 0.01 levels (double tail); *significant at 0.01 levels (double tail).

pollution on Cu was greater than that of domestic pollution stemming from construction land. The distribution of the Cd content was mainly correlated with cultivated land but not related to abandoned farmland. This result demonstrated that farming activities such as fertilization and irrigation were the main sources of Cd pollution. In addition, we found that due to the migration of the population from demolished residential land, Pb pollution decreases. This may be attributed to the reduction in traffic flow and the transfer of topsoil caused by demolition. For the same reason, Cd and Pb pollution in abandoned farmland areas was clearly lower than that in cultivated land areas. In summary, industrial land and other construction land attained a significant correlation with the distribution of the comprehensive pollution index. Among these land use types, industrial land yielded a greater impact on the level of each element in the soil, especially Hg and Pb, while cultivated land significantly affected the Cd level. After demolition, the impact of residential land on Pb and abandoned farmland on Cd significantly decreased.

Conclusions

In this study, the Hg, Cd, Pb, and Cu contents in the soil in the Fengdong District of Xi'an, China, were examined to analyze their pollution conditions and sources. The Nemerow index, geoaccumulation index, and ecological risk assessment method were adopted to evaluate the pollution status in the study area. The results revealed that the soil pollution status in the study area is serious and significantly affected by human activities. The Nemerow index demonstrated that Pb and Cu occur at moderate to high contamination levels, while Hg and Cd occurred at high contamination levels. The geoaccumulation index indicated that Cd and Hg occurred at moderate contamination levels, Pb occurred at moderate contamination levels, and there was no Cu pollution. The ecological risk index showed that Cu and Pb occurred at considerable pollution levels, and Hg and Cd occurred at serious pollution levels. In addition, through comparison of the three methods, the geoaccumulation index is more suitable for source analysis of heavy metals in this study because this approach can clearly distinguish the degree of pollution.

The different concentrations of the heavy metals revealed a heterogeneous spatial pattern. Pb pollution mainly occurred in the northern part of the study area, and Cu pollution was largely observed in the south. The Hg distribution was mainly concentrated in the north and west, while Cd pollution was largely concentrated in the northeast, middle, and south of the study area. The Pb, Cu, Cd, and Hg contents in the soil of in the study area were independent, but there were certain similarities between the pollution distributions and the land use patterns. Therefore, Pearson's correlation analysis was conducted to analyze the possible pollution sources through the relationship between the land use and pollution.

Pearson's correlation analysis indicated that transport land exerted a greater impact on Pb, and industrial land exerted a significant influence on the Hg distribution. The Cu distribution was correlated with construction land, and the Cd distribution was mainly correlated with cultivated land but not related to abandoned farmland. These results indicated that traffic pollution is the main source of Pb pollution, industrial pollution is the main source of Hg pollution, and farming activities such as fertilization and irrigation are the main causes of Cd pollution. In addition, the demolition of residential land and the abandonment of farms could significantly impact Pb and Cd pollution, respectively. The results are consistent with those obtained in other studies and verify the correctness of the method.

This study proposed that a source analysis method when the correlation between metal elements is weak, PCA is unsuitable. By analyzing the correlation between the evaluation results and land use types, the sources of heavy metal pollution can be analyzed. This method does not require correlation between the considered elements. The conclusions pertaining to the heavy metal pollution sources in the study area are consistent with the general conclusions of previous studies. Due to the limitations of the research scope and data, the general applicability of the method should be further studied. This study can provide a valuable reference for similar research and can contribute to the sustainable development of certain rapid urbanization areas in developing countries.

Author contribution Huijuan Hu: conceptualization, methodology writing, reviewing and editing. Ling Han: Data curation, resources, review and editing. Liangzhi Li: software, visualization. Haiyang Wang: data curation, investigation, validation. Tangqi Xu: project administration, supervision.

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Declarations

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Competing interests The authors declare no competing interests.

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