Spatial Distribution and Pollution Assessment of Heavy Metals in Soils in the Jiefangzha Irrigation Area of the Hetao Irrigation District, China

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Spatial distribution and pollution assessment of heavy metals in soils in the Jiefangzha Irrigation Area of the Hetao Irrigation District, China

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Abstract: To explore the characteristics of heavy metal pollution in farmland soils in the Jiefangzha Irrigation Area of the Hetao Irrigation District, Inner Mongolia, 60 samples of the surface soil (0–20 cm) of the irrigation area were collected to detect and analyze the content of the typical heavy metal elements Cu, As, and Pb in the soil. The methods utilized included the single factor index method, the Nemerow index method, the geological accumulation index method, and the potential ecological hazard index method to evaluate their pollution and ecological risks, and these were combined with geostatistical methods using GIS technology to quantitatively analyze their spatial distribution characteristics. The results showed that the average content of Cu, As, and Pb did not exceed the background values in the Hetao Irrigation Area, and the contents showed a moderate variation, with the order of variation as As>Cu>Pb. The multivariate statistical analysis results showed that the three elements, Cu, As, and Pb, had similar sources, being primarily the use of agrochemicals, such as fertilizers and pesticides. The semi-variance function model fitting results showed that Pb was a spherical model, and Cu and As were Gaussian models. The Kriging interpolation showed that the contents of As, Pb, and Cu, in general, showed a trend that was higher in the northwest and lower in the southeast, with a change of gradient increasing from the southeast to the northwest. Human activities were the primary factors that were causing the distribution difference.

Keywords: farmland soils; heavy metals; Jiefangzha Irrigation Area; spatial distribution; pollution assessment

1. Introduction

Soil is an important part of the terrestrial ecosystem and the key to sustaining life on earth. It can supply nutrients necessary for plant growth, and is not only the destination of heavy metals but also the medium for heavy metals to spread to the atmosphere, organisms, and water[1,2]. Heavy metals in soil are complex, concealed, hysteretic, cumulative, and irreversible[3,4], and they are extremely difficult to treat. This leads to crop production reductions and agricultural product pollution[5,6]. Finally, excessive accumulation in the human body through the food chain threatens human health. Heavy metal pollution has become a serious problem in the world, which has attracted extensive attention from society and academic circles.

The Inner Mongolia Hetao Irrigation Area is the national important production base of commodity grain and oil, and the Inner Mongolia autonomous region is one of the largest yellow irrigation areas of our country. In recent years, the Yellow River basin violations of pollutant emission standards have led to increasing degrees of water pollution[7,8], and the use of agricultural chemicals, such as fertilizers and pesticides, and the liberation of brake irrigation field water and soils are serious threats. In addition, Wuliangsu Hai is the only bearing and discharging channel of the Hetao Irrigation Area, and the pollution substances carried by farmland drainage cause ecological risks to Wuliangsu Hai. Currently, many scholars have studied soil salinization[9], persistent organic pollutants[10], and changes in the groundwater level in the Jiefangzha Irrigation Area of the Hetao Irrigation Area[11], but there are a few studies that have examined heavy metals in the farmland soils of this irrigation area. Therefore, single-factor and multi-factor evaluation methods are used in this study to evaluate the pollution degree and potential ecological harm of the heavy metals Cu, As, and Pb in the farmland soils of the Jiefangzha Irrigation Area and to analyze the source and spatial distribution of heavy metals in this study area. This is accomplished by combining a multivariate statistical analysis, GIS, and geostatistical methods. This study provides a scientific basis for farmland protection and the comprehensive control of heavy metal pollution in this area.

2. Materials and methods

2.1. Study area

The Jiefangzha Irrigation Area has a very long history beginning from the Qin and Han Dynasties and prospering in the late Qing Dynasty. According to historical records, it has a development history of more than 2,000 years. It is one of the earliest large-scale irrigation areas of the Yellow River irrigation development in the Hetao Irrigation Area of Inner Mongolia. The Jiefangzha Irrigation Area is located in the central and western side of the Hetao Irrigation Area of Inner Mongolia. Its geographical coordinates are 106°43'–107°27' E and 40°34'–41°14' N. It belongs to the cold and arid area of northwest China. It is a typical irrigated agricultural area. The annual average water volume of the Yellow River diversion irrigation in the irrigated area is approximately 1.2 billion m³, and the annual displacement is approximately 200 million m³. The main crops are corn, wheat, oil, and others.

2.2. Sample collection and determination

According to the Technical Specification for Monitoring Farmland Soil Environmental Quality and the geographical characteristics and irrigation characteristics of the Jiefangzha Irrigation Area, the S-type distribution method was adopted. In June 2019, soil surface samples (0–20 cm) were collected, and a total of 60 sampling points were established, as shown in Figure 1. During the sampling process, approximately 1 kg of soil samples was collected from each sampling point and placed into a polyethylene plastic bag to prevent cross-contamination.

The collected samples were naturally air-dried in the laboratory, and after removing impurities from the samples, the samples were crushed with a wooden tool, ground through a 100-mesh sieve using an agate mortar, and put into a polyethylene plastic bag for use. The soil samples were digested using a microwave with HNO₃-HCL-HF. The contents of the Cu, As,

and Pb were analyzed using inductively coupled plasma mass spectrometry (ICP-MS). All of the reagents in the analysis were of excellent purity, and all the samples were tested in parallel.

Figure 1 Distribution of study area and sampling points

2.3. Data statistics and analysis

During the process of data analysis, SPSS26 software was used for the statistical analysis, the principal component analysis, and the normal distribution test. GS+9.0 software was used for the semi-variance function model fitting. ArcGIS10.2 was used for the Kriging interpolation to draw the distribution map of the sampling points and the distribution map of the soil heavy metal content.

3. Evaluation method of the soil heavy metal pollution

3.1. The single factor index method

The single factor index method was used to grade the cumulative pollution degree of a single heavy metal in the soil[12-16], and its expression is as follows:

$$P_i = C_i / S_i (i = 1, 2, 3, \dots, n),$$

where P_i is the single factor pollution index of a heavy metal, i , and its classification is

shown in Table 1; C_i is the actual test value of a heavy metal, i ($mg \cdot kg^{-1}$); S_i is the evaluation standard value of a heavy metal, i ; and n is the total number of heavy metals participating in the evaluation.

3.2. The Nemero index method

The Nemero index not only highlights the impact of a high concentration of pollutants on environmental quality but also considers the average value of a single factor pollution index that can fully reflect the average pollution level of various pollutants in the soil. It is a comprehensive evaluation method of environmental quality that is widely used. Its expression is as follows:

$$P_N = \sqrt{\frac{(P_i)_{average}^2 + (P_i)_{max}^2}{2}},$$

where P_N is the Nemerow comprehensive pollution index, and its classification is shown in Table 1; P_i average is the average single factor index of each heavy metal; and P_i max is the maximum single factor index of a heavy metal, i .

3.3. The geological accumulation index method

The geological accumulation index[17-19], also known as the Muller index, was first proposed by Muller, a scientist at the University of Heidelberg in Germany in the late 1960s. It is primarily used to study the degree of heavy metal pollution in sediments and other substances. It not only considers the background value of natural processes but also pays attention to the influence of human activities on heavy metal pollution. Its expression is as follows:

$$I_{geo} = \log_2(C_i/K \cdot B_i),$$

where I_{geo} is the geological accumulation index, and its classification is shown in Table 1; C_i is the measured value of a heavy metal, i , in a soil; B_i is the background value of a heavy metal, i , in a soil in the rock strata; and K is the coefficient (generally K is 1.5).

Table 1 Standards for classification of soil heavy metal pollution levels

Single factor index		Nemero index		Geological accumulation index		
P_i	Pollution degree	P_N	Pollution degree	I_{geo}	series	Pollution degree
$P_i \leq 1$	No pollution	$P_N \leq 0.7$	Clean	$I_{geo} \leq 0$	0	No pollution
$1 < P_i \leq 2$	Slight pollution	$0.7 < P_N < 1$	Cordon	$0 < I_{geo} \leq 1$	1	No pollution moderate
$2 < P_i \leq 3$	Light pollution	$1 < P_N \leq 2$	Light pollution	$1 < I_{geo} \leq 2$	2	Moderately polluted
$3 < P_i \leq 5$	Moderately polluted	$2 < P_N \leq 3$	Moderately polluted	$2 < I_{geo} \leq 3$	3	Moderately Pollution Severe
$P_i > 5$	Heavy pollution	$P_N > 3$	Heavy pollution	$3 < I_{geo} \leq 4$	4	Heavy pollution
—	—	—	—	$4 < I_{geo} \leq 5$	5	higher heavy pollution

—	—	—	—	$I_{geo} > 5$	6	Very heavy pollution
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3.4. Methods for assessing the potential ecological risks

The potential ecological risk index method was proposed by Hakanson[20-25], a Swedish scholar, to evaluate heavy metal pollution and its ecological harm. The method combines the ecological effect, environmental effect, and toxicology of heavy metals. It can comprehensively reflect the impact of heavy metals on the ecological environment. Its expression is as follows:

$$E_i = T_r^i \times (C_i / C_{0i}) ,$$

where C_i is the measured values; C_{0i} is parameter ratios of a heavy metal, i ; T_r^i is the toxicity coefficient of a heavy metal, i ; and the toxicity response coefficients of heavy metals As, Cu, and Pb are ten, five, and five, respectively.

The comprehensive potential ecological risk index is as follows:

$$RI = \sum E_i ,$$

where RI is the comprehensive potential ecological risk index of various heavy metals in the study area; and E_i is the potential ecological harm index of a heavy metal, i . Its classification is shown in Table2

Table 2. Potential ecological risk coefficient and potential ecological risk index classification

Rank	potential ecological risk index	Degree of risk	comprehensive potential ecological risk	Degree of risk
1	$E_i \leq 40$	Low potential risk	$RI \leq 150$	Minor ecological hazard
2	$40 < E_i \leq 80$	Medium potential risk	$150 < RI \leq 300$	Moderate ecological hazard
3	$80 < E_i \leq 160$	Medium high potential risk	$300 < RI \leq 600$	Strong ecological hazard
4	$160 < E_i \leq 320$	High potential risk	$RI > 600$	Very strong ecological hazard
5	$E_i \geq 320$	Very high potential risk	—	—

4. Results and analysis

4.1. Statistical analysis of the heavy metals in the soil

According to the test results, the pH values of the soil samples were all greater than 7.5. As can be seen from Table 3, the average contents of Cu, As, and Pb in the soil in the study area were 13.16, 8.28, and 15.971 MGKG, respectively, which were within the range of the second-level national standard and the background value[39,40]. However, a few sample points exceeded the background value of the soil. The proportions of the over-point samples for Cu,

As, and Pb were 8.33%, 16.67%, and 13.33%, respectively. The phenomenon of the over-point values exceeded the background values, and this indicated that the three heavy metal elements in the study area had accumulated to different degrees. Compared with the Yichang Irrigation Area and the Ulate Irrigation Area[26,27], the average As content in the Jiefangzha Irrigation Area was higher, but within the range of the background value. The contents of Pb were similar in the two areas. The content of the As element in the Wuliangsu hai water body was much higher than that in the Inner Mongolia section of the Yellow River[28-29]; however, it was similar to the Jiefangzha Irrigation Area, as shown in Table 4. This indicated that the drainage of the Jiefangzha Irrigation Area had a certain contribution to this value. The degree of spatial variability can be roughly classified according to the variation coefficient ($CV < 10\%$ is weak variability, $10\% \leq CV \leq 100\%$ is moderate variability, and $CV > 100\%$ is strong variability). As shown in Table 3, the variation coefficients of Cu, As, and Pb were 25.46%, 37.56%, and 16.16%, respectively, belonging to moderate variability. The three heavy metal elements were affected by exogenous factors, such as irrigation water, atmospheric deposition, pesticide and fertilizer use, and traffic pollution.

Table 3. Descriptive statistical analyses of the soil heavy metal contents ($\text{mg} \cdot \text{kg}^{-1}$)

The element	The background value	Standard values	range	average	standard deviation	Coefficient of variation	Beyond the background value (%)	Beyond the standards (%)
Cu	19.17	100	7.50 ~ 24.24	13.16	3.55	25.46%	8.33	0
As	9.68	25	3.70 ~ 19.72	8.28	3.11	37.56%	16.67	0
Pb	18.67	350	11.70 ~ 22.81	15.97	2.58	16.16%	13.33	0

Table 4. Soil and water content of heavy metals in parts of Inner Mongolia ($\text{mg} \cdot \text{kg}^{-1}$)

The element	Jiefangzha irrigation area (Farmland soil)	Yichang Irrigation Domain (Farmland soil)	Ulate Irrigation (Farmland soil)	Inner Mongolia Section of the Yellow River (Water)	Wuliangsu hai (Water)
Cu	13.169	—	—	5.69	7.90
As	8.28	2.55	2.33	1.10	6.67
Pb	15.97	14.52	13.70	7.83	1.06

4.2. Evaluation of the soil heavy metal pollution

Using the environmental background value of the Hetao Irrigation Area As value as the evaluation standard, Table 5 shows that the average value of a single factor pollution index for the three heavy metal elements in the study area was $As=Pb>Cu$, between 0.69 and 0.86. This indicated different degrees of pollution. In the samples, 15% and 1.67% of the As elements were slightly polluted or lightly polluted, and approximately 10% of the Pb and Cu elements were slightly polluted. This indicated that the accumulation and enrichment of As in the soil was more serious than that of the Pb and Cu elements. Table 6 shows the evaluation results of the Nemero comprehensive pollution index for heavy metals in the farmland soils in the study

area. When the soil environmental background value of the Hetao Irrigated Area was used as the evaluation standard, the proportion of samples with light pollution and a warning line was 15% and 66.67%, respectively. This indicated that there was a certain degree of heavy metal accumulation in the farmland soil in the study area. The study area was at a clean level when the second-level national soil environmental quality standard was used as the evaluation standard. According to the geological accumulation index results, 3.33% of the soil samples had moderate or no pollution, and both Pb and Cu were in the no pollution range, which was consistent with the evaluation results of the single factor pollution index, as shown in Table 7.

Table 5. Evaluation results of the soil heavy metal single factor pollution index

The element	Single factor index method			The degree of risk			
	range	average	No pollution	Slight pollution	Light pollution	Moderately polluted	Heavy pollution
Cu	0.39 ~ 1.26	0.69	91.67%	8.33%	0	0	0
As	0.38 ~ 2.04	0.86	83.33%	15.00%	1.67%	0	0
Pb	0.63 ~ 1.22	0.86	86.67%	13.33%	0	0	0

Table 6. Overall evaluation results of soil heavy metals in the study area

Standard	Composite pollution index				The degree of risk		
	index				Light pollution	Moderately polluted	Heavy pollution
	range	average	Clean	Cordon			
Background value	0.57 ~ 1.75	0.87	18.33%	66.67%	15.00%	0	0
National Second Standard for Soil Environment	0.12 ~ 0.61	0.26	100%	0	0	0	0

Table 7. Results of the geological accumulation index of soil heavy metals in the study area

The element	Geological accumulation				The degree of risk				
	index								
	range	average	No	No	Moderately polluted	Moder	Heavy pollution	higher	Very
			pollute -on	pollution moderate		atel-y Polluti- on		heavy pollute -on	heavy pollutio -n
Cu	-1.94 ~ 0.25	-1.17	100%	0	0	0	0	0	0
As	-2.06 ~ 0.36	-0.99	96.67%	3.33%	0	0	0	0	0

Pb	-1.26 ~ 0.30	-0.83	100%	0	0	0	0	0	0
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4.3. The potential ecological risk assessment of heavy metals in the soil

The potential ecological harm coefficient and the comprehensive potential ecological harm coefficient of the single heavy metals were evaluated using the soil environmental background value of the Hetao Irrigation Area. Table 8 shows the average potential ecological harm coefficient of each heavy metal As (8.56) >Pb (4.28) >Cu (3.43) was less than 40, which is a low potential risk. The comprehensive potential ecological harm coefficient was 16.27. This indicated that the heavy metals in the soil of the irrigated area showed a slight harm degree, which was consistent with the ecological risk level of the soil from the irrigated area in the Urat region studied by Tian Zhiqiang[22].

Table 8. Ecological Risk Assessment of Soil Heavy Metal Pollution

Item	Cu	As	Pb
E_i	1.96 ~ 6.32	3.82 ~ 20.38	3.13 ~ 6.11
$\overline{E_i}$	3.43	8.56	4.28
Risk level	Low potential risk	Low potential risk	Low potential risk
$\overline{RI}$	16.27		
Risk level	Minor ecological hazard		

5. Soil source analysis and spatial distribution of the heavy metal content

A correlation analysis and principal component analysis can well identify the sources of soil heavy metal pollution[30,31]. Heavy metal elements are primarily affected by human activities and parent rocks. Table 9 shows the correlation analysis values of the three heavy metals. It can be concluded that the three heavy metal elements had greater homology and the hidden danger of compound pollution. The principal component analysis using SPSS showed that the variance contribution rate of PC1 was 86.64%, which attained the analysis standard. The As, Pb, and Cu had a large load on PC1, with obvious high values at 0.937, 0.820, and 0.842, respectively. The possible factors that led to the accumulation of heavy metals in this area were pesticides, chemical fertilizers, excessive use of mulching films, and irrigation that used polluted water.

Table 9. Correlation coefficients of soil heavy metal elements in the study area

The elemen	Cu	As	Pb
Cu	1		
As	0.835**	1	
Pb	0.863**	0.697**	1

Note: **. At the 0.01 level (two-tailed), the correlation is significant

The K-S method in the SPSS software was used to test the normal distribution of the data.

The results showed that the Pb element obeyed a normal distribution, and Cu and As obeyed a normal distribution after logarithmic conversion. GS+9.0 geostatistics software was used to analyze the data by semi-variograms. According to the fitting results of the variograms theory model, Pb was a spherical model, and Cu and As were Gaussian models. In addition, the nugget coefficients of the three types of heavy metals were all 0.502–0.522, indicating a medium spatial correlation. The Geostatistical Analyst function in ArcGIS10.2 was used to interpolate the heavy metal content. The Nemero composite index and potential ecological harm composite index for the study area were found using the ordinary Kriging method[32–38], as shown in Figures 2 and 3.

The contents of the Cu, As, and Pb in the study area generally displayed a trend of high in northwest China and low in southeast China, with an increasing gradient change from the southeast to the northwest. The spatial distribution of the pollution of the three heavy metals was similar, showing a gradient distribution. The pollution of the three heavy metals was more serious in northwest China, and the pollution range was wider and more serious than that of Pb and Cu. Some points beyond the background value were distributed in the northwest area of the liberating gate irrigation area. The primary reason for the above phenomenon was the accumulation of heavy metals caused by the long-term residual accumulation of toxic and harmful substances in irrigation water, pesticides, fertilizers, and mulching film utilized in northwest China where crops are planted.

According to the comprehensive evaluation shown in Figure 3, the accumulation degree of heavy metals in the northwest of the study area was more serious than that in the other polluted areas. According to the evaluation result chart of the potential ecological harm index method, the study area was in slight ecological harm as a whole. However, the ecological element in northwest China was more serious. This was consistent with the Nemero comprehensive pollution index evaluation results.

Figure 2. Spatial distribution map of the heavy metal element contents in the soil

Figure 3. Comprehensive evaluation results of the soil heavy metal elements

6. Conclusions

The contents of Cu, As, and Pb in farmland soil samples from the Jiefangzha Irrigation Area exceeded the background value by 8.33%, 16.67%, and 13.33%, respectively. The variation degree was moderate, and the three heavy metal elements were affected by exogenous factors, such as atmospheric deposition, pesticide, fertilizer use, and traffic pollution. The single factor index method and the geological accumulation index showed that the pollution degree of As was high. The average Nemero composite pollution index was 0.87, indicating the warning level.

In the Hetao Irrigation Area regarding the soil environmental background value of the As evaluation standard, the potential ecological harm coefficient of the three types of heavy metals in the study area had means rated as As > Pb > Cu. This was an overall low potential risk, and the potential ecological comprehensive index was 16.27. This demonstrated that the overall performance of the heavy metals had the potential for slight damage. Hence, the control of heavy metal pollution and soil heavy metal pollution monitoring should be considered for this area.

The correlation analysis showed that there was a significant correlation between As-Pb-Cu, and it was inferred that the sources of the three heavy metals were similar. The principal component analysis results showed that the variance contribution rate of the first principal component was 86.64%, which further indicated that As, Pb, and Cu were probably from the same source. In addition, their accumulation in the soil was caused by human factors.

The results of the semi-variance function model fitting showed that Pb was a spherical model, and Cu and As were Gaussian models. The contents of As, Pb, and Cu in the study area were generally higher in the northwest region and lower in the southeast region. The northwest region is primarily used for crops, and the long-term residual accumulation of toxic and harmful substances in irrigation water, pesticides, fertilizers, and mulching film may have caused the accumulation of heavy metals.

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