



OPEN Spatial differentiation and influencing factors of heavy metals in soils of typical counties in Lhasa river basin

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This paper studied the spatial distribution and influencing factors of heavy metals (HMs) such as Cu, Pb, Zn, Cr, Ni, Cd and As in the soil of Linzhou County in the Lhasa River basin. By collecting 504 surface soil samples, using descriptive statistics, Kriging interpolation and geoaccumulation index methods, combined with the geographic detector model, the spatial distribution characteristics of soil HMs content and its interaction with 19 environmental factors were systematically analyzed. The results showed that the content of heavy metals in the soil in this area was generally higher than the background value of soil in Lhasa, especially Cd and As, which showed strong spatial heterogeneity, suggesting the existence of specific pollution sources. Although the average HMs content was lower than the soil pollution risk screening value, the As, Cd, Pb and Zn contents at some sampling points exceeded the standard, indicating a high pollution risk in some local areas. The spatial distribution of HMs was uneven, with high-value areas of Pb, Zn and Cd mainly concentrated in the west, Cu concentrated in the northwest, while high-value areas of Cr and Ni were similar, mainly concentrated in the west and central regions. Correlation analysis and geodetector models revealed that traffic pollution and soil texture characteristics were the main environmental factors affecting the spatial variation of soil HMs content, and the distance from national highways and urban roads had a particularly significant relationship with Sc and TK. The study provided a scientific basis for the prevention and control of HMs pollution in soil in high-altitude and cold areas, and recommends targeted environmental management and restoration measures.

Keywords Soil heavy metals, Geographic detector, Spatial distribution, Geoaccumulation index, Correlation analysis

Soil is one of the most important natural resources on the earth. With the rapid development of social economy, the content of soil HMs shows an increasing trend and is widely distributed. Soil HMs pollution has the characteristics of toxicity, accumulation, irreversibility and persistence, which can lead to a serious decline in soil quality, while HMs enter the food chain and endanger human health^{1–4}. Since April 2005, China had completed the first national soil pollution survey in eight and a half years. The survey announcement showed that the overall soil environmental condition in the country is not optimistic. The environmental quality of industrial and mining wasteland and cultivated land had become a prominent problem^{5–7}. The overall over-standard rate of soil in the country reached 16.1%. The over-standard rates of eight inorganic pollutants Pb, Cr, Cd, Hg, Zn, Ni, As and Cu were 1.5%, 1.1%, 7.0%, 1.6%, 0.9%, 4.8%, 2.7% and 2.1%, respectively^{8–10}. In the past decade, domestic scholars had carried out a lot of research work on soil HMs content, pollution assessment and source analysis, agricultural product safety and human health risk assessment^{11–15}. By studying and analyzing the characteristics of soil HMs content and spatial distribution, evaluating the status of soil HMs pollution and tracking the sources of soil HMs, we can provide a reference for improving and regulating the ecological environment and formulating social and economic sustainable development plans.

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At present, geographical detector is more and more widely used in the analysis of the sources of soil HMs pollution, mainly because it can quickly and intuitively analyze the effects of spatial distribution factors, and there is no strong model hypothesis. It solves the problem that the traditional method is unable to analyze the spatial distribution of multiple factors and the interaction between factors^{16–18}. For example, Zhou et al.¹⁹ used the geographic detector model to quantitatively evaluate the spatial distribution of five soil HMs, Cu, Zn, Pb, Cr, and Ni, and the interactions of 11 environmental factors. Zhang et al.²⁰ concluded that the distance from rivers and soil type in the transition zone between mountain and plain were the key factors affecting the mountainous area, the multiple cropping index and the distance from industrial and mining enterprises were the key factors affecting the transition zone, and the soil pH and fertilizer application rate were the key factors affecting the plain area. Ma et al.²¹ used geographical detectors to conclude that the dominant factor in the spatial distribution difference of soil Pb content in the Manghe small watershed was the structural factors of topography and land use and other activities that had a greater impact, and land use, industrial and mining enterprises, etc. The cross-over effects of human activities and geology and topography have significantly enhanced the interpretation of the spatial distribution of soil Pb content in the watershed.

At present, the research scope of soil HMs is mainly concentrated in the mining areas of southwest and southeast China, agricultural and industrial areas and along the road traffic, while there are relatively few studies on high-cold and high-altitude areas such as the Lhasa River Basin, and in the source identification analysis, the research methods are mainly qualitative analysis, and quantitative analysis needs to be further explored. For this reason, based on 504 topsoil (0–20 cm) samples collected in 2022 in Linzhou County, Lhasa River Basin, this paper uses descriptive statistical analysis, Kriging interpolation method, geoaccumulation index method, Geographic detector and other analysis methods. Quantitative analysis of pH, soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP), total potassium (TK), Sc, slope aspect, slope, elevation, distance from provincial highway, distance from national highway, distance from urban highway, distance from highway, distance from city and county, distance from tributaries, distance from Lhasa River, distance from Brahmaputra River, distance from lake, Influence factors such as distance from Railway on Spatial Distribution characteristics and influence degree of soil HMs of Linzhou County in Lhasa River Basin, The aim is to provide scientific guidance and methodological references for the prevention and control of soil HMs pollution in high-altitude plateau areas.

Materials and methods

Study area

The Lhasa River Basin is located in the core area of central and southern Tibet, which is a national key development area, flows through Jiali County, Linzhou County, Mozhu Gongka County, Dazi District, Chengguan District and Duilong Deqing District, and joins the Yarlung Zangbo River in Qushui County. Linzhou County in the study area is the largest agricultural county in Lhasa City, accounting for 1/3 of the total cultivated land area of Lhasa City, located between 29°45′~30°08′N and 90°51′~91°28′E, located in the middle and upper reaches of the Yarlung Zangbo River, located in the southeast of Lhasa City, about 60 km north from Lhasa City, Mozhu Gongka County in the south, Dazi County in the east and Motuo County on the western boundary, with a regional area of 4464.4 km². The Gagong Bar fault in the south-central region serves as the dividing line. To the north, it is the Gongbujiangda-Chayu fold belt, formed by the northward subduction of the Indian plate during the Yanshanian period. To the south, it is the Gangdise-Nyingchi Tanggula landmass Gangdise-Lhasa magmatic arc. The climate belongs to the plateau temperate semi-arid plateau monsoon climate zone, cool and rainy in summer and cold and dry in winter. The annual average temperature is about 7 °C, the temperature difference between day and night is large, the solar radiation is strong, and the annual precipitation is abundant, with summer as the main precipitation period. The terrain in the county is relatively flat, with an altitude of between 3600 m and 4000 m above sea level. In stratigraphic division, the north belongs to Lhasa-Chayu stratigraphic division and the south belongs to Lhasa-Waka stratigraphic division. At the same time, the county has Huangshui River, Karoram Zangbu River and other rivers flow through, and has Yangzhuo Yongcuo and other plateau lakes. The study area is rich in natural resources, and the grassland is vast, which is suitable for the development of animal husbandry. The mineral resources mainly include lead, zinc, barite, coal, gypsum and so on. The soil types are mainly tidal soil and alpine scrub steppe soil, which are mainly used for planting highland barley, barley, rape and other crops.

Sampling and analysis

The layout of soil sample sites covers different slope aspects, elevations, distances from roads and railways, and distances from rivers. The average sampling density of soil was 1 point / km², and the range of sampling density was 0.25 point / km² ~ 2 point / km². According to the Geochemical Evaluation Standard of Land quality (DZ/T 0295–2016), a total of 504 soil samples were obtained (Fig. 1). In order to improve the representativeness of each sample, when the sampling plot was rectangular, the “S” shape was used to set the sub-sample points, and when the sampling plot was approximately square, the “X” shape or “chessboard” shape was used to set up the sub-sample points. The collected soil samples were naturally air-dried for a week, remove other debris, pass through a 20-mesh sieve, and complete the analysis and test in the Chengdu Comprehensive Rock and Mineral Test Center of Sichuan Geology and Mineral Exploration and Development Bureau. pH was determined by ion selective electrode (ISE P911), SOM by volumetric (VOL), TN by volumetric (VOL), As and Hg by atomic fluorescence spectrometry (AFS AFS3100), Cu, Pb, Zn, Cr, Ni, Cd, TP and TK by X-ray fluorescence spectrometry (XRF PW:4400/40) and inductively coupled plasma optical (ICP-AES iCAP6300)/mass (ICP-MS XSERIES2).

spectrometry. To ensure the accuracy and reliability of soil HMs content data, strict quality control procedures were implemented in accordance with the Specification for Multi-Objective Regional Geochemical Survey

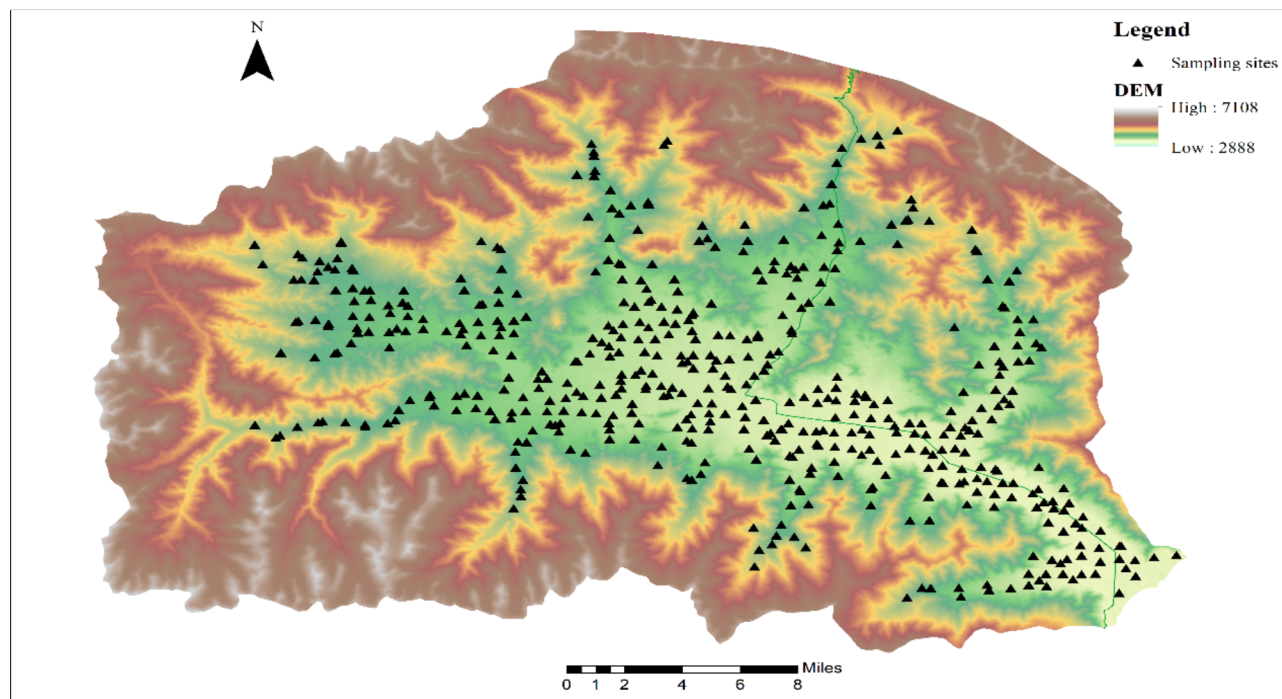


Fig. 1. Distribution of soil sampling sites in the study area.

Pollution degree	No pollution	Light pollution	Medium pollution	Medium-heavy pollution	Heavy pollution	Heavy-extremely heavy pollution	Extremely heavy pollution
I_{geo}	< 0	0~1	1~2	2~3	3~4	4~5	≥ 5

Table 1. Classification standard of soil HMs accumulation index.

(1:250000)²⁰ (DZ/T 0258–2014). This includes adding blank samples to each batch of sample analysis to monitor background contamination, as well as extracting some samples for repeated analysis to assess precision. At the same time, national first-level soil reference materials were inserted to verify the accuracy of the analysis, and outliers were screened from the data to ensure its authenticity. The metal content analyzed in this article refers to the total concentration rather than the pseudo-total concentration.

Geoaccumulation index method

The geoaccumulation index (I_{geo}), proposed by scientist Muller in the 1960s, is a method to reflect soil environmental quality by comparing the measured values of soil HMs with the geochemical background values of corresponding elements¹⁴. It is also one of the soil pollution assessment methods often used by researchers²². This method focuses on the effects of human activities and geological diagenesis²³, and its calculation formula is as follows:

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

where the I_{geo} is the geoaccumulation index of HMs i , C_i is the measured mass fraction of HMs index i in soil, $\text{mg} \cdot \text{kg}^{-1}$; B_i is the background value of soil HMs, $\text{mg} \cdot \text{kg}^{-1}$, this paper selects the soil background value of Lhasa, and k is the correction factor for the natural fluctuation of HMs content in the diagenetic process, which is generally 1.5. The pollution degree of geoaccumulation index is divided into 7 grades (Table 1).

Geographic detector

The geographic detector is a tool based on the theory of spatial differentiation. It uses statistical methods to quantitatively analyze the interactions between various influencing factors and uses the q value to measure the explanatory power of the influencing factors. The geographic detector model has the advantages of clear physical meaning, no linear assumptions, no influence of variable collinearity, and good processing of numerical variables and typological variables. It is widely used in the detection of influencing factors of spatial differentiation of geographical phenomena^{24–26}. The model consists of four sub-models: factor detector, interaction detector, ecological detector and risk detector. This paper mainly uses geographical detector to analyze the correlation

between 7 kinds of HMs and 19 influencing factors and the interaction of multiple influencing factors, and tries to reveal the effects of influencing factors on the spatial distribution of soil HMs in the study area according to the analysis results of factor detector and interaction detector.

Factor detector: used to detect the spatial differentiation of dependent variables and the ability of independent variables to explain the influence of independent variables on dependent variables, which is measured by q ^{16,27,28}:

$$q = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2} = 1 - \frac{SSW}{SST} \quad (2)$$

Where $h=1, \dots, L$ is the classification number of the independent variable X ; N_h and N are classification h and the number of units in the whole region, respectively. σ_h^2 and σ^2 are the variances of classification h and regional dependent variable Y , respectively. SSW and SST represent the sum of the variances of all categories of the independent variable X and the total variance in the region, respectively. The range of q is $[0,1]$, Indicates that the independent variable explains the $100 \times q\%$ dependent variable. The higher the q , the greater the influence of the independent variable X on the dependent variable Y .

Interaction detector: by identifying the q of the interaction between two different independent variables, we can judge the influence of the interaction between the independent variables on the dependent variables. the greater the value, the stronger the explanatory power²⁹⁻³¹. The specific interaction types and judgment basis are shown in Table 2.

Factor index selection and data analysis

For the selection of spatial differentiation factors of soil HMs, based on the studies of Zhang Hongze et al.³⁰, Gong Cang et al.¹⁷ and Yang an et al.³², it was also necessary to comprehensively consider the difficulty of sample acquisition in the study area and the actual situation of the project. This paper selects soil properties (TN, TP, TK, pH, Sc, SOM), topographic factors (slope, aspect, elevation) and distance factors (distance from provincial highways, national highways, urban highways, highways, cities and counties, tributaries, Lhasa River, Yarlung Zangbo River, lake, railway). The elevation and slope aspect data of soil sample points in the study area come from geospatial data cloud (<http://www.gscloud.cn>). The data of Lhasa River and its tributaries, roads and railways were derived from the Wetland Distribution Map of Lhasa City and Lhasa River Basin in Xizang Autonomous region³³. According to Li et al.³⁴ and Zhou et al.³⁵, the data discretization method was put forward, and the natural breakpoint method was used to classify 19 influencing factors into 6 categories. After the soil test data were processed by Microsoft Excel 2021, SPSS 26.0 was used to test the significance of the data at the level of 0.05(*), 0.01 (**), and Origin 2019 was used to complete the mapping. The geographic detector was completed by GeoDetector software (<http://www.geodetector.org/>).

Results and discussion

Descriptive statistical analysis

This paper selected the soil background value of Lhasa as a reference to analyze and evaluate the HMs content, in order to better understand the pollution status of soil HMs in the study area. The descriptive statistical results of soil HMs in the study area were shown in Table 3. It can be seen from Table 3 that the average value of soil pH in the study area was 7.71 and the range was 4.838.86. the proportions of soil acidic ($\text{pH} \leq 6.5$), neutral ($6.5 < \text{pH} \leq 7.5$) and alkaline ($\text{pH} > 7.5$) in the sampling sites were 7.5%, 31.0% and 61.5%, respectively. The average contents and ranges of soil ω (TN), ω (TP), ω (TK), ω (SOM) and ω (Sc) were 1.27 $\text{g} \cdot \text{kg}^{-1}$, 0.67 $\text{g} \cdot \text{kg}^{-1}$, 23.0 $\text{g} \cdot \text{kg}^{-1}$, 20.0 $\text{g} \cdot \text{kg}^{-1}$ and 12.3 $\text{mg} \cdot \text{kg}^{-1}$ and 0.19 ~ 7.39 $\text{g} \cdot \text{kg}^{-1}$, 0.29 ~ 1.66 $\text{g} \cdot \text{kg}^{-1}$, 13.7 ~ 33.8 $\text{g} \cdot \text{kg}^{-1}$, 2.76 ~ 146 $\text{g} \cdot \text{kg}^{-1}$ and 7.32 ~ 23.3 $\text{mg} \cdot \text{kg}^{-1}$, respectively.

The enrichment coefficient was used to characterize the enrichment degree of each element. The enrichment coefficient of HMs in the study area was $\text{Cd} (1.44) > \text{Cr} (1.37) > \text{Zn} (1.24) > \text{Ni} (1.22) > \text{Cu} (1.12) > \text{As} (1.08) > \text{Pb} (1.01)$ in the order from high to low. The enrichment coefficients of the all HMs were all greater than 1, indicating that the soil in the study area had been polluted by HMs, which was closely related to the increasing human activities²⁴. The average value of the HMs were close to the median value, and the distribution was relatively normal. The coefficient of variation of the all HMs in the study area were obviously different, and the order was $\text{Cd} (48.0) > \text{As} (38.3) > \text{Zn} (26.1) > \text{Pb} (25.2) > \text{Cu} (22.5) > \text{Cr} (22.2) > \text{Ni} (21.3)$. The coefficient of variation of Cd was the largest, which was highly variable. The spatial heterogeneity was strong, and there might be point source pollution of Cd element. The coefficient of variation of As, Zn, Pb, Cu, Cr and Ni was between 0.2 and 0.4, which belongs to medium variation. The high coefficient of variation of soil HMs usually indicates the significant impact of human activities on their content distribution^{20,36}. These human activities include industrial emissions, agricultural practices, traffic pollution, urban expansion, mineral development, atmospheric deposition, soil

Interaction type	Judgment basis
Nonlinear weakening	$q(X_a \cap X_b) < \text{Min}[q(X_a), q(X_b)]$
One-factor nonlinear weakening	$\text{Min}[q(X_a), q(X_b)] < q(X_a \cap X_b) < \text{Max}[q(X_a), q(X_b)]$
Two-factor enhancement	$q(X_a \cap X_b) > \text{Max}[q(X_a), q(X_b)]$
Independent of each other	$q(X_a \cap X_b) = q(X_a) + q(X_b)$
Nonlinear enhancement	$q(X_a \cap X_b) > q(X_a) + q(X_b)$

Table 2. Types and judgment basis of interaction among factors.

Element	Maximum value	Minimum value	Mean value	Median	Standard deviation	Coefficient of variation/%	Enrichment coefficient	Lhasa background value	Screening value (agricultural land)			
									A	B	C	D
Cu(mg·kg ⁻¹)	85.0	12.5	24.6	24.1	5.55	22.5	1.12	22	50	100	100	100
Pb(mg·kg ⁻¹)	126	17.3	31.4	30.4	7.93	25.2	1.01	31	70	90	120	170
Zn(mg·kg ⁻¹)	339	46.3	80.6	77.7	21.0	26.1	1.24	65	200	200	250	300
Cr(mg·kg ⁻¹)	135	19.4	57.7	58.2	12.8	22.2	1.37	42	150	150	200	250
Ni(mg·kg ⁻¹)	46.8	10.1	25.7	25.8	5.47	21.3	1.22	21	60	70	100	190
Cd(mg·kg ⁻¹)	0.998	0.054	0.17	0.16	0.08	48.0	1.44	0.12	0.3	0.3	0.3	0.6
As(mg·kg ⁻¹)	55.5	4.42	21.6	20.0	8.26	38.3	1.08	20	40	40	30	25
pH	8.86	4.83	7.71	7.95	40.75	9.74	0.94	8.2	-	-	-	-
TN(g·kg ⁻¹)	0.19	7.39	1.27	1.28	0.58	46.2	-	-	-	-	-	-
TP(g·kg ⁻¹)	0.29	1.66	0.67	0.64	0.19	28.6	-	-	-	-	-	-
TK(g·kg ⁻¹)	13.7	33.8	23.0	22.7	2.61	11.4	-	-	-	-	-	-
SOM(g·kg ⁻¹)	2.76	146	20.0	19.5	11.8	59.2	-	-	-	-	-	-
Sc(mg·kg ⁻¹)	23.3	7.32	12.3	12.2	1.47	12.0	-	-	-	-	-	-

Table 3. Descriptive statistics of soil HMs in the study area. Note: «Soil environmental quality Risk control standard for soil contamination of agricultural land» (GB 15618 – 2018) A: pH ≤ 5.5, B: 5.5 < pH ≤ 6.5, C: 6.5 < pH ≤ 7.5, D: pH > 7.5.

erosion, waste disposal and improper soil remediation, which increase the input of soil HMs, change their natural cycle, and lead to large differences in HMs content between different locations, thus increasing the coefficient of variation, reflecting the widespread and deep impact of human activities on the soil environment. The average content of HMs were all lower than the soil pollution risk screening value (GB 15618–2018), but the content of As in 103 sampling sites, Cd in 9 sampling sites, Pb in 1 sampling site, and Zn in 1 sampling site were higher than the soil pollution risk screening value, indicating that soil quality in the study area was mainly affected by As. We should pay special attention to environmental pollution control and prevention.

Spatial distribution characteristics of soil HMs

In order to further reveal the spatial distribution characteristics of HMs, the spatial distribution maps of HMs in Linzhou County of Lhasa City were obtained by ArcGIS Kriging interpolation (Fig. 2). The distribution map revealed that the high-value areas for Pb, Zn, and Cd were primarily concentrated in the western part of the study area, with maximum values of 126 mg·kg⁻¹, 339 mg·kg⁻¹, and 0.998 mg·kg⁻¹, respectively. Meanwhile, the central and eastern regions had lower levels of these elements. It might be due to the HMs enrichment caused by industrial emissions, traffic pollution, and geological background in the western region, while the content was relatively low in the central and eastern regions due to their distance from pollution sources and different natural conditions. The high value areas of Cu were concentrated in the northwest region, with a maximum value of 85 mg·kg⁻¹, and showed a decreasing trend from north to south. It might be due to the concentration of industrial activities in the region, coupled with possible topographical and hydrological conditions, leading to the natural enrichment of copper and the cumulative effect of human emissions. The distribution of high values of Cr and Ni was relatively similar, with maximum values of 135 mg·kg⁻¹ and 46.8 mg·kg⁻¹, respectively, mainly concentrated in the western and central regions of the study area. It might be due to the geological conditions in the region, which were rich in these metals, while industrial emissions and traffic pollution might also be the cause of this phenomenon. The high value area of As was scattered around the study area, with a maximum value of 55.5 mg·kg⁻¹. The northern region was higher than the southern region, and the western region was higher than the eastern region. The high content in the north and west might be related to the combined effects of geological background, industrial activities, and hydrological migration.

Evaluation results of geoaccumulation index method

Soil accumulation index (I_{geo}) was a method to divide soil into different levels (pollution degree) based on the multiple of soil HMs content and its background value. The calculation results of I_{geo} in the soil of the study area were shown in Table 4. As can be seen from Table 4, the average I_{geo} values of the all HMs in descending order were Cr (-0.161) > Cd (-0.162) > Zn (-0.30) > Ni (-0.33) > Cu (-0.45) > AS (-0.57) > Pb (-0.60), and the mean values were all less than 0. From all sampling points, I_{geo} of most sampling points was below 0, while I_{geo} of Cu, Pb, Zn, Cr, Ni, Cd and As were 3.17%, 2.18%, 6.35%, 29.6%, 11.7%, 33.1% and 13.1%, respectively, between 0 and 1. The HMs in the soil of the study area were mainly pollution-free and light-polluted. The I_{geo} of Cu, Pb, Zn, Cr and Cd at 0.40%, 0.40%, 0.60%, 0.20% and 1.39% sampling points were between 1 and 2, respectively, which belong to medium pollution. In the study area, there might be point pollution sources of HMs Cu, Pb, Zn, Cr and Cd in a few sampling points. The pollution was mainly Cr (-1.07 ~ 1.10) and Cd (-1.74 ~ 2.47). It might be related to intense human activities, such as industrial emissions, agricultural practices, traffic pollution, and waste disposal, as well as natural diagenetic processes, such as geological background, mineral deposit development, and natural weathering. These activities and processes jointly contribute to the spatial heterogeneity of soil HMs, leading to pollution at specific sampling points.

Correlation analysis

The results of correlation analysis were shown in Fig. 3. There was a strong correlation among Cu, Pb, Zn, Cr, Ni, Cd and As in the study area. Except for Cr-As(0.10), there was a significant negative correlation among Cd-As (0.49), Cu-As(0.27), Cu-Cd(0.32), Cu-Cr(0.22), Ni-Cr(0.87), Ni-Cu(0.30), Pb-As(0.45), Pb-Cd(0.79), Pb-Cu(0.22), Pb-Ni(0.16), Zn-As(0.41), Zn-Cd(0.88), Zn-Cu(0.29), Zn-Ni(0.13) and Zn-Pb(0.82). It was speculated that there might be common or similar pollution sources of HMs in the study area. The largest correlation coefficient was Zn-Cd, 0.88 ($P < 0.01$). Relevant studies^{25,37} also showed that the content of Zn and Cd in the surface soil along the highway was high, and there was a very significant positive correlation, which might be released through incomplete combustion of automobile fuel and tire wear and tear. The second was Ni-Cr, with a correlation coefficient of 0.87 ($P < 0.01$), which might be related to the soil widely developed from ultramafite on the Qinghai-Tibet Plateau and accompanied by the release of Ni and Cr during the diagenetic process³⁸. The smallest correlation coefficient was Cr-As, 0.10 ($P < 0.05$). There were incomplete correlations among the all HMs, indicating that the pollution was not a single source, but might have multiple sources. In general, there were significant differences in the correlation between different HMs, and a single HMs was usually affected by multiple sources.

Among the distance factors, most had extremely significant negative correlations with Cr and Ni ($P < 0.01$), and most of the remaining HMs had extremely significant positive correlations ($P < 0.01$) and significant correlations ($P < 0.05$), indicating that the influence of the distance factor in the study area on soil HMs cannot be ignored. The distance from the railway was negatively correlated with Cu, Pb, Zn, Cr, Ni and Cd ($P < 0.01$), with values of 0.16, 0.12, 0.17, 0.21, 0.13 and 0.14, respectively, indicating that the closer the distance from the railway, the higher the HMs content, and the railway operation had an impact on the HMs content. Among the topographic factors, slope and slope had no significant correlation with most HMs, only Cd had a significant negative correlation with slope ($P < 0.05$), with a value of 0.10, and As had a very significant positive correlation with slope ($P < 0.01$), with a value of 0.13, indicating that the slope and slope of topographic factors had a weak impact on soil HMs in the study area. There was significant positive correlation between elevation and As, Cu,

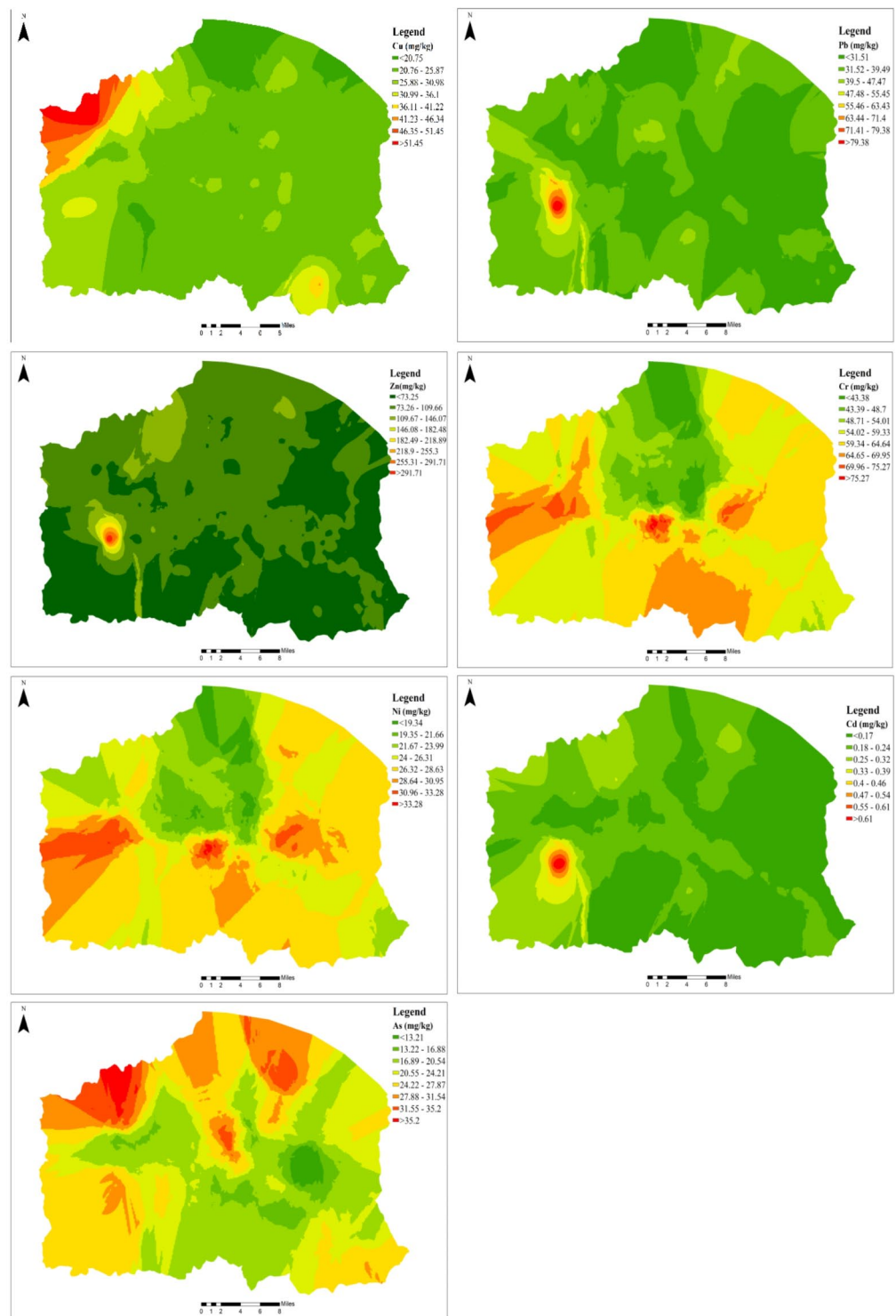


Fig.2 Spatial distribution of soil HMs in the study area

Fig. 2. Spatial distribution of soil HMs in the study area.

Pb and Zn ($P < 0.01$), with values of 0.18, 0.13, 0.18 and 0.13, respectively, but no significant correlation with other HMs. In soil properties, there was a very significant positive correlation between Sc and Cu, Pb, Zn, Cr, Ni, Cd and As HMs ($P < 0.01$), with values of 0.45, 0.17, 0.41, 0.15, 0.25, 0.29 and 0.12, respectively, which might be because Sc was not volatile, had stable chemical properties, had few man-made pollution sources, and showed large spatial heterogeneity in the Qinghai-Tibet Plateau³². It was speculated that the natural factors in the high and cold regions of the plateau will have a great impact on soil HMs. TP and TK had significant or extremely

Element	Cu	Pb	Zn	Cr	Ni	Cd	As	Hg
Mean value	-0.45	-0.60	-0.30	-0.16	-0.33	-0.16	-0.57	-1.45
Maximum value	1.36	1.44	1.80	1.10	0.57	2.47	0.89	4.33
Minimum value	-1.40	-1.43	-1.07	-1.70	-1.64	-1.74	-2.76	-3.65
$I_{geo} \leq 0$	486	491	469	354	445	327	438	470
$0 < I_{geo} \leq 1$	16	11	32	149	59	167	66	22
$1 < I_{geo} \leq 2$	2	2	3	1	0	7	0	7
$2 < I_{geo} \leq 3$	0	0	0	0	0	3	0	2
$3 < I_{geo} \leq 4$	0	0	0	0	0	0	0	1
$4 < I_{geo} \leq 5$	0	0	0	0	0	0	0	2
$I_{geo} > 5$	0	0	0	0	0	0	0	0

Table 4. Soil HMs accumulation index and the number of points of different grades in the study area.

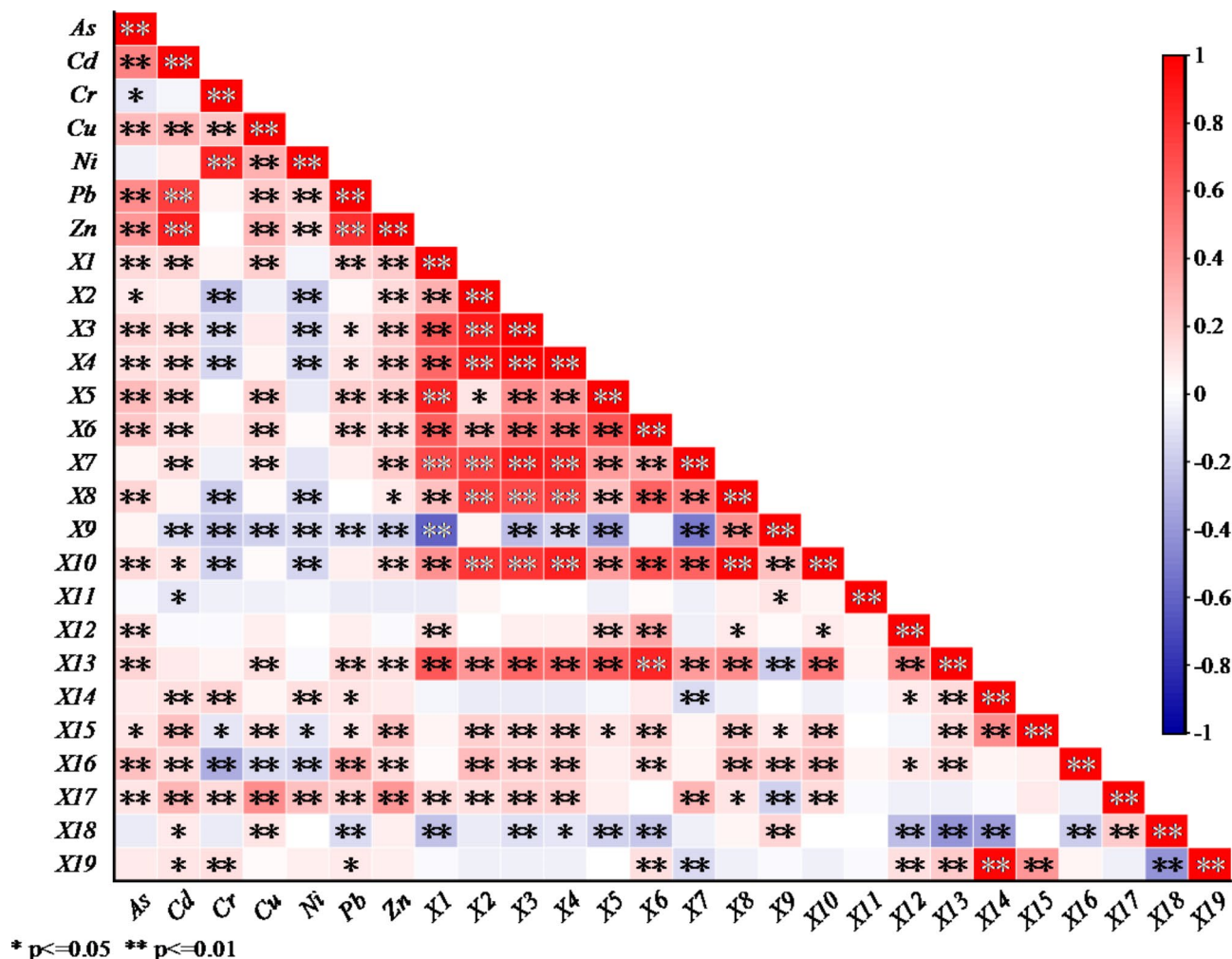


Fig. 3. Pearson correlation coefficient of soil HMs and impact factors. X1. Distance from dart, X2. Distance from national highway, X3. Distance from urban highways, X4. Distance from highway, X5. Distance from city and county, X6. Distance from tributary, X7. Distance from the Lhasa River, X8. Distance from Brahmaputra River, X9. Distance from railway, X10. Distance from lake, X11. Aspect of slope, X12. slope, X13. elevation, X14. Total nitrogen (TN), X15. Total phosphorus (TP), X16. Total potassium (TK), X17.Sc, X18.pH, X19. Soil organic matter (SOM).

significant correlations with all soil HMs, while TN, pH and SOM had no significant correlations with some HMs. Soil properties in the study area had certain effects on soil HMs.

Analysis of influencing factors of soil HMs pollution by geographic detector

Factor detector

The contents of Cu, Pb, Zn, Cr, Ni, Cd and As were taken as dependent variables (Y), and 19 influence factors were taken as independent variables (X1 ~ X19). The explanatory power and influence degree of 19 influence factors on the spatial differentiation of the content of HMs were detected based on factor detector (Fig. 4). In general, distance from national highway, Sc, TK and urban highway had strong explanatory power on the spatial distribution of each element content. The main influencing factor of HMs As was the distance from the urban highway (0.125), followed by the distance from the Yarlung Zangbo River (0.113), the distance from the highway (0.111) and the distance from the city and county (0.110), indicating that the distance factor had a strong explanatory power for the spatial differentiation of As, and human activities were an important factor for the enrichment of As. The most important factor affecting Cd was Sc (0.109), followed by the distance from the urban road (0.104), and the third was TP (0.078). The first factor affecting Cr was the distance from the national highway (0.233), followed by TK (0.153), and the third was the distance from the highway (0.127). The distance from the railway (0.121) factor also had some influence. The first factor affecting Cu was Sc (0.195), followed by distance from city and county (0.072), and distance from provincial highway (0.059). The most important factor affecting Ni was distance from national highway (0.204), the second was distance from expressway (0.130), and the third was TK (0.114). The first, second and third factors influencing Pb were TK (0.151), distance from Lhasa River railway (0.081) and distance from cities and counties (0.076), respectively. The first, second and third influencing factors of Zn were Sc (0.197), distance from urban road (0.116) and distance from lake (0.084), respectively.

Overall, the distance factor had a strong explanatory power for the spatial differentiation of soil HMs of the study area and was an important driving factor affecting HMs pollution and enrichment. It was mainly reflected in the comprehensive impact of human factors such as distance from roads, railways, cities, counties, and rivers on the spatial distribution of soil HMs of the study area. It was speculated that due to the substantial increase in traffic accessibility in Lhasa River basin in recent years, the further development and utilization of natural

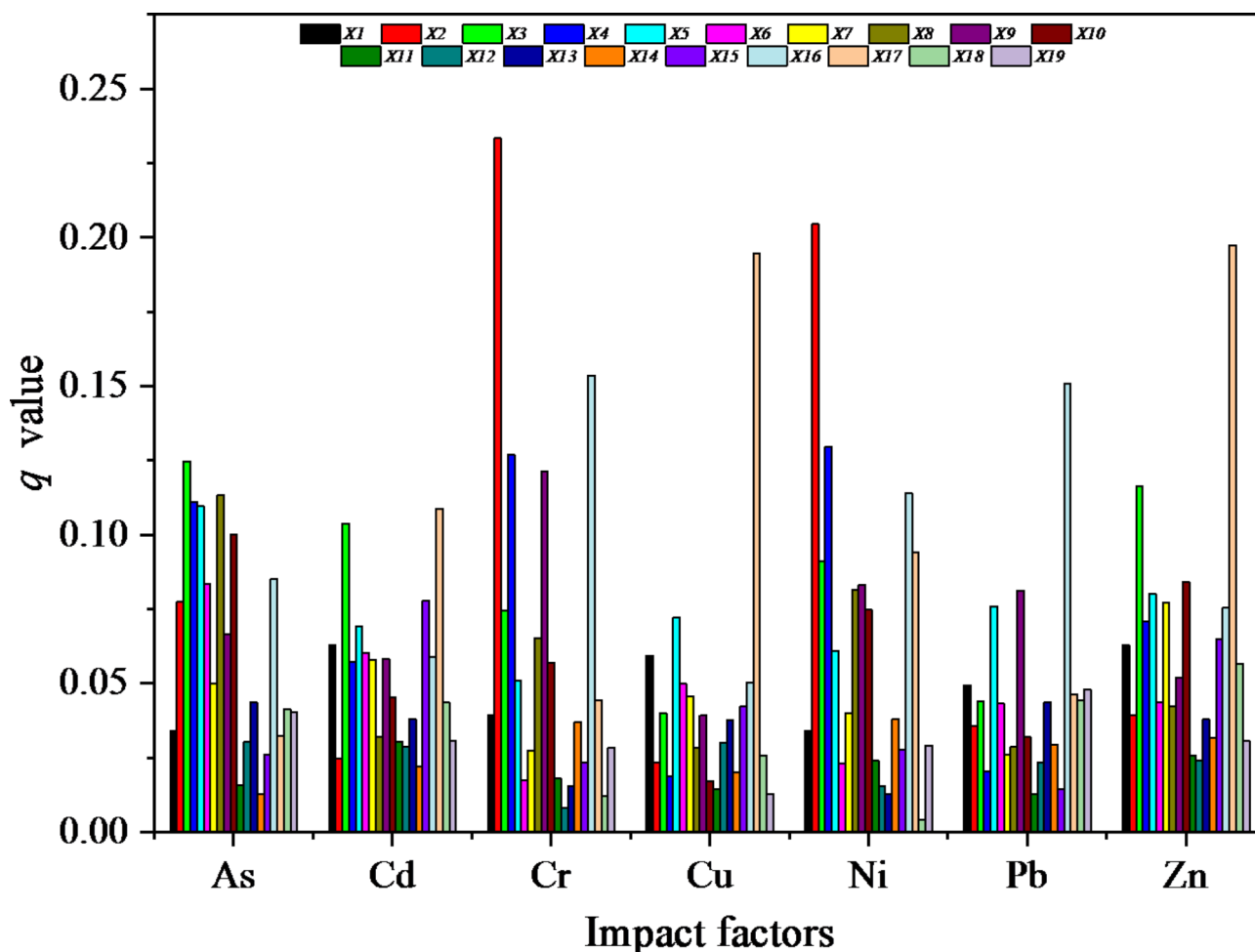


Fig. 4. Effects of different factors on the explanatory power of soil soil HMs with q value.

resources, and the sustainable development of the secondary and tertiary industries, these increased human activities had changed the distribution characteristics of HMs in the original soil under the natural state, and river systems will also cause the enrichment of HMs in water sources due to the development of industry and agriculture. Moreover, HMs enrichment in soil was caused by farmland irrigation and wastewater discharge³⁹. The first influence factor of Cr and Ni was distance from national highway, and the explanatory power was as high as 0.233 and 0.204, respectively. Comparing the detection results of the two factors with Pearson correlation analysis, it was found that the results were consistent. For example, distance from national highway had the strongest explanatory power on the spatial distribution of Cr and Ni. The distance from the national highway was also significantly correlated with Cr and Ni. TK and distance from expressway also had a strong explanatory power for the spatial distribution of Cr and Ni, and they were also significantly correlated with Cr and Ni. Similar commonalities include Zn ($q=0.197$), Cu ($q=0.195$) and Cd ($q=0.109$), and Cu (0.45), Zn (0.41) and Cd (0.29) in the order of Sc's explanatory power for the spatial distribution of HMs. The consistency between Pearson correlation analysis results and factor detection results stems from the fact that correlation analysis explores whether there was a linear relationship between the two variables, while factor detection analysis considers the influence of both linear and nonlinear relationships.

The effect of soil properties on the spatial differentiation of HMs in the study area should not be ignored. Linzhou County in the study area was one of the main grain production bases in Lhasa. Farmland irrigation, fertilization and application of medicine had direct effects on soil properties. Changes in soil properties affect the activity and migration of HMs to a certain extent, and thus further affect the migration and transformation of HMs. Factor detection showed that TP, TK and Sc had strong explanatory power to the spatial differentiation of HMs, and correlation analysis also showed that TP, TK and Sc were significantly correlated with HMs. For both Cu and Zn, the first influencing factor was Sc (X17), with explanatory power as high as 0.195 and 0.197, respectively, which was much higher than other influencing factors. The analysis results were consistent with the correlation analysis. As far as Cr and Ni were concerned, the factor detection results were highly consistent with the correlation analysis results of 19 influencing factors. The distance factor had the strongest explanatory power for the two elements, especially the explanatory power q value of the distance from the national highway was as high as 0.233 and 0.204, respectively. It indicated that pollution might be caused by the combined effects of high traffic volume, high emission vehicles and high altitude, high emission and high accumulation⁴⁰. In the topographic factors, slope direction, slope direction and elevation did not have strong explanatory power for HMs. In the correlation analysis, the correlation between slope direction and slope and HMs was also not significant, and elevation was only significantly correlated with As, Cu, Pb and Zn, which might be due to the flat terrain along both sides of the river in the study area and the small variation range of slope, slope direction and elevation.

Interaction detection

The spatial distribution of soil HMs was the result of the joint action of multiple influencing factors, and there was no single factor that determines its distribution and change³⁴. The interaction detector not only identifies the strength of interaction between different risk factors, but also helps to accurately identify the deep driving mechanism of the spatial distribution of HMs⁴¹. In this paper, the interaction detector was used to investigate the effects of 19 factors on the spatial distribution of all HMs.

Figure 5 showed the effect of the superposition of two influencing factors. The explanatory power of the pairwise interaction on the spatial differentiation of all HMs was greater than that of a single factor, and most of them exhibit non-linear enhancement, that was, the interaction of two different influencing factors was greater than the sum of the independent effects of the two influencing factors, and there was no weakening or independent type of effect. For As, after the interaction between the distance from urban highway and railway, the explanatory power increases to 0.364, the distance from urban highway was increased to 0.359 and the distance from urban highway was 0.319, indicating that the interaction between the distance from urban highway and other distance factors and soil properties can significantly enhance the spatial distribution of As. As far as Cd was concerned, the first impact factor was also the distance from the urban highway. After interactive detection, the explanatory power of the distance from the urban highway to the national highway was the strongest, reaching 0.570. As far as Cr was concerned, the interaction value between the distance from urban highway and other impact factors was above 0.28, and the interaction value between TK and other impact factors was above 0.23. For Cu, the interaction effects of distance from National highway, distance \cap gradient from Lhasa River, pH \cap altitude and distance \cap gradient from lake were the strongest, and terrain factors had a strong enhancement effect on Cu spatial distribution. For Ni, the interaction between distance from national highway and other influencing factors was dominant, followed by TK and Sc. As far as Pb was concerned, the distance from provincial road had the strongest interaction with TK, reaching 0.591, followed by the distance from city and county with the interaction with TK, which was 0.585. In terms of Zn, the strongest interactive explanatory power was the distance from the national highway (0.678) to the urban highway (0.661), and the interaction value of the distance from the national highway (0.661) to the lake (0.678). The above results showed that the interaction between distance factor and other influencing factors had an important effect on the spatial differentiation of soil HMs in the study area, and soil properties (TK, TN, TP, pH and Sc) were also important influencing factors for the accumulation and distribution of HMs.

Conclusion

- (1) The average content of HMs such as Cu, Pb, Zn, Cr, Ni, Cd, and As in the soil of the study area was generally higher than the soil background value in Lhasa City, indicating that the soil in this area had been contaminated to some extent by HMs. The coefficients of variation for Cd and As were relatively high,

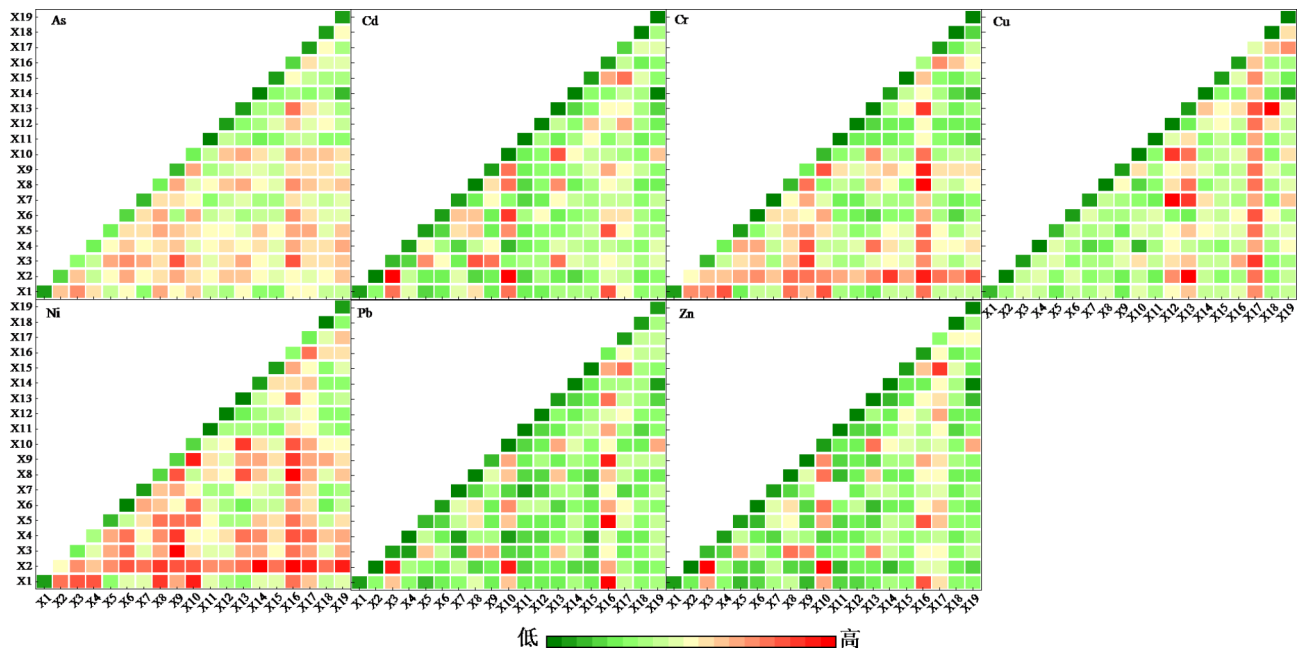


Fig. 5. Interaction of different influence factors on soil HMs.

indicating significant spatial heterogeneity, suggesting the potential presence of specific sources of contamination. Although the average content of HMs was lower than the screening value for soil pollution risk (GB 15618–2018), the content of As, Cd, Pb, and Zn in some sampling points was higher than the screening value for soil pollution risk, indicating that although the overall risk of soil HMs pollution in the study area was controllable, attention needed to be paid to specific areas and corresponding environmental management and remediation measures needed to be taken to prevent HMs at these points from posing a threat to the ecosystem and human health through the food chain. The soil accumulation index showed that HMs in the study area were generally in a pollution-free state, and there might be point pollution sources of Cu, Pb, Zn, Cr and Cd in a few sampling points, and the pollution was mainly Cr (1.07~1.10) and Cd (-1.74~2.47), but the pollution degree was generally not high.

- (2) The spatial distribution map of HMs drawn by ArcGIS software showed that the high-value areas of Pb, Zn, and Cd were mainly concentrated in the western part of the study area, while the contents in the central and eastern regions were at a lower level, which might be due to the enrichment of HMs caused by industrial emissions, traffic pollution, and geological background in the western region. However, due to the distance from pollution sources and different natural conditions, the contents in the central and eastern regions were relatively low. The high-value area of Cu was concentrated in the northwest region, and showed a decreasing trend from north to south, which might be due to the concentration of industrial activities in the region, coupled with possible topographical and hydrological conditions, leading to the cumulative effect of natural enrichment of copper and human emissions. The high-value areas of Cr and Ni were similar, mainly concentrated in the western and central regions of the study area, which might be due to the geological conditions of the region, while industrial emissions and traffic pollution might also be responsible for this phenomenon. The high-value areas of As were scattered around the study area, with higher values in the northern region than in the southern region, and higher values in the western region than in the eastern region. The high content in the northern and western regions might be related to the combined effects of geological background, industrial activities, and hydrological migration.
- (3) The correlation analysis showed that the positive correlation between Cu, Pb, Zn, Cr, Ni, Cd and As in the soil of Linzhou County, Lhasa City, indicated the influence of common pollution sources, especially the strong correlation between Zn and Cd. The correlation between the proximity to national highways and urban roads and the content of HMs revealed the key role of traffic pollution. Soil properties had a significant impact on the behavior of HMs, while topographic factors also played a role under specific circumstances. The negative correlation between Cr and As suggested different pollution pathways, indicating the complexity of pollution control strategies that needed to be considered.
- (4) Through factor detection, this study identified that the distance from national highways and urban roads, as well as the content of Sc and TK in the soil, were the main environmental factors explaining the spatial variation of HMs content in the soil. The significant *q* values of these factors indicate that traffic-related pollution and soil texture characteristics played a decisive role in the regional distribution of HMs. Interaction detection further revealed that the interaction between distance factors and soil properties had a greater explanatory power for the spatial distribution of HMs than a single factor. The interaction between distance from national highways and urban roads and Sc and TK was particularly significant, suggesting that there

might be synergistic or antagonistic effects between traffic pollution and soil texture characteristics in the accumulation of HMs.

Although this study revealed the spatial distribution characteristics of HMs in the soil of Linzhou County, Lhasa City, and their relationship with environmental factors through extensive sampling and geographical detector models, there were still limitations. For example, the distribution of sampling points might not fully capture small-scale spatial variability, and the study was a cross-sectional analysis that failed to reflect dynamic changes over time series. Future research needed to increase sampling density and frequency to achieve dynamic monitoring of soil HMs pollution trends, and to conduct in-depth analysis of pollution sources, especially to distinguish between the effects of natural geological backgrounds and human emissions.

Data availability

The authors declare that all data supporting the findings of this study are available within the article.

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Author contributions

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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