Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-17
DOI: *10.15244/pjoes/235732* ONLINE PUBLICATION DATE: 2026-11-03

Original Research

Characteristics, Source Apportionment, and Ecological and Human Health Risk Assessment of Heavy Metals in Cultivated Soils from the Jiamusi Section of the Lower Songhua River

Wang Xu[1, 2], Shang Jilong[1, 2]*, Zhang Qiwei[3], Guo Lin[1, 2], Zhao Guoqiang[1, 2], Cui Shengyan[1, 2]

[1]Harbin Natural Resources Survey, China Geological Survey, Harbin 150086, Heilongjiang, China
[2]Observation and Research Station of Earth Critical Zone in Black Soil, Ministry of Natural Resources, Harbin 150086, China
[3]Heilongjiang Ranyi Geological Survey Co., Ltd., Harbin 150000, China

Received: 08 April 2026
Accepted: 27 August 2026

Abstract

The Jiamusi section of the lower Songhua River is an important commodity grain production area in China, and the environmental quality of its cultivated soils is directly linked to regional food security and ecosystem stability. To clarify the status of heavy metal pollution in soils in this area, identify pollution sources, and assess potential risks, this study established sampling units in typical cultivated land in the Jiamusi section in 2023, collected 276 topsoil samples (0-20 cm), and determined the contents of eight heavy metals, namely As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn, as well as physicochemical indicators such as soil pH. Correlation analysis and principal component analysis were used to identify heavy metal sources; the single-factor pollution index method, Nemerow comprehensive pollution index method, and geo-accumulation index method were used to evaluate pollution levels; and a human health risk assessment model was used to assess carcinogenic and non-carcinogenic risks for adults and children. The results showed that the average soil pH in the study area was 6.51. The average concentrations of eight heavy metals (As, Cd, Cr, Cu, Hg, Ni, Pb and Zn) were 10.38, 0.23, 53.77, 22.83, 0.09, 21.63, 29.17, and 83.89 mg/kg, respectively, all of which are below the soil background values of the region. Compared with the soil pollution risk screening values for agricultural land, Cd exceedance was the most prominent, with 63 sampling sites exceeding the standard. As, Cr, Cu, Pb, and Zn each had 1-6 sites exceeding the standard, while Hg and Ni had no exceedance sites. Correlation and principal component analyses showed that soil heavy metals mainly originated from natural parent materials (Cr, Ni), industrial activities (Zn, Cu), traffic activities (Pb, Cd), and a composite source associated with other anthropogenic activities (Hg). Pollution assessment results indicated that the soils in the study

*e-mail: 15146615245@163.com
Tel.: +86-15146615245
0009-0006-4285-5236

© 2026 This article is licensed under a Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0)

area generally ranged from unpolluted to mildly polluted: 72.82% of the sampling sites were unpolluted, 11.23% were at the warning level, 11.59% were slightly polluted, and 4.34% were moderately to heavily polluted. Health risk assessment showed that oral ingestion was the main pathway of heavy metal exposure, and the non-carcinogenic risk to children (mean HI 0.87, 19.93% of sampling sites with HI>1) was higher than that to adults (mean HI 0.15). The carcinogenic risk indices at all sampling sites were less than 10^{-4}, within the acceptable range. These results provide a scientific basis for the prevention and control of heavy metal pollution in cultivated soils, green agricultural development, and ecological and environmental protection in the Jiamusi section of the lower Songhua River.

Keywords: black soil, heavy metal pollution, ecological risks, health risks, the lower reaches of the Songhua River in Jiamusi City

Introduction

Soil is a core natural resource that sustains agricultural production and ecological balance. It not only provides essential nutrients and a physical medium for crop growth, but also serves as an important strategic foundation for ensuring national food security and advancing ecological civilization construction [1-4]. With the intensive development of modern agriculture, industrial expansion, and the rapid advancement of the transportation sector, heavy metals enter the soil environment through multiple pathways, including the application of chemical fertilizers and pesticides, the discharge of livestock and poultry breeding waste, the migration of industrial pollutants, and the deposition of traffic exhaust, making soil heavy metal pollution an increasingly prominent issue [5-7]. Heavy metals are characterized by concealment, irreversibility, and bioaccumulation. Once they enter the soil, they are difficult to degrade; they not only damage soil structure and reduce soil fertility [8, 9], but can also accumulate through the "soil-crop-human" food chain, threatening human health, while potentially affecting surrounding aquatic, atmospheric, and other ecosystems, thereby becoming a major environmental issue constraining regional sustainable development [10]. Scholars in China and abroad have conducted extensive and systematic research in key areas such as soil pollution characteristics, heavy metal risk assessment, and pollution source apportionment [11-13]. In studies on soil pollution characteristics, geographic information systems (GIS) combined with geostatistical methods have been widely applied [14-16], effectively revealing the spatial distribution patterns and vertical stratification heterogeneity of soil pollutants; in terms of heavy metal risk assessment, commonly used methods include the single-factor pollution index, the Nemerow comprehensive pollution index, the geo-accumulation index, and the enrichment factor, all of which can quantitatively assess the potential risks posed by heavy metal accumulation to the ecological environment and human health [17-20]; in pollution source apportionment research, methods such as the positive matrix factorization (PMF) model and multivariate statistical analysis are well established, enabling the qualitative identification of pollution sources and the quantitative analysis of the contribution of each source [21-24].

The Jiamusi section of the lower Songhua River, which is one of the seven major rivers in China, is located within the backwaters of the Sanjiang Plain and has abundant cultivated land resources. It has gradually become a primary region for producing high-quality rice and corn in our country as its agriculture is well-developed [25]. The area belongs to the Songnen-Sanjiang Plain agricultural-ecological system and is also under the influence of industry and transportation routes; therefore, cultivated soils have been heavily polluted by multiple pollutants from natural sources and human activities. The Sanjiang Plain, as a major grain-producing area of our country, has an agriculture-based economy, and its soil environmental quality directly affects national food security and ecological safety. The primary soil types in Jiamusi's lower Songhua River area are black soil and meadow soil; the soils also exhibit various stages of pedogenesis. Therefore, the migration and transformation patterns as well as ecological effects of heavy metals have certain features; heavy metals retain relatively higher residual rates in black soil, and their migration risks also have different characteristics. These characteristics, combined with high-intensity regional agricultural activity, further increase the complexity of soil heavy metal contamination [26, 27]. So far, most studies on heavy metals in soils in the Songhua River Basin have mainly covered upstream areas of industrial concentration or mid-stream wetlands; systematic investigations into the pollution features, source determination and health risk of heavy metal contamination in cultivated soils along the Jiamusi riverfront remain limited. Most previous studies focused only on a single heavy metal or a limited area; meanwhile, there is still no overall assessment covering all these pollutants through various testing methods in recent years [28].

To fill the research gap in systematic studies of heavy metal contamination in farmland along the Jiamusi section of the lower Songhua River, this study has three objectives: (1) to measure concentrations of eight heavy metals and analyze their spatial variation, enrichment, and distribution pattern using GIS and geostatistical methods; (2) to integrate three pollution index models

to quantify the extent of soil heavy metal accumulation; and (3) to apply the USEPA health risk assessment model to compare carcinogenic and non-carcinogenic risks for adults and children across three exposure pathways, identifying high-risk elements and vulnerable populations. The findings can provide empirical support for local farmland management, ecological conservation, and sustainable agricultural development [29, 30].

Based on regional industrial activities, land use patterns, and existing research, four testable hypotheses are proposed: (H1) Exogenous inputs from industry and transportation significantly influence spatial differentiation of heavy metals, with Cd showing the strongest anthropogenic disturbance and being the primary element exceeding standards; (H2) Heavy metals originate from two sources – natural and anthropogenic: Cr and Ni originate from alluvial parent materials, while Cu, Zn, Cd, and Hg are controlled by combined industrial, transportation, and agricultural activities; Pb is mainly influenced by transportation, and As results from a combination of natural processes and mild human impact; (H3) Children have more frequent contact with soil and greater intake per unit body weight, leading to significantly higher non-carcinogenic risks than those for adults; (H4) Localized moderate enrichment of Cd, As, and Pb occurs, but overall heavy metal accumulation remains low, with average population carcinogenic risks falling within acceptable limits according to USEPA guidelines, although individual high-As samples for children require continued monitoring.

Materials and Methods

Overview of the Study Area

The study area is located in the concentrated cultivated land zone of the Jiamusi section in the lower reaches of the Songhua River, between 130°05′ and 130°30′ E and between 46°37′ and 46°57′ N. The area has a mid-temperate continental monsoon climate, with synchronized rainfall and heat, an annual average temperature of 3ºC, a frost-free period of approximately 146 d, annual precipitation of 530.7 mm, and an accumulated temperature ≥10ºC of 2866.6ºC, which can meet the hydrothermal requirements of one cropping season [31]. The overall terrain of this area is relatively flat; the northern riverine plain is approximately 80 m above sea level; the southwestern part is 250-350 m higher than the northern riverine plain. The parent rock of this area is alluvium brought by the Songhua River; thus, these soils consist mainly of black earth, meadow soil, and wetland soil, which are rich in nutrients, making them among the most valuable cultivable lands across China. There are three main water systems in this area, together with several provincial rivers, providing water resources for agricultural production and affecting soil material cycling. The core agricultural area of the Sanjiang Plain has achieved a high degree of agricultural intensification, adopting the one-crop-per-year rotation system, and its main crop combinations are rice, maize and soya beans. Agricultural nonpoint-source pollution and industrial/transportation-related activities can further exacerbate existing soil environmental problems. The simultaneous impact of natural causes and human activity leads to intricate patterns of heavy-metal transformation in cultivated soil at this site. Thus, this study's investigations and analyses of heavy-metal-contaminated soil aim to offer some scientific support for cultivated land protection, green agricultural development, and sustainable land use.

Sample Collection and Analytical Testing

Layout of Sampling Points and Sample Collection

Surface soil samples for this study were collected from cultivated land in the Jiamusi section of the lower reaches of the Songhua River during April and May 2023. The sampling procedure strictly followed the requirements of the Specification of Land Quality Geochemical Assessment (DZ/T0295-2016). Systematic sampling points were arranged within the survey area using two grid densities, 1000×1000 m and 200×200 m, with a total of 276 soil monitoring points established. An "X"-shaped five-point composite sampling method was adopted: subsamples were collected from four azimuths and the center point of each sampling unit; the sampling depth of each subsample was 0-20 cm. This depth represents both the primary soil layer for crop uptake of heavy metals and a layer where exogenous heavy metals accumulate through human activities. Furthermore, it is uniformly specified in national standards, ensuring strong representativeness and comparability of sampling data, and closely aligns with the objectives of agricultural product safety assessment. A consistent sampling mass was maintained. After thorough mixing in equal amounts, the subsamples were combined into one analytical sample. In the field, impurities such as gravel, plant roots, and insect bodies were removed from the samples, which were then passed through a 2 mm nylon sieve and transported to the laboratory for subsequent analysis and testing. The specific distribution of the sampling points is shown in Fig. 1.

Sample Analysis and Testing

Sample analysis was conducted at the laboratory of Heilongjiang Ruike Testing Technology Co., Ltd. in accordance with the "Technical Requirements for Analysis of Samples for Ecological Geochemical Evaluation" (DD 2005-03). The analytical parameters, analytical methods, analytical instruments, instrument models, origins, and detection limits are listed in Table 1. Samples were subjected to contamination-free grinding in agate containers, with strict control during sample preparation to prevent contamination by

exogenous contaminants. Accuracy and precision were evaluated using national first-class reference materials; four certified national first-class reference materials (GBW07403, GBW07404, GBW07426, GBW07427) were included with the samples for simultaneous analysis. For each element, the logarithmic difference (ΔlogC) between the measured values obtained from each sample and each reference material was calculated, confirming compliance with the permissible limits for logarithmic differences. Both the accuracy and precision rates for elemental analysis exceeded 97.9%, while the reported element accuracy rate exceeded 99.8%.

The entire analytical process strictly adhered to relevant technical standards, including the Technical Requirements for Sample Analysis in Ecological Geochemical Evaluation (DD 2005-03) and the

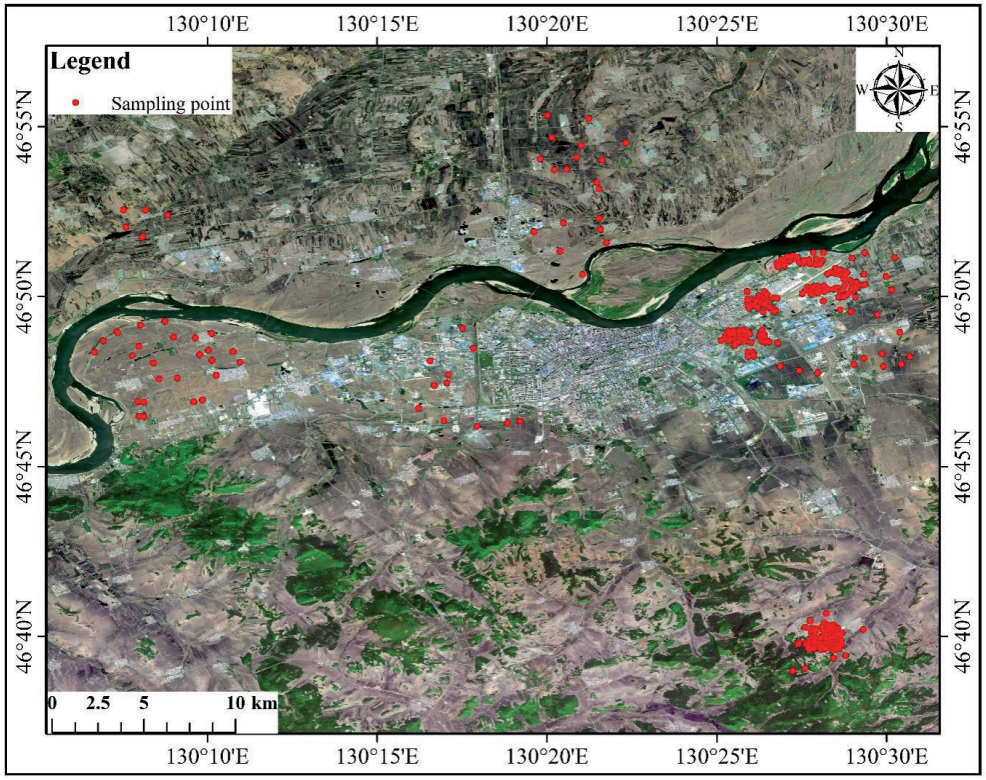


Fig. 1. Distribution of soil sampling sites in the study area.

Table 1. The elemental analysis methods and detection limits (mg/kg).

Element	Analytical method	Instrument	Origin	Model	Detection limit (mg/kg)	Remarks
Hg	Atomic fluorescence spectrometry	Atomic fluorescence spectrophotometer	Beijing China	AFS-8530	0.0005	
As	Inductively coupled plasma mass spectrometry	Inductively coupled plasma mass spectrometer	Shanghai China	7800 ICP-MS	0.2	
Cr	Inductively coupled plasma mass spectrometry	Inductively coupled plasma mass spectrometer	Shanghai China	7800 ICP-MS	5	
Ni	Inductively coupled plasma mass spectrometry	Inductively coupled plasma mass spectrometer	Shanghai China	7800 ICP-MS	2	
Cu	Inductively coupled plasma mass spectrometry	Inductively coupled plasma mass spectrometer	Shanghai China	7800 ICP-MS	1	
Zn	Inductively coupled plasma mass spectrometry	Inductively coupled plasma mass spectrometer	Shanghai China	7800 ICP-MS	4	
Cd	Inductively coupled plasma mass spectrometry	Inductively coupled plasma mass spectrometer	Shanghai China	7800 ICP-MS	0.03	
Pb	Inductively coupled plasma mass spectrometry	Inductively coupled plasma mass spectrometer	Shanghai China	7800 ICP-MS	2	

Specifications for Geochemical Assessment of Land Quality (DZ/T 0295-2016), and key quality-control indicators including accuracy, precision, repeatability, and anomalous points in repeatability testing were systematically controlled. The quality of the testing data met the requirements of the specifications.

Evaluation Methods

Single-Factor Pollution Index Method and Nemerow Comprehensive Pollution Index Method

Based on the technical requirements of the Specification of Land Quality Geochemical Assessment (DZ/T0295-2016) and the Technical Specifications for Soil Environmental Monitoring (HJ/T166-2004), this study employed the single-factor pollution index method (P_i) and the Nemerow comprehensive pollution index method (P_N) to evaluate soil environmental quality. The evaluation results of the two indices were classified into five pollution levels, and the specific classification criteria are shown in Table 2.

The single-factor pollution index method, as a fundamental approach for assessing soil environmental quality, can intuitively characterize the degree of contamination of an individual pollutant indicator in a sample [32, 33].

$$P_i = \frac{C_i}{s_i} \tag{1}$$

Where P_i is the single-factor pollution index of pollutant I in soil; C_i is the mass fraction of the heavy metal element (mg/kg); S_i is the corresponding background value of the heavy metal element (mg/kg).

The Nemerow all-encompassing pollution index, which was well known many years ago for estimating soil contamination caused by heavy metals, is no longer current at present. It can comprehensively represent the total degree of pollution at one sampling point by considering the combined influence of the means and maxima of all individual pollutants for each indicator type under assessment. The calculation formula [32] is:

$$P_N=\sqrt{\frac{P_{iaver}{}^2+P_{imax}{}^2}{2}} \tag{2}$$

Where P_N denotes the Nemerow pollution index of heavy metals, P_{iaver} denotes the average value of the single-factor pollution indices of all heavy metals, and P_{imax} denotes the maximum value among the single-factor pollution indices of all heavy metals.

Geo-Accumulation Index Method

The geo-accumulation index method (Table 3) is used to measure the relative accumulation degree of different heavy metal elements in soil and, on this basis, determine the pollution level. The calculation formula for the geo-accumulation index I_{geo} [34] is:

$$I_{geo}=\log_2\left(\frac{C_n}{1.5\times B_n}\right) \tag{3}$$

In the formula, I_{geo} denotes the geo-accumulation index [34], C_n denotes the measured value of element n, B_n denotes the geochemical background value of element n, and 1.5 is the correction factor.

Human Health Risk Assessment of Heavy Metals in Soil

Heavy metal elements can come into contact with the human body or be ingested by it through multiple pathways, thereby posing a potential threat to human health. Soil heavy metals mainly enter the human body through three exposure pathways: oral ingestion, respiratory inhalation, and dermal contact. The human health risk value can be used to quantitatively assess and predict the degree of potential health hazards to the human body upon exposure to a specific pollutant, and the calculation formula [35] is as follows:

$$ADD_{iing}=C_i\times\frac{IngR\times EF\times ED}{BW\times AT}\times 10^{-6} \tag{4}$$

$$ADD_{iinh}=C_i\times\frac{InhR\times EF\times ED}{PEF\times BW\times AT} \tag{5}$$

Table 2. Classification standards for the single-factor pollution index and the Nemerow comprehensive pollution level [32].

Grade	Single-factor pollution index	Pollution level	Nemerow comprehensive pollution index	Pollution level
Grade I	$P_i \leq 1.0$	Clean	$P_N \leq 0.7$	Clean (safe)
Class II	$1 < P_i \leq 2.0$	Slight pollution	$0.7 < P_N \leq 1.0$	Relatively clean (warning level)
Class III	$2.0 < P_i \leq 3.0$	Mild pollution	$1.0 < P_N \leq 2.0$	Slight pollution
Class IV	$3.0 < P_i \leq 5.0$	Moderate pollution	$2.0 < P_N \leq 3.0$	Moderate pollution
Class V	$P_i > 5.0$	Severe pollution	$P_N > 3.0$	Heavy pollution

Table 3. Classification standard of pollution levels based on the geo-accumulation index [34].

Geo-accumulation index	Class	Pollution level
$I_{geo}<0$	0	Unpolluted
$0\leq_{Igeo}<1$	1	Slightly polluted
$1\leq I_{geo}<2$	2	moderately polluted
$2\leq I_{geo}<3$	3	moderately polluted
$3\leq I_{geo}<4$	4	Moderately to heavily polluted
$4\leq I_{geo}<5$	5	Heavily polluted
$I_{geo}\geq 5$	6	Extremely polluted

$$ADD_{iderm}=C_i\times\frac{SA\times SL\times ABS\times EF\times ED}{BW\times AT}\times 10^{-6} \quad (6)$$

In the formulas, ADD_{iing}, ADD_{iinh}, and ADD_{iderm} represent the average daily exposure doses of heavy metal element i via oral ingestion, inhalation, and dermal contact pathways, respectively; C_i is the measured concentration of heavy metal element i; the specific meanings and reference values of the remaining parameters are given in Table 4.

With reference to the soil health risk model proposed by the United States Environmental Protection Agency (USEPA), the carcinogenic and non-carcinogenic risks arising from human exposure to heavy metals in soil through different pathways were quantitatively assessed.

$$HI=\sum HQ_{i,j}=\sum\frac{ADD_{i,j}}{RFD_{i,j}} \quad (7)$$

$$CR=\sum CR_{i,j}=\sum(ADD_{i,j}\times SF_{i,j}) \quad (8)$$

In formulas (7) and (8) [35], HI is the non-carcinogenic risk index, and CR is the carcinogenic risk index; $HQ_{i,j}$ denotes the non-carcinogenic health risk index of the i-th heavy metal via the j-th exposure pathway, and $CR_{i,j}$ denotes the carcinogenic risk value of the i-th heavy metal via the j-th exposure pathway; $ADD_{i,j}$ is the average daily exposure dose of the i-th heavy metal via the j-th exposure pathway, $RFD_{i,j}$ is the reference dose of the i-th heavy metal via the j-th exposure pathway, and $SF_{i,j}$ is the carcinogenic slope factor of the i-th heavy metal via the j-th exposure pathway (Table 5).

When HI<1, it indicates that the non-carcinogenic health risk of soil heavy metals to humans is low; when HI>1, it indicates that soil heavy metals pose a non-carcinogenic health risk to humans. According to studies by other scholars [36, 37], the acceptable risk range of the carcinogenic health risk index CR is considered to be between 10^{-6} and 10^{-4}; therefore, when $CR>10^{-4}$, it indicates that soil heavy metals pose a relatively high carcinogenic risk to humans.

Results

Concentrations and Distribution Characteristics of Heavy Metals in Soil

As shown in Table 6, the concentrations of all eight heavy metals were below their respective regional background values, indicating relatively good overall soil environmental quality in the study area. However, cadmium (Cd) exhibited the most significant

Table 4. Parameters of exposure factors for the health risk assessment of heavy metal elements.

	Parameter	Meaning	Unit	Adults (reference value)	Children (reference value)
	IngR	Daily oral soil intake	mg/d	100	200
	InhR	Inhalation rate	m^3/d	14.5	7.5
	ABS	Dermal absorption factor	dimensionless	0.01	0.01
	ED	Exposure duration	a	25	6
	BW	Average body weight	kg	56.8	15.9
AT	Non-carcinogenic	Average exposure duration	d	9125	2190
	Carcinogenic			26280	26280
	PEF	Particulate emission factor	m^3/kg	1.36×10^9	1.36×10^9
	EF	Exposure frequency	d/a	350	350
	SL	Skin adherence factor	Mg ($cm^2\cdot d$)	0.07	0.2
	SA	Skin surface area exposed	cm^2	2011	1078

Note: Exposure parameters are obtained from the 2011 edition of the U.S. Environmental Protection Agency's Exposure Factors Handbook.

Table 5. Reference doses (RfD) and slope factors (SF) for different exposure routes.

Element	Oral intake	Inhalation (RfD, $mg \cdot kg^{-1} \cdot d^{-1}$)	Skin contact	Oral ingestion	Inhalation (SF, $kg \cdot d \cdot mg^{-1}$)	Dermal contact
As	3×10^{-4}	1.5×10^{-5}	3×10^{-4}	1.5	4.3×10^{-3}	1.5
Cd	1×10^{-3}	1×10^{-5}	2.5×10^{-5}	6.1	6.3	6.1
Cr	3×10^{-3}	2.55×10^{-5}	7.5×10^{-5}	/	42	/
Cu	4×10^{-2}	/	4×10^{-2}	/	/	/
Hg	3×10^{-4}	3×10^{-4}	2.1×10^{-5}	/	/	/
Ni	2×10^{-2}	2.3×10^{-5}	8×10^{-4}	/	0.84	/
Pb	3.5×10^{-3}	3.5×10^{-3}	5.3×10^{-4}	/	/	/
Zn	3×10^{-1}	/	3×10^{-1}	/	/	/

Note: The RfD and SF values are obtained from the U.S. Environmental Protection Agency's Integrated Risk Information System (IRIS) and the 2011 edition of the Exposure Factors Handbook.

Table 6. Characteristics of soil heavy metal contents in the study area (mg/kg).

Characteristic parameters	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Minimum value ($mg.kg^{-1}$)	3.64	0.04	26.90	9.61	0.01	9.34	17.50	42.20
Maximum value ($mg.kg^{-1}$)	109.00	1.50	205.30	100.26	1.74	84.31	638.10	391.90
Mean value ($mg.kg^{-1}$)	10.38	0.23	53.77	22.83	0.09	21.63	29.17	83.89
Standard deviation ($mg.kg^{-1}$)	9.76	0.25	16.04	9.19	0.14	6.91	37.24	35.63
Coefficient of variation (%)	94.03	111.29	29.83	40.25	158.38	31.94	127.66	42.48
Skewness coefficient	6.25	2.62	4.08	4.02	6.94	3.50	16.02	3.86
Kurtosis coefficient	50.08	7.79	33.72	25.00	68.67	27.21	262.76	24.66
Background value ($mg.kg^{-1}$)	81.40	1.40	159.00	79.00	1.26	58.00	431.00	285.00
Number exceeding the limit	1	3	1	1	1	2	1	2
Exceedance multiple (%)	33.9	3.02	29.12	26.91	38.09	25.91	48.05	19.40
Risk screening value for soil contamination in agricultural land ($6.5<pH\leq7.5$)	30.00	0.30	200.00	100.00	2.40	100.00	120.00	250.00
Number exceeding the limit	6	63	1	1	/	/	1	2
Risk control values for soil contamination of agricultural land ($6.5<pH\leq7.5$)	120.00	3.00	1000.00	/	4.00	/	700.00	/
Excess quantity	/	/	/	/	/	/	/	/

exceedances (at 63 monitoring sites, accounting for 22.83% of the total), highlighting it as the element requiring priority attention. Cr, Cu, Pb, and Zn showed exceedances at only 1 to 6 sites, suggesting they do not pose widespread pollution risks. No exceedances were observed for mercury (Hg) or nickel (Ni). Compared to the soil environmental background values of the Jiamusi section of the Lower Songhua River, it can be seen from these data that there were no exceedances in any heavy metal element at this time; however, some elements still reached or approached the soil background levels. Statistical analysis indicated that the exceedance rates of the metal elements were 1.08% for Cd, 0.72% for Ni and Zn, and 0.36% for the others. Therefore, Cd has a higher pollution level compared to the others in this area. Standard deviation is also included as a measure of the dispersion of soil components. Usually, the higher the value of the coefficient of variation, the greater the disturbance of soil heavy metal concentrations by human activities and the greater the spatial heterogeneity. The coefficients of variation of soil heavy metal elements in the study area were Hg (158.38%)>Pb (127.66%) >Cd (111.29%)>As (94.03%)>Zn (42.48%)>Cu (40.25%) >Ni (31.94%)>Cr (29.83%). Among them, Hg, Pb, and Cd had relatively large coefficients of variation, indicating that these elements were significantly affected by human activities. To assess their potential ecological risks, the heavy metal contents were further compared

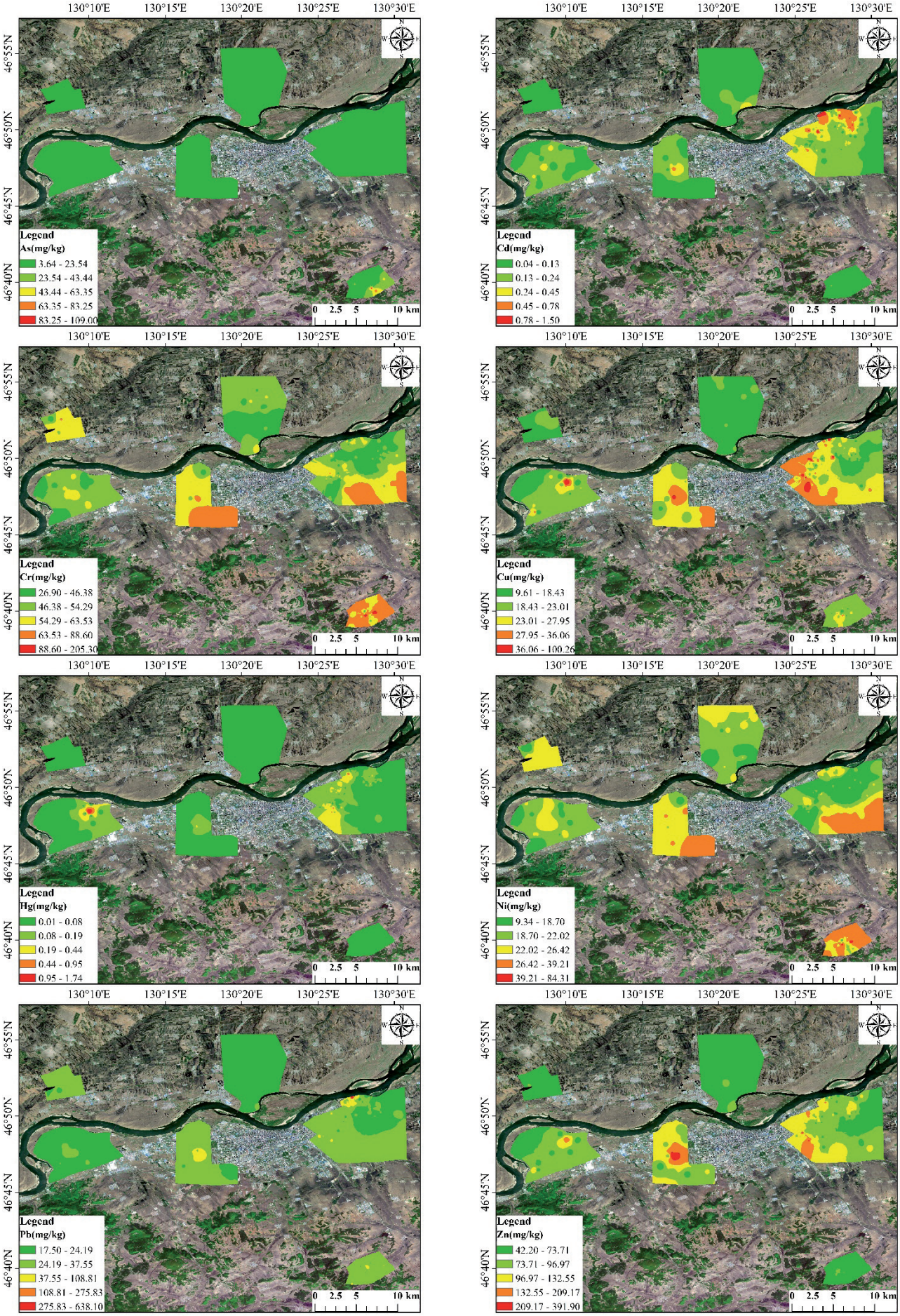


Fig. 2. Geochemical distribution maps of soil heavy metal elements.

with the risk control values for soil contamination risk in agricultural land. The results showed that the soil pH in the study area ranged from 5.03 to 8.57. When the contents of the 8 heavy metals were compared with soil background values, soil environmental quality risk screening values for agricultural land, and risk control values, the elements exceeding the pollution risk screening values were As, Cd, Cr, Cu, Pb, and Zn, with 6, 63, 1, 1, 1, and 2 samples, respectively; the contents of the remaining heavy metal elements were all below the screening values. The measured contents of all heavy metal elements did not exceed the corresponding pollution risk control values.

Fig. 2 shows the geochemical distribution maps of eight heavy-metal elements in this study area; they exhibit a general spatial pattern of higher concentration levels in the east and lower ones in the west. Heavy metal-enriched areas have been highly correlated with regions where people's activities are concentrated. Soil heavy metals Zn, Cu, Cr, Pb, As, and Cd in the study area all show varying degrees of exceedance, with the exceedance areas mainly concentrated in the central and southeastern parts. The high-value areas of each element display spatial distribution characteristics that precisely match specific anthropogenic pollution sources: The zinc exceedance sites are distributed in a point-like pattern and are mainly located around the Jiamusi Thermal Power Plant and the Beifang Water Treatment Plant, which is closely related to the location of industrial facilities; the Cu exceedance area is present only in one area near the Beifang Water Treatment Plant and is directly linked to potential emissions from industrial production and wastewater treatment processes; the overlapping exceedance areas of Cr and As exhibit an areal distribution characteristic similar to agricultural production areas, and high Pb concentrations show this feature as well; there are many Pb exceedance points clustered around Jingchi Logistics Park, a pattern closely related to regional logistics activities in this area and transport network construction. Cd exceeded the screening value at 63 sample locations throughout the study area, and its high-value area was relatively concentrated around Jiamusi International Airport, reflecting the long-term impact of the major transportation hub and surrounding road network on heavy metal dispersion.

Although the concentrations of all eight heavy metals were below regional background levels, the Cd exceedance rate reached approximately 22.83% (at 63 monitoring sites), indicating that the area has been affected by anthropogenic Cd inputs. High coefficients of variation for Hg (158.38%), Pb (127.66%), and Cd (111.29%) suggest strong spatial heterogeneity, typically associated with significant anthropogenic sources such as industrial emissions, vehicle exhaust, and agricultural activities. In contrast, lower coefficients of variation for Cr (29.83%) and Ni (31.94%) indicate that their distribution is primarily determined by soil parent material. The spatial patterns further support this interpretation: Cd-enriched zones are concentrated near Jiamusi International Airport and major transportation routes, suggesting transport-related emissions as potential contributors; Cu- and Zn-rich areas are located adjacent to industrial facilities, indicating inputs from industrial operations and wastewater treatment. These spatial correlations provide crucial insights for identifying pollution sources, which will be analyzed in detail in the next section.

Source Analysis of Heavy Metals

Correlation analysis is one of the commonly used methods for qualitatively identifying the sources of heavy metals, and heavy metals with common-source or mixed-source relationships exhibit significant correlations [38]. If correlations exist among heavy metal elements, their sources may be the same; conversely, if no correlation is observed, their sources are different [39, 40]. The results showed (Table 7) that Cr and Ni exhibited an extremely strong correlation ($r = 0.946^{**}$, $0.8 \leq |r| < 1$), indicating that Cr and Ni have the same or similar sources; Zn was strongly correlated with Cu ($r = 0.703^{**}$), while Zn showed a moderately significant correlation with Hg, as did Cd with Zn ($r = 0.504^{**}$

Table 7. Pearson correlation analysis of soil heavy metal elements.

Indicator	Cr	Ni	Pb	Cu	Zn	Hg	As	Cd
Cr	1							
Ni	.946**	1						
Pb	.026	.023	1					
Cu	.124*	.099	.320**	1				
Zn	-.094	-.139*	.087	.703**	1			
Hg	-.134*	-.140*	-.002	.378**	.504**	1		
As	.224**	.210**	.022	-.072	-.193**	-.135*	1	
Cd	-.225**	-.229**	-.035	.302**	.465**	.251**	-.184**	1

Note: **, Correlation is significant at the 0.01 level (two-tailed). *, Correlation is significant at the 0.05 level (two-tailed).

and 0.465**, respectively), indicating that Cu, Zn, Hg, and Cd share common-source characteristics and have mixed input sources. Cu showed weak-to-moderate significant correlations with Pb, Hg, and Cd, suggesting relatively good associations among these elements; Cr and Ni showed significant negative correlations with Hg and Cd, reflecting different dominant sources for the two groups of heavy metals. The correlations among the remaining elements were relatively weak, indicating comparatively distinct source differences.

Before performing the principal component analysis on the soil heavy metal content at this site, the KMO test and Bartlett's sphericity test were applied; the result showed that these data met the conditions required for conducting principal component analysis. According to the Kaiser criterion for eigenvalues exceeding 1, three principal components were extracted from these features; together, they accounted for 70.29% of the variance and therefore had good explanatory power in subsequent analyses. These components can show the most typical variations in heavy metal pollutants and meet the standards for pollution source attribution analysis (Table 8).

Among them, Principal Component F1 has an explained variance contribution rate of 32.23%, showing strong explanatory capability. F1 had relatively high loading coefficients of Zn, Cu, Hg, and Cd at 0.889, 0.764, 0.693, and 0.637, respectively, suggesting that the four elements have a common source. The correlation analysis result showed that there was an obvious positive relationship between Zn and Cu, Hg and Cd; therefore, these elements might have shared a primary origin together. The statistical results showed that the mean contents of the four elements were generally lower than the regional soil background concentrations; however, their coefficients of variation were quite high (for Cd: 111.29%, Hg: 158.38%, Cu: 40.25%, Zn: 42.48%), which indicated greater spatial heterogeneity and the occurrence of an "over-enrichment" phenomenon in some areas; in addition, there were significant differences among sampling sites, including six cases where cadmium concentrations exceeded the agricultural land risk screening value; the Cu, Zn, and Hg contents also showed low exceedance rates, closely related to the distribution patterns of enrichment driven by human activities. Based on the spatial distribution (as shown in Fig. 2), the high-value areas and exceedance points of Cu and Zn were located near Jiamusi Thermal Power Plant and the northern water treatment plant, mainly due to industrial emissions; the high-value area of Cd was close to Jiamusi International Airport and was closely related to traffic source inputs [41]; although Hg did not show a clear exceedance point, it displayed significant variation, which was also affected by agricultural use as well as industrial deposition. In short, F1 was regulated by the combined influence of industrial pollution, vehicular emission sources and agricultural activities; this interpretation is also in line with the spatial distribution characteristics of these elements and the correlation analysis results.

Table 8. Principal component analysis of soil heavy metals.

	Principal component		
	1	2	3
Cr	-0.044	0.975	-0.001
Ni	-0.070	0.969	-0.014
Pb	0.021	-0.015	0.947
Cu	0.764	0.200	0.435
Zn	0.889	-0.046	0.126
Hg	0.693	-0.086	-0.058
As	-0.306	0.318	0.191
Cd	0.637	-0.239	-0.151
Eigenvalue	2.578	1.985	1.060
Cumulative contribution rate (%)	32.231	57.040	70.289

The variance contribution rate of principal component 2 (F2) was 24.81%. F2 exhibited extremely high loadings for Cr and Ni, at 0.975 and 0.969, respectively; the two elements were significantly correlated (r = 0.946**), indicating a clear common-source characteristic. In terms of statistical characteristics, the mean contents of Cr and Ni were 53.77 $mg \cdot kg^{-1}$ and 21.63 $mg \cdot kg^{-1}$, respectively, both significantly lower than the regional soil background values; meanwhile, the coefficients of variation for both were the lowest, at 29.83% and 31.94%, respectively, indicating a relatively uniform spatial distribution; their concentrations were overall close to baseline geochemical levels. The high correlation, low coefficients of variation, and high degree of agreement with background values indicate that the enrichment levels of Cr and Ni are mainly controlled by the inherent regional geochemical conditions, originating from the natural weathering and pedogenic processes of fluvial alluvial soil parent materials. Accordingly, F2 was identified as mainly representing a natural parent material source [42].

The variance contribution rate of Principal Component 3 (F3) was 13.25%, with a high loading observed only for Pb (0.947). In addition, the overall correlations between Pb and the other heavy metal elements were relatively weak, indicating that its source was relatively independent. The mean Pb content was 29.17 mg kg^{-1}, which was lower than both the regional soil background value and the agricultural land risk screening value; however, this element exhibited a coefficient of variation as high as 127.66%, together with extremely high skewness (16.02) and kurtosis (262.76), showing a strongly non-normal distribution and indicating pronounced local enrichment and point-source anthropogenic input characteristics. As a typical tracer element of traffic pollution, soil Pb mainly originates from pathways such as deposition of lead-

containing exhaust emissions, release from tire wear, and the application of agricultural inputs [43, 44]. Combined with the statistical characteristics of the elements, the spatial distribution pattern, and existing regional research findings, F3 was inferred to be mainly controlled by the superimposed effects of traffic transport and historical legacy point-source pollution, and can therefore be identified as an independent anthropogenic source dominated by traffic.

Evaluation of Heavy Metal Pollution

Evaluation by the Single-Factor Pollution Index Method and the Nemerow Comprehensive Pollution Index

The single-factor pollution evaluation of 8 heavy metals in the soils of the study area (Table 9) showed that Hg and Ni were both at the clean level ($P_i \leq 1.0$); the proportions of clean samples for Cr, Cu, and Pb were all no lower than 99.63%, with only a very few sites (0.36%) showing slight pollution (Cr, Cu) or severe pollution (Pb), exerting very little influence on the overall environment. As, Cd, and Zn were mainly at the clean level (accounting for 77.53%-99.27%), with slight pollution at a small number of sites; As and Cd had very small numbers of slightly or moderately polluted sites (≤4.34%), without forming large-scale pollution.

The Nemerow comprehensive index evaluation indicated that the overall soil pollution level was low: clean sites ($P_N \leq 0.7$) accounted for 72.82%, relatively clean (warning level) sites accounted for 11.23%, slightly polluted sites accounted for 11.59%, and moderately to heavily polluted sites accounted for only 4.34%. In summary, the overall soil environmental quality in the study area was mainly clean to relatively clean.

Geo-accumulation Index Assessment

Using the soil background values of Jiamusi City as the evaluation standard, the results of the geo-accumulation index method (Table 10) showed that the mean geo-accumulation index values of the eight heavy metals in the study area were ranked as Ni (–2.06) >Cr (–2.19)>Zn (–2.43)>Cu (–2.45)>Cd (–3.77)>As (–3.79)>Pb (–4.59)>Hg (–5.04). The geo-accumulation indices of all elements were less than 0, indicating that the soil in the study area as a whole was not contaminated by heavy metals.

Human Health Risk Assessment

The non-carcinogenic daily intake of heavy metals from the soils of the study area for adults and children is shown in Table 11, and the carcinogenic daily intake is shown in Table 12.

For the same heavy metal element in the soils of the study area, the average daily intake via different exposure pathways, whether carcinogenic intake or non-carcinogenic intake, showed the pattern ADD_{iing} >ADD_{iderm}>ADD_{iinh} for both adults and children. Under the same exposure pathway, the non-carcinogenic average daily intake of soil heavy metals for both adults and children followed the order Zn>Cr>Pb>Cu>Ni >As>Cd>Hg, while the carcinogenic average daily intake followed the order Cr>Ni>As>Cd. Therefore, for both adults and children, the principal exposure

Table 9. Proportion of samples in each evaluation grade based on the single-factor pollution index and Nemerow index for soil heavy metals in the study area.

Rating indicators	Class I	Class II	Class III	Class IV	Class V
Single-factor pollution index	$P_i \leq 1.0$	$1<P_i \leq 2.0$	$2.0<P_i \leq 3.0$	$3.0<P_i \leq 5.0$	$P_i>5.0$
Pollution level	Clean	Slight pollution	Mild pollution	Moderate pollution	Severe pollution
As	97.82%	1.08%	0.72%	0.36%	/
Cd	77.53%	14.85%	4.34%	3.62%	/
Cr	99.63%	0.36%	/	/	/
Cu	99.63%	0.36%	/	/	/
Hg	100%	/	/	/	/
Ni	100%	/	/	/	/
Pb	99.63%	/	/	/	0.36%
Zn	99.27%	0.72%	/	/	/
Nemerow composite index	$P_N \leq 0.7$	$0.7<P_N \leq 1.0$	$1.0<P_N \leq 2.0$	$2.0<P_N \leq 3.0$	$P_N>3.0$
Pollution level	Clean (safe)	Relatively clean (warning level)	Mild pollution	Moderate pollution	Severe pollution
P_N	72.82%	11.23%	11.59%	2.53%	1.81%

Table 10. Statistics of the geo-accumulation indices of heavy metals in the soils of the study area.

Geo-accumulation index (I_{geo})	Level	Pollution degree	Proportion (%)							
			As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
$I_{geo}<0$	0	Unpolluted	100%	100%	100%	100%	100%	100%	100%	100%
$0\leq I_{geo}<1$	1	Slight pollution	/	/	/	/	/	/	/	/
$1\leq I_{geo}<2$	2	Moderately polluted	/	/	/	/	/	/	/	/
$2\leq I_{geo}<3$	3	Moderate pollution	/	/	/	/	/	/	/	/
$3\leq I_{geo}<4$	4	Moderately to heavily polluted	/	/	/	/	/	/	/	/
$4\leq I_{geo}<5$	5	Heavily polluted	/	/	/	/	/	/	/	/
$I_{geo}\geq 5$	6	Extremely severe pollution	/	/	/	/	/	/	/	/
Geo-accumulation index		Minimum value	-5.06	-5.78	-3.14	-3.62	-7.56	-3.21	-5.2	-3.34
Maximum value		-0.16	-0.48	-0.21	-0.24	-0.11	-0.04	-0.01	-0.12	
Mean		-3.79	-3.77	-2.19	-2.45	-5.04	-2.06	-4.59	-2.43	

Table 11. Non-carcinogenic daily intake of soil heavy metal elements in the study area.

Element	ADD_{iing}		ADD_{iinh}		ADD_{iderm}		ADD	
	Adults	Children	Adults	Children	Adults	Children	Adults	Children
As	1.75×10^{-5}	1.25×10^{-4}	1.87×10^{-9}	3.45×10^{-9}	2.47×10^{-7}	1.35×10^{-6}	1.78×10^{-5}	1.27×10^{-4}
Cd	3.86×10^{-7}	2.76×10^{-6}	4.12×10^{-11}	7.61×10^{-11}	5.44×10^{-9}	2.97×10^{-8}	3.92×10^{-7}	2.79×10^{-6}
Cr	9.08×10^{-5}	6.49×10^{-4}	9.68×10^{-9}	1.79×10^{-8}	1.28×10^{-6}	6.99×10^{-6}	9.21×10^{-5}	6.56×10^{-4}
Cu	3.85×10^{-5}	2.75×10^{-4}	4.11×10^{-9}	7.59×10^{-9}	5.43×10^{-7}	2.97×10^{-6}	3.91×10^{-5}	2.78×10^{-4}
Hg	1.52×10^{-7}	1.09×10^{-6}	1.62×10^{-11}	3.00×10^{-11}	2.14×10^{-9}	1.17×10^{-8}	1.55×10^{-7}	1.10×10^{-6}
Ni	3.65×10^{-5}	2.61×10^{-4}	3.89×10^{-9}	7.20×10^{-9}	5.14×10^{-7}	2.81×10^{-6}	3.70×10^{-5}	2.64×10^{-4}
Pb	4.92×10^{-5}	3.52×10^{-4}	5.25×10^{-9}	9.70×10^{-9}	6.93×10^{-7}	3.79×10^{-6}	4.99×10^{-5}	3.56×10^{-4}
Zn	1.42×10^{-4}	1.01×10^{-3}	1.51×10^{-8}	2.79×10^{-8}	1.99×10^{-6}	1.09×10^{-5}	1.44×10^{-4}	1.02×10^{-3}
ADD	3.75×10^{-4}	2.68×10^{-3}	4.00×10^{-8}	7.38×10^{-8}	5.28×10^{-6}	2.89×10^{-5}	3.80×10^{-4}	2.70×10^{-3}

pathway for both carcinogenic and non-carcinogenic exposure to soil heavy metals was oral ingestion. From the perspective of non-carcinogenic risk, under the three exposure pathways of oral ingestion (ADD_{iing}), respiratory inhalation (ADD_{iinh}), and dermal contact (ADD_{iderm}), the daily intake of children was significantly higher than that of adults. For example, the oral daily intake of Cr for children (6.49×10^{-4}) was more than 7 times that for adults (9.08×10^{-5}); the dermal-contact daily intake of Zn for children (1.09×10^{-5}) was 5 times that for adults (1.99×10^{-6}), indicating that children are at a higher risk level in non-carcinogenic exposure. From the perspective of carcinogenic risk, population differences across exposure pathways exhibited a differentiated pattern: the daily intake of children via oral ingestion and dermal contact remained higher than that of adults (e.g., Cr oral intake: children 5.40×10^{-5} versus adults 3.15×10^{-5}; As dermal contact: children 1.12×10^{-7} versus adults 8.56×10^{-8}), whereas the daily intake via respiratory inhalation was lower than that of adults (e.g., Ni inhalation intake: children 6.00×10^{-10} versus adults 1.35×10^{-9}), which may be related to children's respiratory frequency and their relatively lower dust exposure in the environment.

From the total average daily dose (ADD) of elements integrating both non-carcinogenic and carcinogenic risks, it can be seen that children have higher daily intakes of all target heavy metals than adults (e.g., in the non-carcinogenic dimension, Zn: 1.02×10^{-3} for children versus 1.44×10^{-4} for adults; in the carcinogenic dimension, Cr: 5.46×10^{-5} for children versus 3.20×10^{-5} for adults). This difference is closely related to the physiological and behavioral characteristics of children – children frequently come into contact with soil and suck

Table 12. Carcinogenic daily intake of soil heavy metal elements in the study area.

Element	ADD_{iing}		ADD_{iinh}		ADD_{iderm}		ADD	
	Adults	Children	Adults	Children	Adults	Children	Adults	Children
Cr	3.15×10^{-5}	5.40×10^{-5}	3.36×10^{-9}	1.49×10^{-9}	4.44×10^{-7}	5.82×10^{-7}	3.20×10^{-5}	5.46×10^{-5}
Ni	1.27×10^{-5}	2.17×10^{-5}	1.35×10^{-9}	6.00×10^{-10}	1.78×10^{-7}	2.34×10^{-7}	1.29×10^{-5}	2.20×10^{-5}
As	6.08×10^{-6}	1.04×10^{-5}	6.48×10^{-10}	2.88×10^{-10}	8.56×10^{-8}	1.12×10^{-7}	6.17×10^{-6}	1.05×10^{-5}
Cd	1.34×10^{-7}	2.30×10^{-7}	1.43×10^{-11}	6.34×10^{-12}	1.89×10^{-9}	2.48×10^{-9}	1.36×10^{-6}	2.32×10^{-7}
ADD	5.04×10^{-5}	8.64×10^{-5}	5.37×10^{-9}	2.38×10^{-9}	7.09×10^{-7}	9.32×10^{-7}	5.11×10^{-5}	8.73×10^{-5}

Table 13. Non-carcinogenic risk index of soil heavy metal elements in the study area.

Element	Statistical value	HQ_{iing}		HQ_{iinh}		HQ_{iderm}		HQ	
		Adults	Children	Adults	Children	Adults	Children	Adults	Children
As	Average value	5.84×10^{-2}	4.17×10^{-1}	1.24×10^{-4}	2.30×10^{-4}	8.22×10^{-4}	4.50×10^{-3}	5.93×10^{-2}	4.22×10^{-1}
	Maximum value	6.13×10^{-1}	4.38	1.30×10^{-3}	2.42×10^{-3}	8.63×10^{-3}	4.72×10^{-2}	6.23×10^{-1}	4.43
Cd	Average value	3.86×10^{-4}	2.76×10^{-3}	4.11×10^{-6}	7.61×10^{-6}	2.17×10^{-4}	1.19×10^{-3}	6.08×10^{-4}	3.96×10^{-3}
	Maximum value	2.53×10^{-3}	1.81×10^{-2}	2.69×10^{-5}	4.99×10^{-5}	1.43×10^{-3}	7.81×10^{-3}	3.99×10^{-3}	2.59×10^{-2}
Cr	Average value	3.03×10^{-2}	2.16×10^{-1}	3.79×10^{-4}	7.01×10^{-4}	1.70×10^{-2}	9.32×10^{-2}	4.77×10^{-2}	3.10×10^{-1}
	Maximum value	1.16×10^{-1}	8.25×10^{-1}	1.45×10^{-3}	2.68×10^{-3}	6.51×10^{-2}	3.56×10^{-1}	1.82×10^{-1}	1.18
Cu	Average	9.63×10^{-4}	6.42×10^{-3}	0	0	1.36×10^{-5}	7.42×10^{-5}	9.77×10^{-4}	6.50×10^{-3}
	Maximum	4.23×10^{-3}	3.02×10^{-2}	0	0	5.96×10^{-5}	3.26×10^{-4}	4.29×10^{-3}	3.06×10^{-2}
Hg	Average value	5.08×10^{-4}	3.63×10^{-3}	5.41×10^{-8}	1.00×10^{-7}	1.02×10^{-4}	5.59×10^{-4}	6.10×10^{-4}	4.18×10^{-3}
	Maximum value	9.79×10^{-3}	6.99×10^{-2}	1.04×10^{-6}	1.93×10^{-6}	1.97×10^{-3}	1.08×10^{-2}	1.18×10^{-2}	8.07×10^{-2}
Ni	Average value	1.83×10^{-3}	1.30×10^{-2}	1.69×10^{-4}	3.13×10^{-4}	6.34×10^{-4}	3.52×10^{-3}	2.64×10^{-3}	1.69×10^{-2}
	Maximum value	7.12×10^{-3}	5.08×10^{-2}	6.59×10^{-4}	1.22×10^{-3}	2.50×10^{-3}	1.37×10^{-2}	1.03×10^{-2}	6.58×10^{-2}
Pb	Average value	1.41×10^{-2}	1.01×10^{-1}	1.50×10^{-6}	2.77×10^{-6}	1.31×10^{-3}	7.16×10^{-3}	1.54×10^{-2}	1.08×10^{-1}
	Maximum value	3.08×10^{-1}	2.19	3.28×10^{-5}	6.06×10^{-5}	2.86×10^{-2}	1.56×10^{-1}	3.36×10^{-1}	2.35
Zn	Average value	4.72×10^{-4}	3.37×10^{-3}	0	0	6.64×10^{-6}	3.63×10^{-5}	4.78×10^{-4}	3.41×10^{-3}
	Maximum value	2.21×10^{-3}	1.58×10^{-2}	0	0	3.10×10^{-5}	1.69×10^{-4}	2.24×10^{-3}	1.59×10^{-2}
HQ	Mean	1.07×10^{-1}	7.63×10^{-1}	6.79×10^{-4}	1.25×10^{-3}	2.01×10^{-2}	1.10×10^{-1}	1.28×10^{-1}	0.87
	Maximum	1.06	7.59	3.47×10^{-3}	6.42×10^{-3}	1.08×10^{-1}	5.92×10^{-1}	1.17	8.19

their fingers, among other behaviors, which increase the probability of heavy metal intake; therefore, they are more susceptible to the potential negative effects of soil heavy metals [45].

The health risks of soil heavy metals to adults and children in the study area were assessed separately. The non-carcinogenic risk assessment results are shown in Table 13, and the carcinogenic risk assessment results are shown in Table 14. According to the evaluation results of the non-carcinogenic health risks of soil heavy metal elements in the study area, for the same heavy metal element, the non-carcinogenic health risks through different exposure pathways were consistent with the pattern of intake, with both adults and children showing $HQ_{iing}>HQ_{iderm}>HQ_{iinh}$; oral ingestion was the main pathway causing non-carcinogenic health risks from soil heavy metals, and the non-carcinogenic risk of heavy metal elements in soil to children was higher than that to adults. The HQ contribution rates of soil heavy metal elements in the study area for both adults and children were As>Cr>Pb>Ni>Cu>Hg>Cd>Zn. Among them, As, Cr, and Pb had the highest proportions of HQ contribution rates, which were 48.22%, 35.43%, and 12.30%, respectively, for adults; the corresponding proportions for children were exactly the same. These three elements were the main factors causing non-carcinogenic health risks. Among the 276 soil samples, all HI values for adults were less than 1;

Table 14. Carcinogenic risk index of soil heavy metal elements in the study area.

Element	Statistic	CR_{iing}		CR_{iinh}		CR_{iderm}		CR	
		Adults	Children	Adults	Children	Adults	Children	Adults	Children
Cr	Average value	0	0	1.41×10^{-7}	6.26×10^{-8}	0	0	1.41×10^{-7}	6.26×10^{-8}
	Maximum value	0	0	5.39×10^{-7}	2.39×10^{-7}	0	0	5.39×10^{-7}	2.39×10^{-7}
Ni	Average value	0	0	1.14×10^{-9}	5.04×10^{-10}	0	0	1.14×10^{-9}	5.04×10^{-10}
	Maximum value	0	0	4.43×10^{-9}	1.96×10^{-9}	0	0	4.43×10^{-9}	1.96×10^{-9}
As	Average value	9.13×10^{-6}	1.57×10^{-5}	2.79×10^{-12}	1.24×10^{-12}	1.29×10^{-7}	1.68×10^{-7}	9.25×10^{-7}	1.58×10^{-5}
	Maximum value	9.58×10^{-5}	1.64×10^{-4}	2.93×10^{-11}	1.30×10^{-11}	1.35×10^{-6}	1.77×10^{-6}	9.72×10^{-5}	1.66×10^{-4}
Cd	Average value	8.18×10^{-7}	1.43×10^{-6}	9.01×10^{-11}	3.99×10^{-11}	1.15×10^{-8}	1.51×10^{-8}	8.30×10^{-7}	1.42×10^{-6}
	Maximum value	5.36×10^{-6}	9.20×10^{-6}	5.91×10^{-10}	2.62×10^{-10}	7.55×10^{-8}	9.91×10^{-8}	5.44×10^{-6}	9.30×10^{-6}
CR	Average value	9.94×10^{-6}	1.71×10^{-5}	1.42×10^{-7}	6.31×10^{-7}	1.40×10^{-8}	1.84×10^{-7}	1.02×10^{-5}	1.73×10^{-5}
	Maximum value	1.01×10^{-4}	1.73×10^{-4}	5.44×10^{-7}	2.41×10^{-7}	1.42×10^{-6}	1.87×10^{-6}	1.03×10^{-4}	1.76×10^{-4}

among children, 80.07% of HI values were less than 1 and 19.93% were greater than 1, indicating that the non-carcinogenic risk of soil in the study area was greater for children than for adults.

Based on the evaluation results of the carcinogenic hazards caused by soil heavy metal contamination in this study area, it can be seen that there are similar trends in the impact of various exposure pathways on adults and children; the pathway showing a high-exposure pattern showed a corresponding increase in carcinogenic hazard (CR_{iing}>CR_{iderm}>CR_{iinh}). In terms of the CR contribution rate, the CR contribution rates for both adults and children followed the order As>Cd>Cr>Ni. Among them, the CR contribution rate to adults' as well as children's blood lead levels were as high as 63.63% and 91.44%, respectively, while that of Cd was up to 35.39%; of the total of 276 soil samples collected, none had a carcinogenic health risk index exceeding 10^{-4}; therefore, it can be concluded from this that there was no significant carcinogenic risk to humans based on these data.

Discussion

The average heavy metal concentrations in black soil farmland within the study area were generally lower than the corresponding regional geological background values; however, highly variable elements such as Cd, Hg, and Pb exceeded thresholds at certain local sites, exhibiting a pattern of "overall low contamination with localized anthropogenic enrichment", consistent with patterns observed in black soil farmlands across Northeast China's cold regions [46-48]. The soil accumulation index (using parent material background as reference) indicated no significant heavy metal accumulation throughout the area; however, when using agricultural land screening thresholds as benchmarks, the Cd exceedance rate reached 22.83%. The discrepancy between the two evaluation conclusions stems from differing assessment benchmarks: the former focuses solely on anthropogenic secondary accumulation, while the latter emphasizes food chain health risks [49]. Cd has significantly higher bioavailability than Cr or Ni, making it readily taken up by crops even at low soil concentrations; thus, reliance solely on the soil accumulation index may underestimate the ecological risks posed by Cd in farmland, underscoring the importance of assessing its bioavailability. Low coefficients of variation for Cr and Ni suggest natural parent material origins [50-52], whereas high spatial dispersion for Hg, Pb, and Cd is attributable to industrial and traffic-derived inputs, reflecting a pronounced dual-source differentiation pattern [53-56].

Oral ingestion is the primary route of heavy metal exposure. Children, due to their lower body weight and frequent hand-to-mouth contact [57], exhibit significantly higher exposure doses for all elements than those for adults, indicating substantial risk differences between the two populations. This study analyzes risk contributions on a per-element basis to avoid methodological bias associated with mean-based calculations. As, Cr, and Pb are the principal non-carcinogenic risk elements, collectively accounting for 95.95% of non-carcinogenic risks; the average non-carcinogenic hazard index (HI) for children is 0.87, with nearly 20% of cases showing HI>1, indicating potential health risks, whereas no excess risks were observed among adults in the study area. Carcinogenic risk is predominantly driven by As, contributing up to 91.44% in children; overall carcinogenic risks for both adults and children across the region fall within the acceptable range of 10^{-6} to 10^{-4}, but children in areas with elevated As levels approach critical thresholds, highlighting the importance of addressing long-term exposure risks [58, 59].

The overall environmental quality of black soil farmland in Jiamusi is good, with no widespread severe pollution; however, two key areas require particular

attention: first, combined inputs from transportation and industrial activities lead to localized Cd exceedances, and its high bioavailability poses a threat to food safety; second, children exhibit higher sensitivity to As, Cr, and Pb, and field soil exposure poses non-carcinogenic risks. Based on similar studies in the Northeast black soil region [56], black soil organic matter has limited capacity to immobilize Cd and As, while neutral-to-acidic conditions readily mobilize heavy metals. It is recommended to implement routine monitoring of Cd-enriched plots around airports, industrial sites, and major roads, complemented by immobilization measures and cultivation of low-accumulation crops; promote public awareness of measures to protect children f rom soil exposure; establish a long-term monitoring network to strictly control continued external inputs of Cd and As and prevent long-term accumulation of heavy metals.

Conclusions

This study investigated the contamination levels, sources, ecological risks, and health risks of heavy metals in cultivated soils along the Jiamusi section of the lower Songhua River. Results indicated that overall soil quality was good, with localized cadmium accumulation being the primary concern. Source analysis identified natural parent materials (Cr, Ni) and human activities (industrial, transportation, and agricultural) as the main sources. Ecological risk assessment revealed that soils were generally non-contaminated to mildly contaminated. Health risk assessment showed that the non-carcinogenic risk for children was higher than that for adults, with As, Cr, and Pb being the principal contributing factors; the average carcinogenic risk remained within acceptable levels, although individual As samples from children require ongoing monitoring.

These findings provide a scientific basis for soil environmental management and pollution control in the Jiamusi region. To protect soil quality and human health, it is recommended to conduct long-term monitoring of Cd, As, and Pb, implement source control measures, promote sustainable agricultural practices, and enhance public awareness (particularly among children) of the health risks associated with soil exposure.

Acknowledgments

This research was funded by the Hydrogeological Survey Project of the China Geological Survey, “Hydrogeological and Water Resources Survey of the Erguna River Basin”, project code: (DD202605102104). We sincerely express our gratitude for this support.

AI Usage Disclosure Statement

The experimental design, data analysis, and manuscript writing of this study were independently completed by the authors; artificial intelligence was used solely for proofreading formatting and did not participate in the research design, data analysis, or conclusion generation.

Conflict of Interest

The authors declare no conflict of interest.

References

1. BHANDARI S., YADAV B., YADAV P.K., LAHUTIYA V., KOIRALA S. Exploring Agroecological Approaches for Sustainable Agriculture and Rural Development: A Comprehensive Review. Asian Journal of Research in Agriculture and Forestry, **10** (1), 79, **2024**.
2. DENG X., GIBSON J., SONG M., LI Z., HAN Z., ZHANG F., CHENG W. Agricultural land-use system management: Research progress and perspectives. Fundamental Research, **5** (6), 2908, **2024**.
3. NIU S., LYU X., GU G. What Is the Operation Logic of Cultivated Land Protection Policies in China? A Grounded Theory Analysis. Sustainability, **14** (14), 8887, **2022**.
4. SU Y., LIU Y., ZHOU Y., LIU J. Research on the Coupling and Coordination of Land Ecological Security and High-Quality Agricultural Development in the Han River Basin. Land, **13** (10), 1666, **2024**.
5. LONG X., LIU W., QIU R. Research Progress and Prospects of Human Health Risk Assessment of Heavy Metal Pollution in Farmland Soils of China. Acta Pedologica Sinica, **61** (5), 1188, **2024**.
6. WAN Y., LIU J., ZHUANG Z., WANG Q., LI H. Heavy Metals in Agricultural Soils: Sources, Influencing Factors, and Remediation Strategies. Toxics, **12** (1), 63, **2024**.
7. RASHID A., SCHUTTE B.J., ULERY A., DEYHOLOS M.K., SANOGO S., LEHNHOFF E.A., BECK L. Heavy Metal Contamination in Agricultural Soil: Environmental Pollutants Affecting Crop Health. Agronomy, **13** (6), 1521, **2023**.
8. WANG Z., LIANG H., ZHANG D., LI L., WEI L., WAN Y., CHEN Q. Accumulation Characteristics and Control Technologies of Heavy Metal Contamination in Facility Soil of China: A Review. Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE), **40** (9), 1, **2024** [In Chinese].
9. ZHANG F., CHEN J., FAN P., NIU Y., FANG N., WU Z., TAN T., LONG W., TAI L. Research Progress on the Effects of Soil Erosion and Sedimentation on the Forms, Concentration, and Enrichment of Heavy Metals. Bulletin of Soil and Water Conservation, **44** (6), 222, **2024** [In Chinese].
10. LIU H., WEI W., SONG Y., PAN Y., HUANG J.M. Health Risk Assessment and Environmental Benchmarks of Heavy Metals in Cultivated Land in the Wanjiang Economic Belt. Environmental Science, **44** (6), 3531, **2023** [In Chinese].
11. DONG Q., WEN H., WANG P., SONG C., LAI S.Y., YANG Z.J., ZHAO Y.Y., YAN M.J. Health risk assessment

of heavy metals in soils and crops in a mining area (Au-Ag-Cutrona-oil et al.) of the Nanyang Basin, Henan Province, China. China Geology, **6** (4), 567, **2023**.
12. GUO X., LIU Q., ZHANG H.R., SHI X.F., QIN C.Y., ZHANG Z.Q. Harmful evaluation of heavy metals from soil layer to the groundwater: Take the Jilin Hunchun Basin as an example. China Geology, **7** (1), 116, **2024**.
13. ZHANG Y., LI T., GUO Z., XIE H., HU Z., RAN H., LI C., JIANG Z. Spatial heterogeneity and source apportionment of soil metal(loid)s in an abandoned lead/zinc smelter. Journal of Environmental Sciences, **127**, 519, **2023**.
14. ABUZAID A.S., JAHIN H.S., SHOKR M.S., EL BAROUDY A.A., MOHAMED E.S., REBOUH N.Y., BASSOUNY M.A. A Novel Regional-Scale Assessment of Soil Metal Pollution in Arid Agroecosystems. Agronomy, **13** (1), 161, **2023**.
15. WANG S., HU Z., WANG E., YAN K., WANG H. Research Hotspots and Evolution of Global Soil Heavy Metal Pollution Evaluation from 1991 to 2022. Environmental Pollution & Control, **46** (4), 589, **2024** [In Chinese].
16. ROUHANI A., MAKKI M., HEJCMAN M., SHIRZAD R., GUSIATIN M.Z. Risk Assessment and Spatial Distribution of Heavy Metals with an Emphasis on Antimony (Sb) in Urban Soil in Bojnourd, Iran. Sustainability, **15** (4), 3495, **2023**.
17. ZHANG Z., TANG Z., LIU Y., HE H., GUO Z., FENG P., CHEN L., SUI Q. Study on the Ecotoxic Effects of Uranium and Heavy Metal Elements in Soils of a Uranium Mining Area in Northern Guangdong. Toxics, **11** (2), 97, **2023**.
18. ASGHARI F., SALAVATI M., ASIABAR S.H., SHARIATI F. Geochemical and environmental assessment of river sediments in the East of Gilan province (case study: Otaghvarrud, Shalmanrud, and Polrud rivers), Northern Iran. Toxin Reviews, **42** (4), 681, **2023**.
19. LI Y., ZHU Q., TANG X., WANG C., ZHAI S. Ecological and Health Risk Assessment of Heavy Metals in Farmland in the South of Zhangbei County, Hebei Province, China. Applied Sciences, **12** (23), 12425, **2022**.
20. DELIBORAN A., VAROL M., AYTOP H. Evaluation of ecological and health risks of trace elements in soils of olive orchards and apportionment of their sources using the APCS-MLR receptor model. Environmental Geochemistry and Health, **46** (9), 320, **2024**.
21. LIU H., ANWAR S., FANG L., CHEN L., XU W., XIAO L., ZHONG B., LIU D. Source apportionment of agricultural soil heavy metals based on PMF model and multivariate statistical analysis. Environmental Forensics, **25** (1-2), 40, **2022**.
22. WANG J., XIAO Y., WANG L., ZHANG Y., FENG M., ZHU W., YANG W., SHI W., YANG H., HAN J., HU W., WANG N. Deciphering pollution sources and mechanisms controlling groundwater chemistry in a typical dense agricultural plain on Yungui Plateau. Water Environment Research, **96** (12), e11156, **2024**.
23. LI X., DING D., XIE W., ZHANG Y., KONG L., LI M., LI M., DENG S. Risk assessment and source analysis of heavy metals in soil around an asbestos mine in an arid plateau region, China. Scientific Reports, **14** (1), 7552, **2024**.
24. ZHANG S., WANG S., LI F., LIU S., YOU Y., LIU C. Enhanced Assessment of Water Quality and Pollutant Source Apportionment Using APCS-MLR and PMF Models in the Upper Reaches of the Tarim River. Water, **16** (21), 3061, **2024**.
25. LIU S.G., XU Y.D., PEI J.B., WANG J.K. Promoting the Scientific Protection and Utilization of Black Soil through the Third National Soil Survey Results. Chinese Journal of Soil Science, **55** (4), 1185, **2024** [In Chinese].
26. QI L., ZHANG J., GE W., SUN P., HAN Y., QIU H., ZHOU S. Geochemical Baseline Establishment and Source-Oriented Ecological Risk Assessment of Heavy Metals in Lime Concretion Black Soil from a Typical Agricultural Area. International Journal of Environmental Research and Public Health, **18** (13), 6859, **2021**.
27. TONG Y., ANGELINI M.E., YIĞINI Y., LUOTTO I. Global black soil distribution. Frontiers of Agricultural Science and Engineering, **11** (2), 271, **2024**.
28. LI W., CAO X., HU Y., CHENG H. Source Apportionment and Risk Assessment of Heavy Metals in Agricultural Soils in a Typical Mining and Smelting Industrial Area. Sustainability, **16** (4), 1673, **2024**.
29. NGUYEN T., PHAN K., HUYNH T. Groundwater quality assessment using groundwater quality index and multivariate statistical methods and human health risk assessment in a coastal region of the Vietnamese Mekong Delta. Applied Environmental Research, **44** (2), 68, **2022**.
30. RASHID A., AYUB M., ULLAH Z., ALI A., SARDAR T., IQBAL J., GAO X., BUNDSCHUH J., LI C., KHATTAK S.A., ALI L., El-SEREHY H.A., KAUSHIK P., KHAN S. Groundwater Quality, Health Risk Assessment, and Source Distribution of Heavy Metals Contamination around Chromite Mines: Application of GIS, Sustainable Groundwater Management, Geostatistics, PCAMLR, and PMF Receptor Model. International Journal of Environmental Research and Public Health, **20** (3), 2113, **2023**.
31. FU Q., WU Y., WU Z., YU Y., ZHANG G., SUN Y. Dynamic assessment of groundwater vulnerability under land use change scenarios: A case study of Jiamusi City, Sanjiang Plain. Acta Scientiae Circumstantiae, **45** (10), 463, **2025** [In Chinese].
32. JIANG H., SUN W., LIU L., CAO Y., ZHU W., ZHANG C. Topographical Discrepancy in Heavy Metal Pollution and Risk Assessment from Cornfields in the Licheng District, China. Sustainability, **17** (10), 4420, **2025**.
33. CAI L., LIN J., HUANG M., HONG Y., ZHONG X., GUO Y., YOU W., XIAO Q., LIN R. Effects of Different Remediation Treatments and Rice Intercropping on the Integrated Quality of Paddy Soils Mildly Contaminated by Cadmium and Copper. Sustainability, **16** (24), 11120, **2024**.
34. ZHANG W., TENG Y., LIU H., HAN X., JIANG B., LI H. Distribution characteristics, ecological risks, and source apportionment of heavy metals in soils of typical agricultural areas in Liaocheng City. Journal of Arid Land Resources and Environment, **38** (4), 171, **2024** [In Chinese].
35. FENG B., ZHOU H., XU Y. The health risk assessment of farmland contaminated with heavy metals in Daye mine area. Industrial Minerals & Processing, **51** (7), 54, **2022** [In Chinese].
36. EID M.H., EISSA M., MOHAMED E.A., RAMADAN H.S., TAMÁS M., KOVÁCS A., SZŰCS P. New approach into human health risk assessment associated with heavy metals in surface water and groundwater using Monte Carlo Method. Scientific Reports, **14** (1), 1008, **2024**.
37. PANQING Y., ABLIZ A., XIAOLI S., AISAIDULI H. Human health-risk assessment of heavy metal–contaminated soil based on Monte Carlo simulation. Scientific Reports, **13** (1), 7033, **2023**.
38. HAN C., LUO B., CHANG C., DENG Y., XIONG J., WANG J. Analysis of the causes of heavy metal pollution in regional agricultural soils based on multiple methods.

Journal of Ecology and Rural Environment, **38** (2), 176, **2022** [In Chinese].
39. YI S., LI X., CHEN X., CHEN W. Research on spatial risk zoning of soil heavy metal pollution based on the "source–pathway–sink" relationship. Acta Pedologica Sinica, **61** (5), 1323, **2024** [In Chinese].
40. AKOTO O., YAKUBU S., OFORI L.A., BORTEY-SAM N., BOADI N.O., HORGAH J., SACKEY L.N. Multivariate studies and heavy metal pollution in soil from gold mining area. Heliyon, **9** (1), e12661, **2023**.
41. KABIR M.H., KORMOKER T., SHAMMI R.S., TUSHER T.R., ISLAM M.S., KHAN R., OMOR M.Z.U., SARKER M.E., YEASMIN M., IDRIS A.M. A comprehensive assessment of heavy metal contamination in road dusts along a hectic national highway of Bangladesh: spatial distribution, sources of contamination, ecological and human health risks. Toxin Reviews, **41** (3), 860, **2021**.
42. GAO J., GONG J., YANG J., WANG Z., FU Y., TANG S., MA S. Spatial distribution and ecological risk assessment of soil heavy metals in a typical volcanic area: Influence of parent materials. Heliyon, **9** (1), e12993, **2023**.
43. AGUILERA A., BAUTISTA F., GUTIÉRREZ-RUIZ M.E., CENICEROS-GÓMEZ A.E., CEJUDO R., GOGUITCHAICHVILI A. Heavy metal pollution of street dust in the largest city of Mexico, sources and health risk assessment. Environmental Monitoring and Assessment, **193** (4), 193, **2021**.
44. GIECHASKIEL B., GRIGORATOS T., MATHISSEN M., QUIK J., TROMP P., GUSTAFSSON M., FRANCO V., DILARA P. Contribution of Road Vehicle Tyre Wear to Microplastics and Ambient Air Pollution. Sustainability, **16** (2), 522, **2024**.
45. LI J., FENG L. Health risk assessment of heavy metal pollution in soil of a tin mining area in Hunan Province. Geology in China, **50** (3), 897, **2023**.
46. WEN M., MA Z., GINGERICH D.B., ZHAO X., ZHAO D. Heavy metals in agricultural soil in China: A systematic review and meta-analysis. Eco-Environment & Health, **1** (4), 219, **2022**.
47. MI N., LU Y., SONG Z., SHENG F., CHEN Y., CHEN Z., HE J., FAN T. Leaching of Heavy Metals from Farmland Soil in China: The Status and Ecological Risk Assessment. Agronomy, **15** (9), 2126, **2025**.
48. SUN Q.F., YANG K., SUN Z.A., WANG J.H., XING W.G., HAO G.J. Study on Risk Model of Heavy Metals and Risk Element Pollution in Surface Farmland Soil in Cold Black Soil Region of China – Qianjin Town as an Example. Polish Journal of Environmental Studies, **32** (4), 3309, **2023**.
49. YANG Q., YANG Z.F., FILIPPELLI G.M., JI J.F., JI W.B., LIU X., WANG L., YU T., WU T., ZHUO X., ZHANG Q. Distribution and secondary enrichment of heavy metal elements in karstic soils with high geochemical background in Guangxi, China. Chemical Geology, **567**, 120081, **2021**.
50. ZHANG Y.F., MA Q., SHI Z.M., HE L.Z., MA N., WANG S., DAI L. Pollution Assessment and Source Apportionment of Heavy Metals in Soil of Qinghai Section of the Yellow River Basin. Huan Jing Ke Xue, **46** (10), 6612, **2025** [In Chinese].
51. MA Y., NING J., YANG H., ZHANG L., XU C., HUANG C., LIANG J. Distribution characteristics, risk assessment, and source analysis of heavy metals in farmland soil of a karst area in Southwest China. Land, **13** (7), 979, **2024**.
52. LIU J., KANG H., TAO W., LI H., HE D., MA L., TANG H., WU S., YANG K., LI X. A spatial distribution–Principal component analysis (SD-PCA) model to assess pollution of heavy metals in soil. Science of the Total Environment, **859**, 160112, **2023**.
53. RASUL A.K., FATAH K.K., HAMED M.H., TOBIA F.H. Evaluation of Trace Metal Pollution and Ecological Risk in the Soils of Koy Sanjaq, Northeastern Iraq. The Iraqi Geological Journal, **59** (1B), 36, **2026**.
54. WANG X.K., ZHANG Y.X., HUANG B., XIE E.Z., FAN Y.N., HU W.Y., QIU Y.G. Accumulation characteristics and sources of heavy metals in agricultural soils of a typical city in the Yangtze River Delta, China. Acta Pedologica Sinica, **58** (1), 82, **2021** [In Chinese].
55. MAO K., WANG X., YU K., LI M., WANG Y., GAO G., GENG S., SONG H., NING W., AN H., YAN B. Source apportionment and ecological risk assessment of heavy metals in sediments of Dongping lake based on PCA-PMF model. Scientific Reports, **15** (1), 32026, **2025**.
56. SUN Q.F., SUN Z.A., WANG J.H., HU C., WANG X., YANG D., ZHAO J. Soil Heavy Metal Pollution and Ecological Risk Health Risk Assessment in Gengzhen Town, China. Polish Journal of Environmental Studies, **2025**.
57. ZHANG H., DONG C.Y., SUN S.J., HUANG Z.Z., ZHANG N.M., BAO L. Pollution characteristics and source apportionment of heavy metals in soils of typical carbonate rock areas in Yunnan, China. Environmental Chemistry, **44** (1), 174, **2025** [In Chinese].
58. CUSTODIO M., PIZARRO S., HUARCAYA J., ORTEGA K., CCOPI D. Ecological and human health risk assessment of heavy metals in mining-affected river sediments in the Peruvian Central Highlands. Toxics, **13** (9), 783, **2025**.
59. SUN Q.F., ZHENG J.L., SUN Z.A., WANG J.H., LIU Z.J., XING W.G., HAO G.J., LIU T., SUN Z.L., TIAN H. Study and risk assessment of heavy metals and risk element pollution in shallow soil in Shanxi Province, China. Polish Journal of Environmental Studies, **31** (4), 3819, **2022**.