Ecological risks and sensitivity distribution of soil heavy metals in Altay Prefecture, Xinjiang, Northwest China

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Abstract

Purpose Restricted by its own environment and climate factors, the ecological environment in Altay Prefecture, Xinjiang, is very fragile. Heavy metal pollution caused by economic development has further deteriorated the regional ecological environment. This study is aimed at describing the spatial distribution of heavy metals in the soil of Altay Prefecture and at exploring the response of the ecological environment to heavy metal pollution.

Materials and methods Forty-one soil sampling points were arranged in Altay Prefecture, the collected soil samples were tested and analyzed, and a spatial distribution map of heavy metals in soil was drawn. The modified ecological risk index method was employed to evaluate the heavy metal ecological risk.

Results and discussion The spatial distribution of heavy metals in the soil of Altay Prefecture showed that Cu and Zn substantially exceeded the standard, accounting for 28.73% and 19.37%, respectively, of the soil background values. In addition, the ecological risk assessment results of heavy metals in the soil environment of Altay Prefecture showed that the low-risk area was the largest, accounting for 34.06%. The total high-risk area and very high-risk area accounted for approximately 1/4 of Altay Prefecture. The comprehensive evaluation results of eco-environmental sensitivity showed the following proportions of each ecological sensitivity level in Altay Prefecture from high to low: medium-sensitivity area (59.74%), > low-sensitivity area (18.79%), > high-sensitivity area (12.09%), > extremely sensitive area (9.38%).

Conclusions The spatial zone with frequent human activities was the main enrichment area of heavy metals. In addition, surface runoff and rivers will further expand the risk of heavy metal pollutants to the ecological environment, intensifying the ecological sensitivity.

Keywords Heavy metal · Potential ecological risk index method · Ecological sensitivity assessment · Belt and Road · Altay Prefecture

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1 Introduction

At the beginning of the twenty-first century, the Chinese government implemented the Western Development Strategy for backward places in the west. Since the implementation of the Western Development Strategy more than two decades ago, Xinjiang's economic development has made a qualitative leap (Yang et al. 2018). According to statistics, over the past two decades, Xinjiang's GDP has increased nearly 10 times, and the value of industrial production has increased 9.14 times. Rapid economic development has also led to rapid population growth in the region, with a population growth rate of approximately 29.2% in Xinjiang during the two decades (National Bureau of Statistics (NBS) 2001, 2020). However, while the Western Development Strategy has promoted economic growth in Xinjiang, it has also caused harm to the ecological environment of Xinjiang (Liao et al. 2014; Zhu et al. 2016). For example, the desertification of land has been expanding, making Xinjiang the largest, most widely distributed and most critical area of desertification in China (Wang et al. 2012; Jiang et al. 2019). In addition, soil erosion has gradually intensified, grassland area has been reduced and degraded, and biodiversity has also been seriously threatened (Dai et al. 2011; Zhang et al. 2015, 2020).

In September 2013, Chinese President Xi Jinping proposed the strategic concept of the "Belt and Road" (including the "Silk Road Economic Belt" and "21st Century Maritime Silk Road"), which runs through Asia, Europe, and Africa, connecting the East Asian economic circle with the European economic circle and reaching a wider region (Cuiyun and Chazhong 2020). Xinjiang has become the front and core area of this strategy due to its unique location and important window role of opening up to the west. The "Belt and Road" strategy has enabled Xinjiang to take over the transfer of certain industries from eastern China and to further attract foreign heavy industries, resulting in a large proportion of resource-based industries and heavy chemical industries in this region (Xu et al. 2017). However, due to certain enterprises in the development and production process, heavy metals enter the soil ecosystem from natural sedimentation and rainwater leaching, which endangers people's production and lives and the local ecological environment.

Heavy metal pollution is mainly derived from industrial pollution, followed by traffic pollution and domestic waste pollution (Madyima et al. 2002; Peng et al. 2019). Heavy metals are emitted via mining, metal smelting, metal processing, chemical production wastewater, the burning of fossil fuels, the application of pesticides and fertilizers, household waste, and other man-made sources of pollution, as well as geological erosion, weathering, and pollution from other natural sources into the water or soil environment (Alloway 2013; Cabral Pinto et al. 2015; Dinter et al. 2021), through a variety of exposure pathways in humans and animals and plant enrichment (David et al. 2012; Batvari et al. 2015; Abarshi et al. 2017). Common heavy metal elements include mercury, chromium, arsenic, lead, copper, cadmium, and zinc, which are highly toxic, are not easily metabolized in the environment, are easily biologically enriched, have biomagnification effects, etc., and endanger the ecological environment and human health (Heidari et al. 2021; Mielke et al. 1999; Maas et al. 2010; De Miguel et al. 2007; Lim et al. 2008).

Xinjiang is a resource-rich region in China, but due to the limitations of climate and ecological conditions, its ecological carrying capacity is low, its ability to attract large-scale industries and large-scale populations is weak, and its ecological environment is extremely fragile (Luo et al. 2018; Frankl et al. 2013; Zhou 2021). The implementation of the Western Development Strategy has led to the rapid development and utilization of mineral resources in Xinjiang, while the "Belt and Road' strategy has introduced foreign heavy industry enterprises into Xinjiang, resulting in economic development showing the economic characteristics of "high consumption and high emission" (Ahmad et al. 2018; Zhang et al. 2019). The interweaving of limited environmental carrying capacity and external factors has exacerbated existing ecological problems. Therefore, achieving synchronization of economic growth and ecological environmental protection is the primary challenge facing Xinjiang today. Moreover, the road of sustainable development also determines that Xinjiang must carry out economic transformation and take the new road of green and intensive economic development to achieve a benign mutual promotion of regional economic development and ecological civilization construction.

To resolve the contradiction between ecological environmental protection and economic development, identifying the spatial distribution of soil heavy metals and ecologically sensitive zones in Xinjiang has become a top priority. Based on the ecological strategic planning of Xinjiang, selecting important strategic nodes for demonstration has become the primary work. The setting of strategic points involves mainly the selection of nodes with strategic importance to regional ecological security, such as ecological corridor intersections, ecologically sensitive and fragile areas, biodiversity conservation, and natural geography (Peng et al. 2017).

Altay Prefecture is located in northern Xinjiang, bordering Kazakhstan, Russia, and Mongolia. Altay Prefecture is an important fulcrum in the circulation channel of Xinjiang's commercial goods and an important part of the "Silk Road Economic Belt" in the northern section of Xinjiang. As an important nonferrous strategic resource reserve area in China, Altay Prefecture is rich in mineral deposits and a mining

resource center in Xinjiang, accounting for 60% of the entire Xinjiang GDP (Liu et al. 2021). Altay Prefecture not only provides raw materials for the development of Xinjiang's metal industry but also boosts China's economic development in the process of exporting. Therefore, to meet the requirements of national and regional ecological strategies, this study selects Altay Prefecture as a strategic demonstration site. By analyzing the distribution of heavy metal pollution and identifying ecologically sensitive areas, this study provides certain theoretical guidance for government agencies to formulate reasonable heavy metal pollution prevention and control policies. Guidelines for constructing an effective ecological spatial pattern and proposing refined policies for a hierarchical control system in Xinjiang are provided.

To the best of our knowledge, studies on the ecological risk of heavy metal pollution have rarely been reported in Xinjiang (Mao et al. 2020; Wei et al. 2020a). Our present work investigates the spatial distribution characteristics of heavy metals and quantitatively assesses the regional ecological risk. The first case is Altay Prefecture, Xinjiang.

2 Materials and methods

2.1 Study area

Altay Prefecture is located in the northernmost part of the Xinjiang Uygur Autonomous Region. Altay Prefecture is located in the center of the Eurasian continent, far from the ocean, and belongs to a medium-temperate continental climate zone. The bounding longitudes are 85° 31′ and 91° 2′ E, while the bounding latitudes are 44° 59′ and 49° 11′ N (Fig. 1). Winter in Altay Prefecture is long and cold, summer is short, and the temperatures are mild. The coldest month is January, with an average temperature of − 16 °C. The hottest month is July, with an average temperature of 21 °C. The average annual precipitation is approximately 200 mm, and precipitation amounts can reach 400 ~ 600 mm in mountainous areas. The highest altitude is 4374 m.

The terrain of the whole area is high in the west and low in the east, and the hilly plain is high in the east and low in the west. From the northern Altay ridge line to the southern
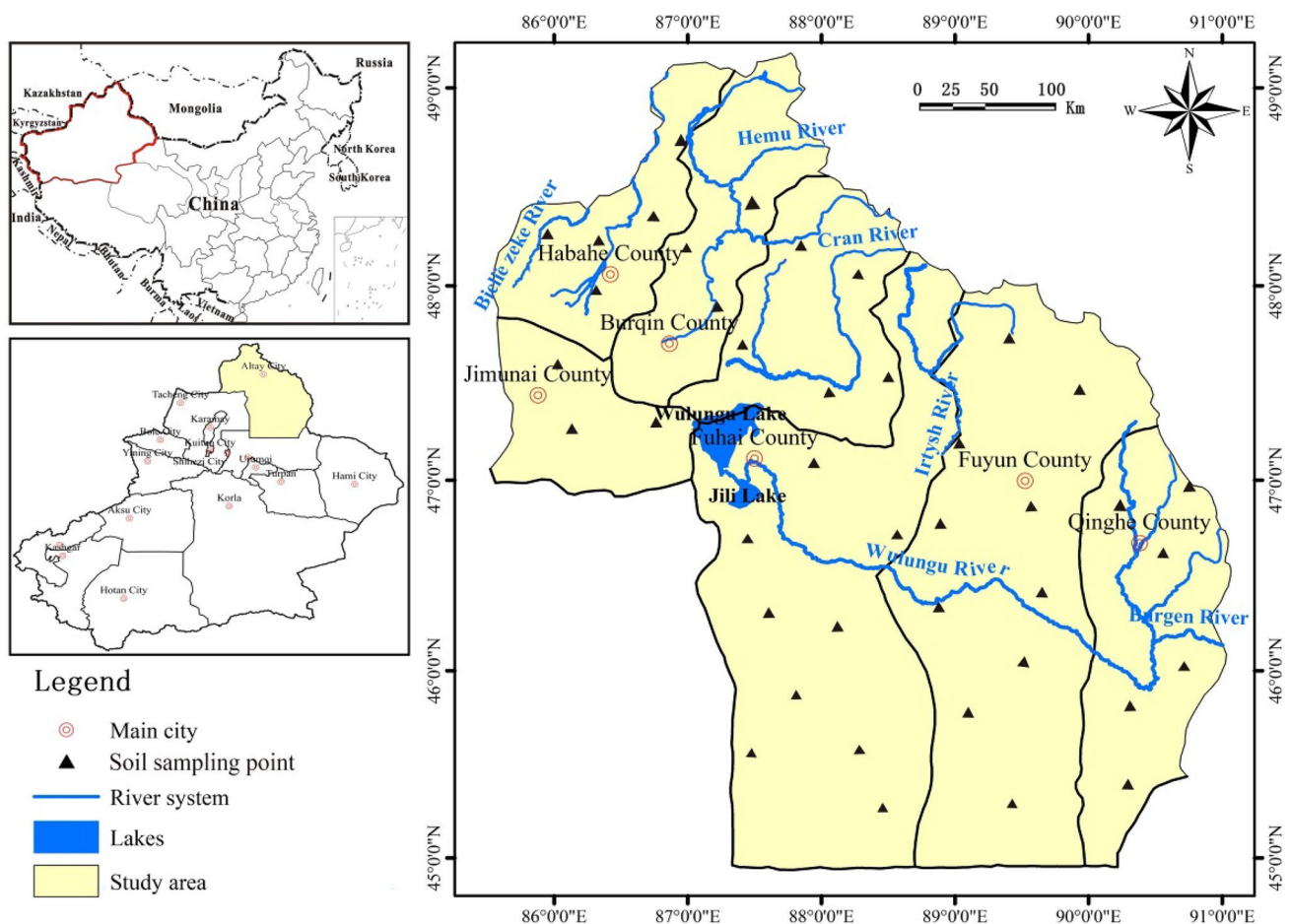

Fig. 1 Sketch of the study area and layout of the sampling points

hilly plain, Altay Prefecture has obvious stepped topography. The landforms are complex and diverse, with mountainous areas accounting for 32% of the total area, hilly valleys and plains accounting for 22%, and Gobi deserts accounting for 46%. The territory is mainly composed of the three major water systems of the Irtysh River, Wulungu Lake, and Jimunai Mountain Stream, with a drainage area of 9.57×10^5 km^2.

Altay Prefecture belongs to the polymetallic metallogenic belt, and deposits of Fe, Pb, Zn, Cu, and other metals have been detected in the region (Yu and Zheng 2019; Zheng 2020). Of the 118 discovered deposits in Xinjiang, Altay Prefecture accounts for 84 species, of which 49 species have proven reserves, accounting for 62.20% of the proven deposits in Xinjiang.

2.2 Sampling and testing

To analyze the characteristics of the content and spatial distribution of heavy metals in the soil of Altay Prefecture, with the cooperation of the Altay District Environmental Protection Bureau and county monitoring stations, survey, and sampling work was carried out in the entire Altay Prefecture from April to July 2017. To make the sampling points more representative and meaningful, a total of 41 sampling points were arranged throughout the region; the distribution locations are shown in Fig. 1. The soil samples were collected from the top layer of soil (0–20 cm) three times at the same sampling point, and the final test average was used as the result value of the sampling point. The collection method was ring knife sampling, and the soil samples were weighed in the field and sealed in aluminum boxes. Quality assurance and quality control (QA/QC) during soil sample collection and preparation were carried out in strict accordance with the relevant regulations in "Technical Specification for Soil Environmental Monitoring" (HJ/T 166-2004).

The soil samples were placed in an indoor ventilated place for natural air drying, and then large particles of impurities (such as animal and plant residues and gravel) were removed. After grinding in an agate mortar and sieving through a 200-mesh nylon soil sample sieve, the pretreated soil samples were preserved for testing. Common heavy metal elements—Hg, Cr, As, Pb, Cu, Cd, and Zn—were selected for testing based on the metal resource content of the study area. The test and analysis of soil samples were completed by the Environmental Monitoring Center Station of Altay Prefecture, and the test work was completed in mid-July 2017. The contents of heavy metals Cd and Pb were determined by graphite furnace atomic absorption spectrophotometry (the whole process of the test was based on the standard GB/T 17141-1997), and the contents of Cu, Cr, and Zn were determined by flame atomic absorption spectrophotometry (the test process of Cu and Zn was based on the standard GB/T 17138-1997, and the test process of Cr was conducted according to the standard HJ 491-2009). The test instrument was an AA-7001 flame/graphite furnace atomic absorption spectrophotometer. The detection limits were Cd < 0.06 mg/kg, Pb < 0.006 mg/kg, Cu < 0.02 mg/kg, Zn < 0.05 mg/kg, Cr < 5 mg/kg, and precision ≤ 0.7%. The contents of Hg and As were determined by atomic fluorescence spectrometry (the whole process of the test was based on the standard HJ 680-2013). The test instrument was an AF-7500 atomic fluorescence photometer. The limits of detection were Hg < 0.001 mg/kg, As < 0.01 mg/kg, precision ≤ 1.0%, and test linear range ≥ 10^3. Xinjiang soil standard material GBW07426 (GSS-12) was used for quality control during the test, and the recovery rate of heavy metals ranged from 89.90 to 112.44%, which was within the allowable range of the quality control requirements of the test results stipulated in the national standard sample.

2.3 Analysis methods

2.3.1 Ecological risk index method

The ecological risk index method, which was proposed by the Swedish scholar Hakanson in 1980, is a relatively fast, simple, and standard method to classify the degree of sediment pollution and the pollution risk of the water environment (Hakanson 1980). This method is based on ecology, environmental science, biotoxicology, and other multidisciplinary theories. According to the differences in geochemical properties and migration behavior of heavy metals, the ecological risk indices of various heavy metals are calculated by formulas, and the calculated results are graded and evaluated (Al-Mutairi and Yap 2021). Presently, this method is widely utilized in international and domestic sediment (soil) heavy metal research. The ecological risk index value (RI) reflects the content, category, and toxicity level of heavy metals in surface sediments and the sensitivity of the soil or water environment to heavy metal pollution. The specific calculation method of RI is expressed as follows:

$$E_r^i = T_r^i \times C_f^i = T_r^i \times \frac{C_n^i}{B_n^i} \tag{1}$$

$$RI = \sum_{i=1}^{n} E_r^i \tag{2}$$

where E_r^i is the ecological risk index value of heavy metal element i; T_r^i is the toxicity response coefficient of heavy metal element i; C_f^i is the influence coefficient of heavy metal element i; C_n^i is the test value of heavy metal element i (mg/kg); B_n^i is the soil background value of heavy metal element i (mg/kg), and the results of Gu et al. (2019) on the background value of soil in Xinjiang are selected as a

reference; and RI is the ecological risk index value of heavy metals in the soil or water environment. Toxicity response coefficients and background values of heavy metals are shown in Table 1.

The RI is easily affected by the content, quantity, and composition of heavy metal elements in the sediment, as well as the toxicity and sensitivity of heavy metal elements. The grading and evaluation criteria of RI are shown in Table 2.

2.3.2 Modified ecological risk index method

In the process of regional ecological risk assessment, the traditional ecological risk index method only considers the properties of heavy metals in sediments or water environments, that is, their pollution toxicity, but disregards the properties of receptors in sediments or water environments, such as their tolerance to pollutants and their own value properties.

For different land use types, their tolerance degree to heavy metal pollutants varies; for example, the sensitivity degree to heavy metal pollutants in human activity areas is much higher than that in desert sandy areas. Similarly, for different ecological functional areas, their value attributes and their sensitivity to heavy metal pollutants vary; the higher the value attributes of the ecological functional area are, the higher the sensitivity to heavy metals, and vice versa. Specifically, the properties and spatial structure of the receptors at different spatial and temporal scales influence their responsiveness (ability to resist, adapt, and transform) to heavy metal pollutants (Ortega et al. 2020; González 2017).

Therefore, on the basis of comprehensive consideration of the toxicity of heavy metals, the value of ecological function area and the type of land use, the traditional ecological risk index method has been improved. We researched numerous studies, and the main query topic was the correlation between different land use types and the ecological risk of soil heavy metals (Xia et al. 2011; Liang et al. 2017; Hou et al. 2017). Based on an expert scoring system (Combined with the relevant experience of many experts engaged in ecology, soil and other disciplines, the final weight value is obtained based on the analytic hierarchy process), different

Table 1 Toxicity response coefficient and background reference value of heavy metal elements

Number	Heavy metal	T_r	B_n (mg/kg)
1	Hg	80	0.017
2	Cd	30	0.12
3	As	10	11.2
4	Pb	5	19.4
5	Cu	5	26.7
6	Cr	2	49.3
7	Zn	1	68.8

Table 2 Ecological risk index value (RI) and ecological risk level (Hakanson 1980)

E_r^i values	Single-factor risk level	RI values	Total ecological risk level
< 40	Low risk	< 150	Low risk
40–80	Moderate risk	150–300	Moderate risk
80–160	Considerable risk	300–600	Considerable risk
160–320	High risk	≥ 600	Significant risk
≥ 320	Very high risk		

ecological function value areas, and land use types were categorized and ranked according to their tolerance level to heavy metal pollutants and assigned weight values (Table 3).

Based on the above factors, the improved calculation method of the ecological risk index value is expressed by the following formula:

$$\mathrm{RI}_M = \sum_{i=1}^{n} E_r^i \times W_a \times W_b \tag{3}$$

where RI_M is the improved ecological risk index value of heavy metal pollution, W_a is the weight value of the ecological function value area corresponding to the ith heavy metal element, W_b is the weight value of the land use type corresponding to the ith heavy metal element, and E_r^i is the ecological risk index value of the ith heavy metal element.

2.3.3 Ecological sensitivity assessment method

Referring to the evaluation methods recommended in the Guide for Delineation of Ecological Protection Red Line (2017) and the method of selecting indicator factors in the ecological sensitivity evaluation study of the Sichuan Western Plateau (Lü et al. 2016), the following eight indicators were selected by investigating the main influencing factors causing ecological damage and ecological function degradation in the Altay Prefecture: topography, precipitation, soil type, soil media, vegetation types, lithology, geological disasters, and heavy metal pollution, as the indicator factors of

Table 3 Classification and weighting of ecological function value areas and land use types

Ecological function value area	W_a	Land use type	W_b
Water conservation area	5	Human activity area	5
Ecological safety maintenance area	3	River and lake area	4
Ecological conservation area	2	Farmland farming area	3
-	-	Vegetation coverage area	2
-	-	Desert sand area	1

the comprehensive ecological sensitivity evaluation system in the Altay Prefecture of Xinjiang.

The sensitivity classification of a single factor is based on a combination of the natural breakpoint method and qualitative analysis. Based on the likelihood of problems in the ecosystem due to human activities or changes in the natural environment, the factors are classified into five sensitivity classes and assigned a score (from 1 to 5). The single-factor weight values were determined using hierarchical analysis and combined with several experts in ecology and geography to judge the relative importance of the evaluation factors. After passing a consistency check, the combined weight value of each evaluation index is calculated. The results of sensitivity classification and weight values of each evaluation factor are shown in Table 4.

The comprehensive ecological sensitivity value of the Altay Prefecture of Xinjiang was obtained by the weighted sum of the sensitivity grading values and weight values of the above 8 index factors. The calculation formula is presented as follows:

$$ES = \sum_{i=1}^{n} D_i W_i \tag{4}$$

where ES is the comprehensive evaluation result of ecological sensitivity, D_i is the ecological sensitivity score value of the ith evaluation factor, and W_i is the weight value of the ith evaluation factor.

Topography Topography is less affected by external factors such as time and climate and is one of the relatively stable basic geological conditions. For greater slopes, the greater the probability of soil and water loss, debris flow, and other natural disasters, the greater the impact on the regional ecological environment, resulting in a more sensitive ecological environment. Mountain areas in Altay Prefecture have a wide coverage, the slope undergoes obvious changes, and southern regions comprise mostly desert areas with gentle slopes. According to the slope size, the natural breakpoint method is employed to divide Altay Prefecture into five levels of ecologically sensitive areas (Table 4) and to draw the sensitivity map of terrain slope (Fig. 2a).

Precipitation Precipitation is the direct driving factor of soil erosion. The greater the amount of precipitation, the stronger the erosion force on the surface. In particular, heavy precipitation will accelerate erosion of the ground surface and cause soil and water loss, which is reflected in higher ecological sensitivity. The precipitation in Altay Prefecture is mainly concentrated in the mountains, while less precipitation occurs in the piedmont plains and desert areas. Similarly, according to the size of precipitation, it is divided

into 5 levels, and the sensitivity of precipitation to regional ecology is drawn (Fig. 2b).

Soil type Soil is the basic condition for ecological and environmental problems. Under the action of external forces such as hydraulic, wind, freezing and thawing, and gravity, the surface soil will be subject to different erosion forces such as destruction, separation, transportation, and deposition (Troeh and Thompson 1993). Different soil types will also show different ecological sensitivities. According to the "Soil Erosion Classification and Grading Standard" (SL 190–2007), the industry standard established by the Ministry of Water Resources of China in 2007, the soil types in Altay Prefecture are divided into different ecologically sensitive zones (Fig. 2c).

Soil media The soil media affects the anti-interference ability of the area. Regions with loose soil media structures are more significantly affected by surface runoff and human activities, and their ecological sensitivity is relatively higher (Montero 2005). According to the size of soil media particles, Altay Prefecture is divided into different ecologically sensitive zones (Fig. 2d).

Vegetation types Vegetation has a very important role in protecting regional biodiversity and improving the quality of the ecological environment. Vegetation has the effect of retaining water and soil, and to a certain extent, can improve the soil structure, physical, chemical, and hydrogeological properties of the topsoil, as well as the microtopography, and can increase the soil's anti-erosion ability (Davidson et al. 2000; Song et al. 2021). The interception of vegetation also resists the erosion of precipitation on the ground (Iida et al. 2017; Wei et al. 2020b). In areas with rich vegetation coverage, soil and water conservation and ecological adjustment capabilities are strong, and ecological sensitivity is weak. The ecological sensitivity map of vegetation is shown in Fig. 2e.

Lithology The soil formed after weathering of parent rocks with different lithologies has different material components, and the soil fertility and thickness are also different, which will affect the growth of vegetation (Ott 2020). Among them, carbonate rock is the most unfavorable to the growth of vegetation because carbonate will dissolve and make the distribution of soil thin, thus affecting the ecological sensitivity (Hou and Gao 2020). Carbonate rock covers a wide area in Altay, and pure carbonate rock or carbonate rocks with a certain proportion account for 34.8% of the whole area. Poor soil conditions, low nutrient content, and the vegetation growth environment are relatively poor. Ecological sensitivity based on lithology factors is generally high (Fig. 2f).

Table 4 Ratings, weights, and classes for the comprehensive evaluation system of ecological sensitivity parameters

Parameter	Rating	Weight	Ranges/classes
Topography (%)	1	0.221	0~2
	2		2~6
	3		6~12
	4		12~18
	5		>18
Annual precipitation (mm)	1	0.061	<400
	2		401~800
	3		801~1500
	4		1501~2000
	5		>2000
Soil type	1	0.092	Frozen soil, rock soil, alpine meadow soil
	2		Dark brown soil, yellow cinnamon soil, brown coniferous soil
	3		Brown earth, gray cinnamon soil, dry red soil, lime soil, brick red soil, cinnamon soil, latosolic red soil
	4		skeletal soil, red soil, yellow soil, yellow brown soil
	5		Purple soil
Soil media	1	0.064	Gravel, sand
	2		Coarse sand, fine sand, clay
	3		loamy soil
	4		Sandy loam, silt clay, loam clay
	5		Sand silt, silt
Vegetation types	1	0.039	Water body, swamp
	2		Shrub, coniferous forest, meadow, broad-leaved forest, coniferous and broad-leaved mixed forest
	3		Economic forest, grass, alpine vegetation, grassland
	4		desert
	5		No vegetation
Lithology	1	0.319	Noncarbonate rock
	2		Interbedded carbonate rocks
	3		Dolomite carbonate rock
	4		interlayered carbonate rock
	5		Pure limestone, limestone and dolomite interbedded
Geological disasters	1	0.116	/
	2		Small geological hazards
	3		Medium-sized geological hazards
	4		Large geological disasters
	5		Extremely large geological hazards
Heavy metal pollution	1	0.088	$RI_M \leq 300$
	2		$300 < RI_M \leq 1000$
	3		$1000 < RI_M \leq 2500$
	4		$2500 < RI_M \leq 5000$
	5		$RI_M > 5000$

Geological disasters Geological disasters destroy the structure of ecological land, affect the material and energy cycle within the system, and thus affect the ecological function of ecological land (Ambrosi et al. 2018; Ouyang et al. 2019). Regions with a high frequency of geological disasters have higher ecological risks and unstable ecosystems,

so ecological sensitivity is high. According to the "Geological Hazard Classification and Grading Standard (T/CAGHP 001-2018)" issued by the China Geological Hazard Prevention Engineering Industry Association in 2018, Altay Prefecture is divided into 4 levels: small, medium, large, and extralarge geological disasters. The ecological
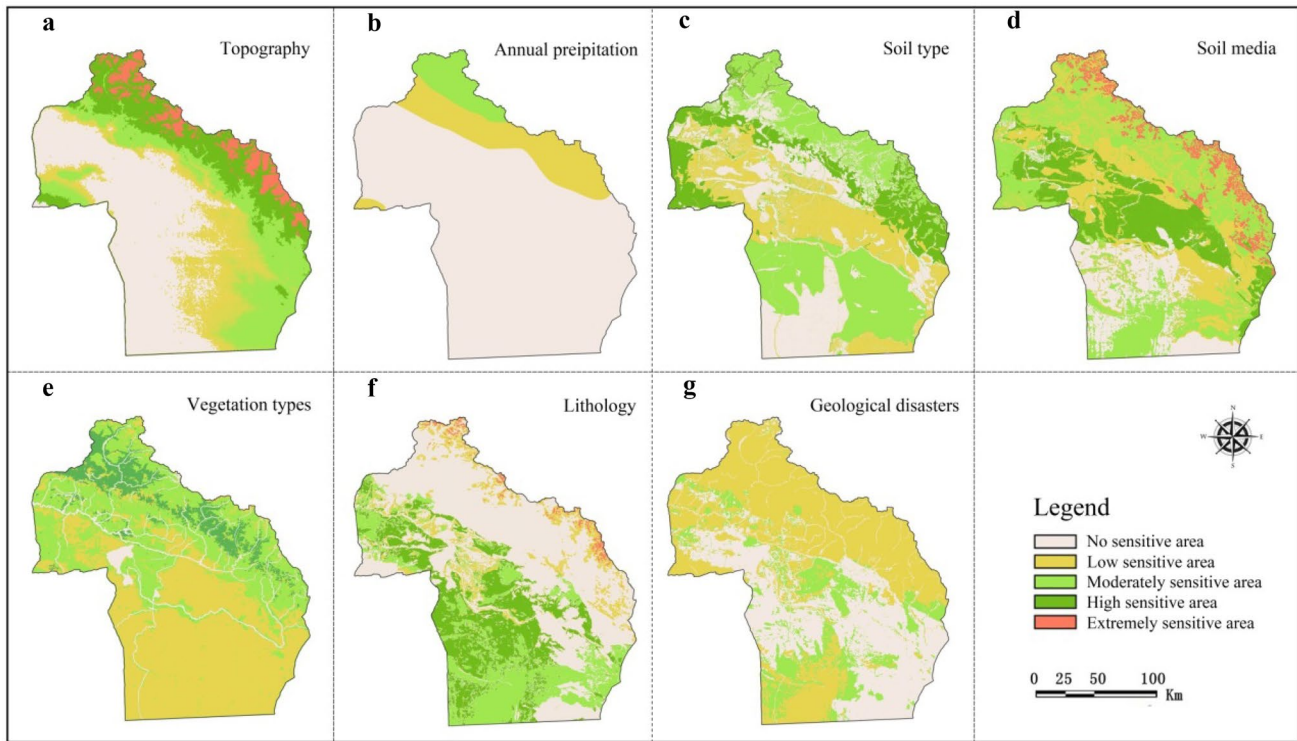
Fig. 2 Rating maps of ecological sensitivity evaluation system parameters

sensitivity map based on geological disaster factors is shown in Fig. 2g.

Heavy metal pollution The heavy metal elements in the soil are absorbed and enriched by vegetation. When the content of heavy metal elements exceeds the self-purification capacity of the plant itself, it will have an adverse effect on the growth and development of the plant. Therefore, the more serious the heavy metal pollution, the higher the ecological risk value and the greater the potential threat to the ecosystem, which will lead to a significant increase in the probability of ecosystem problems. Therefore, there is a significant positive correlation between ecological risk and ecological sensitivity. The higher the ecological risk, the higher the ecological sensitivity degree. According to the ecological risk level of heavy metals, from low to high corresponds

to different ecological sensitivity degrees. These data are applied to obtain the ecological sensitivity zoning map based on heavy metal pollution factors in Altay Prefecture.

3 Results

3.1 Spatial distribution and pollution degree of heavy metals in soil

The test value of soil heavy metal content and the recovery rate of heavy metals in Altay Prefecture are shown in Table 5. For ease of presentation, the administrative units of Altay Prefecture are represented by Roman numerals from northwest to southeast. The corresponding relations are listed as follows: Zone I (Habahe County), Zone II (Burqin

Table 5 Statistical analysis of the test value of the heavy metal content in soil (mg/kg)

Heavy metal	As	Cd	Cr	Cu	Hg	Pb	Zn
Maximum	26.00	0.24	182.00	79.20	0.286	91.50	270.00
Minimum	1.10	0.05	13.50	3.40	0.002	6.13	26.50
Average value	7.76	0.14	74.01	58.75	0.02	42.59	92.86
Median	6.53	0.15	39.50	27.10	0.02	20.80	76.00
Standard deviation	5.09	0.05	30.72	12.60	0.01	9.07	53.07
Coefficient of variation (%)	65.64	35.29	56.87	43.81	42.06	40.13	57.15
Recovery rate (%)	89.90	98.12	112.44	96.03	101.50	104.37	94.86

Table 6 Classification of soil heavy metal pollution degree in Altay Prefecture

| Heavy metal content (mg/kg)	Pollution degree of heavy metals
$< 0.7\ B_n$	Safe area
$0.7–1.0\ B_n$	The warning area
$1.0–1.5\ B_n$	Lightly polluted area
$1.5\ B_n$	Heavily polluted area

County), Zone III (Jeminay County), Zone IV (Altay City), Zone V (Fuhai County), Zone VI (Fuyun County), and Zone VII (Qinghe County).

The test results of soil heavy metals showed that extreme concentrations existed for all investigated heavy metals. With the exception of the average concentrations of As, which were lower than the soil background values, all other heavy metal contents (average values) were higher than the soil background values, approximately 1.08 to 1.35 times the soil background values. Although the mean values of each soil heavy metal fluctuated less than the background values, their extreme concentration values far exceeded the soil background values, with Zn, Cr, and Pb performing particularly well, being 3.92 times, 2.66 times, and 2.65 times higher, respectively, than the background values. The coefficient of variation (CV) reflected the change degree of heavy metal content at the sampling point. The CV values of As, Cd, Cr, Cu, Hg, Pb, and Zn were 65.64%, 35.29%, 56.87%, 43.81%, 42.06%, 40.13%, and 57.15%, respectively.

Using Sufer 12.0 software, the distribution maps of seven heavy metal elements in soil were drawn by the kriging spatial interpolation method. Referring to the analysis results

of Zheng and Chen (1995) on the content of heavy metals in domestic soil and the degree of soil harm, the author considers the soil load capacity, selects the background value of heavy metals in the soil as the critical point, and divides the degree of heavy metal pollution in Altay Prefecture. The specific classification and the spatial distribution of heavy metals in Altay Prefecture are shown in Table 6 and Fig. 3, respectively.

According to the spatial distribution map of heavy metals, the contamination of heavy metals Cu and Zn in the soil of Altay Prefecture is the most serious, and their contaminated areas are the most widely distributed and account for a relatively large proportion. Cu and Zn are followed by Pb, Cr, and As, which have smaller contaminated areas, but there are local high-value areas. The contents of Cd and Hg are the lowest, both of which are lower than the corresponding soil background values and are in the safe area. Among them, the peak value of the Cu content in soil was 79.20 mg/kg, and the mean value was 58.75 mg/kg, which was higher than the background value of Cu in soil (26.7 mg/kg). Its overall spatial distribution characteristics showed a gradually decreasing trend from west to east (Fig. 3a). With the exception of Zone VII, there is a certain range of light pollution areas in the soil of other zones. At the junction of Zone II and Zone III, the content of Cu is the most abundant, which is in the heavy pollution area. The light and heavy pollution areas of Cu accounted for 24.16% and 4.60%, respectively, of the total area. The overall spatial distribution of Zn in soil shows a gradually increasing trend from southwest to northeast (Fig. 3b). There were light pollution areas in northern part of Zone IV, western part of Zone VI, and southern part of Zone VII, which peaked in the southern part of Zone VII,

Fig. 3 Spatial distribution map of heavy metals in soil in Altay Prefecture (B_n is the soil background value of heavy metal)
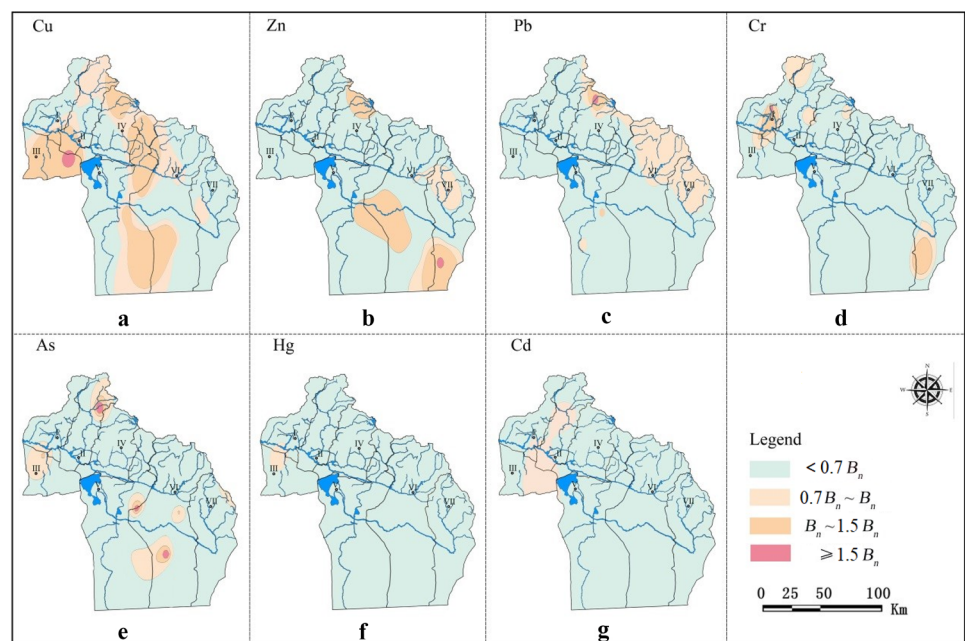
and its content reached 270 mg/kg, which was 3.92 times the soil background value. The light and heavy pollution areas of Zn accounted for 15.37% and 4.00%, respectively, of the total area.

The contents of Pb, Cr, and As are lower than the soil background value in more than 90% of the surface soils in Altay Prefecture, and the areas with contents higher than the soil background value are mostly distributed in a point pattern (Fig. 3c, d, and e). The pollution area of Pb exists in the northern part of Zone IV, the pollution area of Cr is mainly distributed in the middle of Zone I and southern part of Zone VII, and the pollution area of As is distributed in northeastern part of Zone II and southern Zone VI. The pollution areas of the above three heavy metals accounted for 3.43%, 7.62%, and 3.51% of the total area.

Compared with the content of other heavy metals, the content of Cd and Hg in the soil of Altay Prefecture is the smallest and basically lower than the soil background value (Fig. 3f, g). Notably, a large area of Cd in Zone II and Zone III is in the warning area.

The polluted areas of 7 kinds of soil heavy metals in Altay Prefecture were extracted and processed by spatial overlay (Fig. 4). The result showed that the area contaminated with soil heavy metals in Altay Prefecture accounted for 32.58% of the whole area. It is worth noting that in addition to the abnormal high values of individual heavy metal elements in some areas, there are also different degrees of heavy metal combined pollution in Altay Prefecture, such as areas A, B, a, b, c and d in Fig. 4. The compound pollution area of heavy metals accounts for 15.21% of the whole area of Altay Prefecture, among which the compound pollution area of b (Cu+Zn) accounts for the largest area of 7.58%.

3.2 Ecological risk assessment of heavy metals

In this study, the traditional ecological risk index method was improved based on the comprehensive consideration of factors such as the toxicity of heavy metals, land use types, and the value attributes of ecological function areas. According to the differences in ecological function area value and land use types in Altay Prefecture, it is divided into three ecological function areas and five land use types.

The main ecological function areas are the northern water conservation area, central ecological security maintenance area and southern ecological conservation area (Fig. 5a). The water conservation area is the source area of the river system in Altay Prefecture, which mainly has the functions of water conservation, biodiversity maintenance, and soil and water conservation. The distribution range mainly includes mountainous and hilly areas in the northern part of Altay Prefecture, accounting for 36.68% of the whole area. The ecosystem is dominated by grassland and forest. The ecological security maintenance area, which mainly has the role of ecological buffer regulation, is not only the
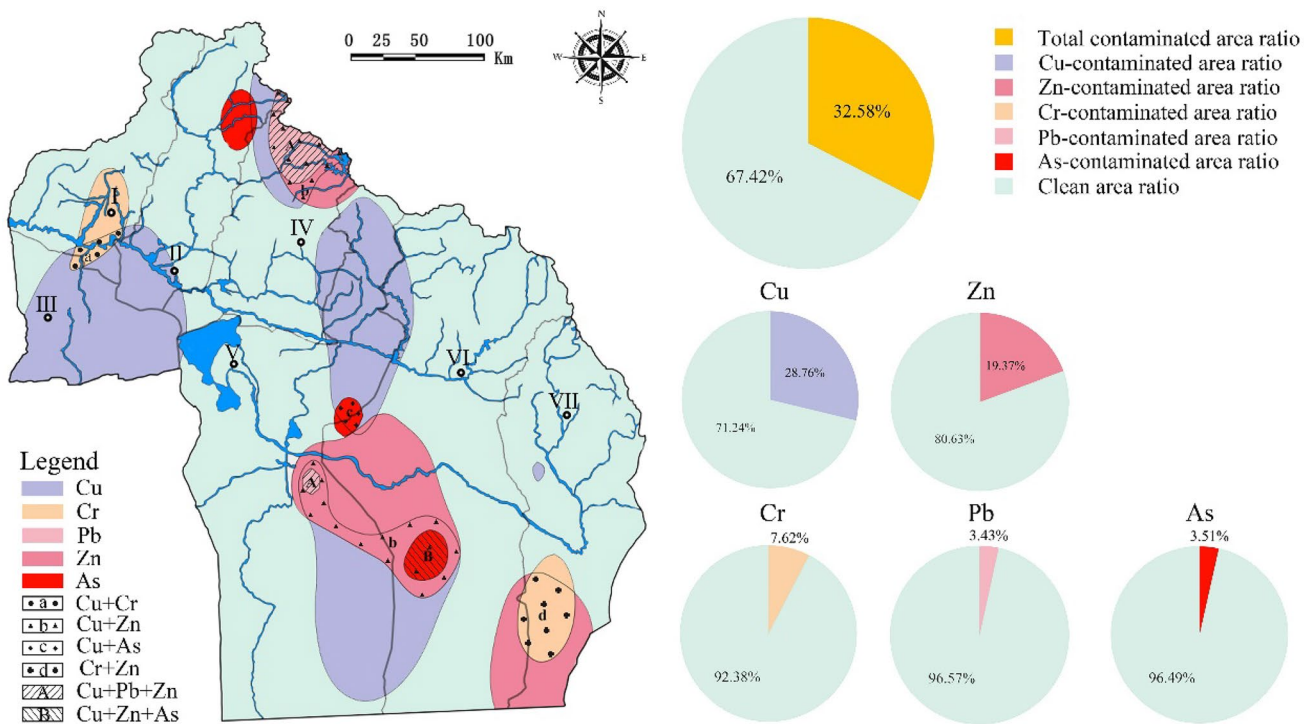

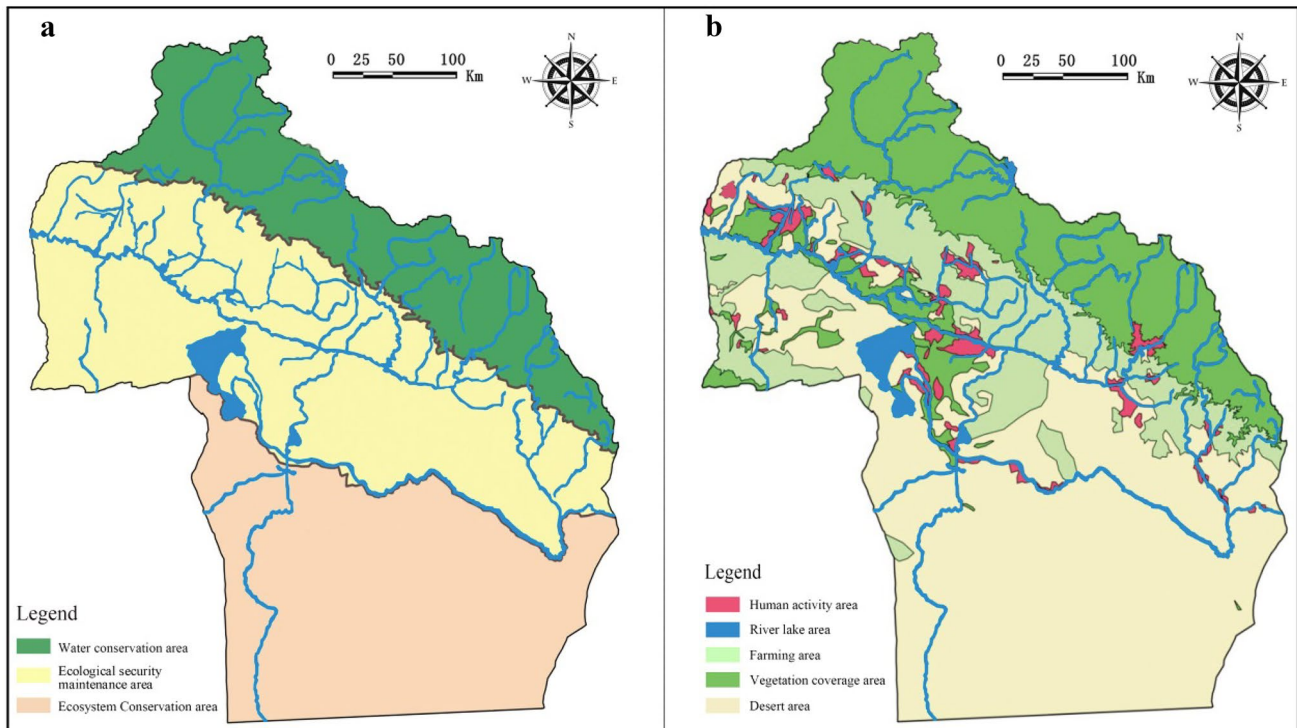**Fig. 4** Distribution map of contaminated areas and area proportion of seven heavy metals

Fig. 5 Ecological function zone and land use type map of Altay Prefecture

concentrated area of human activities but also the key area of the survival and reproduction of the Altay people. This main area for the supply of ecological products such as water, animal husbandry and agriculture is located in the central area of Altay Prefecture, accounting for 33.67% of the whole area. The area is dominated by mountains, hills, and piedmont alluvial plains, supplemented by desert and grassland ecosystems. Ecological conservation areas are the key areas for desertification control and biodiversity protection. The main range is the low mountain and hilly desert area in the southern part of Altay Prefecture, accounting for 29.65% of the whole area. The population density in the area is low, and the desert ecosystem is the dominant type. The ecological environment in this area is very fragile, but the mineral resources are well preserved. The land use types in the Altay Prefecture comprise mainly the following five categories: human activity areas, river and lake areas, farming areas, vegetation coverage areas, and desert sand areas (Fig. 5b).

Based on the improved ecological risk index method, the ecological risk value of heavy metal pollution in the soil is calculated (Eq. 3). The calculation results are classified, and the ecological risk map of heavy metals in Altay Prefecture is drawn (Fig. 6a). When the ecological risk value of heavy metal pollution is less than 300, the ecological sensitivity score is 1; when the value is between

300 and 1000, the ecological sensitivity score is 2, where we classify the above areas as low-risk areas. When the value falls between 1000 and 2500, the ecological sensitivity score is 3, the soil environment is in a moderate-risk area. When the value is between 2500 and 5000, the ecological sensitivity score is 4, the soil environment is in a high-risk area. And when the value is greater than 5000, the ecological sensitivity score is 5, the soil environment is in a very high-risk area.

As shown in Fig. 6a, the no risk area accounts for 12.33%, which is mainly distributed in the southwestern part of Altay Prefecture. The low-risk area has the largest range, accounting for 34.06%. This area is mainly located in the southern part of Altay Prefecture, with a low ecological function value. The land use type is mainly desert and sandy land, and its tolerance to heavy metal pollutants is relatively high. The moderate risk area accounts for 28.63%. This risk area has the highest ecological function value, and the land use type is mainly vegetation. The proportions of high-risk areas and very high-risk areas are 20.87% and 4.11%, respectively, which are mainly distributed in the central part of Altay Prefecture. These proportions are obviously affected by human activities, and the pollutants are strongly affected by the propagation effect of surrounding rivers.
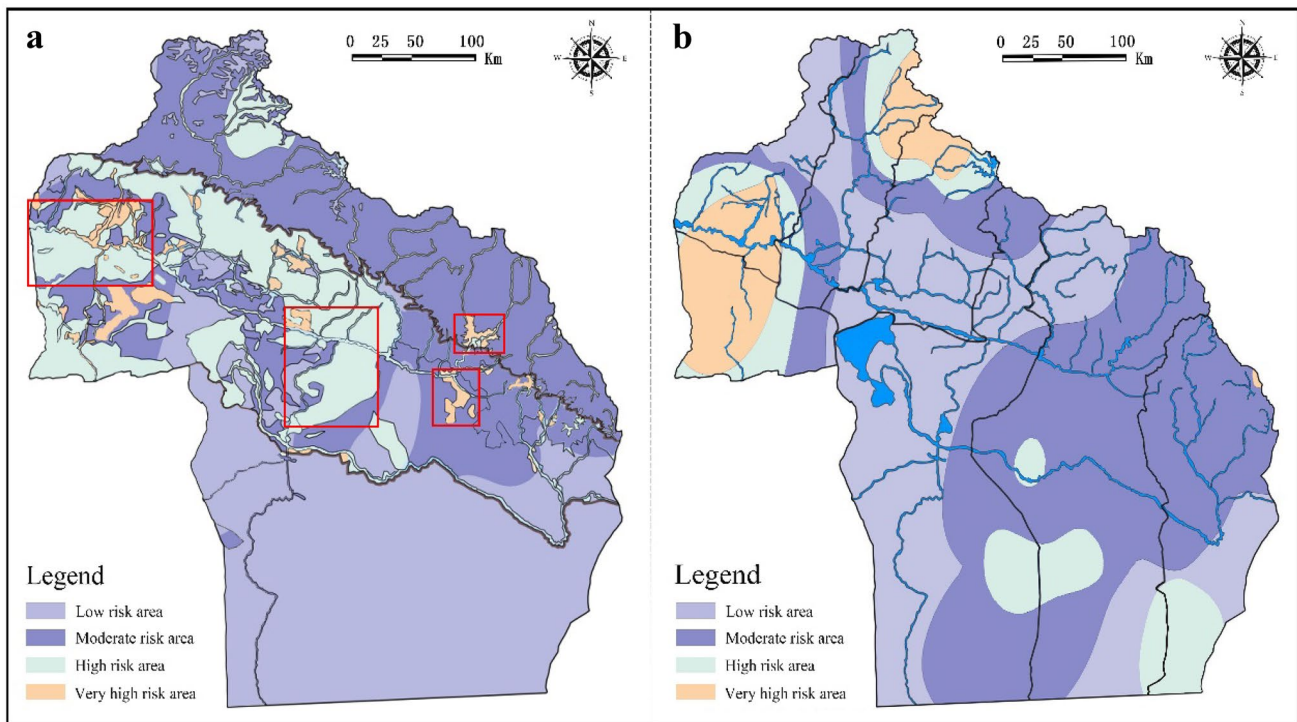
Fig. 6 Ecological risk map of heavy metals in Altay Prefecture (**a** ecological risk map under modified methods; **b** ecological risk map under traditional methods)

4 Discussion

4.1 Rationality analysis of the modified ecological risk index method

In order to explore the rationality and scientificity of the modified ecological risk index method, we use the traditional ecological risk index method to calculate the ecological risk value of Altay Prefecture (Eq. 2) and draw the ecological risk map (Fig. 6b).

Based on the results of traditional ecological risk index methods, the ecological risk level of Altay Prefecture is relatively high. Among them, the very high-risk area and high-risk area are mainly distributed in the west and north of the study area, and some are distributed in the southern desert area. To a certain extent, the distribution range of high-risk areas and very high-risk areas has a high degree of fit with the distribution of high pollution areas of heavy metals, and is mainly affected by heavy metals Cu and Zn. Comparing Figs. 5b and 6b, it can be seen that in areas where humans interact with the ecological environment frequently and intensively, and there are many risk driving factors, the results of traditional ecological risk index method are more conservative and the risk level is correspondingly lower. In some areas, the density of human activities is low and the disturbance to the natural ecological environment is less, but

the results of traditional ecological risk index method are relatively radical, such as the high ecological risk area in the desert area of southern Altay Prefecture. We speculate that the main reason for this phenomenon is that the traditional ecological risk index method only considers the single transfer of heavy metals to the ecosystem, but ignores the value of the ecosystem itself and its response mechanism to heavy metal toxicity. Previous studies can also support this speculation. In Xiang et al. (2022) study, it was shown that the establishment of surface plants can effectively absorb soil heavy metals, such as grassland and forest land, which have a negative correlation with the ecological risk of soil heavy metals. In short, human production and lifestyle are the main sources of soil heavy metals and the main driving factors for the risk of soil heavy metals acting on ecosystems. However, at the same time, differences in land use types will in turn affect the distribution of heavy metals, and thus strengthen or weaken regional ecological risks (Candeias et al. 2014; Hu et al. 2013).

Comparing Figs. 4 and 5b, the correlation between heavy metal distribution and land use types can be seen more intuitively: There are serious heavy metal pollution in the land use types of human activity areas, vegetation coverage areas, river and lake areas, and farming areas in Altay Prefecture. In the desert sand areas of Altay Prefecture, except for heavy metals Cu and Zn, the pollution level of other heavy metals

is generally low. Among them, the area contaminated with Cu has the widest distribution, basically including five types of land use. Human living and production activities are the main sources of Cu, and the dense river network in Altay Prefecture further expands the spatial distribution of Cu. The distribution range of Zn is the second largest, and the majority of polluted areas are in close proximity to the river network and are more influenced by the propagation of surface runoff. This finding further confirms those in the study of Gao et al. (2022) on the evaluation of river water quality in Altay Prefecture: the content of Cu and Zn in rivers is highly enriched.

The land use types of Cr-contaminated areas are human gathering areas and desert sand areas, and it is speculated that their local high-value areas are influenced by chromium factories and chromium waste residues. The main sources of As are mining development, industrial pollution, agricultural activities, and natural background. The land use types of the contaminated areas of As in Altay Prefecture are mainly vegetation coverage areas and desert sand areas, so it is speculated that the enrichment of As is mainly attributed to the high content of heavy metals in the geological background. There is an abnormally high value of Pb in the northern part of Zone IV of Altay Prefecture, which is a mountainous area with high vegetation cover that is far from the human activity area. With reference to the sampling and investigation results by Agbenin (2002) for the soil in the Nigerian savanna area, it is speculated that the Pb in this area is absorbed and accumulated by the surface layer of soil rich in organic matter and humus, which leads to abnormal accumulation of soil Pb content.

The above analysis shows that the land use type and the spatial distribution of heavy metals in Altay Prefecture have a high correlation. On the one hand, it verifies the previous research results, on the other hand, it also becomes the theoretical support point for the author to modify the traditional ecological risk index method.

According to the statistics of the distribution range of each ecological risk level in Fig. 6b, it can be seen that the area of very high-risk area in Altay Prefecture accounts for 12.83%, and the area of high-risk area accounts for 17.22%. The area of moderate risk area accounted for 34.50%, and the area of low-risk area accounted for 35.45%. Compared with the ecological risk assessment results of traditional methods, the modified method highlights the risk pressure caused by the scope of human activities on the ecological environment and weakens the risk pressure faced by the ecological environment in areas with low human disturbance frequency. The results of modified ecological risk index method showed that the area of very high-risk areas decreased by 8.72% year-on-year. The proportion of high-risk areas is 3.65% lower than that of traditional methods, and the distribution areas of high-risk and above risk levels

are concentrated in the human gathering areas in the two river basins. In addition, after considering the land use type, the modified ecological risk index method focuses on the patchy distribution of the evaluation results of the region, which improves the accuracy of the ecological risk index method and provides more accurate guidance for the formulation and implementation of subsequent ecological restoration programs.

4.2 Ecological sensitivity assessment

According to the calculation result of the comprehensive evaluation value of ecological sensitivity (ES) (Eq. 4), the ecological environment of Altay Prefecture is divided into 4 sensitive areas. The specific score interval and ecological sensitivity zoning results are shown in Table 7.

According to the ecological sensitivity zoning map (Fig. 7), the ecological environment of Altay Prefecture is mainly in a moderate-sensitivity area, and its area accounts for the largest proportion of 59.74%, which is more than half of the study area. The second largest area is the low-sensitivity area, which accounts for 18.79% of the whole area. The high-sensitivity area and extremely sensitive area accounted for 12.09% and 9.38%, respectively, and their total area exceeded 1/5 of the study area. A comparison of Figs. 6a and 7 shows that the high-risk and very high-risk areas of heavy metal pollution coincide with the high-sensitivity and extremely sensitive areas of ecologically sensitive zoning to some extent (red box area). The coincident areas are mainly distributed in the areas with frequent human activities in Altay Prefecture, so we speculate that heavy metal pollution due to unreasonable human activities is the main cause of ecological fragility in Altay Prefecture and that the surrounding developed river network system intensifies the diffusion and release of heavy metal pollution from point to surface.

Macroscopically, the higher the ecological risk, the higher the ecological sensitivity level, and there is a nonlinear positive correlation between the two. However, due to the differences in the internal storage mechanism and biotransformation rate of ecosystems, not all organisms show the same sensitivity to heavy metals and other pollutants, and different types of organisms (animals and plants) have different sensitivity to heavy metals (Bo et al. 2015). Similarly, the effect

Table 7 Classification of ecological sensitive in Altay Prefecture

ES value	Ecological sensitive zoning
<2	Low-sensitivity area
2–3	Moderate-sensitivity area
3–4	High-sensitivity area
≥4	Extremely sensitive area

Fig. 7 Ecological sensitivity zoning map of Altay Prefecture

Legend

- Low sensitive area
- Moderate sensitive area
- High sensitive area
- Extremely sensitive area
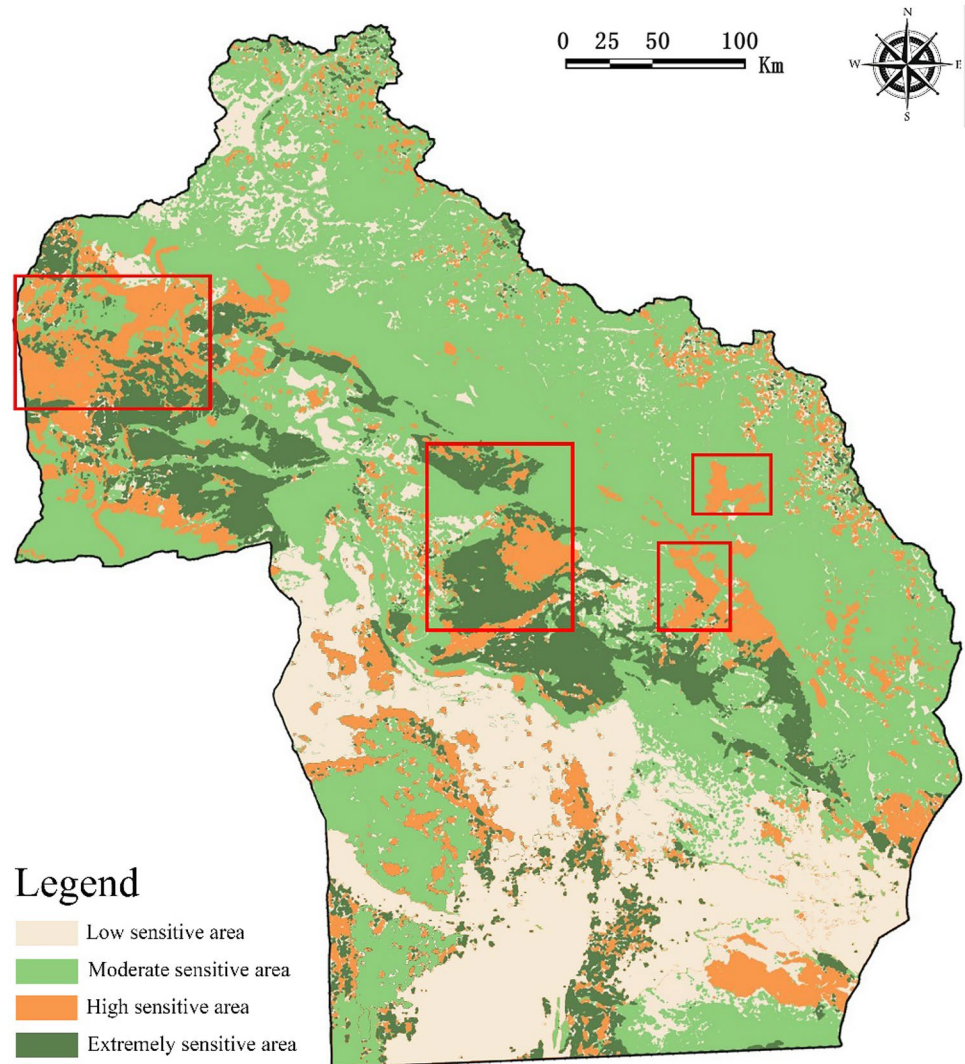
of compound pollution of heavy metals on the ecology is different from the pollution of single heavy metal elements because the occurrence forms of various heavy metals in the soil environment are subject to the mutual restriction of the physical and chemical effects of heavy metals (Shute and Macfie 2006; Rosen and Chen 2018). Therefore, exploring the mechanism of action between heavy metal elements and the interaction mechanism between heavy metals and organisms will be one of the issues that we need to focus on in the future research on evaluating the ecological risk and ecological sensitivity of heavy metals.

5 Conclusions

Among the soil heavy metals in the Altay Prefecture of Xinjiang, Cu and Zn were the most serious contaminants, both far exceeding the soil background values, and the proportion of contaminated areas was also the largest, 28.76% and 19.37%,

respectively. Pb, Cr, and As exist in local high-value areas, and the percentage of contaminated areas was 3.43%, 7.62%, and 3.51%, respectively. In addition, the areas contaminated with heavy metals are mostly distributed in human gathering areas and areas with dense river systems. Transmission routes such as surface runoff and rivers increase the possibility of pollution diffusion, and preventive measures should be taken.

The modified ecological risk index method was employed to evaluate the ecological risk of heavy metals in Altay Prefecture. The results showed that the low-risk area had the largest extent and was mainly distributed in the desert sand area. The total of high-risk and very high-risk areas accounted for 24.98%, which was approximately 1/4 of the whole region, basically covering all human activity areas. Different land use types directly affect the content of soil heavy metals, which in turn affects the fluctuation of ecological risk values. The proportion of ecological sensitivity areas in Altay Prefecture from high to low was medium-sensitivity area (59.74%), > low-sensitivity area

(18.79%), > high-sensitivity area (12.09%), > extremely sensitive area (9.38%).

In this study, the occurrence forms and physical and chemical effects of heavy metals were not considered in the ecological risk assessment of heavy metals and the comprehensive evaluation of regional ecological sensitivity. The compound pollution risk and impact on the ecological sensitivity of heavy metals were different from those of single heavy metals. Therefore, the conclusions of this study can only serve as a preliminary proposal for the prevention and control of heavy metal pollution and ecological protection in Altay Prefecture, and further investigation is needed to better guide the relevant government agencies.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

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