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Characterization of heavy metal content distribution and evaluation of soil pollution in Maqin County, Qinghai Province, China

**Qingyu Liu · Yao Niu · Hao Zhang · Haixu Zhang ·
Jie Luo · Siyao Feng · Haoran Zhang**

Abstract The Qinghai-Tibet Plateau stands as the loftiest geographical area on our planet, frequently denoted as the "Crown of the Globe." To acquire an exhaustive comprehension of the heavy metal contamination situation in the topsoil of Maqin County, Qinghai Province, a total of 1616 surface soil specimens were gathered across a 6300 km^2 area. An examination was carried out on 12 metallic elements to investigate the impact of diverse geological contexts, soil categorizations, and land utilization practices on the levels of heavy metals. Additionally, the fundamental factors contributing to these trends were probed. The findings unveiled that the mean levels of the 12 metallic elements in the topsoil of Maqin County surpassed or equaled the baseline values of soil heavy metal concentrations within the research region. The coefficients of variation (CV) values for Hg, Sb, Ni, and Pb exceeded 30%, with Hg showing strong variation. The overall pollution level in the study area was classified as mild, posing a moderate ecological risk. In this study, we performed a multi-factor analysis of the significant differences in heavy metal concentrations among different geological backgrounds, soil types, and land-use types. The results showed that geological background had extremely significant impacts on elements such as Ba, Be, Cd, Cr, Cu, Hg, Ni, Sb, Tl, and Zn ($p < 0.01$). Soil type had an extremely significant influence on Be, Cd, Cu, and Zn ($p < 0.01$), as well as a significant influence on Ba ($p < 0.05$). Land-use type had an extremely significant impact on Ba ($p < 0.01$) and a significant impact on Cd ($p < 0.05$). Building upon the amalgamation of the outcomes from the Pearson correlation analysis, it was inferred that the main source of heavy metals in Maqin County, Qinghai Province, was the geological background.

Haoran Zhang and Siyao Feng contributed equally to this work and should be considered co-corresponding authors.

Q. Liu · Y. Niu · H. Zhang · H. Zhang
Fifth Institute of Geological and Exploration of Qinghai Province, Xining 810000, China

J. Luo · S. Feng (✉) · H. Zhang (✉)
College of Resources and Environment, Yangtze University, Wuhan, China
e-mail: sy15572183610@163.com

H. Zhang
e-mail: 1455426856@qq.com

Introduction

Soil is an essential component of various systems on Earth and serves as a crucial support system for

sustaining human life, exhibiting a close connection with human productivity and habitation (Mielke and Reagan, 1998). This acts as a conduit for the movement and alteration of heavy metals into different systems, serving as the central location for the accumulation of heavy metals (Yang et al., 2018). In recent years, there has been a growing severity of soil heavy metal pollution, attributed to factors such as atmospheric deposition (Li et al., 2021; Liu et al., 2023), metal mining (Liu et al., 2019; Zhong et al., 2020) and smelting (Luo et al., 2023; Zang et al., 2020), transportation (Meng et al., 2018; Zhang et al., 2015), pesticide (He et al., 2020; Shen et al., 2005) and fertilizer use (Cheraghi et al., 2013; Soleimani et al., 2023), agricultural irrigation (Huang et al., 2021; Wang et al., 2022a), and coal combustion (Chen et al., 2019; Galiulin and Galiulina, 2013). Because of their resistance to decomposition by soil microorganisms and propensity for accumulation, heavy metals not only degrade the soil environment and affect crop growth but can also be transferred to the human body via the food chain, thereby impacting human health (Bi et al., 2018; Nkwunonwo et al., 2020). When the accumulation of heavy metals surpasses the soil's natural self-cleaning ability, it presents a significant threat to both the ecological ecosystem and human well-being (Stan et al., 2011).

The Qinghai-Tibet Plateau stands as the world's loftiest geographic region, significantly influencing the regional climate, water resources, ecological surroundings, and human endeavors in the adjacent areas. Its unique geographical location gives rise to a distinct high-altitude and arid climate that is highly susceptible to climate change and environmentally vulnerable (Pan et al., 2020; Qiu, 2008). Influenced by this unique geographical environment, industrial and agricultural activities on the Qinghai-Tibet Plateau are relatively underdeveloped, resulting in relatively minor anthropogenic impacts (Yan et al., 2013). The plateau formation process is complex, with diverse geological and geomorphological features such as mountain ranges, basins, plateaus, and deep canyons. The unique geological background, geographical environment, and weathering processes of the plateau may have resulted in the formation of high-background soils. However, with industrialization and urbanization, the ongoing utilization of natural resources, and the accelerated development of secondary and tertiary industries, pollution on the Qinghai-Tibet Plateau has intensified, and heavy metal contamination has already occurred to a certain degree (Jiujiang et al., 2012; Wu et al., 2016). Research has indicated that the primary origins of heavy metal contamination on the Qinghai-Tibet Plateau are linked to transportation, pesticide and fertilizer application, atmospheric deposition, and large-scale religious and ritual activities conducted in certain areas (Huang et al., 2019; Yin et al., 2019; Zhang et al., 2012). Currently, soil contamination within Qinghai Province has reached a relatively critical level (Wu et al., 2016). For example, Luo et al. (2015) analyzed the Pb content in 307 plant samples from four regions of the Tibetan Plateau. The average Pb content in the aboveground parts of plants was 3.60 mg/kg. Mao et al. (2015) analyzed heavy metals (Mn, Cu, and Zn) in harvested vetch seeds and the maximum Zn concentration exceeded 48 mg/kg as the main contaminant. Therefore, it is necessary to examine the distribution patterns and ecological perils posed by heavy metals in this area (Gongbuzeren et al., 2018).

In recent years, scientists have undertaken a range of examinations pertaining to heavy metals in Qinghai Province, with a particular focus on assessing their accumulation traits, source apportionment, and risk assessment. Shen et al. (2014) evaluated the condition of heavy metal contamination in eastern Qinghai and concluded that it was generally not severe. Wang et al. (2021) employed the pollution load index, Nemerow Comprehensive Pollution Index, and potential ecological risk index to evaluate the enrichment of heavy metals and the associated ecological hazards in the vicinity of Qinghai Lake. As per their investigation, it was evident that heavy metal contamination had transpired in the area, presenting potential ecological threats. However, many researchers have a tendency to analyze heavy metals from the overall perspective of the study area, often overlooking the impacts of different geological backgrounds, soil types, and land-use types, leading to incomplete evaluation results.

Maqin County in Qinghai Province has a rich diversity of geological backgrounds, soil types, and land-use types, making it representative of heavy metal research in Qinghai Province. Within this research, a total of 1616 topsoil specimens were obtained from a 6300 km^2 expanse situated in Maqin County, Qinghai Province. Following that, these

samples were subjected to analysis for 12 heavy metals, specifically As, Ba, Be, Cd, Cr, Cu, Hg, Ni, Pb, Sb, Tl, and Zn. The distribution traits were thoroughly examined, and the assessment of pollution levels and potential ecological hazards was conducted using the single-factor pollution index, Nemerow comprehensive pollution index, and potential ecological risk evaluation techniques. Additionally, considerable disparities in heavy metal concentrations were examined across various geological contexts, soil classifications, and land utilization practices within the research locale. Building upon this analysis, the impacts of differing geological backgrounds, soil types, and land-use patterns on heavy metals were explored, with a subsequent analysis of their underlying factors. The primary objective of this research was to offer a more in-depth examination of the distribution traits, pollution conditions, and prospective ecological threats stemming from heavy metals within the study domain. The results derived from this study offer a scientific underpinning for the management and mitigation of soil contamination in Qinghai Province. Additionally, they endeavor to expedite the adoption of effective approaches for the avoidance or targeted eradication of heavy metals, with the overarching goal of promoting sustainable practices in soil utilization.

Materials and methods

Study region

The study area is located in the eastern part of Maqin County, Golog Tibetan Autonomous Prefecture, Qinghai Province (99° 38′ 29″–100° 00′ 41″ E, 34° 10′ 18″–34° 55′ 57″ N) (Fig. 1). It is situated at the junction of the Zeku composite basin and the Muzitag-West Datang-Buqingshan ophiolite melange belt. The exposed strata consist of the Triassic Longwuhe and Gulangdi Formations, the Cretaceous Wanxiu Formation, and the Neogene Linxia Formation. The study area falls within the Indo-Sinian epoch mercury, arsenic, copper, lead, zinc, and gold (antimony,
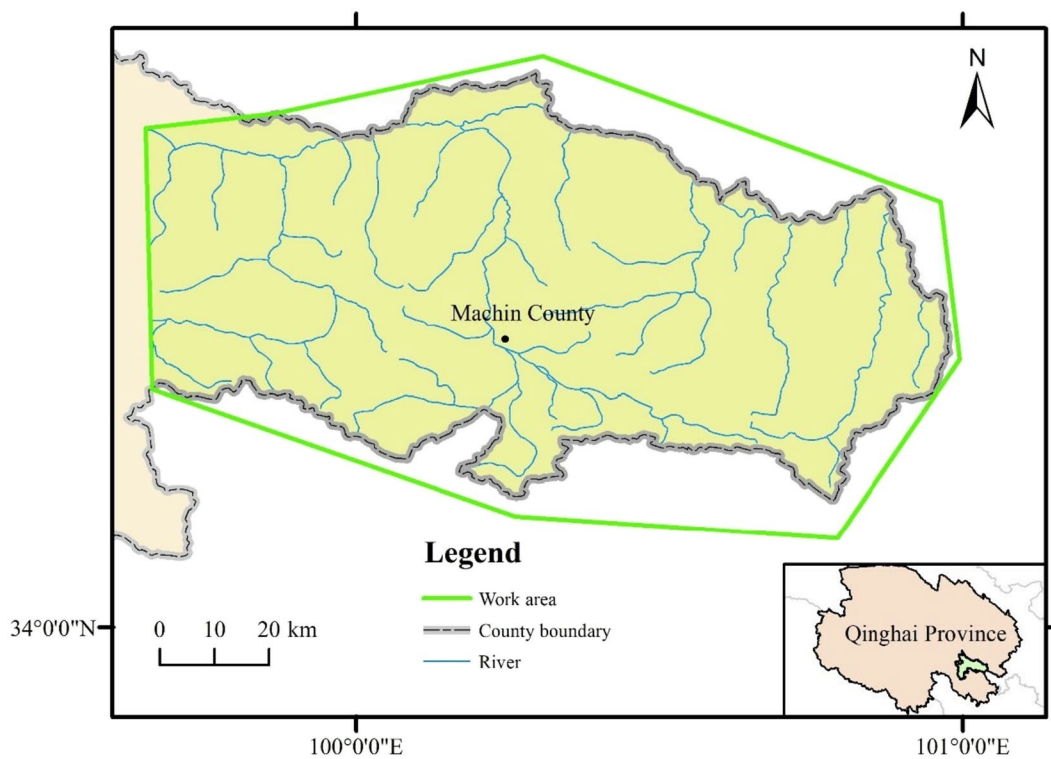

Fig. 1 Location of the study area

tungsten, bismuth, tin) metallogenic belt and the Hua-lixi epoch copper and cobalt (gold, antimony) metallogenic belt. The terrain in the study area is generally undulating, with a diverse and changing topography and an elevation range of 2900–6251 m. The climate in this region is continental and chilly, featuring an average annual rainfall of 508.1 mm, primarily concentrated during the period from June to September. The total annual sunshine duration ranges from 2313 to 2607 h, with a relative sunshine duration of 45–63%. The average annual temperature ranges from −3.8 to 3.5 °C, with significant daily temperature fluctuations. Except for the area surrounding Lajia Town along the Yellow River, which has a frost-free period of 80–95 days, the rest of the study area does not have an absolute frost-free period.

The geological background includes the Paleoproterozoic Jinshuikou Formation, Permian ultramafic rocks, Middle Carboniferous-Middle Permian Shuweimen Formation, Middle Permian Maerzheng Formation, Lower-Middle Triassic Xiadawu Formation, Lower-Middle Triassic Longwuhe Formation, Middle Triassic Gulangdi Formation, Lower Cretaceous Wanxiu Formation, Upper Neogene Linxia Formation, Upper Pleistocene, and Holocene alluvium (Fig. 2). The soil compositions prevalent in the research region primarily encompass alpine cold desert soil, alpine meadow soil, alpine meadow grassland soil, leached brown soil, and mountain meadow grassland soil (Fig. 3). The land-use types consisted of glaciers and snow cover, shrubland, bare land, grassland, other woodland, forested areas, artificial grassland, and natural grassland (Fig. 4).

Sample collection and testing

In 2022, field sampling was conducted in Maqin County, Qinghai Province, using a combination of 1:100,000 topographic maps and the land-use map from the third land survey (Fig. 5). The layout of the sampling points was carefully considered, taking into account factors such as geological background,
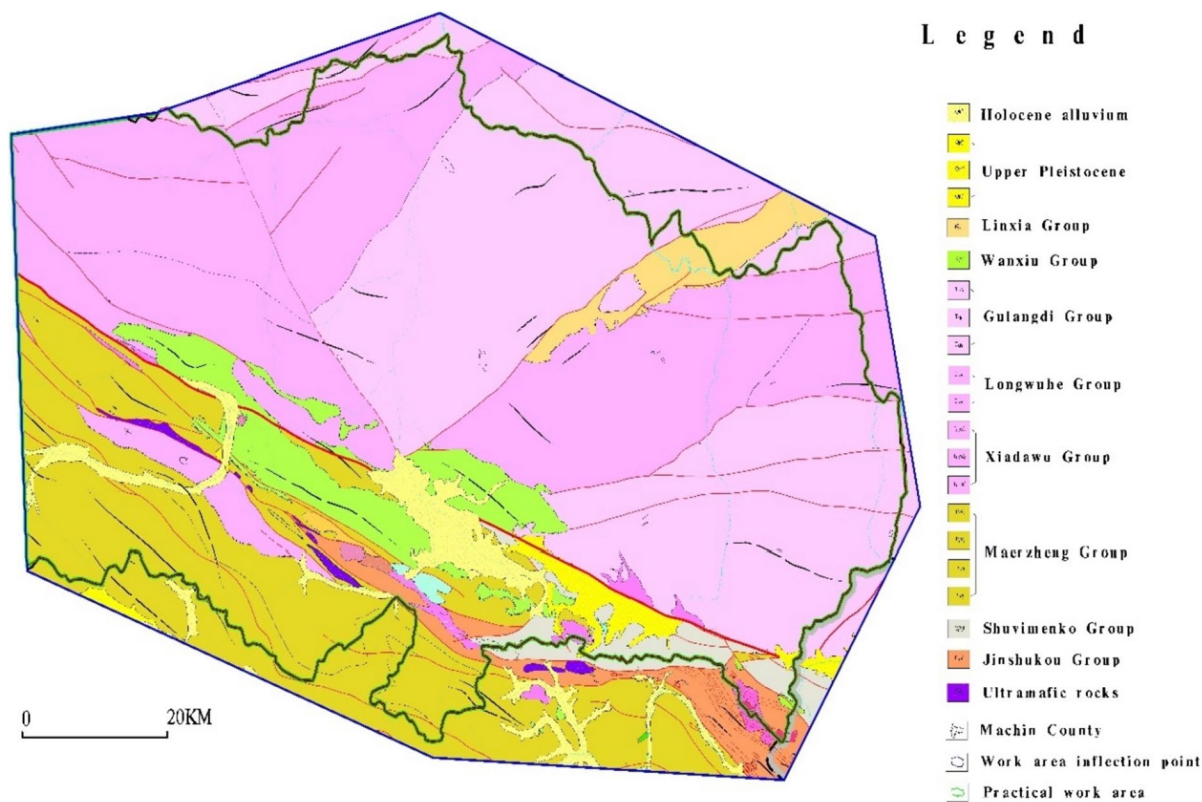

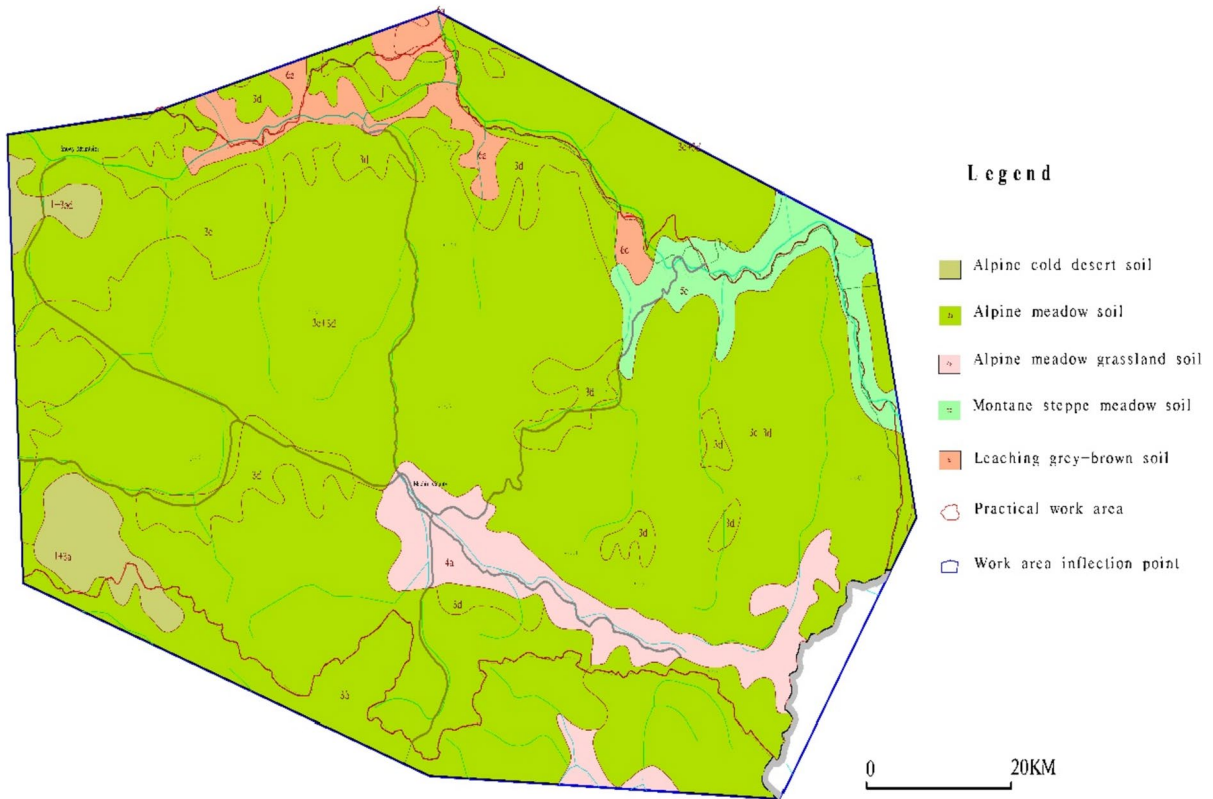**Fig. 2** Geological background map of the study area

Fig. 3 Soil type map of the study area

soil type, and land-use type in order to ensure both uniformity and representativeness (the location of specific sampling points can be found in Supplementary file). During the sampling process, obvious point-source pollution and recently accumulated soil areas were avoided, and sampling points were located at least 100 m from major highways. Sampling was conducted using a combination of main and auxiliary points, with an overall point density of 1 point per 4 km^2 for the main points and 1.5 points per 4 km^2 when auxiliary points were included. The double-diagonal method was employed, with five sampling points collected around each main point. A grand total of 1616 surface soil specimens were procured from a depth ranging between 0 and 20 cm. During sample collection, animal and plant residues, as well as gravel, were removed from all samples. Field-collected samples were subjected to pollution prevention measures, followed by air drying in cloth bags. They were then thoroughly sieved using nylon screens, and the fraction that passed through the screen was collected in

plastic bottles and paper bags. The amount of residue on the sieve during sample processing did not exceed 5 g when checked and received. Samples with a mass of ≥200 g were sent to the laboratory for testing and analysis.

Data were statistically analyzed and calculated using Microsoft Excel 2019. SPSS 26.0 was utilized to conduct a multi-factor significance analysis of heavy metal content with respect to geological background, soil type, and land-use type. To contrast the heavy metal concentrations across various geological backgrounds, soil categories, and land-use types within the research locale, a single-factor analysis of variance (ANOVA) was applied. Pearson correlation analysis and plotting of heavy metals were conducted using Origin 2021 software.

The entity responsible for analyzing samples was the Chengdu Comprehensive Rock and Mineral Testing Center of the Sichuan Geological and Mineral Exploration and Development Bureau. The analysis and testing were conducted in strict accordance with
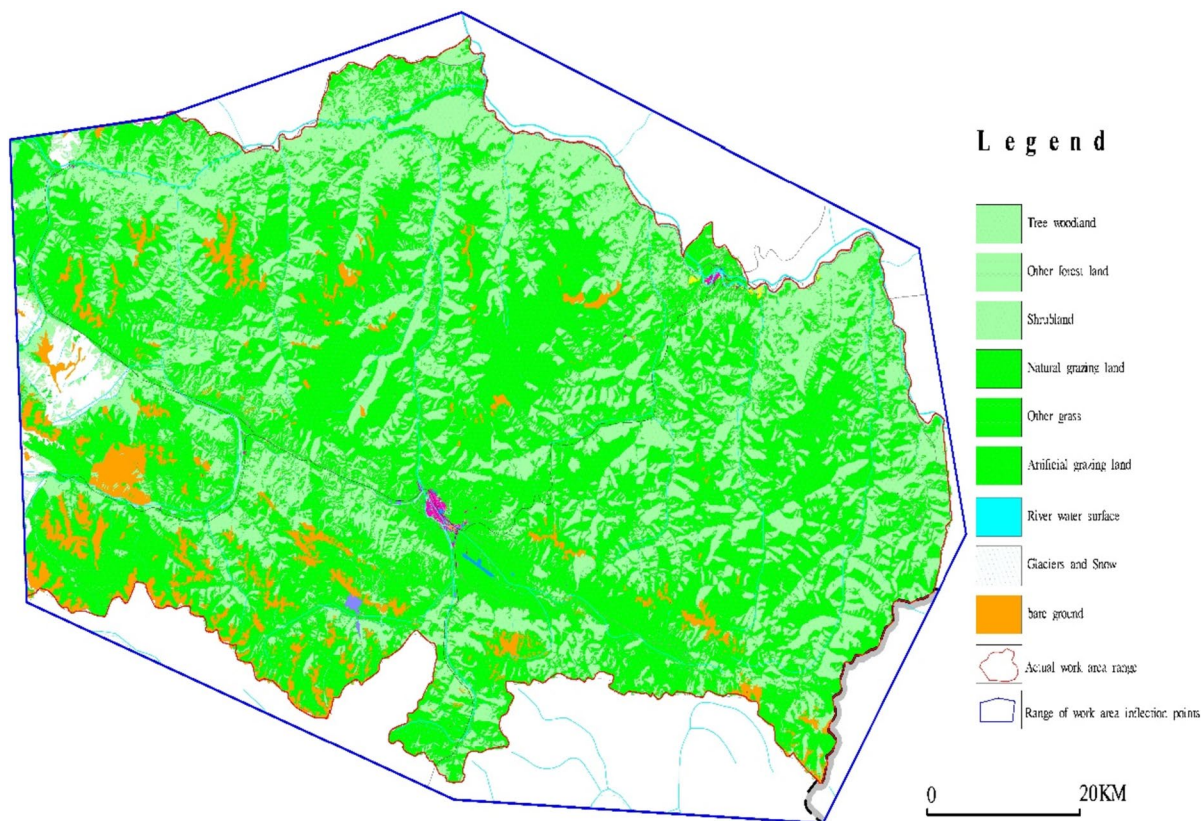
Fig. 4 Land-use type map of the study area

the "Multi-Target Regional Geochemical Survey Specification (1:250,000)" (DZT 0258-2014) issued by the China Geological Survey. This project determined and analyzed As, Ba, Be, Cd, Cr, Cu, Hg, Ni, Pb, Sb, Tl, and Zn. These elemental analyses involved the use of X-ray fluorescence spectroscopy (XRF) and inductively coupled plasma mass spectrometry (ICP-MS) as primary analytical methods, complemented by atomic fluorescence spectroscopy (AFS), emission spectroscopy (ES), ion-selective electrode (ISE) method, and volumetric method (VOL) as secondary analysis methods. The accuracy was evaluated by inserting 12 pieces of standard substances (GSS1a–GSS8a and GSS1a–GSS4a) into every 500 samples. The precision was assessed by analyzing four pieces of China's first-class standard substances (GSS1a, GSS2a, GSS3a, and GSS4a) inserted into the reserved blank positions in every 50 test samples. The method detection limits (MDLs) for As, Ba, Be, Cd, Cr, Cu, Hg, Ni, Pb, Sb, Tl, and Zn were 0.5, 10,

0.3, 0.03, 2.5, 1, 0.0005, 2, 2, 0.05, 0.03, and 4 mg/kg, respectively.

Data processing

Evaluation of heavy metal pollution

As the studied elements included Ba, Be, Sb, and Tl, which are rare metal elements, they were not included in the national soil environmental quality standards. Therefore, the regional background values (Table 2) of the study area were uniformly used to assess the pollution caused by the 12 heavy metals in the soil. The regional background values were calculated as the arithmetic mean of the elemental contents in the samples of the second environment, that is, surface soil samples, after the removal of outliers with ± 3S (standard deviation) and recalculation. These reflected the characteristics of the actual values of the
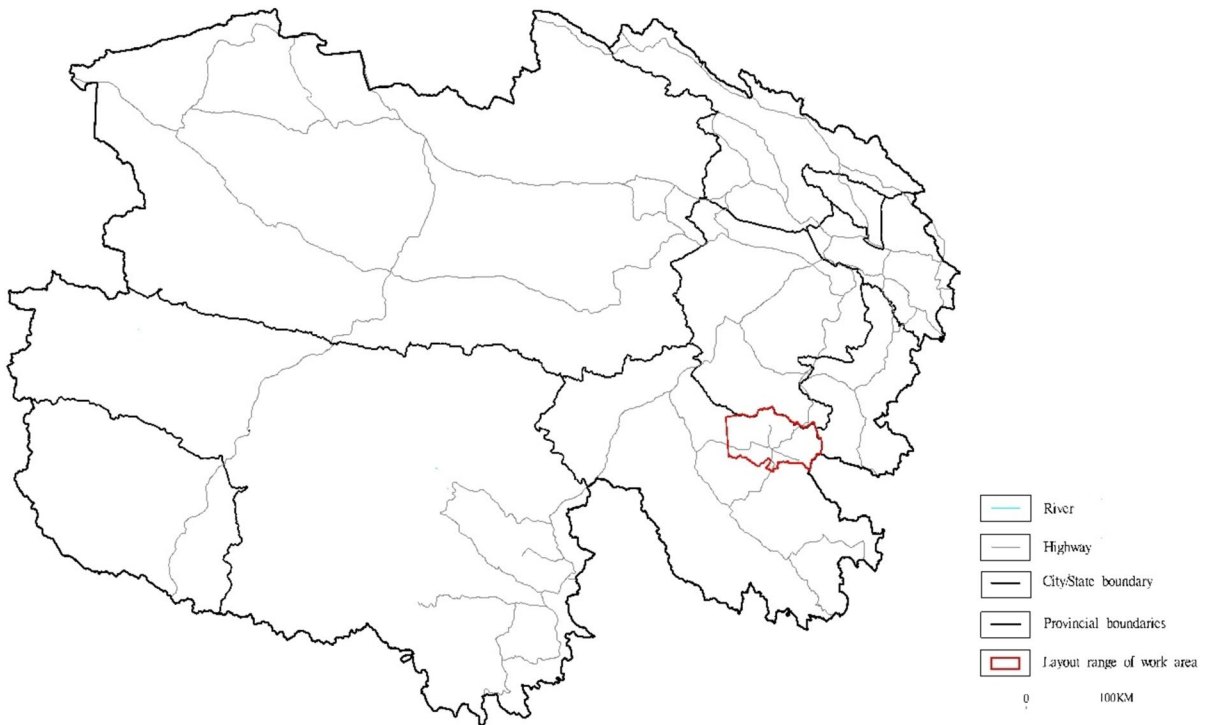
Fig. 5 Sample sampling location

elements and served as references for measuring environmental quality changes.

Single-factor pollution index method: The single-factor index method stands as the most frequently employed approach for assessing soil heavy metal concentrations. The formula used for calculating the environmental quality index in the single-factor pollution index method is as follows:

$$P_i = C_i/S_i \tag{1}$$

where P_i represents the environmental quality index of soil pollutant i, C_i denotes the measured value of soil pollutant i (mg/kg), and S_i indicates the evaluation standard of soil pollutant i (mg/kg).

Comprehensive pollution index assessment method: The Nemerow comprehensive pollution index method stands as one of the most universally employed approaches for calculating comprehensive pollution indices, holding acclaim both at the national and international levels. The Nemerow index gauges the effects of contaminants on soil

quality and underscores the sway of the pollution index of the most crucial pollutants on the environmental quality of the soil. The evaluation formula is as follows:

$$P_{com} = \left[\left(C_i/S_i \right)^2_{max} + \left(C_i/S_i \right)^2_{ave} \right]^{1/2}/2 \tag{2}$$

where P_{com} represents the comprehensive pollution index, $(C_i / S_i)_{max}$ is the maximum pollution index of the soil elements, and $(C_i / S_i)_{ave}$ denotes the arithmetic average of the pollution index for each pollutant.

When $P_{com}(P_i) \leq 0.7$, it indicates a clean condition, and the pollution level is considered safe; when $0.7 < P_{com}(P_i) \leq 1$, it represents a clean condition, and the pollution level is on the alert line; when $1 < P_{com}(P_i) \leq 2$, it indicates mild pollution, and the pollution level is considered light pollution; when $2 < P_{com}(P_i) \leq 3$, it represents moderate pollution, and the pollution level is considered moderate pollution; and when $P_{com}(P_i) > 3$, it indicates severe pollution, and the pollution level is considered heavy.

Evaluation of potential ecological risks

The potential risk assessment method integrates pollutant concentrations with their ecological, environmental, and toxicological impacts to gauge the potential risk associated with heavy metal contamination in the soil. The potential ecological hazard index (PEHI) methodology, introduced by Swedish scientist Hakanson, is one such approach used for this purpose (Lars, 1980), reflects the comprehensive potential ecological impact of heavy metals on a specific environment, and quantitatively assesses the degree of potential ecological risk. The potential risk assessment method combines pollutant concentrations with their ecological, environmental, and toxicological effects to evaluate the potential risk of heavy metal pollution in the soil. The PEHI methodology, pioneered, serves as one of the techniques employed for this purpose.

The formula for calculating the PEHI proposed by Hakanson (Lars, 1980) is as follows:

$$R_I = \sum_{i=1}^{n} E_r^i \qquad (3)$$

$$E_r^i = T_r^i C_f^i = C_i / C_n^i \qquad (4)$$

where R_I represents the PEHI for multiple heavy metals; E_r^i denotes the potential ecological hazard coefficient for a specific heavy metal; T_r^i indicates the toxicity response coefficient for an individual pollutant, reflecting the degree of harm of heavy metals to humans and ecological systems; C_f^i is the pollution parameter for a specific heavy metal; C_i represents the measured heavy metal content in the soil; C_n^i denotes the reference value required for calculation; and n is the number of heavy metal species.

Hakanson (Lars, 1980) showed that different metals have different toxicity response coefficients. In general, the toxicity response coefficients for As, Ba, Be, Cd, Cr, Cu, Hg, Ni, Pb, Sb, Tl, and Zn are 10, 2, 30, 30, 2, 5, 40, 5, 5, 7, 10, and 1, respectively (Kang et al., 2017; Lars, 1980; Li et al., 2008). The regional background values of the study area were used as reference values for calculations. The potential ecological risk index (R_I) comprehensively reflects the pollution levels and potential ecological hazards of the 12 intermediate elements As, Ba, Be, Cd, Cr, Cu, Hg, Ni, Pb, Sb, Tl, and Zn in the soil (Table 1).

Table 1 Assessment index of potential ecological harm

E_r^i	Multi-factor potential ecological hazard index R_I	The degree of potential ecological harm
0~40	0~150	Mild
40~80	150~300	Moderate
80~160	300~600	Stronger
160~320	>600	Very strong
>320		Very strong

Results and discussion

Statistical examination to describe heavy metal characteristics in the soils

Table 2 exhibits the outcomes of the statistical assessment of the examination outcomes from topsoil specimens collected within the research region. The concentration ranges of As, Ba, Be, Cd, Cr, Cu, Hg, Ni, Pb, Sb, Tl, and Zn in the surface soil of the study area were 4.77–73.3, 311–795, 1.35–3.52, 0.063–0.448, 43.1–471, 14.6–132, 0.013–0.298, 17.4–371, 14–319, 0.544–9.96, 0.446–1.08, and 47.2–278 mg/kg, respectively. The mean values of the 12 heavy metals in the topsoil were equivalent to or higher than the baseline values of those metals in the study area's soil, suggesting a noticeable tendency for the accumulation of these 12 heavy metals in the surface soil. The CV values of the different elements in the soil followed the order of Hg > As > Sb > Ni > Pb > Cd > Cr > Cu > Zn > Be > Tl > Ba. Based on the CV values (Table 2), most elements were homogenized by pedogenic processes in the surface environment, exhibiting a uniform or relatively uniform distribution (CV < 30%). However, the CV values of Hg, Sb, Ni, and Pb all exceeded 30%, with Hg showing the highest CV of 50.46%, indicating strong variation and a non-uniform or extremely non-uniform distribution. This indicates the local enrichment of ore deposits or accumulation of pollutants in geological phenomena. Therefore, these elements can be considered key monitoring indicators for mineral exploration and pollution prevention and control.

Correlation analysis between elements in the soils

The presence of multiple polluting elements in the same soil sample results in a certain degree of

Table 2 Descriptive statistics of soil heavy metal content

| Element	The content of heavy metals (mg kg^{-1})					Mutation coefficient
	Max	Min	Ave	Standard deviation	Background value	
As	73.3	4.77	17.31	3.93	16.9	22.71%
Ba	795	311	491.79	36.26	491	7.37%
Be	3.52	1.35	2.22	0.21	2.21	9.40%
Cd	0.448	0.063	0.17	0.04	0.17	23.20%
Cr	471	43.1	87.47	18.15	85.6	20.75%
Cu	132	14.6	25.45	4.56	25.1	17.93%
Hg	0.298	0.013	0.04	0.02	0.03	50.46%
Ni	371	17.4	32.61	12.19	31.4	37.37%
Pb	319	14	22.97	7.92	22.7	34.49%
Sb	9.96	0.544	1.14	0.50	1.06	43.38%
Tl	1.08	0.446	0.65	0.05	0.65	8.15%
Zn	278	47.2	73.39	10.67	72.9	14.53%

correlation between their concentrations. Significant correlations between elements may indicate common or similar sources, whereas non-correlation may result from different sources. A correlation analysis was conducted on the content of each soil element, and the results showed that there were correlations among all 12 elements (Fig. 6). The substantial correlations noticed among several elements (Logan et al., 1986) imply their strong uniformity, pointing to the fact that most heavy metals are affected by natural factors and chiefly stem from parent materials during the soil formation process.

Evaluation of elemental pollution indices in the study area

Table 3 exhibits the assessment findings of the single-factor pollution index and comprehensive pollution index concerning heavy metal concentrations at 1616 sampling locations within the Maqin County

Fig. 6 Correlation coefficient of heavy metals in soil
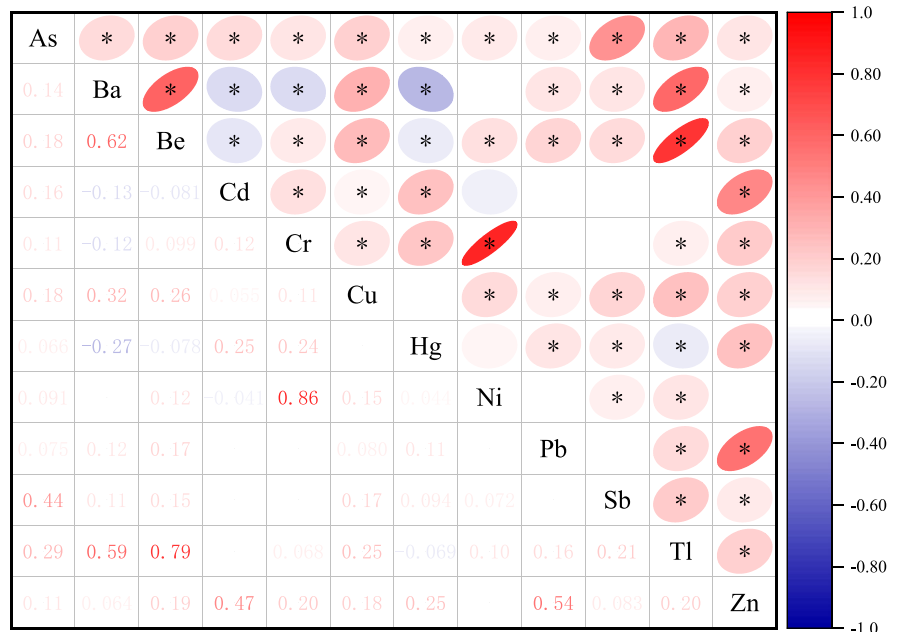
* p<=0.05

research zone. The average single-factor pollution index values for As, Ba, Be, Cd, Cr, Cu, Hg, Ni, Pb, Sb, Tl, and Zn in the soil were 1.02, 1.00, 1.00, 1.02, 1.02, 1.01, 1.09, 1.04, 1.01, 1.08, 1.00, and 1.01, respectively. The pollution level was generally classified as "slightly contaminated," indicating that the majority of areas in the study region had only slight exceedances of heavy metals. However, at specific sampling points, As, Cr, Cu, Hg, Ni, Pb, and Sb exceeded the moderate or severe pollution thresholds, suggesting localized enrichment of these elements. The average comprehensive pollution index value for the soil in the study area was 0.88, indicating that the environmental quality of the soil in most areas was classified at the "slight pollution" level. Among the gathered soil samples, 92% of the sampling points had a comprehensive pollution index, indicating a "slight pollution" level.

Assessment of the potential ecological hazard associated with soil heavy metals

The potential ecological risk of the study area in Maqin County, Qinghai Province, was assessed using the PEHI method developed by Hakanson (Lars, 1980). From Table 4, the following can be observed: E_r^i values for As in the soil ranged from 2.82 to 43.37, with an average of 10.24; E_r^i values for Ba ranged from 1.27 to 3.24, with an average of 2.00; E_r^i values for Be ranged from 18.33 to 47.78, with an average of 30.08; E_r^i values for Cd ranged from 11.12 to 79.06, with an average of 30.45; E_r^i values for Cr ranged from 1.01 to 11.00, with an average of 2.04; E_r^i values for Cu ranged from 2.91 to 26.29, with an average of 5.07; E_r^i values for Hg ranged from 15.76 to 361.21, with an average of 43.52; E_r^i values for Ni ranged from 2.77 to 59.08, with an average of 5.19; E_r^i values for Pb ranged from 3.08 to 70.26, with an average of 5.06; E_r^i values for Sb ranged from 3.59 to 65.77, with an average of 7.54; E_r^i values for Tl ranged from 6.86 to 16.62, with an average of 9.99; and E_r^i values for Zn ranged from 0.65 to 3.81, with an average of 1.01. According to the evaluation criteria in Table 1, the ecological risk levels of As, Ba, Be, Cd, Cr, Cu, Ni, Pb, Sb, Tl, and Zn elements were classified as "slight," and for Hg, it was classified as "moderate" ecological risk. The order of potential ecological risk levels for the 12 elements was as follows: Hg > Cd

Table 3 Single-factor index and comprehensive pollution index of heavy metals in soil

Project	P_i (single pollution index)												P_{com}
	As	Ba	Be	Cd	Cr	Cu	Hg	Ni	Pb	Sb	Tl	Zn	
Ave	1.02	1.00	1.00	1.02	1.02	1.01	1.09	1.04	1.01	1.08	1.00	1.01	0.88
Max	4.34	1.62	1.59	2.64	5.50	5.26	9.03	11.82	14.05	9.40	1.66	3.81	7.14
Min	0.28	0.63	0.61	0.37	0.50	0.58	0.39	0.55	0.62	0.51	0.69	0.65	0.57

Table 4 Evaluation results of potential ecological risk index

Element	Potential ecological hazard coefficient E_r^i			Potential ecological hazard index R_I
	Max	Min	Ave	
As	43.37	2.82	10.24	152.20
Ba	3.24	1.27	2.00	
Be	47.78	18.33	30.08	
Cd	79.06	11.12	30.45	
Cr	11.00	1.01	2.04	
Cu	26.29	2.91	5.07	
Hg	361.21	15.76	43.52	
Ni	59.08	2.77	5.19	
Pb	70.26	3.08	5.06	
Sb	65.77	3.59	7.54	
Tl	16.62	6.86	9.99	
Zn	3.81	0.65	1.01	

> Be > As > Tl > Sb > Ni > Cu > Pb > Cr > Ba > Zn. The overall potential ecological risk index (R_I) was calculated as 152.20, indicating a moderate ecological risk in the study area that warrants a certain degree of attention.

Factors affecting soil heavy metal characteristics and their potential ecological risks

The concentration of soil heavy metals in the research area is primarily shaped by both natural processes and human activities. This is particularly notable due to the existence of elements with substantial CV values (Hg, Sb, Ni, and Pb), further analysis of the relationship between different geological backgrounds, soil types, land-use types, and heavy metal contents can provide a deeper understanding of the sources of heavy metals. A multiple-factor significance analysis was conducted on the heavy metal content in relation to different geological backgrounds, soil types, and land-use types. The results showed that the significance values (p) for the geological background of As, Ba, Be, Cd, Cr, Cu, Ni, Pb, Sb, Tl, and Zn were 0.173, 0.000, 0.000, 0.000, 0.000, 0.000, 0.003, 0.000, 0.781, 0.006, 0.000, and 0.000, respectively. The geological background had an extremely significant effect on Ba, Be, Cd, Cr, Cu, Hg, Ni, Sb, Tl, and Zn ($p < 0.01$). The significance values (p) for the soil type of As, Ba, Be, Cd, Cr, Cu, Ni, Pb, Sb, Tl, and Zn were 0.771, 0.043, 0.000, 0.003, 0.057, 0.001, 0.151, 0.735, 0.970, 0.804, 0.076, and 0.006, respectively. Soil type had an extremely significant impact on Be, Cd, Cu, and Zn ($p < 0.01$) and a significant impact on Ba ($p < 0.05$). The significance values (p) for the land-use type of As, Ba, Be, Cd, Cr, Cu, Ni, Pb, Sb, Tl, and Zn were 0.930, 0.001, 0.146, 0.048, 0.182, 0.128, 0.534, 0.782, 0.940, 0.846, 0.053, and 0.160, respectively. Land-use type had an extremely significant impact on Ba ($p < 0.01$) and a significant impact on Cd ($p < 0.05$).

Influence of the geological context

Figure 7 displays the concentrations of Ba, Be, Cd, Cr, Cu, Hg, Ni, Sb, Tl, and Zn in the topsoil of the research region across 11 distinct geological settings. Ba, Be, and Sb had the highest concentrations in the Upper Neogene Linxia Formation, a lake delta composed of conglomerates, sandstones, and mudstones, indicating a lake sedimentary environment. Ba can readily precipitate with S in lake sedimentary environments, which results in higher Be and Sb concentrations. This finding is consistent with that of Laing et al. (2008), who discovered that S and heavy metals tend to precipitate in surface sediments in flooded environments. Cd, Hg, and Tl had the highest concentrations in the Middle Permian to Middle Triassic Shuweimen Formation, which consists of grayish-white laminated biogenic limestone and interbedded quartz sandstone. This geological background leads to higher levels of Cd, Hg, and Tl, which are incompatible elements in this context (Zengqian et al., 2003). Cr, Cu, Ni, and Zn had the highest concentrations in the Permian ultrabasic rocks. Cr and Ni are compatible elements and tend to have higher contents in ultrabasic rocks, whereas Cu content is closely related to large-scale marine sedimentary strata in the area. Overall, Zn showed a moderate to high background, which was influenced by mineralization. As none of the above-mentioned elements exceeded the regional risk screening values, it was inferred that their main source was the geological background (Wan et al., 2022).

The soil comprehensive pollution indices for the Permian ultrabasic rocks, Holocene alluvium, Precambrian Jinshuikou Formation, Middle Triassic Gulangdi Formation, Upper Pleistocene, Upper Pleistocene Linxia Formation, Middle Permian to Middle Triassic Shuweimen Formation, Lower-Middle Triassic Longwuhe Formation, Middle Permian Maerzheng Formation, Lower Cretaceous Wanxiu Formation, and Lower-Middle Triassic Xiadawu Formation were 1.17, 0.84, 1.05, 0.84, 0.80, 0.90, 0.86, 0.94, 1.31, 0.85, and 1.06, respectively, indicating an alert line or mild pollution level in most areas. The Shuweimen Formation had the highest comprehensive pollution index owing to its extensive fault development and intense magmatic activity, which resulted in the accumulation of various heavy metals in its stratified water system and severe soil heavy metal contamination. The Gulangdi Formation had the lowest comprehensive pollution index because of its lithological combination of gray, light gray, gray-green, and dark gray mud-calcareous shale interbedded with gray thin-layered fine-grained feldspathic sandstone with low heavy metal content.

Fig. 7 Contents of Ba, Be, CD, CR, Cu, Hg, Ni, Sb, Tl, and Zn in topsoil under different geological backgrounds. Note: "PU" represents Permian ultrabasic rocks, "HD" represents Holocene alluvium, "PG" represents Paleoproterozoic Jinshuikou group, "TG" represents middle Triassic Gulangdi formation, "UP" represents upper Pleistocene, "PL" represents upper Pleistocene Linxia formation, "TL" represents the lower-middle Triassic Longwuhe formation, "PM" represents the middle Permian Maerzheng formation, "PS" represents the middle carboniferous-middle Permian Shuweimen formation, "CW" represents the Lower Cretaceous Wanxiu District formation, and "LD" represents the lower-middle Triassic Xiadawu Formation.
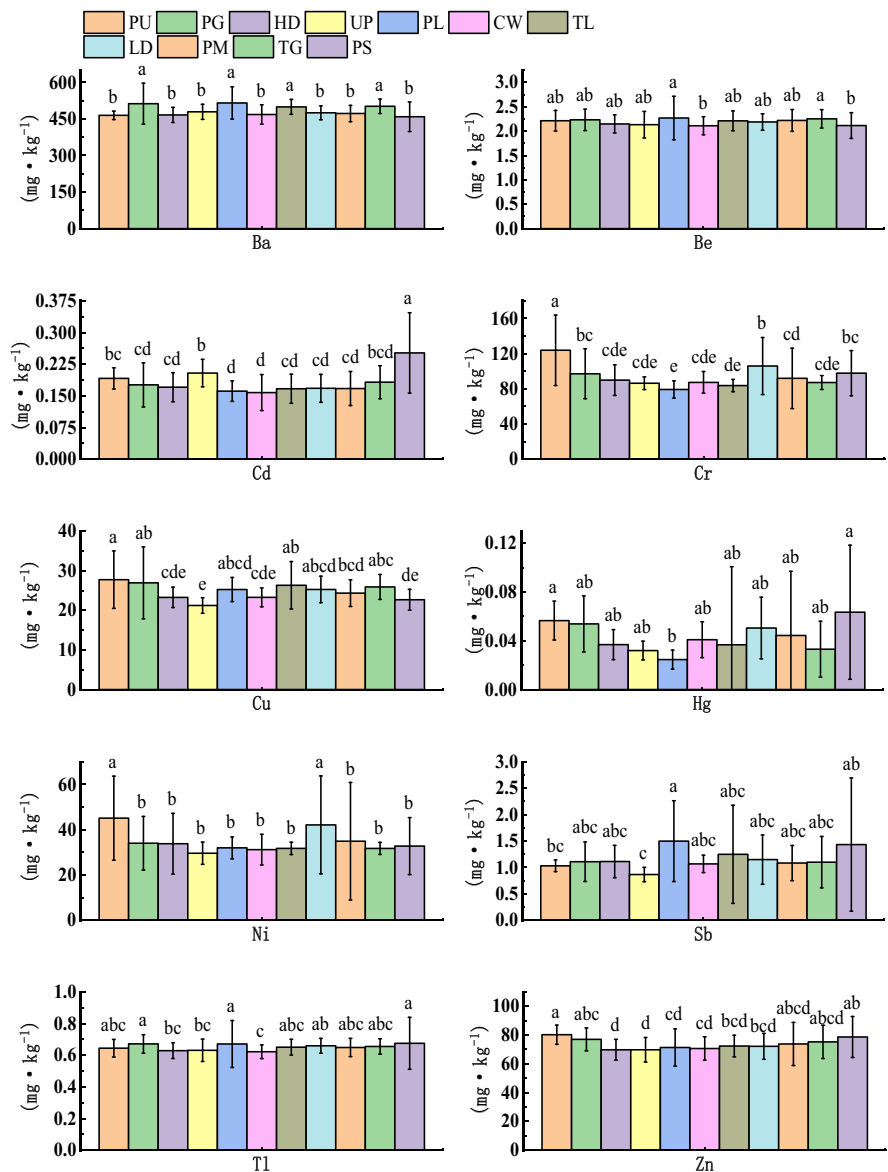

Table 5 depicts the evaluation results of the potential ecological risk assessments of the 12 elements under different geological backgrounds. The single-factor potential ecological hazard coefficients (E_r^i) for Cd in Middle Permian to Middle Triassic Shuweimen Formation and Hg in Permian ultrabasic rocks, Holocene alluvium, Precambrian Jinshuikou Formation, Middle Permian to Middle Triassic Shuweimen Formation, Lower-Middle Triassic Longwuhe Formation, Middle Permian Maerzheng Formation, Lower Cretaceous Wanxiu Formation, and Lower-Middle Triassic Xiadawu Formation ranged from 40 to 80, indicating a moderate ecological hazard. The E_r^i values for Ba, Be, Cr, Cu, Ni, Sb, and Zn in the 11 geological backgrounds were all less than 40, indicating a mild ecological hazard. The E_r^i values for the 12 elements in the Permian ultrabasic rocks, Holocene alluvium, Precambrian Jinshuikou Formation, Middle Triassic Gulangdi Formation, Middle Permian Maerzheng Formation, Lower Cretaceous Wanxiu Formation, Middle Permian to Middle Triassic Shuweimen Formation, and Lower-Middle Triassic Xiadawu Formation were all greater than 150, indicating a moderate ecological hazard for the potential ecological risk

Table 5 Evaluation results of potential ecological risk index of soil heavy metals under different geological backgrounds

Type	Potential ecological hazard coefficient E_r^i												Potential ecological hazard index R_I
	As	Ba	Be	Cd	Cr	Cu	Hg	Ni	Pb	Sb	Tl	Zn	
PU	9.33	1.89	30.06	33.76	2.89	5.53	68.57	7.18	4.88	6.80	9.91	1.10	181.92
HD	9.84	1.90	29.17	30.08	2.10	4.64	44.65	5.38	4.95	7.34	9.67	0.96	150.68
PG	10.81	2.09	30.31	31.05	2.27	5.37	65.29	5.42	5.07	7.32	10.33	1.06	176.38
TG	10.56	2.05	30.58	32.14	2.03	5.15	39.10	5.05	5.09	7.25	10.08	1.03	150.13
UP	10.02	1.95	28.96	35.99	2.02	4.23	38.79	4.72	4.80	5.71	9.71	0.96	147.85
PL	8.78	2.10	30.81	28.43	1.85	5.03	29.77	5.09	4.65	9.89	10.32	0.98	137.73
TL	10.21	2.04	30.02	29.34	1.95	5.24	40.82	5.05	5.04	7.97	10.01	0.99	148.68
PM	10.16	1.93	30.13	29.46	2.15	4.84	48.85	5.56	5.23	7.11	9.98	1.01	156.41
PS	10.63	1.86	28.37	42.50	2.29	4.50	76.92	5.24	4.79	9.29	9.73	1.04	197.16
CW	9.27	1.91	28.65	27.82	2.04	4.64	49.58	4.97	4.79	7.05	9.57	0.97	151.26
LD	10.45	1.94	29.71	29.59	2.47	5.04	61.21	6.71	4.85	7.58	10.15	0.99	170.70

in soil. The Shuweimen Formation had the highest PEHI, indicating that heavy metal pollution was more likely to occur in this geological background and that strict regulation of heavy metal levels was required.

Effect of soil type

The study area has complex topography and geomorphology, and various factors such as altitude variations, temperature changes, precipitation differences, parent material differences, and solar radiation changes have led to the formation of numerous soil types. Soil type influences the accumulation of heavy metals (Wang et al., 2022b), thereby affecting the elemental contents in the soil. The Ba, Be, Cd, Cu, and Zn contents in the topsoil of the six soil types in the study area are shown in Fig. 8. Ba and Cu had the highest concentrations in the leached brown soil. The parent materials of the leached brown soil primarily consist of loess and loess-like materials, as well as various rock weathering slope deposits and residual materials, with acidic rock bodies such as volcanic debris and granite being the main cause of the elevated Ba and Cu contents (Bin et al., 2000; Hildreth and Moorbath, 1988). The gray-brown soil in this region is mainly utilized for forestry and timber production and serves as winter and spring pastures. Therefore, the Ba and Cu contents were also influenced by human activities to some extent. Cd had the highest content in the alpine meadow soil, and its

high-value area coincided with the Yalugou Pb-Zn ore deposit, suggesting that Cd could be enriched in the form of elements associated with Pb and Zn mineralization. Be had the highest content in the mountain meadow grassland soil, which could also be related to mineralization processes. Zn had the highest content in the ordinary alpine meadow soil, which was widely distributed in the study area, accounting for more than 70% of the area. The eastern part of Maqin County generally exhibited a high-background Zn in the soil, and the study area was almost entirely covered by a high Zn background, indicating a high likelihood of soil enrichment with Zn.

The comprehensive pollution indices for the alpine meadow grassland, ordinary alpine meadow, alpine shrub meadow, alpine desert, leached brown, and mountain meadow grassland soils were 0.99, 0.87, 0.89, 0.84, 0.86, and 0.85, respectively, all reaching an alert line pollution level. The alpine meadow grassland soil had the highest comprehensive pollution index. This was because of its coarse and thin texture, its low fertility, the extreme high-altitude conditions, the intense climate variations, the frequent natural disasters, the instability of pastoral production, and the relatively severe environmental damage. Alpine desert soil had the lowest comprehensive pollution index, primarily because its distribution area experienced harsh climatic conditions, a low degree of soil weathering development, insufficient nutrients, extremely sparse vegetation, and low

Fig. 8 Contents of Ba, Be, Cd, Cu, and Zn in topsoil under different soil types. Note: in the table, "MG" stands for alpine meadow soil; "AM" stands for ordinary alpine meadow soil; "SM" stands for alpine shrub meadow soil; "CD" stands for alpine cold desert soil; "LS" stands for leached lime cinnamon soil; and "MS" stands for alpine meadow soil.
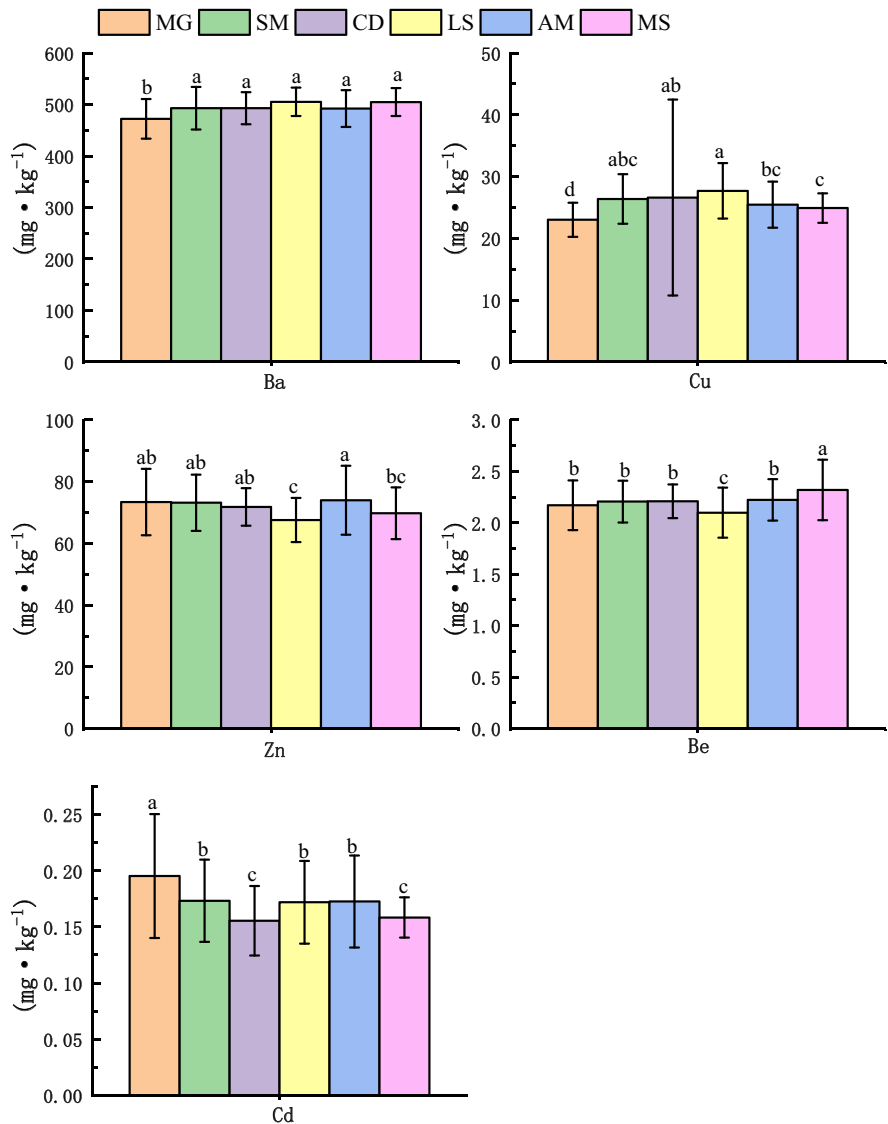
agricultural and pastoral value, resulting in relatively mild environmental pollution.

Table 6 displays the potential ecological risk assessments for the 12 elements in different soil types. Be, Cd, Cu, and Zn had single-factor potential ecological hazard coefficients (E_r^i) of < 40, indicating a mild ecological hazard. Alpine meadow grassland, ordinary alpine meadow, and alpine shrub meadow soils had multi-factor potential ecological hazard indices (R_I) greater than 150, indicating moderate ecological hazards. The alpine meadow grassland soil had the highest R_I. Therefore, it is essential to avoid overgrazing and maintain the regional ecological environment.

Impact of land-use type

The ecosystem structure of the Qinghai-Tibet Plateau is simple, and its resistance to disturbances is low, making it susceptible to impact from anthropogenic activities (Li et al., 2009). To a certain extent, land use reflects human activities, and changes in land use can lead to substantial alterations in the physical and chemical properties of soil (Fu et al., 1999; Fu et al., 2000). The concentrations of Ba and Cd in the topsoil of the nine land-use types in the study area are shown in Fig. 9. The Ba content was the highest in the coniferous forest, which included both natural and artificial

Table 6 Evaluation results of potential ecological risk index of heavy metals in different soil types

Type	Potential ecological hazard coefficient E_r^i												Potential ecological hazard index R_I
	As	Ba	Be	Cd	Cr	Cu	Hg	Ni	Pb	Sb	Tl	Zn	
MG	10.24	1.92	29.43	34.08	2.13	4.58	55.69	5.20	4.92	7.53	9.84	1.00	166.57
AM	10.16	2.00	30.16	30.39	2.06	5.06	43.52	5.21	5.09	7.41	9.99	1.01	152.08
SM	10.56	2.01	29.93	30.37	2.02	5.25	44.38	5.10	4.98	7.74	9.95	1.00	153.28
CD	10.64	2.01	29.99	27.44	1.97	5.30	38.03	5.00	5.07	7.63	10.26	0.98	144.31
LS	11.85	2.06	28.48	30.35	1.83	5.52	32.54	5.07	5.04	9.05	9.88	0.93	142.59
MS	9.32	2.06	31.47	27.95	1.88	4.96	31.54	5.27	4.84	8.79	10.34	0.96	139.40

forests. Improper or excessive use of fertilizers during afforestation can lead to excessive Ba content in the soil. The Cd content was highest in artificial grassland, as it was cultivated using agricultural techniques (Zhang et al., 2022). The use of Cd-containing fertilizers and irrigation water with high Cd levels can lead to Cd accumulation (Chien et al., 2003). Cd can be easily absorbed by crops, causing excessive Cd levels in agricultural products. Consequently, it is imperative to address the issue of Cd pollution in order to mitigate its adverse effects.

The comprehensive pollution indices for natural grassland, shrubland, coniferous forest, artificial grassland, bare land, river water surface, glaciers and snow cover, grassland, and other forests were 0.88, 0.89, 0.89, 0.80, 0.90, 0.82, 0.76, 0.99, and 0.76, respectively, indicating an alert line pollution level. Grassland had the highest comprehensive pollution index, mainly because of its relatively dense population (Mariyanto et al., 2019) and developed

agricultural and industrial activities (Yang et al., 2018), resulting in severe heavy metal pollution. Glaciers and snow cover had the lowest comprehensive pollution index, suggesting less human interference and lower exogenous soil pollution.

Table 7 displays the potential ecological risk assessments for the 12 elements under different land-use types. Both Ba and Cd had single-factor potential ecological hazard coefficients (E_r^i) of < 40, indicating a mild ecological hazard. Natural grassland, shrubland, and bare land had multi-factor potential ecological hazard indices (R_I) greater than 150, signifying moderate ecological risks in their soils. Bare lands had the highest R_I. Therefore, attention must be paid to human disturbances in the study area and to controlling the discharge of wastewater and emission of waste gases containing elements from industrial production processes, as well as the excessive discharge of heavy metal pollutants during urban construction processes.

Fig. 9 Contents of Ba and CD in topsoil under different land-use types. Note: in the table, "NG" stands for natural grassland; "SD" stands for shrub woodland; "AD" stands for arbor woodland; "AG" stands for artificial grassland; "BD" stands for bare land; "RS" stands for river water; "GS" stands for glacier and snow cover; and "GD" stands for grassland "FD" stands for other woodlands.
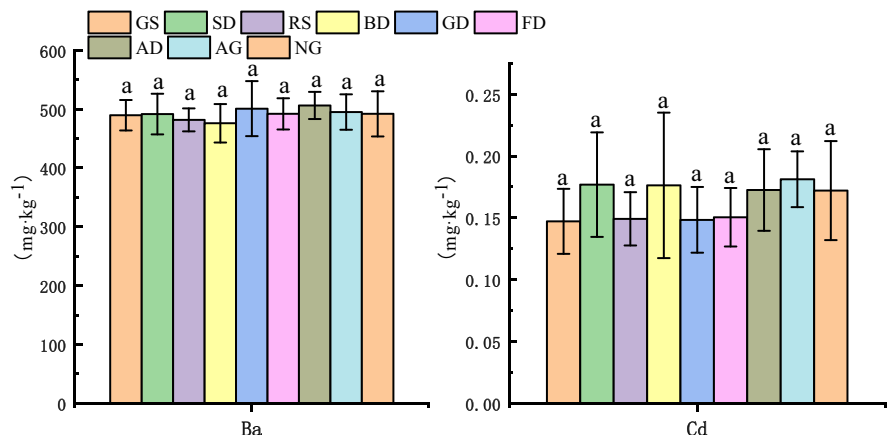
Table 7 Evaluation results of potential ecological risk index of soil heavy metals under different land-use types

Type	Potential ecological hazard coefficient E_r^i												Potential ecological hazard index R_I
	As	Ba	Be	Cd	Cr	Cu	Hg	Ni	Pb	Sb	Tl	Zn	
NG	10.08	2.00	30.18	30.31	2.06	5.05	43.64	5.21	5.09	7.39	9.99	1.01	152.01
SD	10.33	2.00	29.95	30.98	2.04	5.08	44.92	5.17	5.01	7.60	9.97	1.00	154.05
AD	11.91	2.06	30.15	30.49	1.91	5.48	33.27	5.21	5.14	9.01	10.15	0.97	145.76
AG	10.49	2.02	30.45	31.99	2.01	4.57	37.78	5.17	4.85	7.35	9.98	0.95	147.62
BD	10.06	1.94	29.70	31.11	2.12	4.83	48.09	5.32	4.99	7.40	9.96	1.05	156.58
RS	10.30	1.96	29.64	26.32	1.91	4.81	38.79	4.90	4.84	8.36	9.73	0.97	142.53
GS	10.51	1.99	30.14	25.97	1.93	5.17	35.59	4.98	5.03	7.45	10.15	0.96	139.88
GD	8.60	2.04	31.38	26.18	1.96	5.12	40.40	5.19	5.25	9.74	11.04	1.03	147.93
FD	9.82	2.00	27.80	26.55	1.83	5.00	34.75	4.95	4.53	7.70	9.49	0.91	135.32

Conclusions

In this study, we analyzed the contents of 12 heavy metals (As, Ba, Be, Cd, Cr, Cu, Hg, Ni, Pb, Sb, Tl, and Zn) in the topsoil of Maqin County, and investigated the effects of different geological backgrounds, soil types, and land-use types on heavy metal concentrations.

The results showed a certain degree of accumulation of the 12 heavy metals, with an overall mild pollution level and a moderate ecological risk. As, Sb, Ni, and Pb showed moderate variations, whereas Hg showed strong variations. Therefore, a multi-factor analysis of significant differences was conducted for heavy metal content under different geological backgrounds, soil types, and land-use types. The analysis indicated that the geological background exerted a remarkably significant impact ($p < 0.01$) on the concentrations of Ba, Be, Cd, Cr, Cu, Hg, Ni, Sb, Tl, and Zn. Soil type exhibited a highly significant influence ($p < 0.01$) on Be, Cd, Cu, and Zn, and a significant influence ($p < 0.05$) on Ba. Furthermore, land-use type had a highly significant effect ($p < 0.01$) on Ba and a significant effect ($p < 0.05$) on Cd.

For different geological backgrounds, the highest Ba, Be, and Sb contents were found in the Upper Neogene Linxia Formation. Cd, Hg, and Tl showed the highest contents in the Middle Carboniferous-Middle Permian Shuweimen Formation, whereas Cr, Cu, Ni, and Zn showed the highest contents in the Permian ultrabasic rock. For different soil types, the results were as follows: Ba and Cu had the highest contents in the leached brown soil; Cd had the highest content in the alpine meadow grassland soil; Be had the highest content in the mountain meadow grassland soil; and Zn had the highest content in ordinary alpine meadow soil. For different land-use types, Ba had the highest content in coniferous forest land, and Cd had the highest content in artificial grassland. Considering that the concentrations of all 12 heavy elements did not surpass the screening thresholds, along with the findings from Pearson correlation analysis and multi-factor significant difference analysis, it was deduced that the primary origin of heavy metals in Maqin County, Qinghai Province, stemmed from the geological background, albeit with some influence from human activities. Therefore, it is necessary to plan and control the production and habitation activities in the region.

This study provides a comprehensive analysis of heavy metals in the topsoil of Maqin County, Qinghai Province, and makes preliminary predictions regarding their sources based on different geological backgrounds, soil types, and land-use types. The geological background, soil type, and land-use type all exerted considerable influence over the Ba content. In the future, additional targeted research on Ba sources should be conducted to obtain more precise results.

Author contribution   Qingyu Liu: formal analysis; writing—original draft

Yao Niu: investigation, formal analysis

Hao Zhang: funding acquisition

Haixu Zhang: investigation, methodology

Jie Luo: formal analysis, supervision

Siyao Feng: conceptualization; writing—review and editing; supervision

Haoran Zhang: methodology, formal analysis; writing—original draft

All authors have read, understood, and complied as applicable with the statement on "Ethical responsibilities of Authors."

Data availability The datasets used or analyzed during the current study are available from the corresponding author on reasonable request. All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and consent to participate Not applicable. This work did not describe experiments with animals, human subjects, or human tissue samples.

Competing interests The authors declare no competing interests.

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