Heavy Metal Enrichment in Surface Soils and Ecological Risk Assessment in the Qinghai Lake Region (Postprint)

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Date: 2021-04-23T00:00:00+00:00

Abstract

To assess the enrichment levels of heavy metals and ecological risk conditions in surface soils of the Qinghai Lake region, 87 soil samples were collected using a grid-based approach. Heavy metals including Cd, Cr, Pb, As, Cu, Zn, and Ni were measured via Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES). The Nemerow comprehensive pollution index method, pollution load index method, correlation analysis, and factor analysis were utilized to examine heavy metal concentrations, pollution degrees, ecological risks, and pollution sources within the study area. The results indicated that Cd and Pb contamination were the most severe among the investigated elements in surface soils of the Qinghai Lake region, followed by Cr, As, Cu, Zn, and Ni. Furthermore, heavy metal pollution in grassland surface soils was more pronounced compared to farmland and sandy soils. Based on the pollution load index method, the overall soil heavy metal content in the study area did not reach pollution levels; however, certain sampling sites exhibited severe contamination. Nemerow comprehensive index analysis demonstrated that the study area was generally heavily polluted, with individual pollution indices exceeding standards to varying degrees. The pollution severity followed the sequence: Cd > Pb > As > Cu > Zn > Ni > Cr. The potential ecological risk index method revealed that the comprehensive potential ecological risk across the entire study area was moderate, with Cd and As accounting for nearly 80% of the risk contribution, and some subregions exhibiting relatively high potential ecological risk. Correlation and factor analysis identified significant correlations among Cr, Pb, As, Cu, Zn, and Ni, with essentially consistent pollution levels, suggesting a likely common origin. In conclusion, soil heavy metal pollution has occurred in the Qinghai Lake region, accompanied by potential ecological risks, warranting appropriate monitoring and corresponding remediation measures.

Full Text

Enrichment Content and Ecological Risk Assessment of Heavy Metals in Surface Soil Around Qinghai Lake

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Abstract

To evaluate the enrichment content and ecological risk of heavy metals in surface soils around Qinghai Lake, 87 groups of soil samples were collected using a grid-based sampling method. The concentrations of heavy metals (Cd, Cr, Pb, As, Cu, Zn, and Ni) were determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES). The Nemerow pollution index, pollution load index, correlation analysis, and factor analysis were employed to investigate the heavy metal content, pollution degree, ecological risk, and pollution sources in the study area. The results showed that Cd and Pb pollution was the most severe in surface soils around Qinghai Lake, followed by Cr, As, Cu, Zn, and Ni. Grassland surface soils exhibited more serious heavy metal contamination compared to farmland and sandy land. According to the pollution load index, the overall soil heavy metal content in the study area did not reach the pollution level, though some sampling points were severely contaminated. The Nemerow pollution index analysis indicated that the entire study area was heavily polluted overall, with single pollution indices exceeding standards to varying degrees. The pollution degree followed the order: Cd > Pb > As > Cu > Zn > Ni > Cr. The potential ecological risk index method revealed that the comprehensive potential ecological risk for the entire study area was at a medium level, with the contribution rates of Cd and As approaching 80%, and some areas showing high potential ecological risk. Correlation and factor analyses revealed significant correlations among Cr, Pb, As, Cu, Zn, and Ni, with consistent pollution degrees likely indicating a common source. In conclusion, soil heavy metal pollution has occurred in the Qinghai Lake area, posing potential ecological risks that warrant appropriate monitoring and remediation measures.

Keywords: soil heavy metals; pollution sources; ecological risk assessment; Qinghai Lake

Introduction

With rapid economic development, continuous technological advancement, and improving living standards, environmental issues have attracted increasing attention. Soil constitutes an important component of the human environment, providing food production resources and living space while continuously receiving various pollutants discharged by human activities. As the most persistent and toxic pollutants in soil, heavy metals are characterized by their difficulty to degrade, "three-causing" properties (carcinogenic, teratogenic, and mutagenic), and continuous accumulation, having become a global issue posing potential risks to ecosystems and human health. Heavy metals accumulate in soil through wastewater irrigation, waste composting, pesticide formulations, industrial production, and atmospheric dust deposition.

Since the 1970s, China has focused on soil heavy metal pollution, particularly on pollutant accumulation and transformation in key areas such as thermal power plants, mining areas (coal, metal mines, etc.), industrial smelters, and some agricultural sewage irrigation zones. Since the 1990s, soil heavy metal pollution has intensified, and since 2000, research has entered a new peak period focusing on cultivated land, pastoral grassland, traffic roads, urban street sediments, and basins. Currently, domestic research on lake heavy metals primarily concentrates on water quality and sediments of coastal lakes, industrial park lakes, and important urban landscapes, including speciation studies, ecological assessments, and risk evaluations.

As China' s largest inland saltwater lake and a famous tourist destination, Qinghai Lake and its surrounding area represent an important pastoral region on the northeastern Tibetan Plateau and a national key ecological protection zone with a relatively fragile ecological environment. Previous studies on soil heavy metals in the Qinghai Lake area have yielded important findings. For instance, Tian Yuming et al. suggested that although the soil ecological environment around Qinghai Lake has been affected by human activities, the increase in soil heavy metals reflects elevated regional background values. Lu Baoliang et al. analyzed the spatial distribution characteristics of soil heavy metals in typical wetlands (Heima River Wetland) around Qinghai Lake. Chang Huajin et al. evaluated the pollution degree and characteristics of heavy metals in sediments from the lower reaches of the Shaliu River and assessed their ecological risk. However, these studies mainly focused on heavy metals in lake water and sediments, and were limited to small areas or specific landform types. A systematic study on soil heavy metal pollution across the entire Qinghai Lake area is urgently needed. Therefore, this paper takes the entire Qinghai Lake area as the research object to deeply investigate the pollution distribution characteristics, potential ecological risks, and source apportionment of heavy metals in surface soils, providing theoretical support and practical references for protecting the ecological environment and human health in the Qinghai Lake area.

1.1 Study Area Overview

The study area is located in the Qinghai Lake region on the northeastern Tibetan Plateau, within the area bounded by National Highway 109, Huanhu East Road, and Huanhu West Road. Situated at the intersection of China' s eastern monsoon region, northwest arid region, and southwest alpine region, it is a typical plateau semi-arid and alpine area with an average altitude above 3000 m. The terrain slopes from west to east, showing a northwest-high and southeast-low trend, combining both Tibetan Plateau and Loess Plateau landforms, and integrating continental monsoon and plateau climates. The area is characterized by low temperatures, large diurnal temperature variations, low and concentrated rainfall, long sunshine hours, and strong solar radiation, with an annual average temperature of -4.6~4.0°C and annual precipitation of 291.0~579.0 mm, mostly concentrated in May-September. Recent climate change and human activities have caused ecological problems such as grassland degradation and desertification around Qinghai Lake.

The vertical migration and distribution of heavy metal elements in soil are mainly influenced by the chemical properties of the elements and the physicochemical properties of the soil itself. Soil types in the Qinghai Lake area include mountain meadow soil, mountain shrub meadow soil, black calcium soil, chestnut soil, swamp soil, and aeolian sandy soil. The development of land for grassland, sandy land, and agricultural use faces limitations due to environmental degradation. Industries such as coal mining, animal husbandry processing, and tourism have developed to varying degrees, all of which have been somewhat restricted due to environmental damage. These uncertain factors from multiple sources have caused different distributions of heavy metals in soil and affected their migration and transformation.

1.2 Sample Collection and Determination

The study area was divided into grids using a grid method, with one sampling point established per grid at a sampling density of [MATH_1]. During sampling, some points were appropriately adjusted due to rivers, buildings, bridges, etc. The sampling point distribution is shown in [Figure 1: see original paper]. Sampling was conducted in late July 2018. Using the five-point method, 87 groups of mixed soil samples (0-20 cm) were collected, including 53 grassland points, 21 farmland points, and 13 sandy land points. The highest sampling point altitude was 3237 m and the lowest was 3140 m.

Samples were air-dried, crushed, and passed through a 0.15 mm nylon sieve. A 0.5 g sample was microwave-digested with nitric acid, hydrochloric acid, and hydrofluoric acid to ensure complete mixing. After digestion, the solution was diluted to 25 mL, mixed evenly, and left to stand for 60 minutes. The supernatant was then analyzed using inductively coupled plasma-atomic emission spectrometry (ICP-AES) following the “Microwave Digestion Method for Total Metal Elements in Soil and Sediment (HJ832-2017)” issued by the Ministry of Ecology and Environment to determine heavy metal concentrations.

1.3 Quality Control and Data Processing

To ensure data reliability and accuracy, blank samples were analyzed and replicate tests were conducted on 10% of the samples during determination. The measured deviations met quality control requirements. Excel software was used for descriptive statistical analysis of soil heavy metal data, SPSS 20.0 for correlation and factor analyses, and Origin 2019b for mapping.

2.1 Analysis of Soil Heavy Metal Content Characteristics

The heavy metal content and statistical analysis results for surface soils around Qinghai Lake showed average concentrations of Cd, Cr, Pb, As, Cu, Zn, and Ni as 0.62, 41.35, 11.73, 19.33, 63.51, 21.18, and 11.66 $mg \cdot kg^{-1}$, respectively, with ranges of 0.05-5.57, 11.50-60.93, 7.46-35.09, 0.96-18.52, 2.06-74.38, 6.23-31.62, and 17.30-98.62 $mg \cdot kg^{-1}$. Overall, the mean Cd content exceeded the Qinghai Lake soil background value (0.14 $mg \cdot kg^{-1}$) by 4.43 times, while other heavy metals did not exceed background values. For individual elements, Cd had the most sample points exceeding background values (59.8%), with some points exceeding 5 $mg \cdot kg^{-1}$ (about 36 times the background value). Pb had the second-highest proportion of exceedances (63.3%), though all within 5 times the background value. The variation coefficient of soil heavy metals was only 0.09-0.41, indicating that Cd was more affected by external factors than other elements. In summary, heavy metal pollution has occurred in the study area, with Cd being the most serious contaminant, followed by Pb.

Sampling points around Qinghai Lake were classified by functional area for comparative analysis of surface soil heavy metal content, including 53 grassland points, 21 farmland points, and 13 sandy land points. The results (Table 2) showed that: (1) The mean content of Cd, Cr, Pb, As, Cu, Zn, and Ni in grassland exceeded the Qinghai Lake background values; in farmland, the mean content of Cd, Cr, Pb, As, and Cu exceeded background values while Zn and Ni did not; in sandy land, only Cd and Cu exceeded background values while the other five elements did not. (2) For Cd, 84.8% of grassland points and all farmland and sandy land points exceeded background values; for Pb, 63.3% of grassland points and all farmland points exceeded background values; for As, 15.2% of grassland points and all farmland points exceeded background values; for Cu, 41.8% of grassland points and all farmland points exceeded background values; for Zn, only 15.2% of grassland points exceeded background values; for Ni, only grassland points exceeded background values. Overall, grassland surface soil heavy metal pollution was more severe than that of farmland and sandy land.

2.2.1 Pollution Load Index Method

The pollution load index (PLI) can intuitively reflect the contribution degree of heavy metal elements to soil pollution and classify pollution standards: PLI ≤ 1 (unpolluted), $1 <$ PLI ≤ 2 (moderately polluted), $2 <$ PLI ≤ 3 (strongly polluted), PLI > 3 (extremely strongly polluted). The pollution load index for the entire study area (PLIzone) was 0.98, indicating that overall, the soil heavy metals were unpolluted. However, the pollution coefficient (CF) mean values for soil heavy metals showed Cd with a CF mean > 3, classified as heavily polluted; Pb and As with CF means between 1-2 (moderately polluted); and Cr, Cu, Zn, and Ni with CF means < 1 (unpolluted). For individual sampling points, the average PLI was 0.98, ranging from 0.24-1.80, indicating pollution levels from unpolluted to moderately polluted.

2.2.2 Nemerow Pollution Index

The Nemerow pollution index is a weighted multi-factor environmental quality index that considers both maximum and average values, widely used for comprehensive environmental pollution assessment. It is expressed as P_ 综合 and classified as: P_ 综合 ≤ 0.7 (clean and safe), 0.7 < P_ 综合 ≤ 1.0 (warning line), 1.0 < P_ 综合 ≤ 2.0 (lightly polluted), 2.0 < P_ 综合 ≤ 3.0 (moderately polluted), P_ 综合 > 3.0 (heavily polluted). The mean Nemerow comprehensive pollution index for the 87 samples was 4.27, indicating heavy pollution overall. The single pollution index showed pollution levels of: Cd (heavy pollution), Pb (moderate pollution), As (light pollution), and Cr, Cu, Zn, Ni (unpolluted). For individual samples, 86.7% had P_ 综合 > 3 (heavy pollution), with some values far exceeding 3. The Nemerow pollution index for each element (Table 4) showed pollution degrees from high to low as: Cd > Pb > As > Cu > Zn > Ni > Cr. In summary, both the pollution load index and Nemerow comprehensive pollution index methods indicated that while the overall heavy metal level did not reach pollution status, the combined pollution effect at some sampling points had already caused heavy pollution, with Cd being the most severe element in the region, reaching light to heavy pollution levels.

2.3 Soil Heavy Metal Ecological Risk Assessment

The potential ecological risk index method proposed by Swedish scientist Hakanson comprehensively considers heavy metal toxicity and its migration and transformation patterns in soil and sediment, and is widely applied for ecological risk assessment. The risk levels are classified as: Er < 40 (slight), 40 ≤ Er < 80 (moderate), 80 ≤ Er < 160 (strong), 160 ≤ Er < 320 (very strong), Er ≥ 320 (extremely strong); and RI < 150 (slight), 150 ≤ RI < 300 (moderate), 300 ≤ RI < 600 (strong), RI ≥ 600 (very strong).

Results showed that the single heavy metal potential ecological risk coefficient Er and comprehensive potential ecological risk index RI for the study area were 16.49-1298.78 and 86.80-640.32, respectively. All seven heavy metals had Er < 40, indicating slight potential ecological risk. However, the overall RI was 166.49, indicating medium risk. Notably, 13.3% of sampling points had RI > 300 (strong risk), and 86.7% had RI < 150 (slight risk). The contribution rates of Cd and As to RI were 67.6% and 12.0%, respectively, indicating that the comprehensive potential ecological risk in the study area was mainly caused by Cd, consistent with pollution assessment results. The RI values were 2.06 times, 1.66 times, and 1.31 times those of the Minjiang River Basin in the western Sichuan Plateau, the Xiaojiang River Basin at the southwestern foot of the Daba Mountains, and the Bosten Lake Basin on the southern slope of the Tianshan Mountains, respectively, demonstrating the serious potential ecological risk situation around Qinghai Lake. It is worth noting that Cd was also the primary pollutant in these comparable high-altitude basins.

Correlation analysis (Table 5) showed significant correlations (P < 0.01) among

Cr, Pb, As, Cu, Zn, and Ni, indicating similar pollution sources and degrees, likely with a common origin. Cd also showed significant correlations with these elements, suggesting similar or identical sources and pollution levels. However, Ni showed generally weak correlations with other heavy metals, indicating low homology and different pollution sources.

2.4 Source Apportionment of Soil Heavy Metals

To analyze pollution sources, correlation and factor analyses were applied to sampling data. Correlation analysis assesses linear relationships between variables—higher correlation coefficients indicate stronger relationships. Significant correlations among elements suggest they may share pollution sources and degrees.

Cd is typically found in zinc and lead-zinc ores, originating from mining, smelting, electroplating, fertilizer production, and other industrial processes. It is also used to manufacture alloys for electrical appliances, pigments, pesticides, and even aviation and marine applications. In addition to natural sources like parent rock weathering and volcanic eruptions, Pb mainly comes from coal, petroleum, and gasoline combustion, industrial waste gas emissions, and fertilizer application, including feed additives. Therefore, heavy metals in the surface soil of the study area likely originate from anthropogenic sources such as transportation, industry, and agricultural production.

Factor analysis was further employed to determine heavy metal sources. Bartlett' s test confirmed the data suitability. The first two factors explained 83.65% of variance, and according to the principle of cumulative contribution rate, two main factors were extracted. The rotated factor analysis results (Table 6) showed that Factor 1 had high loadings for Cr, Pb, Cu, Zn, and Ni (loadings of 0.84, 0.88, 0.90, 0.86, and 0.78, respectively), suggesting these five elements share a common source and can be grouped as one factor. Factor 2 had high loadings for As and Cd (0.87 and 0.85, respectively), forming another factor. Thus, Cr, Pb, Cu, Zn, and Ni in the study area soil share the same pollution source, while As and Cd represent different sources, consistent with correlation analysis results.

3 Conclusion

Through determination and analysis of 87 surface soil samples around Qinghai Lake, this study found varying degrees of heavy metal pollution, with grassland being the most severely affected. The overall comprehensive potential ecological risk was medium, but some sampling points showed serious soil heavy metal pollution, mainly caused by Cd, indicating high ecological pollution risk. Preliminary source apportionment based on correlation and factor analyses revealed that Cr, Pb, As, Cu, Zn, and Ni had significant correlations with consistent pollution degrees, likely sharing common anthropogenic sources from petroleum/gasoline combustion, industry, and agricultural production. Cd and

As mainly originated from transportation, industry, and agricultural activities, while Ni had different sources with low homology.

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Note: Figure translations are in progress. See original paper for figures.