Accumulation Characteristics and Ecological Risk of Heavy Metals in Green Space Soils in the Core Urban Area of Urumqi: Postprint

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Abstract

With the acceleration of urban expansion and industrialization, soils in the core urban areas of large cities in China have suffered varying degrees of heavy metal pollution. Taking typical urban park green spaces and transportation hub green spaces in the core urban area of Urumqi City as the research objects, this study systematically investigated the accumulation characteristics and ecological risks of six heavy metals (Cd, Cr, Cu, Pb, Zn, and Ni) in soils. The results showed that: (1) The heavy metal content in soils of transportation hub green spaces was higher than that in urban park green spaces. Compared with the soil background values of Urumqi City, heavy metals in urban park green space soils represented slight pollution, while those in transportation hub green space soils represented moderate pollution. (2) The comprehensive pollution indices of heavy metals in urban park green space soils across different administrative districts were: Toutunhe District (2.85) > Shuimogou District (2.13) > Tianshan District (1.91) > Xinshi District (1.85) > Midong District (1.23), whereas the comprehensive pollution indices for transportation hub green space soils were: Midong District (4.17) > Saybag District (3.24) > Xinshi District (2.84) > Shuimogou District (2.70) > Toutunhe District (2.50) > Tianshan District (2.37). (3) The potential ecological risk indices of heavy metals in urban park green space soils across different administrative districts were: Shuimogou District (101.68) > Toutunhe District (98.83) > Xinshi District (88.56) > Tianshan District (73.43) > Midong District (58.24), while those for transportation hub green space soils were: Midong District (177.60) > Shuimogou District (131.75) > Saybag District (120.25) > Xinshi District (105.76) > Toutunhe District (105.63) > Tianshan District (82.12). The maximum comprehensive pollution index and potential ecological risk index for urban park green space soils were observed in Toutunhe District and Shuimogou District, respectively, whereas both the maximum comprehensive pollution index and potential ecological risk index for urban transportation hub green space soils were observed in

Midong District. (4) In terms of spatial distribution characteristics, high-value areas of urban park green space soils were generally distributed in an island-like pattern across the central urban area, while for transportation hub green space soils (except for Ni), high-value areas were island-like distributed in the southwestern part of Midong District and the eastern part of Saybag District. The significant agglomeration of industrial enterprises, dense traffic arteries, and high population density constitute the main factors influencing the differences in soil heavy metal pollution levels across different administrative districts.

Full Text

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Accumulation Characteristics and Ecological Risks of Heavy Metals in Green Land Soils in Core Urban Area of Urumqi City

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Abstract

Owing to rapid urban expansion and industrialization in China, the core urban areas of large cities have suffered from varying degrees of heavy metal pollution in the soil. Herein, the accumulation characteristics and ecological risks of six heavy metals (Cd, Cr, Cu, Pb, Zn, and Ni) in the soils of two distinct urban land types (urban park and transportation hub green lands) within the core urban areas of Urumqi City were systematically studied. The study yielded multiple key results: (1) Soil heavy metal concentrations in the green land soils of transportation hubs were higher than urban parks. Compared with the soil background values of heavy metals in Urumqi City, urban park green land of the core urban area exhibited light pollution, while the green land in transportation hubs demonstrated moderate pollution. (2) The comprehensive pollution index for soil heavy metals within urban park green land varied among different administrative regions, with Toutunhe District (2.85) showing the highest level, followed by Shuimogou District (2.13), Tianshan District (1.91), Xinshi District (1.85), and Midong District (1.23). Conversely, for green land in transportation hubs, the comprehensive pollution index of soil heavy metals differed across administrative regions, with Midong District (4.17) being the most heavily affected, followed by Sayibak District (3.24), Xinshi District (2.84), Shuimogou District (2.70), Tuotunhe District (2.50), and Tianshan District (2.37). (3) Regarding the potential ecological risk index for heavy metals in green soil of urban parks, the rankings among different administrative regions were as follows: Shuimogou District (101.68) > Toutunhe District (98.83) > Xinshi District (88.56) > Tianshan District (73.43) > Midong District (58.24). In addition, for transportation hubs green land, the potential ecological risk index of heavy metals for each administrative region exhibited regional disparities, with Midong District (177.60) being the most adversely affected, followed by Shuimogou District (131.75), Sayibak District (120.25), Xinshi District (105.76), Toutunhe District (105.63), and Tianshan District (82.12). The largest comprehensive pollution index and potential ecological risk index for urban park green land were observed in the Toutunhe and Shuimogou Districts, respectively, while the largest values for urban transportation hubs green land were documented in Midong District. (4) Spatial distribution characteristics revealed that high-value urban park green land was generally distributed in the central urban area, resembling islands of green amidst the urban landscape. Conversely, high-value heavy metal pollution of green land in transportation hubs was distributed in an island shape in the southwestern region of Midong District and the eastern part of Sayibak District, except for Ni. This study identifies key factors affecting the varying degrees of soil heavy metal pollution in different administrative regions, including the concentration of industrial enterprises, dense transportation arteries, and high population density. This study potentially provides a scientific basis and reference for the protection of the soil ecological environment in the core urban area.

Key words: soil heavy metals; urban park; transportation hub; environmental risk; Urumqi City

1 Introduction

With the acceleration of urban expansion and industrialization, soils in the core urban areas and surrounding transportation hubs of large Chinese cities have suffered from varying degrees of heavy metal contamination. Core urban areas are characterized by dense populations, concentrated industrial production, and traffic congestion. Compared with farmland and forest soils, green land soils in core urban areas are more susceptible to anthropogenic influences across both temporal and spatial dimensions. According to data from the China City Statistical Yearbook, Urumqi's built-up area expanded from 343 km^2 to 521.60 km^2 between 2011 and 2021, while its permanent population grew from 3.11 million to 4.05 million and its civilian vehicle ownership increased from 0.87 million to 1.29 million. The resulting domestic waste, fossil fuel consumption, vehicle emissions, industrial "three wastes" discharge, and sewage irrigation introduce heavy metal elements into urban soils through surface runoff, subsurface flow, and atmospheric deposition.

Urban park green spaces serve both as recreational areas for residents and as regulators of local ecosystems, while transportation hub green lands function as transit points for travel and contribute to urban ecological aesthetics. Therefore, investigating the accumulation characteristics and ecological risks of heavy metals in different types of urban green land soils holds significant practical importance for creating ecological cities and healthy living environments. Previous studies have examined heavy metal accumulation in various urban green land types. Research on central Shanghai revealed that heavy metals in urban green space soils primarily originated from traffic emissions and industrial activities, with roadside green spaces being particularly affected by traffic discharge. Studies in major cities of Hubei Province showed complex sources of heavy metals in urban green space soils, with significant impacts from human production activities, necessitating strengthened pollution prevention and control. Investigations in Baoding's main urban area found that roadside green spaces exhibited the highest comprehensive pollution levels, reaching severe contamination, while most areas showed moderate ecological risks except for school green spaces within the third ring road. These findings demonstrate that heavy metal pollution levels vary among different green land types across cities.

Located at the northern foothills of the central Tianshan Mountains and the southern edge of the Junggar Basin, Urumqi serves as the capital of Xinjiang Uygur Autonomous Region and represents an important central city in northwestern China and an international trade center facing Central and West Asia. However, research on heavy metal contamination and ecological risks in Urumqi's core urban green land soils remains limited. This study systematically investigates the pollution status, accumulation characteristics, and ecological risks of heavy metals in different types of green land soils within Urumqi's core urban area, aiming to provide theoretical support for ecological environmental protection and soil quality management while offering valuable insights for harmonious development between urban and natural ecosystems.

1.2 Sample Collection and Analysis

Surface soil samples (0–20 cm) were collected from typical urban park green spaces and transportation hub green lands significantly impacted by urban residents' activities using a random sampling method. A total of 32 soil samples were collected from urban park green lands and 30 samples from transportation hub green isolation belts [Figure 1: see original paper]. Within each green land plot, five samples were collected using the plum blossom sampling method and combined using the quartering method to obtain one representative sample for subsequent analysis. During sampling, surface litter, plant roots, and large stones were removed. Samples were sealed in labeled bags with information on location, number, coordinates, and sampling date.

Soil samples were air-dried, impurities were removed, and the samples were ground into powder using an agate mortar and passed through a 100-mesh nylon sieve. Following pretreatment, heavy metal contents were determined using inductively coupled plasma mass spectrometry (ICP-MS). Statistical analysis was performed using SPSS 26.0, mapping was conducted with ArcGIS 10.8, and spatial distribution characteristics were analyzed using the inverse distance weighting method [17].

1.3.1 Single-Factor Index Method

The single-factor index method is widely used for soil heavy metal pollution assessment and is calculated as:

$$P_i = \frac{C_i}{S_i}$$

where P_i is the single-factor index for heavy metal i; C_i is the measured content of heavy metal i in soil ($\mathrm{mg \cdot kg^{-1}}$); and S_i is the background value of heavy metal i in soil ($\mathrm{mg \cdot kg^{-1}}$). This study adopted the soil background values of Urumqi City as the reference standard . Higher P_i values indicate more severe pollution: $P_i \leq 1$ indicates no pollution, $1 < P_i \leq 2$ indicates light pollution, $2 < P_i \leq 3$ indicates moderate pollution, and $P_i > 3$ indicates heavy pollution.

1.3.2 Comprehensive Pollution Index Method

The comprehensive pollution index method (Nemerow index) evaluates multiple soil heavy metal pollutants and is calculated as:

$$P = \sqrt{\frac{[average(P_i)]^2 + [max(P_i)]^2}{2}}$$

where P is the comprehensive pollution index: $P \leq 0.7$ indicates clean, $0.7 < P \leq 1.0$ indicates still clean, $1.0 < P \leq 2.0$ indicates light pollution, $2.0 < P \leq 3.0$ indicates moderate pollution, and $P > 3.0$ indicates heavy pollution; P_i is the single-factor index for each heavy metal; $average(P_i)$ is the mean of all single-factor indices; and $max(P_i)$ is the maximum single-factor index.

1.3.3 Potential Ecological Risk Index Method

The potential ecological risk index method, established by Swedish scholar Hakanson in 1980, is widely applied for soil heavy metal ecological risk assessment and is calculated as:

$$RI = \sum_{i=1}^{n} E_i = \sum_{i=1}^{n} (T_i \times P_i)$$

where RI is the potential ecological risk index; E_i is the potential ecological risk index for heavy metal i; T_i is the toxicity coefficient for heavy metal i (Cd = 30, Cr = 2, Cu = 5, Pb = 5, Zn = 1, Ni = 5) [9]; and P_i is the single-factor index for heavy metal i. The risk classification standards are: $RI < 150$ indicates slight ecological risk, $150 \leq RI < 300$ indicates moderate ecological risk, $300 \leq RI < 600$ indicates strong ecological risk, and $RI \geq 600$ indicates very strong ecological risk.

2 Results and Analysis

2.1 Accumulation Characteristics of Heavy Metals in Green Land Soils

The analytical results for heavy metal elements in different types of green land soils in Urumqi's core urban area are presented in . Comparison with regional soil background values revealed that average heavy metal contents in urban park green land soils exceeded background values. Except for Ni content, which was close to the background value, Cr content was nearly 1.5 times higher, Cu and Zn contents were nearly 2 times higher, Pb content was nearly 4 times higher, and Cd content was nearly 13 times higher than background values. In transportation hub green land soils, Ni content was close to the background value, while Cr content was nearly 1.5 times higher, Cu content was nearly 2 times higher, Zn content was nearly 3 times higher, Pb content was nearly 6 times higher, and Cd content was nearly 16 times higher than background values, indicating strong enrichment in transportation hub green land soils.

Single-factor pollution indices showed the following order for urban park green land soils: Cd (12.96) > Pb (3.93) > Zn (1.94) > Cu (1.92) > Cr (1.48) > Ni (0.96). Cd exhibited the most severe accumulation, reaching heavy pollution levels, while Pb showed moderate pollution. These findings align with research by Zhu Li'an et al. [10] on surface soil heavy metal accumulation in Foshan's urban forest parks, which found that most forest parks and forest areas had heavy metal contents exceeding the Pearl River Delta soil background values, indicating widespread anthropogenic impacts on large urban park soils during urbanization and industrialization. Over the past decade, Urumqi's urban park green space area expanded from 20.63 km^2 to 38.55 km^2, significantly increasing the soil's capacity to retain heavy metals. Core urban areas are particularly vulnerable to industrial and traffic sources, leading to heavy metal accumulation in park green land soils.

For transportation hub green land soils, single-factor pollution indices followed the order: Cd (15.84) > Pb (5.94) > Zn (2.86) > Cu (2.37) > Cr (1.55) > Ni (0.98). Cd accumulation was most severe (heavy pollution), while Pb showed moderate pollution. Sun Xuefei et al. [11] studied heavy metal sources in a typical petrochemical industrial city and found that Pb and Cd were significantly influenced by transportation, with multiple highways and busy traffic being primary causes for their elevated concentrations. Urumqi's urban road area expanded from 20.05 km^2 to 70.13 km^2 over the past decade, accompanied by a surge in civilian vehicle ownership. Tire wear, exhaust emissions, and windblown sand abrasion of vehicle paint contribute multiple heavy metal input sources to transportation hub green land soils.

Ecological risk assessment revealed that for urban park green land soils, the potential ecological risk followed the order: Cd (64.80) > Pb (19.65) > Cu (9.60) > Ni (4.80) > Cr (2.96) > Zn (1.94), with a total potential ecological risk index of 103.75, indicating moderate ecological risk. For transportation hub green land soils, the order was: Cd (79.20) > Pb (29.70) > Cu (11.85) > Ni (4.90) > Cr (3.10) > Zn (2.86), with a total index of 131.61, approaching the moderate ecological risk threshold and warranting attention. Notably, Cd posed moderate ecological risk in both green land types, representing the primary ecological risk element in Urumqi's study area.

To contextualize Urumqi's pollution status among other major Chinese cities, comparative analysis of single-factor pollution indices, comprehensive pollution indices, and potential ecological risk indices was conducted . Results showed that Urumqi's urban park green land had higher single-factor pollution indices for all six heavy metals than Shanghai, Wuhan, and Chongqing. Beijing, Guangzhou, Xi'an, and Tianjin exhibited higher Cd single-factor pollution indices than Urumqi, likely due to earlier urbanization and industrialization. Guangzhou's urban park green land Cd index reached heavy pollution levels, closely related to its industrial layout, traffic emissions, and population density [16]. Meanwhile, some newly established parks in Beijing's urban area evolved from industrial or agricultural land, making urbanization history, park age, and former land use important factors influencing soil heavy metal accumulation [13,27]. Regional environmental conditions also affect heavy metal accumulation differences. Coastal cities generally show higher heavy metal contents than inland cities, and economically developed cities exceed less developed ones [29]. Urumqi's arid climate, characterized by dryness and high winds, facilitates dust accumulation and resuspension from industrial emissions and winter coal burning [33], introducing substantial heavy metals into urban park soils through atmospheric deposition.

2.2 Spatial Distribution and Regional Variations of Heavy Metal Pollution

2.2.1 Spatial Distribution Characteristics Spatial interpolation results for heavy metal contents in Urumqi's core urban area green land soils are shown in [Figure 2: see original paper] and [Figure 3: see original paper]. For urban park green land, high-value areas of Cd, Cr, Cu, Pb, and Zn were primarily distributed as islands in the central urban area, with lower concentrations in peripheral areas. The central urban area hosts numerous industrial parks whose emissions contribute significantly to heavy metal inputs. High-value Ni areas appeared in the southwest of Shuimogou District and at the northwest junction with Tianshan District, as well as in eastern Toutunhe District, likely related to local industrial structure. Research by Yu Ruilian et al. [29] indicated that Ni originates from industrial processes, tire wear, and historically, leaded gasoline use. Toutunhe District, adjacent to Urumqi International Airport and housing Xinjiang's largest railway marshalling yard and freight depot, experiences substantial aviation and road traffic emissions that settle into surrounding green land soils.

For transportation hub green land, high-value areas of all heavy metals generally appeared as islands in southwestern Midong District and eastern Sayibak District. Midong District leads the city in both energy consumption (48.81%) and particulate matter emissions (40.93%), with rapid construction expansion (7.23% annual growth) making it a major heavy industry base. The district also contains the city's largest commercial service land area, with dense population and traffic flow accelerating heavy metal accumulation through tire and brake pad wear and vehicle exhaust. Sayibak District, with numerous industrial enterprises, sees heavy metal accumulation from the production of calcium carbide, printed materials, and ready-mixed concrete. High-value Zn areas appeared sporadically in southern Xinshi District and Shuimogou District. Xinshi District, as a recent development focus area, has experienced surging human and vehicle traffic, intensifying heavy metal accumulation.

2.2.2 Heavy Metal Pollution Characteristics by Administrative Region Comprehensive pollution and potential ecological risk indices for different administrative regions are illustrated in [Figure 4: see original paper]. For urban park green land, comprehensive pollution indices ranked as: Toutunhe District (2.85) > Shuimogou District (2.13) > Tianshan District (1.91) > Xinshi District (1.85) > Midong District (1.23). Toutunhe and Shuimogou Districts showed moderate pollution, while others exhibited light pollution. Potential ecological risk indices ranked as: Shuimogou District (101.68) > Toutunhe District (98.83) > Xinshi District (88.56) > Tianshan District (73.43) > Midong District (58.24), with all regions showing slight ecological risk. Both indices were highest in Toutunhe and Shuimogou Districts, where industrial pollution sources significantly impact soils.

For transportation hub green land, comprehensive pollution indices ranked as:

Midong District (4.17) > Sayibak District (3.24) > Xinshi District (2.84) > Shuimogou District (2.70) > Toutunhe District (2.50) > Tianshan District (2.37). Midong and Sayibak Districts showed heavy pollution, while others exhibited moderate pollution. Potential ecological risk indices ranked as: Midong District (177.60) > Shuimogou District (131.75) > Sayibak District (120.25) > Xinshi District (105.76) > Toutunhe District (105.63) > Tianshan District (82.12). Midong District showed moderate ecological risk, while others showed slight risk. Midong District's indices were highest across all administrative regions, with its energy consumption and particulate emissions being the city's highest. Rapid built-up area expansion and intensive industrial activity serve as major heavy metal input sources. Xie Shaowen et al. [1] demonstrated that in core urban areas, more economically developed regions with concentrated industrial enterprises, dense transportation networks, and frequent human activities experience continuous heavy metal input and accumulation.

3 Conclusions

(1) The average content of heavy metals in different types of green land soils in Urumqi's core urban area followed similar patterns: Pb > Zn > Cr > Cu > Ni > Cd. Transportation hub green land soils contained higher heavy metal concentrations than urban park green land soils, indicating more severe anthropogenic impacts on transportation hub green lands.

(2) Compared with Urumqi's soil background values, the primary heavy metal pollution factors in urban park green land soils were Cd and Pb, while transportation hub green land soils were mainly polluted by Cd, Pb, and Zn. Cd reached heavy pollution levels in both green land types. While both green land types showed slight ecological risk overall, Cd posed moderate ecological risk in each, representing the most significant ecological risk element in the study area.

(3) The maximum comprehensive pollution index for urban park green land soils occurred in Toutunhe District, while the maximum potential ecological risk index appeared in Shuimogou District, where soils were significantly impacted by industrial pollution sources. For transportation hub green land soils, both the maximum comprehensive pollution index and potential ecological risk index occurred in Midong District, where built-up area expansion, intensive industrial activity, and traffic pollution likely represent the primary sources of soil heavy metals.

(4) Spatially, high-value urban park green land soil heavy metal areas were generally distributed as islands in the central urban area. For transportation hub green land soils, high-value areas (except for Ni) appeared as islands in southwestern Midong District and eastern Sayibak District. Different land use types significantly influence the degree of soil heavy metal pollution across administrative regions. In economically developed, industrially concentrated areas with dense transportation arteries and frequent

human activities, ecological risk levels of heavy metal pollution in core urban green land soils increase substantially—a factor that warrants greater attention in future urban soil ecological environmental protection efforts.

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