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RESEARCH

Will different land uses affect heavy metal pollution in soils of roadside trees? An empirical study from Shanghai

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Abstract Heavy metal pollution in roadside soil may harm humans, animals, plants, and local ecosystems. This study aimed to explore the sources and potential ecological risks of heavy metals in soils of roadside trees under different land uses, using soil samples collected from 136 roads across 16 administrative districts in Shanghai. The contents, pollution characteristics, potential ecological risks, and sources of seven heavy metals were analyzed, including Cr, Ni, Cd, Pb, As, Cu, and Zn. Results showed that (1) land use patterns affected the heavy metal contents, with industrial and construction areas showing higher contents while agricultural and forestry areas lower; (2) the ranking of heavy metal pollution levels was Cd > As > Pb > Cu > Ni > Cr > Zn. Cd exhibited the highest potential ecological risk, falling within the moderate to considerable potential ecological risk interval; (3) the sources of Cu, Zn, Cr, Ni, Cd, and Pb were associated with traffic emissions, whereas As had independent other sources and Pb in industrial and construction areas was also influenced by industrial emissions. These results provide valuable references on the control of heavy metal pollutants and the management of land uses in megacities.

Keywords Land use types · Heavy metal content · Ecological risk · Source identification · Megacity

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Introduction

Because of its non-degradability and long residual time, heavy metal pollution has the potential to harm humans, animals, plants, and local ecosystems (Mwesigye et al., 2016; Viana et al., 2008). With rapid urbanization, dusts generated from human activities, industrial production activities, and road traffic have become pollution sources in cities (Anahi et al., 2021). These polluted dusts deposit on the surfaces of buildings, streets, and green spaces, ultimately contaminating the urban soil (Rahman et al., 2019). Soils for roadside trees are the main channel connecting the surface and underground of road spaces and are also the main reservoir of heavy metal pollutants in cities. The heavy metal pollutants may infiltrate with rainwater, thereby affecting groundwater quality, soil microorganisms, and plant growth (Calace et al., 2012). During dry weather, heavy metals in roadside soil may become inhalable particles and enter the human body through respiratory tracts, digestive system, and skin, thus damaging human health (Li et al., 2014; Roy & Mcdonald, 2015). Hence, it is important to explore the sources and potential ecological risks of heavy metals in urban soils of roadside trees.

Urbanization and different land uses in cities have a notable impact on heavy metal pollution. Different degrees of heavy metal pollution can be detected in soil, water, sediments, and road dusts under different land uses (Mohiuddin et al., 2010). Studies have shown that the soil heavy metal contents were relatively high in industrial and commercial areas in cities, while low in newly developed agricultural, forested, commercial, and residential areas (Shi et al., 2010). Their sources also varied with the patterns of land use (Ghosh et al., 2018). A study in Bangladesh showed that heavy metals Ni, Pb, Mn, Cu, and Zn in soil mainly came from human activities (Islam et al., 2022). Another study in the northwest region of China showed that traffic emissions were the primary sources of Cu and Zn; industrial activities caused Pb, Hg, and As pollution; and Cr and Ni came from natural sources (Li, Yang, et al., 2022). However, the existing literature was mainly focused on the spatiotemporal variations of heavy metal levels at large spatial scales, such as agricultural soil versus natural soil and urban versus suburban areas (Yan et al., 2018). Limited research has been performed to study heavy metal contamination in soils under different land uses within a specific region.

Heavy metal pollution in soils has been a long-term issue that is caused by industrial emissions, construction waste, and human activities during urban development (Li, 2016). Compared with soils in green spaces, soils for street trees are within open and complex environments and thus are more influenced by urban development, land uses, and human activities (Konstantinova et al., 2019). Therefore, it can be used to study the association between soil heavy metal pollution with different land uses. In highly urbanized areas, changes related to urbanization level and land uses may cause variations in heavy metal contents in soils of roadside trees, such as population density, road age, number of vehicles, and road network density (Silva et al., 2016). Researchers have studied heavy metals in roadside soils in different countries, such as Germany (Björn & Gerd, 2012), Canada (Wiseman et al., 2013), Australia (Silva et al., 2016). Most of these reports were about the pollution characteristics (including pollution levels, metal distribution, and migration), pollutants comparison with green space soils, or sources identification of heavy metals (Li et al., 2012). Other studies also showed that different land uses could affect the accumulation of heavy metals in urban soil (Wang et al., 2012), river networks (Zeng et al., 2020), and sediments (Li, Li, et al., 2022; Mohammadi et al., 2022). The sources of soil heavy metal pollution were also found to be related to land use types (Anaman et al., 2022; Islam et al., 2019). However, it remains unclear what are the heavy metal pollution characteristics and potential ecological risks under common land use types in highly urbanized megacities. The source correlation between various heavy metals also needs to be elucidated.

Understanding heavy metal pollution in roadside soils in megacities is indispensable for safeguarding public health, ensuring environmental sustainability, and guiding effective urban planning (Shi et al., 2023). In this study, we selected Shanghai, a highly urbanized city, as the research area to link heavy metal pollution in soils of roadside trees with urbanization. The main objective of this study was to examine how different types of land use affect the characteristics and ecological risks of heavy metal pollution in the soils of roadside trees. As a second objective of this study, we also analyzed the source association of different heavy metals. The results will provide a scientific basis for the control of heavy metal pollution, as well as urban planning and land use management in the context of rapid urbanization.

Materials and methods

Study area

Located in the eastern part of China's Yangtze River Delta region, Shanghai (30° 40′~31° 53′ N, 120° 52′~122° 12′ E) is characterized by a terrain that is higher in the southwest and lower in the northeast, with a flat landscape. The city has a humid subtropical monsoon climate, with an average annual temperature of 17.9 °C, and a rainfall of approximately 1178.2mm.

By 2020, the permanent population of Shanghai had reached nearly 25 million, and the total length of road mileage was approximately 13,000 km. As one of the most urbanized cities in China, the common land use types in the central area of Shanghai include residential, commercial, and industrial land, while other areas also include rural construction, agricultural and forestry land.

Sampling method

The land use types in Shanghai were determined using Landsat TM/ETM satellite imageries combined with field investigation, with a spatial resolution of 30 m for the output land use layer. Based on the obtained data, sampling points covering 136 roads of different land uses were selected from 16 municipal districts in Shanghai. The replication in sampling was set by randomly selected three tree pools on each road. For each tree pool, the soil sample was generated by mixing up the soils collected from 0 to 30 cm depth from four directions around the tree pool. A total of 408 mixed soil samples from 136 roads were air-dried to constant weight and stored after removing debris such as stones and plant roots. The average value of three replicates of each road was applied for further analysis.

After the laboratory analysis of the soil samples, the data was summarized to form POI (point of interest) data, which was then imported into the raster data of land use types in Shanghai. According to the national three-level classification standards for land uses and the construction intensity around sampling sites, the selected areas were further divided into five land use types. Among the 136 study areas, 37 areas were urban residential land (L1), 30 areas were commercial and service land (L2), 32 areas were industrial and mining construction land (L3), 19 were rural residential land (L4), and 18 areas were agricultural and forestry land (L5) (Vrscaj et al., 2008; Yu et al., 2018) (Fig. 1).

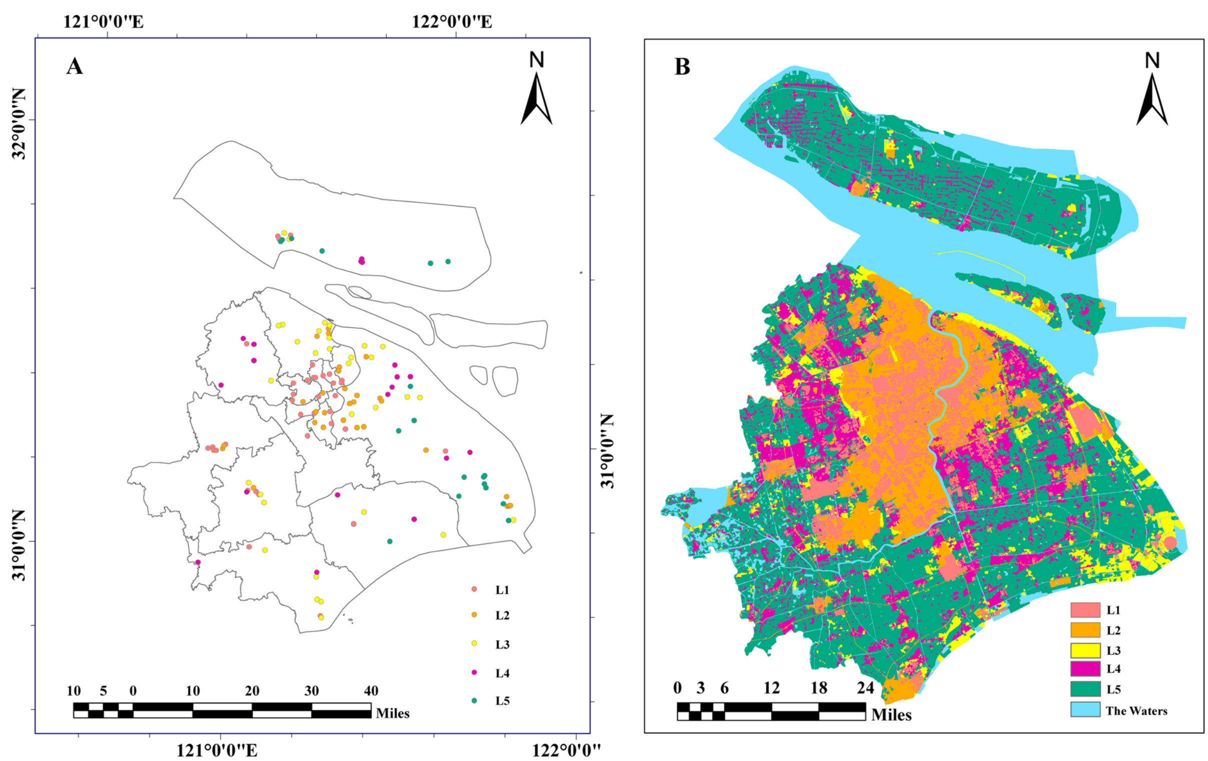

Fig. 1 Location of sampling sites

Laboratory analysis of heavy metal contents

Inductively coupled plasma atomic emission spectroscopy (ICP-AES) is a well-established analytical method to analyze trace elements in soil (Payá-pérez et al., 1993). In this study, we used the ICP-AES method to measure the contents of heavy metals. Briefly, 0.20 g of freeze-dried soil samples was taken and placed in PTFE (Polytetrafluoroethylene) digestion flasks. Then, 2 ml of nitric acid and 6ml of hydrochloric acid were added sequentially and mixed thoroughly. After the reaction, the digestion flask was placed in a microwave digestion instrument to obtain the sample solution. The standard curve was obtained by measuring a series of standard solutions using an atomic emission spectrometer (BOVEI ICP-700T). Then, the contents of Cr, Cd, Cu, As, Pb, Zn, and Ni of each sample solution were quantitatively measured and analyzed.

Assessment of soil heavy metal pollution

This study used single pollution index (PI) and single index of ecological risk factor (Er) as pollution indices to assess heavy metal contamination in soils (Kowalska et al., 2018; Weissmannová & Pavlovský, 2017). According to the Hakanson risk evaluation method (Hakanson, 1980), PI is calculated from the content of each individual metal and the reference values. Er is calculated based on PI and the toxic response factor of individual metals Ti. The following equations were used:

$$PI = Ci/Cn \tag{1}$$

where PI is the pollution index of heavy metal *i*. Ci is the measured content value of heavy metal *i*, and Cn is the background value of soil heavy metals in Shanghai. $I \leq 1$ indicates that there is no heavy metal pollution, and $I > 1$ indicates that there is heavy metal pollution in the soil.

$$Er = PI \times Ti \tag{2}$$

where Er is the single index of ecological risk factor of heavy metal *i*, with Er < 40 indicating low potential ecological risk caused by the heavy metal element, 40 ≤ Er < 80 indicating moderate potential ecological risk, 80 ≤ Er < 160 indicating considerable potential ecological risk, 160 ≤ Er < 320 indicating high potential ecological risk, and Er ≥ 320 indicating very high potential ecological risk; Ti represents the toxic response factor of heavy metal element *i* (Hakanson, 1980), with Zn as 1; Cr as 2; Cu, Pb, and Ni as 5; As as 10; and Cd as 30.

Data analysis

IBM SPSS Statistics 26 was used for multiple data analysis. ANOVA analysis was primarily conducted to determine the heavy metal contents and potential ecological risks under different land uses, while Pearson's correlation was performed to identify the source association between different heavy metals. The KMO (Kaiser-Meyer-Olkin) and Bartlett tests of the samples showed a KMO measure of sampling adequacy of 0.722 and Bartlett's test value < 0.001, indicating the adequacy of sampling and the fitness of applying principal component analysis (PCA). PCA and factor analysis were then applied to determine the potential sources of heavy metals under different land uses (Sungur, 2016). Specifically, RStudio (version R 4.0.6) was employed for data processing and visual analysis, with R-packages including tidyverse, readr, factoextra, ggplot2, scatterplot3d, and rgl. The codes are available in Supplementary material.

Results

Heavy metal contents and pollution characteristics of soils of roadside trees in Shanghai

This study determined the contents of different heavy metals in the soils of roadside trees in Shanghai. As shown in Table 1 and Table S1, the average contents of Cr, Ni, Cu, Zn, As, Cd, and Pb were 80.82 mg/kg, 35.14 mg/kg, 35.75 mg/kg, 131.78 mg/kg, 16.54 mg/kg, 0.51 mg/kg, and 40.07 mg/kg, respectively, all of which were higher than those of the soil background. The coefficient of variation (CV) reflected the average degree of variation of different sampling points. The CVs of all heavy metals were greater than 30% except for Cr and Ni, suggesting a significant spatial differentiation of these heavy metals and a difference in their sources.

Table 1 Contents of heavy metal elements in soils of roadside trees (mg/kg)

Elements	Soil background value in Shanghai	Average contents	Standard error	Range	CV (%)
Cr	75	80.82 ± 17.87	1.53	50.53–159.47	22.11%
Ni	31.9	35.14 ± 6.92	0.59	23.03–79.42	19.69%
Cu	28.59	35.75 ± 22.05	1.89	16.64–247.84	61.68%
Zn	86.1	131.78 ± 55.42	4.75	61.55–464.39	42.05%
As	9.1	16.54 ± 21.04	1.80	3.04–129.43	127.2%
Cd	0.132	0.51 ± 0.25	0.22	0.16–1.82	49.02%
Pb	25.47	40.07 ± 31.75	2.72	16.77–331.63	79.24%

The heavy metal pollution characteristics in soils of roadside trees were analyzed, using reference standards of "Background Values of Soil Elements in China (BVC)," "Standards for the Control of Soil Pollutant Risk for Agricultural Land Use (Trial)," and "Standards for the Control of Soil Pollutant Risk for Construction Land Use (Trial)". As shown in Table 2, when BVC was used as the reference standard, more than 75% of the soils were polluted by Cr, Ni, Zn, Cd, Cu, and Pb; 100% of the soils were polluted by Cd. When "Standards for the Control of Soil Pollutant Risk for Agricultural Land Use (Trial)" was used as the reference standard, 46.3% of the soils were polluted by Cd; 14% were polluted by As; Cu and Pb pollution were relatively low; and there were no Cr and Ni pollution. When taking "Standards for the Control of Soil Pollutant Risk for Construction Land Use (Trial)" as the reference standard, 100% had Cr pollution and 5.1% had As pollution, and there was no other heavy metal pollution. Varied protection focuses on different land uses resulted in the differences in soil background values and corresponding risk control reference values. This led to the variation in the pollution level and characteristics of heavy metals under different land uses.

Heavy metal content and potential ecological risk of soils of roadside trees under different land uses

The heavy metal contents and potential ecological risks of soils of roadside trees were assessed under different land uses. Except for Cu, the heavy metal content under industrial and mining construction land (L3) was higher compared with other types of land uses (Fig. 2). The heavy metal content in agricultural and forestry land (L5) was the lowest. Cu content was the highest in commercial and service land (L2), with little difference in other land uses. Pb and Cd contents were ranked as follows: industrial and mining construction land (L3) > rural residential land (L4) > commercial and service land (L2) > urban residential land (L1) > agricultural and forestry land (L5). Under different land uses, the Zn and Ni contents varied little. The Cr contents in industrial and mining construction land (L3) and rural residential land (L4) were slightly

Table 2 Percentage of polluted areas by each heavy metal in the study areas using different reference standards

Elements	BVC		Standards for the Control of Soil Pollutant Risk for Agricultural Land Use (Trial)		Standards for the Control of Soil Pollutant Risk for Construction Land Use (Trial)	
	$I \leq 1$	$I > 1$	$I \leq 1$	$I > 1$	$I \leq 1$	$I > 1$
Cr	13 (9.6%)	123 (90.4%)	136 (100%)	/	/	136 (100%)
Ni	8 (5.9%)	128 (94.1%)	136 (100%)	/	136 (100%)	/
Cu	17 (12.5%)	119 (87.5)	135 (99.3%)	1 (0.7%)	136 (100%)	/
As	78 (57.4%)	58 (42.6%)	117 (86%)	19 (14%)	129 (94.9%)	7 (5.1%)
Cd	/	136 (100%)	73 (53.7%)	63 (46.3%)	136 (100%)	/
Pb	32 (23.5%)	104 (76.5%)	135 (99.3%)	1 (0.7%)	136 (100%)	/

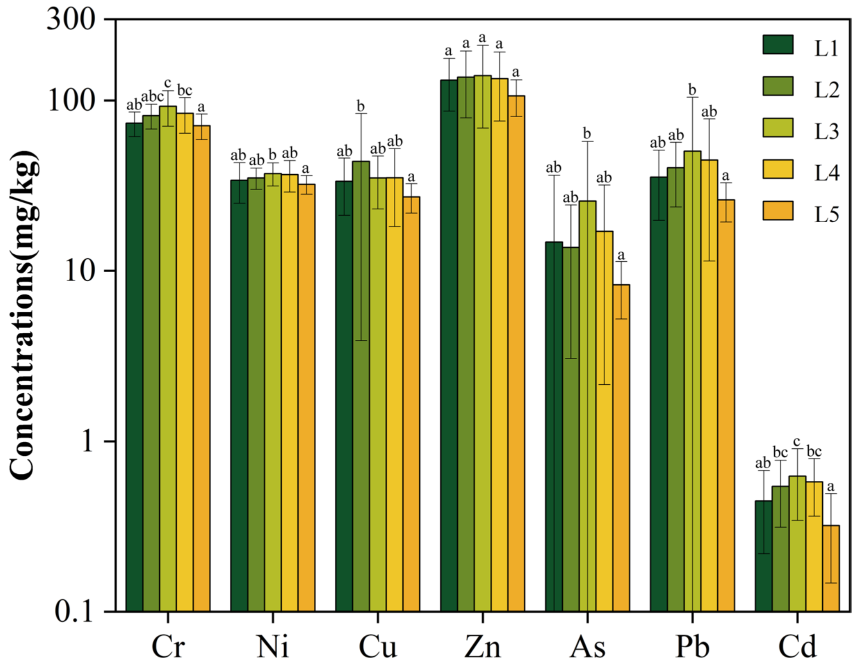

Fig. 2 Heavy metal contents in soils of roadside trees under different land uses. Different lower-case letters indicate significant differences under different land uses ($p < 0.05$)

higher than those of land uses. There was a large difference in As contents under different land uses, with the ranking order as follows: industrial and mining construction land (L3) > rural residential land (L4) > urban residential land (L1) > commercial and service land (L2) > agricultural and forestry land (L5).

The potential ecological risk index considers both the content and the toxicity of heavy metals. As shown in Fig. 3, the potential ecological risks of different heavy metals were in the following order: Cd > As > Pb > Cu > Ni > Cr > Zn. Cr, Ni, Cu, Zn, As, and Pb all showed low potential ecological risk under different land uses. However, in urban residential land (L1) and industrial and mining construction land (L3), the potential ecological risks of As in multiple discrete samples fell in the range of moderate and severe risk ($40 \le Er < 160$). The potential ecological risk of Cd was no lower than moderate under all land uses, with both L3 and L4 in the considerable risk interval ($80 \le Er < 160$) and several discrete samples in the high and very high potential ecological risk interval. Cd in L5 was of moderate risk, with a few discrete samples in more serious intervals.

Analysis of the heavy metal sources in soils of roadside trees under different land uses

The PCA analysis (Fig. 4) of heavy metal contents in the soil samples indicated that principal components 1 (PC1) accounted for 43.3% of the total variance. The factor loadings of Cr, Cd, and Ni on PC1 were all greater than 0.7, suggesting their similar sources. PC2, PC3, and PC4 had variance contribution rates greater than 10%, with PC2 accounting for 17.4% and being mainly related to Cu and Zn (factor loadings were 0.691 and 0.614, respectively). This indicated similar sources of Cu and Zn. PC3 was related to As (0.827), and PC4 was related to Pb (0.818), both of which may have other sources. All seven heavy metal elements were positively correlated with PC1; Cu and Zn were positively correlated with PC2; Cr, Ni, and Cd were negatively correlated with PC2 (Fig. 4a). The performances of heavy metals in PC1 and PC2 under L3 and L4 were similar, with largely overlapped confidence intervals. Some elements could also be fully explained by different principal components as shown by their factor loadings. Therefore, the sources of these heavy metals under the five land uses were similar to a certain extent.

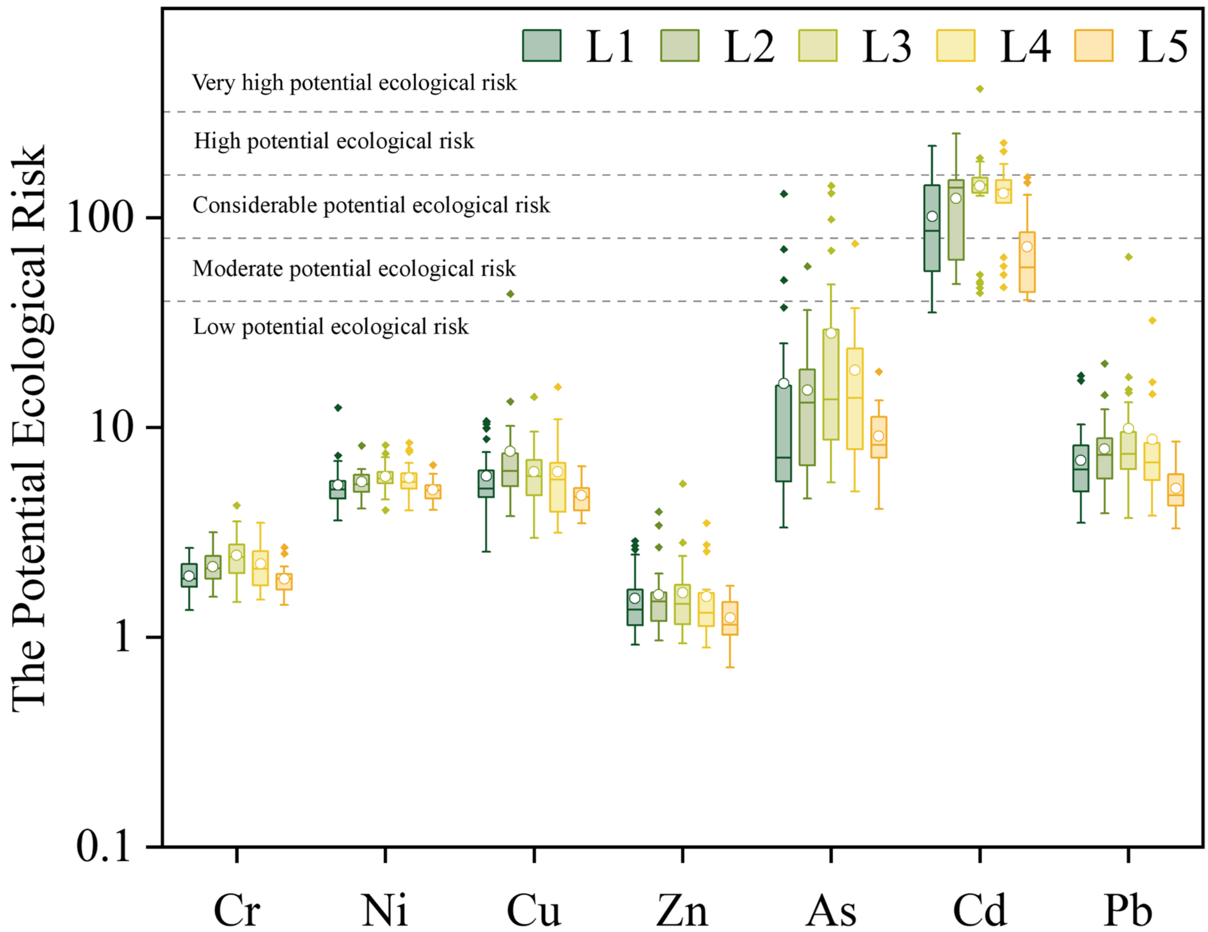

Fig. 3 Potential ecological risks of heavy metals in soils of roadside trees under different land uses

The source analysis results of heavy metals in soils of roadside trees under different land uses are shown in Table 3. In L1, all seven heavy metals could be well explained by PC1. The factor loadings of Cu and Zn were greater than 0.5 on both PC1 and PC2, indicating their similar sources in L1. In commercial and service land (L2), the factor loadings of Cr, Ni, and Cd were all greater than 0.8 on PC1, while Cu, Zn, and Pb were well explained by PC2, suggesting that the sources of these two groups may be alike in L2. As was well explained only by PC3, indicating that the sources of As were different from other heavy metals. In L3, As and Pb were fully explained by PC2 and PC3, respectively, which were significantly different from other heavy metals. In L4, all heavy metal elements except for As were fully explained on PC1, while the factor loadings of As on PC1 and PC2 were both greater than 0.5, which suggested the different sources of As. In L5, As and Cd could be sufficiently explained on PC2, yet the factor loading of Cd on PC1 was also greater than 0.5, indicating that there may be other sources of Cd in L5.

Pearson's correlations were performed to further explore the sources of heavy metals (Table 4). In L1, a highly significant positive correlation was observed between Cu and Zn ($p < 0.001$, $r = 0.621$); Cr showed positive correlations with Ni, As, Cd, and Pb; As was significantly correlated with Cd and Zn; Pb was also associated with Cu and Cd. In L2, Cu and Zn exhibited a significantly positive correlation; As had a correlation with Cd, which was the same as in L1; Cr was only significantly correlated with Ni and Cd; Pb had a correlation with Zn. In L3, Cr, Ni, Cu, Zn, and Cd were significantly

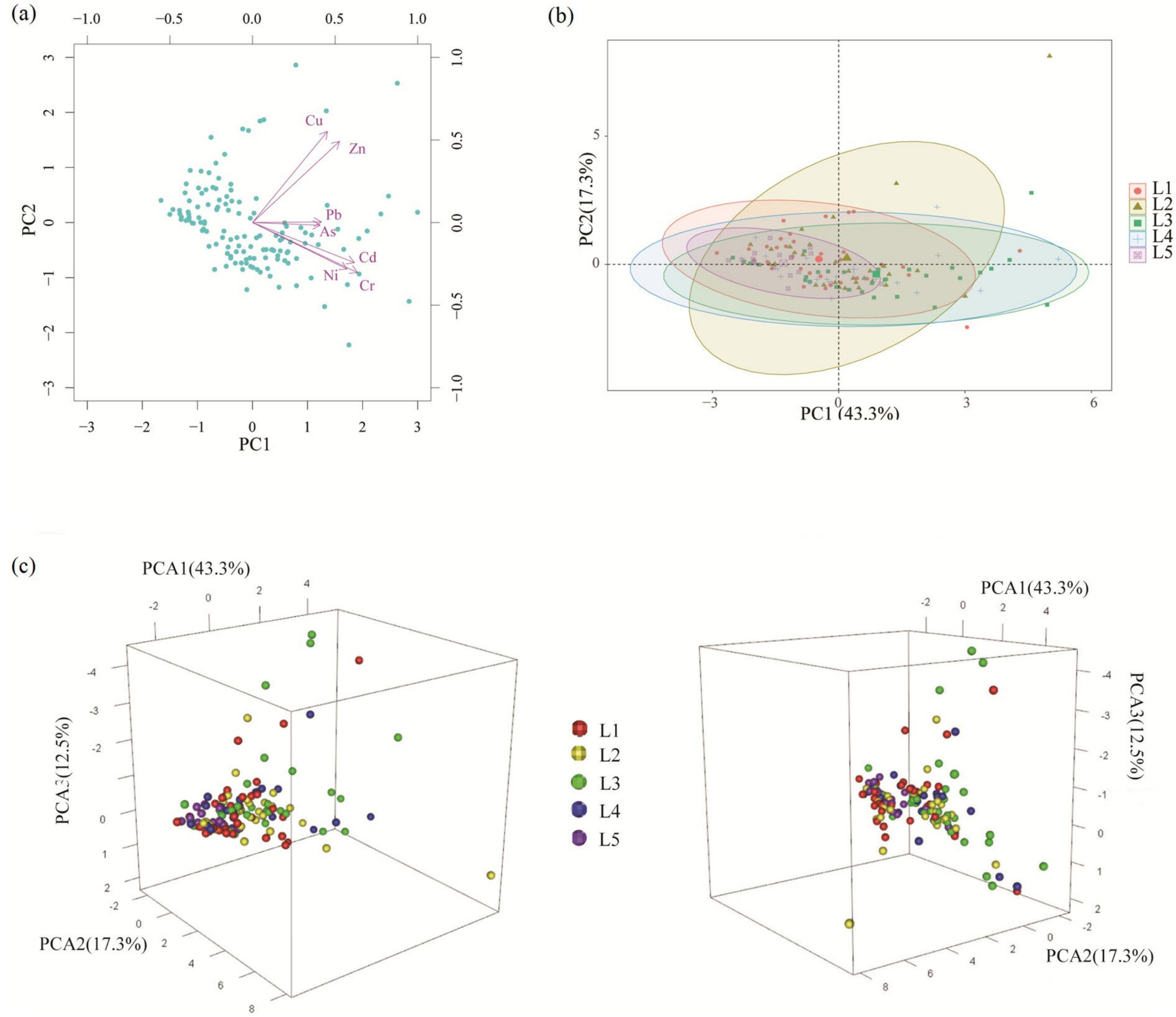

Fig. 4 Principal component analysis (PCA) plot of heavy metal content in soils of roadside trees

related and only As was correlated with Zn; Pb did not show significant correlations with other heavy metals, indicating its independent sources. In L4, there was a significant positive correlation between all heavy metals except Cr and Zn; Cu, Zn, and Ni were still significantly associated; Cd was positively correlated with all heavy metals except Pb; Pb was significantly positively correlated with Cr, Ni, and Cu, which was different from L1 and L2. In L5, As was not significantly correlated with other elements; Cu was also found to be significantly positively associated with Zn. The correlation of Cu with Zn in all five land use types suggested their relevance to traffic emissions.

Discussion

The pollution level and pollution characteristics of heavy metal in soils of roadside trees varied among different land uses

With the rapid expansion of the city, a large proportion of the land in Shanghai has been converted into residential, commercial, and industrial land (Zhao et al., 2006). Soils of roadside trees are generally more affected by human activities than soils in green spaces and thus are more prone to heavy metal pollution (Morel et al., 2015; Rezayani et al., 2022; Roy et al., 2017). The average heavy metal content in soils

Table 3 Factor loadings for source analysis of different heavy metals in soils of roadside trees under different land uses, emerging from principal component analysis (PCA) (values > 0.5 are marked in bold, indicating the adequacy in explaining their sources with the corresponding PC)

Land use types	Elements	PC1	PC2	PC3
L1	Cr	**0.800**	−0.450	0.173
	Ni	**0.556**	−0.326	0.706
	Cu	**0.604**	**0.605**	0.267
	Zn	**0.509**	**0.767**	0.034
	As	**0.701**	0.024	−0.275
	Cd	**0.750**	−0.276	−0.421
	Pb	**0.676**	−0.036	−0.296
% of variance explained		44.056	19.162	13.449
L2	Cr	**0.849**	−0.297	−0.289
	Ni	**0.811**	−0.288	−0.439
	Cu	0.313	**0.826**	0.249
	Zn	0.289	**0.899**	−0.009
	As	0.432	−0.118	**0.86**
	Cd	**0.818**	−0.253	0.366
	Pb	0.389	**0.58**	−0.373
% of variance explained		36.673	29.647	19.300
L3	Cr	**0.781**	−0.276	−0.014
	Ni	**0.866**	−0.169	−0.128
	Cu	**0.88**	−0.085	−0.029
	Zn	**0.744**	0.311	−0.257
	As	0.264	**0.893**	−0.168
	Cd	**0.784**	−0.123	0.176
	Pb	0.268	0.244	**0.916**
% of variance explained		49.209	15.445	14.012
L4	Cr	**0.876**	−0.042	−0.433
	Ni	**0.831**	−0.271	−0.328
	Cu	**0.844**	−0.238	0.37
	Zn	**0.772**	0.079	0.603
	As	**0.586**	**0.73**	−0.089
	Cd	**0.824**	0.346	−0.057
	Pb	**0.676**	−0.46	−0.04
% of variance explained		60.646	14.335	11.554
L5	Cr	**0.574**	0.177	−0.67
	Ni	**0.774**	0.42	0.011
	Cu	**0.888**	−0.32	0.188
	Zn	**0.721**	−0.588	0.264
	As	−0.091	**0.756**	0.548
	Cd	**0.644**	**0.505**	−0.179
	Pb	**0.902**	0.028	0.204
% of variance explained		49.629	21.186	13.246

of roadside trees was higher than that of the background in Shanghai. Consistent with Teng's study (Teng, 2021), a notable spatial difference in the heavy metal contents was observed, as shown by the large coefficients of variation of most elements. The differentiation was largely attributed to the surrounding traffic conditions and local constructions, which were closely related to the land use types where the soils of roadside trees were located (Bakht et al., 2022; Lu et al., 2022).

When using different reference standards to evaluate the pollution level of soil heavy metals, there can be different results due to the variation in the standards' emphasis (Gao et al., 2015). In this study, when using "Standards for the Control of Soil Pollutant Risk for Construction Land Use (Trial)" as the reference standard, there was a significant risk of Cr pollution in soils of roadside trees. However, when taking "Standards for the Control of Soil Pollutant Risk for Agricultural Land Use (Trial)" as the reference standard, there was no Cr pollution risk. The difference may result from the varied focus and suitability of different reference standards. For example, agricultural land focuses on pollutants that may pose risks to the soil ecological environment, the growth of crops, and the quality and safety of agricultural products, while construction land is dedicated to soil pollutants that may harm human health through migration and exposure (Chen et al., 2021; Liu et al., 2016).

The potential ecological risks of heavy metals in soils of roadside trees varied among different land uses

Soil heavy metal pollution exhibited unique and complex spatial distribution characteristics. The soil heavy metal contents in urban areas were generally higher than those of suburban areas, with significant differences in different functional areas and the existence of heavy metal "islands" (Keydoszius et al., 2007). Land use conditions, frequency of human interference, and distances from pollution sources will all cause notable spatial differences in heavy metal contents of urban soil (Cannon & Horton, 2009). This study displayed that the heavy metal contents and potential ecological risk of soils of roadside trees varied among different land use types. Most

Table 4 Correlation coefficients and significance levels of soil different heavy metals in soils of roadside trees under different land uses

Land use types	Elements	Cr	Ni	Cu	Zn	As	Cd	Pb
L1	Cr	1						
	Ni	0.619***	1					
	Cu	0.3	0.24	1				
	Zn	0.045	0.121	0.621***	1			
	As	0.533***	0.19	0.274	0.387*	1		
	Cd	0.598***	0.245	0.182	0.198	0.516**	1	
	Pb	0.44**	0.206	0.356*	0.241	0.266	0.556***	1
L2	Cr	1						
	Ni	0.898***	1					
	Cu	0.039	−0.058	1				
	Zn	−0.002	0.004	0.806***	1			
	As	0.133	0.019	0.217	−0.012	1		
	Cd	0.592***	0.521**	0.056	0.003	0.659***	1	
	Pb	0.129	0.234	0.341	0.519**	−0.143	0.141	1
L3	Cr	1						
	Ni	0.639***	1					
	Cu	0.64***	0.709***	1				
	Zn	0.422*	0.564***	0.656***	1			
	As	0.049	0.12	0.121	0.353*	1		
	Cd	0.552**	0.664***	0.589***	0.387*	0.138	1	
	Pb	0.131	0.088	0.202	0.102	0.097	0.25	1
L4	Cr	1						
	Ni	0.885***	1					
	Cu	0.625**	0.674**	1				
	Zn	0.412	0.46*	0.828***	1			
	As	0.483*	0.328	0.271	0.457*	1		
	Cd	0.739***	0.517*	0.565*	0.603**	0.624**	1	
	Pb	0.549*	0.56*	0.544*	0.441	0.165	0.426	1
L5	Cr	1						
	Ni	0.521*	1					
	Cu	0.338	0.634**	1				
	Zn	0.222	0.277	0.856***	1			
	As	−0.135	0.246	−0.21	−0.291	1		
	Cd	0.393	0.543*	0.316	0.072	0.093	1	
	Pb	0.321	0.582*	0.745***	0.678**	−0.002	0.693**	1

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

heavy metal contents were higher in L3 and lower in L5 than other land use types, which suggested traffic and human activities had made roadside soil more complex. Heavy metals in the soils of roadside trees mainly came from urban construction and traffic emissions, and the accumulation of heavy metals was more severe in L3. This is probably due to the busier traffic and more intense industrial activities, especially coal combustion in industrial and mining construction areas (Kang et al., 2022). In agricultural and forestry land, there is less traffic, but the utilization of fertilizers and pesticides could result in heavy metal accumulation (Rahman, 2022).

According to the potential ecological risk assessment result, the risks of heavy metal pollution in soils of roadside trees were ranked as Cd > As > Pb > Cu > Ni > Cr > Zn. Cd had significant ecological hazard as its potential ecological risk index was in the moderate to high interval in all five land use types. Mainly, in acid-soluble and oxidizable forms, Cd has high bioavailability and is the most hazardous heavy metal to the environment (Wiseman et al., 2013). The Cd content in L3 was significantly higher than that of other land use types, illustrating that besides traffic activities, industrial activities were also important sources of Cd (Shi et al., 2010). Compared with other heavy metals, Cd has stronger toxicity and higher carcinogenic risk (Lin et al., 2021; Rezapour et al., 2022). It may enter the human body through skin contact, inhalation, and so forth. A small amount of Cd in the soil may cause serious damage to human health. Therefore, it is crucial to monitor and control Cd contents in soils of roadside trees to reduce the risk of Cd migration (Mi et al., 2023).

The sources of different heavy metals were correlated in soils of roadside trees

Apart from natural sources, heavy metals in the soils of roadside trees are mostly from atmospheric dust deposition, vehicle abrasion, gasoline combustion, and road paint (Alsanad & Alolayan, 2020). The sources of Cu and Zn in all five land use types were extremely similar and were both attributed to traffic emissions (Shi et al., 2010). Specifically, the main source of Cu was the abrasion of the vehicle braking system, while Zn mostly came from tire wear (Padoan et al., 2017). Traffic emissions were also the sources of Cr, Cd, and Ni (Viana et al., 2008). Although traffic emissions are important sources of most heavy metals (Rodriguez et al., 2009), there exist other sources (Yin et al., 2013). The sources of As and Cd differed among different land use types. In L2, As may come from the extensive application of metal work, wood preservation facilities, and semiconductor materials; in L3, As may be from the diffusion of industrial production leakage; in L4, As may come from agricultural supplies such as pesticides, herbicides, and fertilizers (Swab et al., 2019; Wang & Mulligan, 2006). Unlike other land uses, the use of agricultural fertilizers and sewage irrigation may be the main sources of Cd in L5 (Amir et al., 2020; Zhao et al., 2014).

Soil Pb pollution is highly correlated with traffic emissions and can be considered an indicator of vehicular pollution. However, in L3, Pb was not significantly correlated with other heavy metals, which indicated that factories were also important sources of Pb in soils of roadside trees as Pb is an important raw material for industrial production (Cong et al., 2022). Cr and As in urban soil displayed characteristics of combined pollution. In this study, as the Cr content increased, the content of other heavy metals also increased significantly, which may result from the fact that heavy metal pollution in soils of street trees is also influenced by soil parent material. Cd may come from the large amount of yellow paint used for road markings in Shanghai, which was reported to contain much higher Cd content than other heavy metals (Lee et al., 2018). The high correlation between Pb and Cd in L1 and L2 might arise from the colored paint which contains heavy metals such as Cd, Cu, and Pb.

Conclusions

This study conducted an analysis of heavy metal pollution in soils of roadside trees under five different land uses, focusing on Cr, Ni, Cu, Zn, As, Cd, and Pb. The results indicated that the average heavy metal content in roadside soils was higher than that of the soil background. The highest heavy metal content was observed in industrial and construction land (L3), while the lowest was in agricultural and forestry land (L5). Among the seven heavy metals, Cd had the highest potential ecological risk across all five land use types. Furthermore, L3 exhibited significantly higher concentrations of Cr, Ni, As, Cd, and Pb than other land types, while commercial and service land (L2) displayed notably higher Cu content. Within residential land, rural residential land (L4) showed higher heavy metal content compared to urban residential land (L1). The study also identified correlations in the sources of heavy metals in soils of roadside trees under different land uses. Similar to Cu and Zn, heavy metals of Cr, Ni, and Cd also displayed similar sources, which were all linked to traffic emissions. As exhibited characteristics of combined pollution with multiple sources. Pb in L3 originated from both traffic and industrial emissions, whereas Cd contamination in L5 could be attributed to the use of fertilizer and wastewater irrigation. These findings establish a relationship between land uses and the characteristics of heavy metal pollution in soils of roadside trees. It also identified the potential ecological risks and sources of heavy metals under different land uses in large cities. The results will provide valuable references for the guiding of urban land planning, as well as for the monitoring of heavy metal pollution to ensure human health and environmental sustainability.

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Author contribution H. K. and W. B. conceived the idea and designed the research workflow. H. K. and W. J. carried out the experiment and wrote the manuscript. G. H. and Z. Y. performed the data analysis. H. K. and F. S. provided resources needed in the research. Q. Z. and L. N. provided guidance for data analysis. Y. R. revised the manuscript. All authors have read, revised, and approved the submitted version of the manuscript.

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Data availability All data generated or analyzed during this study are included in this published article. Additional information is freely available from the corresponding author.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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