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Correlation Analysis of Ecosystem Reduction and Retention Effects and Spatial Distribution of Soil Potential Toxicity Elements

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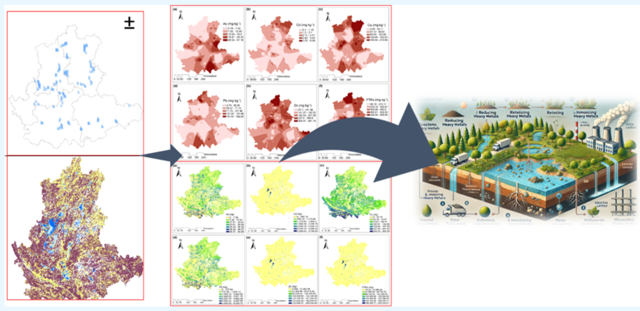

ABSTRACT: Soil contamination by potentially toxic elements (PTEs) poses a significant threat to crop quality and human health, making it a global concern. However, the distribution patterns of PTEs across different land-use types are not well understood. To investigate the relationship between the reduction and retention effects of various ecosystem types on soil PTEs, we analyzed five categories of target elements in 299 soil samples from the southeastern Yunnan Province. Using the intelligent urban ecosystem management system's surface source control (runoff) model, descriptive statistical methods, spatial interpolation analyses, and GIS, we simulated the effects of different ecosystem types on soil heavy metals. This approach allowed us to examine the spatial correlations among ecosystem reduction, retention, and PTE distribution in soils. Our results indicate that soil PTE concentrations were indicative of a high-background value area, with concentrations of arsenic, cadmium, copper, lead, and zinc exceeding risk screening values. The coefficients of variation for arsenic, cadmium, and lead were extremely high and attributable to high external anthropogenic interference. Soil heavy metal reduction and spatial distribution were affected by the ecosystem's control function, and different ecosystems had different reduction effects. The reduction simulations for As and Pb were concentrated in building areas, while those for Cd and Zn were primarily focused on water bodies. The reduction simulations for Cu were concentrated in the forested areas. In conclusion, ecosystem reduction and retention influence heavy metal distribution, which is essential when planning green ecological development and construction.

1. INTRODUCTION

Potential toxicity elements (PTEs) are persistent pollutants with a high potential for toxicity, bioaccumulation, and degradation in soil.[1,2] Among them, arsenic (As), cadmium (Cd), copper (Cu), lead (Pb), and zinc (Zn) are of particular concern in ecological environmental management.[3] Excessive accumulation of PTEs in soil can disrupt its original structure, leading to varying degrees of degradation and loss of soil function and negative impacts on crop yield and quality.[4] In addition to damaging soil, studies have shown that PTEs pose significant threats to human health through physiological and molecular pathways such as inhalation, ingestion, dermal exposure, and through the food chain.[5−9] Long-term exposure to cadmium (Cd) has been linked to cancer, inhibition of protein synthesis, and an increased risk of bone fractures. Lead (Pb) burdens the kidneys, affects the reproductive system, and is associated with an increased risk of miscarriage. It also impairs intellectual development in children. Copper (Cu) toxicity may lead to hemolysis, multiorgan failure, and other symptoms.[10,11] While micronutrients like copper and zinc are essential for human health, excessive intake can result in a range of health problems.[12] With the rapid societal development in recent years, large-scale heavy metal mining and the extensive use of heavy metals in industrial and agricultural production have exacerbated the accumulation of PTEs in soil, thereby increasing the associated health risks.[13,14] Therefore, studying the distribution characteristics and sources of soil PTE pollution is crucial for providing the necessary data for mitigating and controlling PTE pollution and predicting future pollution trends.

The background concentration of heavy metals in soil is primarily associated with soil components that are minimally disturbed or unaffected by human activities, and heavy metals are present in various solid-phase fractions.[15,16] Compared to other provinces in China, certain areas of Yunnan Province exhibit higher background levels of heavy metals due to their unique geological characteristics.[17,18] Previous studies have shown that heavy metal enrichment in high-background areas is

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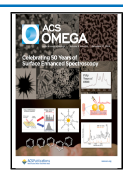

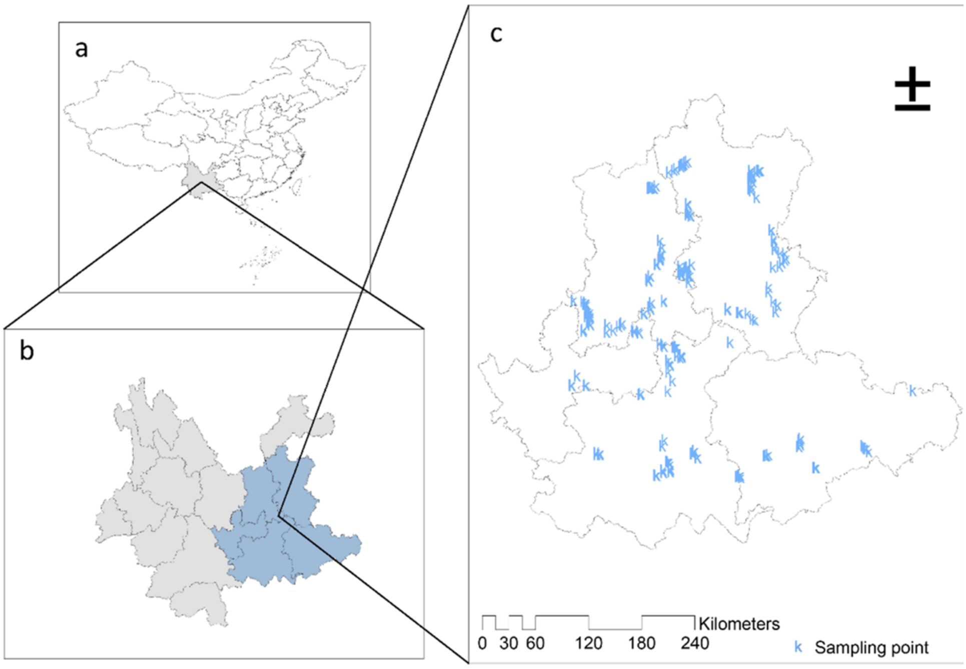

Figure 1. Maps show the study area's location in (a) southwest China, (b) southeast Yunnan Province, and (c) the soil sampling points throughout the study area.

closely related to soil weathering processes, particularly influenced by minerals such as carbonate rocks and basalt, which contribute to favorable conditions for mineralization through weathering and migration.[19−21]

However, the distribution and accumulation of heavy metals in soil are influenced not only by natural geological factors but also significantly by human activities. Industrial emissions, agricultural fertilization, and urbanization introduce additional heavy metals, altering their concentrations in the soil with varying degrees of impact depending on the region. Previous research has utilized various receptor models (such as APCS/MLR, PMF, and UNMIX),[22−24] geological statistical analysis methods, and pollution source risk assessments based on Monte Carlo simulations, including the integrated index of contamination quality (IICQ) and hazard index (HI),[25,26] to analyze potential sources of soil PTEs. These methods have clarified the extent to which human activities influence heavy metal concentrations in soil.

The karst landscape covers a large area with steep terrain, and the annual average rainfall exceeds 1000 mm, concentrated from June to September. As a result, PTEs enriched in surface soils are more likely to migrate with runoff during rainfall washout and surface leaching compared to those in other areas. The interception of surface runoff by ecosystems during transport leads to varying degrees of reduced pollutants trapped, altering[27] the distribution and enrichment patterns of soil PTEs as the ecosystem structure changes. Understanding the distribution patterns of soil PTEs has recently been recognized as a critical aspect of ecological restoration, a topic that has not been fully studied.

Ecosystems play a significant role in the migration and transformation of soil heavy metals. Heavy metals in soil can be converted into nontoxic or less toxic substances through biological processes, such as the metabolic activities of plants, animals, and microorganisms, as well as through artificial interventions employed in ecological remediation. Phytoremediation removes heavy metals from the soil through mechanisms, such as extraction, immobilization, volatilization, root filtration, and degradation.[28] Plant root growth can compact the soil and alter the composition of soil aggregates, thereby affecting the distribution and morphology of the heavy metals. Microorganisms reduce the toxicity of heavy metals by adsorbing, transforming, and solubilizing them and by producing small-molecule organic acids that increase the solubility and bioavailability of heavy metals.[29] Various fungi and bacteria have been used in the microbial remediation of heavy metals, and soil aggregates often control the survival of soil microorganisms.[30] Guan et al. demonstrated that supplementing plants and microorganisms with heavy metal solidifying agents during remediation is a promising research focus.[31] They found that altering the chemical form of heavy metals through adsorption, transformation, and immobilization can reduce their activity and bioavailability in soil. However, the transformation of heavy metals through solidification and stabilization remains a challenge. Ecosystem intercept and precipitate substances carried by runoff, and through the biochemical and synergistic interactions of plants, animals, and microorganisms, they facilitate the enrichment, absorption, degradation, and inactivation of pollutants within sediments. This process ultimately affects the natural transfer of heavy metals. The varying states of dissolution and adsorption of heavy metals in runoff and the structural differences among ecosystems result in distinct capacities for intercepting these metals. Consequently, this variability influences the migration, transformation, and distribution of soil heavy metals as simulated in this study.

This study aimed to enhance our understanding of the distribution and contamination characteristics of soil heavy metals as influenced by ecosystems and to predict potential dynamic changes. This was accomplished by (1) conducting spatial interpolation and statistical analysis of soil PTEs in southeastern Yunnan Province; (2) analyzing the reduction and retention of soil PTEs by different ecosystems using the IUEMS platform model and the geospatial data processing and mapping functions of GIS; and (3) investigating the influence of

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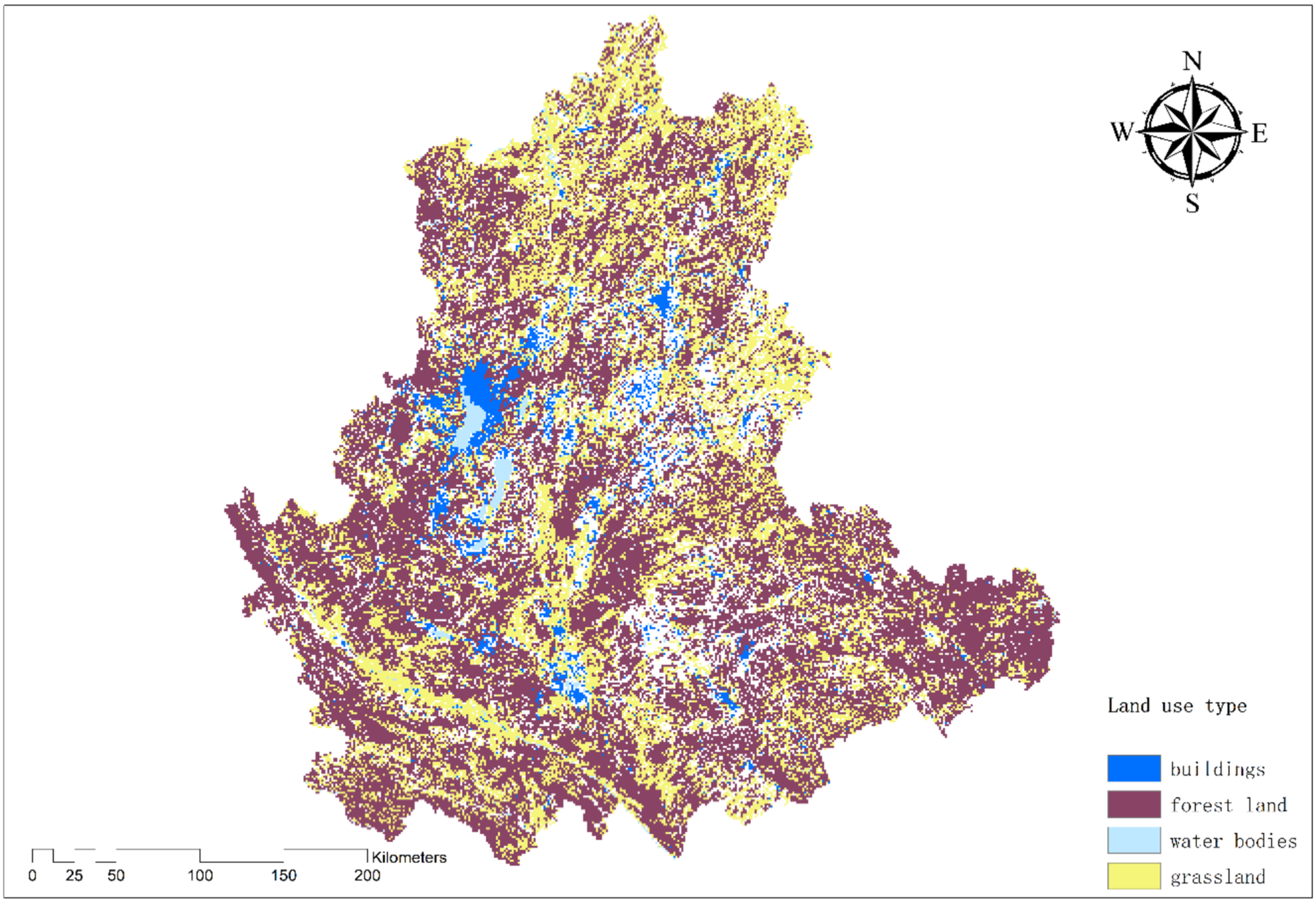

Figure 2. Map showing the four major classes of land-use types in southeast Yunnan identified using the IUEMS platform.

ecosystems on soil heavy metal distribution based on two-factor spatial correlation analysis. The results can inform regional ecological planning and restoration efforts, supporting the development of more rational and orderly strategies that align with green and sustainable development principles.

2. MATERIALS AND METHODS

2.1. Study Area. The study area is based in southeastern Yunnan Province, southwestern China (22.44−27.05° N; 101.28−106.20° E). The region incorporates the five cities of Qu Jing, Wen Shan, Hong He, Yu Xi, and Kun Ming, under the jurisdiction of Yunnan. According to the 2020 Seventh Population Census of Yunnan Province, the combined population of these five cities was approximately 24,456,000, accounting for 51.8% of Yunnan's total population. The study area comprises 12.93 km^2 of mixed land-use types, dominated by karst topography, rolling hills, and low mountains. The parent rocks in the study area are predominantly carbonate rocks; the main soil types are laterite and red loam, and the main minerals are copper and lead−zinc ores. The mean annual temperature ranges from 14 to 16 °C, with an annual precipitation ranging between 1000 and 1200 mm.

2.2. Sample Collection. A total of 299 soil samples were collected from the study area between 2017 and 2019. The sampling sites were mainly undisturbed plots away from cities, factories, mining areas, and other areas polluted by humans. Sample collection followed the principle of uniform distribution, with mixed samples taken from 3 to 5 sampling points. The sampling area and distribution of sampling points are shown in Figure 1. The samples were stored in numbered plastic Ziplock bags, and photographs of the sampling sites were taken to record the GPS coordinates and soil types.

The soil samples were immediately transported back to the laboratory. The samples were air-dried, and debris such as plant residues, animal remains, and root stubble were removed. Samples were then ground and double-sieved to 2 and 0.149 mm, respectively. The processed samples were categorized, preserved, and labeled with information, such as the sample number, sampling site, soil type, and sieve size.

2.3. Data Acquisition. The raster map of land-use types in the study area in 2021 was obtained from the Earth Resources Data Cloud Platform (www.gis5g.com), which classifies land-use types into six primary classes and 25 secondary classes according to the land-use and cover change (LUCC) classification system at a resolution of 1000 m. The land-use data reclassification panel of the IUEMS (www.iuems.com) platform was used to reclassify the study area into four major classes: forest land, grassland, buildings, and water bodies (Figure 2).

The 2019 annual cumulative rainfall and annual cumulative runoff raster data for the study area were obtained from the Earth Resources Data Cloud platform (www.gis5g.com) at a resolution of 1000 m.

Runoff coefficients for the five target heavy metals in each ecosystem type were obtained through a literature review. Field sampling of the target data or estimation of the target data through simulation experiments was conducted to obtain more accurate data where conditions permitted.

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2.4. Sample Analysis. Soil samples were air-dried, ground, screened, and then analyzed for their heavy metal and trace element contents according to national standards. The digestion procedures for the soil samples followed method 3050B (USEPA, 1996). Each powdered soil sample was digested with a mixture of HNO_3 and H_2O_2. Elemental As was detected using an atomic fluorescence spectrophotometer (Haikou Instruments AES-230E); Cd and Pb were detected using a graphite furnace atomic absorption spectrophotometer (GGX-830, Beijing Hai Guang Instrument Co., Ltd., Beijing, China); and elemental Cu and Zn were determined using a flame atomic absorption spectrophotometer.

2.5. Data Processing. Microsoft Excel 2019 was used for the basic processing of the collected soil sample data. The sampling points and spatial distribution of heavy metals were mapped using ArcMap 10.4.1 (ESRI, Redlands, CA). The data were analyzed using descriptive statistics generated in SPSS 24.0 (IBM Inc. Armonk, NY).

2.6. Simulation and Analysis of Ecosystem Clipping and Retention Effects. Using the surface source pollution control (runoff) model of the ecological model panel of the IUEMS platform, we analyzed and studied the reduction and retention of heavy metals by ecosystems in the region in combination with relevant basic data. The simulation results were visualized by using ArcMap 10.4.1. The relevant principles of the model are as follows

Rapid societal development has led to land-use changes, resulting in numerous pollution problems. Ecosystems can abate runoff during precipitation, thereby reducing the amount of pollutants dissolved in water. This model is based on a curve model (SCS-CN model) that calculates the amount of runoff reduction provided by ecosystems, from which the amount and rate of pollutant reduction are calculated as follows[32]

$$\Delta Q_i = \sum_j P_{i,j} - Q_{i,j} \tag{1}$$

$$Q_j = \begin{cases} \dfrac{(P_i - 0.2s)^2}{P_i - 0.8S}, & P_j \geq 0.2S \\ 0, & P_j < 0.2S \end{cases} \tag{2}$$

$$NS_i = \sum_j \frac{\Delta Q_{i,j} \times A_i \times \text{EMC}_i}{30 \times 10^9} \tag{3}$$

$$ns_i = \frac{NS_i}{NS_i + Q_i \times \text{EMC}_h \times A_i} \tag{4}$$

where ns_i is the annual average surface pollutant abatement rate of the ith plot; NS_i is the annual average surface pollutant reduction of the ith plot (g/yr); $\Delta Q_{i,j}$ is the depth of runoff generated on the ith raster during rainfall event j (mm); $Q_{i,j}$ is the depth of runoff generated on the ith raster during rainfall event j (mm); P_j is the daily rainfall in rainfall event j (mm); EMC_i is the average event concentration of surface source pollutants on the ith grid (mg/L); and A_i is the area of the ith grid (m^2); S is the potential maximum water storage load of the soil (mm); Q_j is the runoff depth in rainfall event j (mm); ΔQ_i is the runoff depth cut in rainfall event j (mm); $P_{i,j}$ is the daily rainfall generated on the ith grid in rainfall event j (mm); EMC_h is the average event concentration of surface source pollutants on the hth grid (mg/L).

2.7. Spatial Correlation Analysis. ArcMap 10.4.1 was used to analyze the correlation between the spatial distribution data of heavy metals in the study area and the simulation results of ecosystem chipping and stagnation. In ArcMap 10.4.1, the two types of raster data were normalized using the "Raster Calculator" with eq 5, so that the image data were between 0 and 1, and the processed data were dimensionless,

$$y = (x - \text{value\_min})/(\text{value\_max} - \text{value\_min}) \tag{5}$$

where x is the target raster data, Value_min is the minimum value of the image elements within the raster data, and Value_max is the maximum value of image elements within the raster data.

The tool "band set statistics" was used to conduct the correlation analysis, and the covariance and correlation matrices were calculated simultaneously so that the single-layer statistics, covariance matrix, and correlation matrix of the two raster data types were used for the correlation analysis. Pearson's correlation coefficients were derived from the band set statistical analysis, which can be used to show the correlation between two layers. Thus, spatial correlation analyses were performed between the data.

2.8. Statistical Analyses. Statistical analyses were performed using SPSS 24.0 (IBM Inc., Armonk, NY), and statistical significance was set at $p \leq 0.05$.

3. RESULTS

3.1. Heavy Metal Concentrations and Distribution in Soils. Based on the results of heavy metal detection in the soil samples, the concentrations of five target elements (As, Cd, Cu, Pb, and Zn) were analyzed by using descriptive statistics (Table 1). The concentration ranges (mg kg^{-1}) were 0.07−68.18 (As), 0.09−8.57 (Cd), 2.86−454.11 (Cu), 3.35−411.24 (Pb), and 3.88−560.78 (Zn), respectively.

Table 1. Descriptive Statistics of Soil Heavy Metal Concentrations in the Study Area[a]

target elements	As	Cd	Cu	Pb	Zn
sample size (n)	291	292	293	288	296
minimum (mg kg^{-1})	0.07	0.09	2.86	3.35	3.88
maximum (mg kg^{-1})	68.18	8.57	454.11	411.24	560.78
median (mg kg^{-1})	7.80	0.70	61.40	31.44	173.70
average mean (mg kg^{-1})	11.00	1.37	85.20	54.70	198.84
standard deviation	11.52	1.61	71.52	70.85	123.18
geometric mean	5.94	0.87	57.60	33.50	155.14
CV (%)	107.70	117.04	83.94	129.53	61.95
MBV	10.90	0.08	28.70	35.70	86.00

[a]CV, coefficient of variation; MBV, median geological background value; As, arsenic; Cd, cadmium; Cu, copper; Pb, lead; Zn, zinc.

The mean concentrations of the five heavy metals were higher than the corresponding median concentrations. According to the China National Environmental Monitoring Centre (CNEMC),[33] the geometric mean values of soil PTE concentrations, except for As and Pb, in the study area were significantly higher than the median geological background values (MBV) in Yunnan Province. The geometric means of Cd, Cu, and Zn were 10.88, 2.01, and 1.81 times higher than the median values of their corresponding background values, respectively. In addition, the mean soil PTE concentrations in this study exceeded the risk screening value of soil PTEs set by

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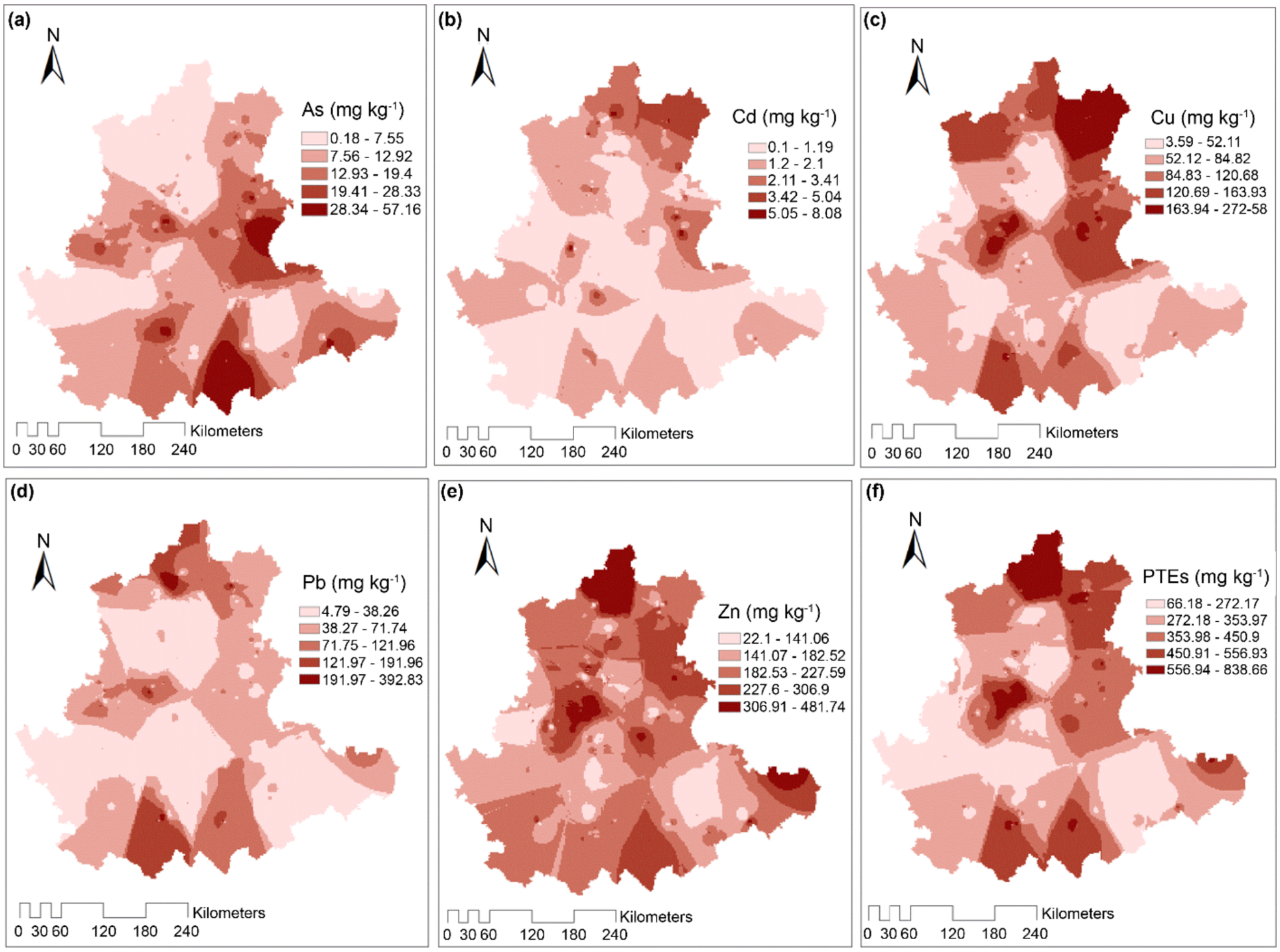

Figure 3. Spatial distribution patterns of (a) arsenic, (b) cadmium, (c) copper, (d) lead, (e) zinc, and (f) overall target elements in the soils of southeast Yunnan. The color gradients indicate hotspots (dark red) of the highest concentrations (mg kg^{1-}).

the Environmental Monitoring Centre of the Ministry of Environmental Protection (GB15618−2018).[34] Among them, 14.43% (As), 91.10% (Cd), 58.70% (Cu), 19.80% (Pb), and 42.57% (Zn) of the soil samples had concentrations exceeding the risk screening value for heavy metals. The calculated coefficients of variation (CV) for the five heavy metals were greater than 60%; As (107.70%), Cd (117.04%), and Pb (129.53%) had the highest CVs, indicating that these soil PTEs were more exposed to external disturbances.

To better reflect the spatial distribution of soil PTEs in the study area, a spatial interpolation technique was used to create a distribution map of soil heavy metals using the five cities in southeastern Yunnan as the base map (Figure 3). The areas with high concentrations of Cu and Zn showed a high degree of overlap, characterized by a pronounced triple high-value zone in the northern, southern, and central regions, similar to the distribution pattern of total PTEs. The concentrations of Cd and Pb were relatively evenly distributed, with fewer high-value areas compared to those of Cu and Zn, and the main high-value areas were close to densely populated urban areas with heavy traffic. The high-value areas for As were concentrated in the central and southern parts of the study area, most notably in the east-central and southeastern regions.

3.2. Soil PTE Reduction and Retention Analysis. Ecosystems have buffering, cutting, and retention effects on pollutants; however, PTEs vary depending on the type and structure of the ecosystem. Furthermore, the unique characteristics of different pollutants impact how they are reduced and retained.[35] These factors cannot be overlooked during the transformation, management, and protection of ecological environments. Vegetation is a key component of the ecological buffer zone. Differences in vegetation type and structure directly affect the pollutant interception capacity of buffer strips, which also varies depending on the age of the vegetation. Vegetation root systems can reduce or minimize the entry of pollutants into streams by regulating the surface runoff. The combined planting of herbaceous plants and trees can significantly enhance the pollutant interception and purification effects of an ecosystem, and natural vegetation is more effective at absorbing pollutants. Forest ecosystems can significantly reduce the diffuse loss of sediment.[36] In ecological planning, construction, and restoration, it is necessary to select native vegetation or vegetation types suitable for the local environment and to strengthen the protection and management of vegetation to improve the overall functional effectiveness of the ecosystem.[37]

Using a surface pollution control (runoff) model, we simulated reductions in heavy metals within the ecosystem of the target area (Figure 4). The reduction patterns of the ecosystems in the study area differed for each heavy metal; however, those for As and Pb were similar (Figure 4a,d), and Cd

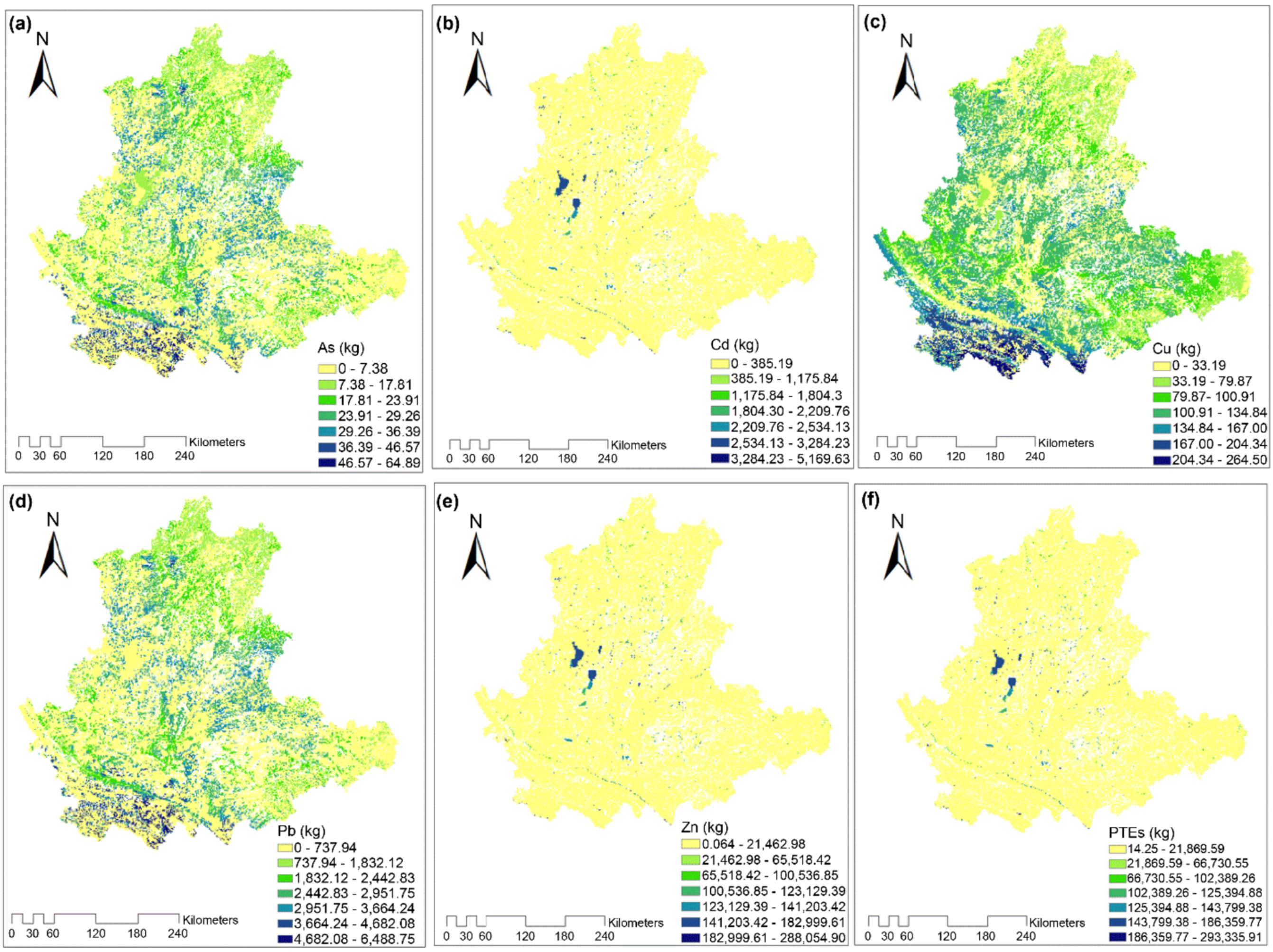

Figure 4. Modeling of reduction and retention of (a) arsenic, (b) cadmium, (c) copper, (d) lead, (e) zinc, and (f) overall target elements by different land-use types in Southeast Yunnan (yellow = low concentration; blue = high concentrations).

and Zn were similar (Figure 4b,e). The reduction in Cu (Figure 4c) exhibited an opposite pattern compared to those in Pb and As, and the overall reduction in target elements was primarily concentrated in the water body area (Figure 4f). When examining these results about the land-use types in the target area, the order of Pb and As reduction across each land-use type was building > grassland > forest land > water body. The most apparent reductions were observed in a southwesterly direction toward urban areas (Figure 4a,d). Furthermore, it should be noted that Pb and As concentrations exceeded acceptable standards in the "building" area. The reduction patterns for Cd and Zn were concentrated in water bodies, including Dianchi Lake, Fuxian Lake, Isolong Lake, river basins, and paddy fields. The remainder of the distribution was relatively uniform; however, these simulated results indicate that paddy fields, rivers, and lakes with high Cd and Zn levels should be the focus of management actions, particularly those with heavy metal concentrations exceeding the accepted standard. The order of Cu reduction was forest land > grassland > water bodies > buildings.

Notably, the overall reduction of target elements was remarkably influenced by Cd and Zn, and the reduction distribution maps for the overall target elements, Cd and Zn, were similar (Figure 4b,e,f). Therefore, reductions in Cd and Zn should be emphasized in ecological restoration projects, focusing on overall target elements.

3.3. Correlation Analysis between Ecosystem Cutback Retention and Distribution of soil PTEs. The results of the correlation analysis between ecosystem reduction, retention, and spatial distribution of soil heavy metals are shown in Table 2. For three heavy metals (As, Pb, and Zn), ecosystem reduction, retention, and spatial distribution were positively correlated, with correlation coefficients of 0.08, 0.07, and 0.04, respectively. The distribution of ecosystem reduction for these three heavy metals was positively correlated with their spatial distribution. In contrast, the ecosystem reduction and retention effects of Cd and Cu were negatively correlated with the spatial distribution of soil heavy metals, with correlation coefficients of −0.02 and −0.12, respectively. Thus, the ecosystem reduction effects of Cd and Cu were inversely related to the spatial distribution of heavy metals. However, in the analysis of overall target elements, it was found that the ecosystem reduction and retention of overall target elements were positively correlated with their spatial distribution, yielding a correlation coefficient of 0.05, which may have been influenced by Cd and Cu. This correlation value was not significant compared to those of As, Pb, and Zn.

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Table 2. Spatial Correlation Analysis Table[a]

	DT	MEAN	STD	SD	COVA
As	SDD	0.21	0.13	0.01	0.08[b]
	DR	0.15	0.20	0.02	
Cd	SDD	0.17	0.10		−0.02[b]
	DR	0.01	0.06		
Cu	SDD	0.31	0.17	0.01	−0.12[c]
	DR	0.27	0.23	0.02	
Pb	SDD	0.14	0.20	0.00	0.07[b]
	DR	0.13	0.10	0.02	
Zn	SDD	0.39	0.12	0.01	0.04[b]
	DR	0.01	0.06	0.00	
PTEs	SDD	0.38	0.15	0.01	0.05[b]
	DR	0.01	0.06	0.00	

[a]DT: Data type, including spatial distribution data of heavy metals (SDD) and ecosystem reduction stagnation analysis data (DR); MEAN: normalized data image mean; STD: standard deviation of normalized data image; SD: sample variance; COVA: data correlation coefficient. [b]Statistically significant at the 0.05 level. [c]Statistically significant at the 0.01 level.

4. DISCUSSION

4.1. Heavy Metal Distribution and Ecosystem Reduction and Retention Effects. Statistical analyses of the soil data clarified the distribution characteristics of heavy metals in areas with high-background values and provided a basis for determining the potential risk of soil PTEs in the study area. The coefficients of variation for the five target heavy metals indicated that the pollution enrichment of some soil heavy metals was related to human activities; however, the enrichment levels varied among different land-use types. This variation was attributed to differences in pollution enrichment characteristics related to anthropogenic land-use changes.[38] The retention role of different ecosystems not only varied under different land-use modes but also affected the soil heavy metal reduction performance.

By simulating a particular ecosystem's role in heavy metal reduction and retention and conducting a spatial correlation analysis with the distribution of soil heavy metals, this study characterized the patterns of the ecosystem's reduction of the five types of heavy metal elements and revealed the positive and negative correlations between them. There was a positive correlation among As, Pb, and Zn and a negative correlation between Cd and Cu. These two modeling approaches provide an ecological perspective on heavy metal remediation in contaminated soils, and the results can be used to inform future land development.

4.2. Effects of Ecosystem Structure and Function on the Distribution of Soil PTEs. The structure and function of different ecosystems (forest land, grassland, construction land, and water bodies) significantly influence the distribution of soil PTEs. The compositions of fauna, flora, and microorganisms vary among these ecosystems. The results of the simulation and analysis of the effects of ecosystems on the reduction and retention of soil heavy metals showed clear differences in their ability to reduce and retain the same types of heavy metals.

Woodland ecosystems typically consist of trees, shrubs, and other vegetation with complex root systems and rich soil biomes. Vegetation in woodlands effectively reduces the concentration of PTEs in the soil through adsorption and transport. Simultaneously, woodland vegetation has a strong enrichment effect on soil PTEs, which can be immobilized by organisms, thereby decreasing soil pollution.

Grassland ecosystems consist primarily of herbaceous vegetation, which tends to have shallow root systems but provides dense vegetative cover. Grassland vegetation adsorbs and translocates PTEs through the root system to minimize their spread in the soil. Similar to woodland vegetation, grassland vegetation can reduce soil contamination by enriching PTEs and immobilizing them on the surface or within the vegetation.[39]

Constructed land was developed and utilized by humans. It has low vegetation and soil cover, is frequently a hotspot for soil pollution, and generally contains hardened road surfaces. The results of the simulation analysis were compared with the spatial distribution map of heavy metals, the effect of constructed land on the reduction and retention of soil PTEs was not evident, and it had a promoting effect on the enrichment of soil PTEs. Simultaneously, the emission of pollutants from constructed land and soil damage increases the concentration of soil PTEs, the risk of soil pollution, and the difficulty of remediating soil PTE pollution.

Water bodies also have a significant effect on the distribution of certain elements in the soil. They can carry PTEs away from the soil or deposit them at the bottom through transportation and deposition.[40] According to the simulation analysis of the ecosystem reduction and retention effects in this study, heavy metals were found to be highly enriched in water bodies; therefore, it is essential to address heavy metal pollution in watersheds and paddy fields.

The structure and function of different ecosystems have complex effects on the distribution of PTEs in soil. Forest and grassland ecosystems are conducive to reducing the concentration and pollution of soil PTEs, whereas construction land and water bodies may lead to the accumulation and spread of soil PTEs. For soil environmental protection and management, it is necessary to comprehensively consider the characteristics of different ecosystems and develop measures to reduce the pollution and risk of soil PTEs.

5. CONCLUSIONS

In this study, the spatial distribution characteristics of soil heavy metals and high-risk zones were explored through a spatial interpolation analysis of heavy metals in southeastern Yunnan. Furthermore, when combined with the surface pollution control (runoff) model, the simulation analysis of ecosystem reduction and retention in the study area visually demonstrated the reduction and retention of heavy metals by different ecosystem types. A correlation analysis was also conducted to verify the influence of the ecosystem type on the distribution of heavy metals, leading to the following conclusions:

(1) The analysis of heavy metal concentrations in soil samples revealed that levels of arsenic (As), cadmium (Cd), copper (Cu), lead (Pb), and zinc (Zn) significantly exceeded the median geological background values in Yunnan Province, particularly for Cd, Cu, and Zn. The mean concentrations of these heavy metals were consistently higher than their corresponding median values, indicating potential environmental risks. Notably, a significant percentage of samples exceeded the risk screening value for these metals, suggesting widespread contamination. The coefficients of variation (CV) for the metals were >60%, with As, Cd, and Pb exhibiting the highest variability, indicating considerable exposure to

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external disturbances. These findings underscore the urgency of addressing heavy metal contamination in the study area.

(2) Ecosystems exhibit varying buffering and retention effects on pollutants, influenced by their type, structure, and the characteristics of the pollutants. Vegetation plays a crucial role in ecological buffer zones, where its type and age affect pollutant interception. Simulation results showed distinct reduction patterns for heavy metals, with significant reductions in urban areas for As and Pb, both of which exceeded acceptable standards. The reductions in Cd and Pb concentrated in water bodies, and paddy fields highlight areas needing targeted management. The reduction in total PTEs was heavily influenced by Cd and zinc (Zn), emphasizing the need for ecological restoration efforts to focus on these metals to improve ecosystem health.

(3) A spatial correlation was observed between the reduction and retention of ecosystems and the distribution of soil PTEs: As, Pb, and Zn were positively correlated, while Cd and Cu were negatively correlated. The reduction and retention of heavy metals by ecosystems influenced the enrichment status of heavy metals in soil species.

This study simulated the reduction and retention effects of different ecosystem types on soil PTEs, and the findings can be used to better manage land, ensure minimal disturbance of soil heavy metals, and inform remediation measures.

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Notes

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ABBREVIATIONS

PTEs, potential toxicity elements; As, arsenic; Cd, cadmium; Cu, copper; Pb, lead; Zn, zinc; CV, coefficient of variation; MBV, median geological background value; DT, data type, including spatial distribution data of heavy metals (SDD) and ecosystem reduction stagnation analysis data (DR); MEAN, normalized data image mean; STD, Standard deviation of normalized data image; SD, sample variance; COVA, data correlation coefficient

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