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Characteristics and Risk Assessment of Heavy Metal Contamination in Arable Soils Developed from Different Parent Materials

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Abstract: This study analyzes the heavy metal pollution in cultivated soils developed from different parent materials in Yunnan Province and assesses their risk levels. The results show significant regional differences in soil heavy metal pollution, greatly influenced by the type of parent material. Cadmium (Cd) pollution is most severe in multiple parent material soil regions, particularly in areas with carbonate and purple rocks, exhibiting a high pollution risk. Other heavy metals such as zinc (Zn), copper (Cu), and lead (Pb) also show varying degrees of enrichment in different parent material zones, posing potential pollution risks. The soil pollution levels of heavy metals were classified using the geo-accumulation index method. It was found that soils developed from carbonate rocks and purple rocks have the most severe heavy metal pollution, while soils from quartzitic rocks, acidic crystalline rocks, and basalt exhibit relatively lower pollution levels. By analyzing the characteristics of heavy metal pollution in different parent materials, this study provides a scientific basis for regional soil pollution management and sustainable agricultural development.

Keywords: parent material; cultivated soil; pollution characteristics; risk assessment

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1. Introduction

Soil is a vital resource for human survival and agricultural production in the natural environment [1]. As one of the major environmental issues today, soil heavy metal pollution has significant impacts on the ecological environment and poses threats to human health [2–4]. Soil heavy metal pollution is characterized by high toxicity, persistence, and bioaccumulation [5–7]. Cadmium (Cd) is one of the most toxic heavy metals to humans, causing harmful effects on the structure and physiological and biochemical functions of the body [8–11]. Lead (Pb) can damage the nervous, skeletal, reproductive, hematopoietic, renal, and cardiovascular systems [12–16]. Long-term exposure to zinc (Zn), manganese (Mn), and chromium (Cr) at doses exceeding tolerance levels can also have adverse effects on human health [17–19]. Therefore, understanding soil heavy metal pollution and conducting risk level assessments on a regional scale is of great significance [20].

Parent material is the foundation of soil formation, and it contains varying amounts of heavy metals, which results in different heavy metal contents in soils formed from different types of parent materials [21,22]. For example, in the Tianshan region of China, under the same climatic conditions, the heavy metal content in soils varies due to differences in parent material between the eastern, western, and central sections of the northern slope. The average content of Cr, Cu, Ni, Pb, and Zn in soils from the eastern section is higher than in the western and central sections [23]. The differences between various soil types developed from different parent materials also lead to variations in their capacity for the desorption and adsorption of heavy metals [24]. Previous studies have shown significant regional differences in the adsorption of heavy metals by soils across China [25]. For instance, black soil from different regions has the highest adsorption capacity for heavy metals, higher than that of brown soil, cinnamon soil, and yellow-brown soil. Regarding specific elements, brown soil has the weakest adsorption capacity for lead but the strongest for copper [26,27]. The mineral composition of the parent material, which is the basic material for soil formation, directly determines many important chemical properties in the soil. This has been extensively studied and confirmed in soil science [28].

Equally significant is the profound impact of agricultural practices on soil quality. For instance, the long-term application of phosphate fertilizers can lead to the accumulation of heavy metal cadmium, which can adversely affect soil and environmental health [29]. However, according to previous research, the cultivated soils in Yunnan Province generally remain in a relatively clean state [30]. For heavy metals such as Cr, Cu, Cd, and Zn, studies have shown that their distribution and accumulation are primarily controlled by the composition of the parent rock during soil formation, rather than being driven by anthropogenic factors like agricultural fertilization [31]. Despite this, land use practices remain a key factor influencing the enrichment of heavy metals in soils. Various agricultural practices, such as intensive fertilization, herbicide application, and changes in cropping patterns, may exacerbate the accumulation of certain heavy metals [32]. Particularly in areas where the parent material naturally contains higher concentrations of heavy metals, improper land management may accelerate the bioavailability and mobility of these elements. Although heavy metal pollution in some parts of Yunnan is largely controlled by the parent rock, differences in soil management practices may still influence the accumulation of heavy metals through fertilization, irrigation, and pesticide usage. During soil sampling, we ensured uniformity in land management practices at the sampling sites, ensuring that the differences in parent material were the primary factors influencing changes in soil chemical properties, thereby eliminating uncertain factors. In conclusion, the enrichment and distribution patterns of heavy metals in soils derived from different parent materials hold significant research value for soil pollution management and the sustainable development of green and healthy agricultural systems. The patterns of heavy metal enrichment and distribution in soils formed from different parent materials have substantial research value for soil pollution management and sustainable green development.

This study is based on the classification of parent material types in Yunnan Province from the “Seventh Five-Year Plan” survey. Through field sampling and laboratory analysis, we measured the heavy metal content in cultivated soils developed from different parent materials in Yunnan. The aim is to analyze the heavy metal pollution in soils from different parent materials and to assess the pollution levels using the geo-accumulation index method. This research holds significant value for the targeted reduction and identification of heavy metal pollution in cultivated soils, as well as for predicting soil heavy metal pollution risks.

2. Materials and Methods

2.1. Study Area

Yunnan Province is located in the southwestern border of China, roughly between 21°8′ to 29°15′ N latitude and 97°31′ to 106°11′ E longitude [33]. Yunnan borders Guizhou Province and Guangxi Zhuang Autonomous Region to the east, Sichuan Province to the north and the Tibet Autonomous Region to the northwest, and shares international borders with Myanmar, Laos, and Vietnam to the south, with a total international boundary of approximately 4060 km. Yunnan is also one of China’s major agricultural regions, rich in arable land resources, with a total cultivated area of approximately 5.3955 million hectares, of which about 40% is plain farmland and 60% is mountainous farmland [34]. The soil types in Yunnan are diverse, influenced mainly by topography, climate, biota, and parent materials. Being a highland region with a varied climate and complex topography, the soils across Yunnan show significant variation. Red soils are mainly distributed in the low mountains, hills, and plains of central and southern Yunnan. Yellow soils are widespread in the mid and low mountainous regions of central and southern Yunnan. Purple soils are primarily found in eastern Yunnan, especially in river valleys such as the Jinsha and Lancang Rivers. Paddy soils are mainly distributed in the plains of central and southwestern Yunnan, such as in Kunming, Yuxi, and Honghe. Yellow-brown soils are found in mid- to high-altitude regions of northwestern and southwestern Yunnan, at elevations typically between 1500 and 3000 m. Limestone soils are primarily distributed in southeastern Yunnan, in karst landscapes such as Honghe Prefecture and Wenshan Prefecture [35]. The diversity of soil types in Yunnan, influenced by its topography and climate, supports the cultivation of various crops.

This study, combined with the "Seventh Five-Year Plan" background survey results for Yunnan Province, classifies the main soil parent materials into seven types: quartzite; mudstone; purple rock; carbonate rock; metamorphosed mudstone; granite of the acidic crystalline rock type; basalt of the basal crystalline rock type. These seven types of soil parent material regions were studied separately [36].

2.2. Sample Collection and Analysis

In accordance with the requirements of the 'Soil Environmental Quality—Risk Control Standard for Soil Pollution in Agricultural Land' (GB15618-2018) [37], between 2018 and 2023, the research team randomly set sampling points in farmlands with different parent materials and recorded the coordinates of the sampling points. Surface soil samples (0–20 cm) were collected using the five-point sampling method, resulting in a total of 2823 soil samples, categorized as follows: metamorphic rocks of the mudstone type, 46 copies; mudstone type, 38 copies; quartzite type, 552 copies; granite of the acidic crystalline type, 286 copies; basalt of the basal crystalline type, 772 copies; purple rocks, 338 copies; carbonate rocks, 800 copies (Figure 1). The collected soil samples were stored in polyethylene plastic bags and immediately transported to the laboratory. All soil samples were air-dried naturally. During the drying process, large stones, plant debris, and other impurities were removed. Once the soils were dried, the samples were ground and passed through a 20-mesh (2 mm) nylon sieve to obtain soil samples smaller than 2 mm. These 2 mm soil samples were further crushed and passed through a 100-mesh (0.149 mm) nylon sieve for heavy metal content analysis.

In the analysis of soil samples, we classified and statistically summarized soil types and textures across different parent material areas within the study region based on the WRB 2022 standard [38]. In the 46 samples of metamorphosed mudstone, there are 30 Cambisols and 16 Leptosols, with soil textures including 23 Loam, 14 Clay Loam, and 9 Sandy Loam. In the 38 samples of mudstone, there are 20 Cambisols, 10 Regosols, and 8 Leptosols, with textures of 15 Clay Loam, 11 Loam, and 12 Sandy Loam. In the 552 quartzite samples, there are 360 Arenosols, 126 Leptosols, and 66 Regosols, with textures of 331 Sand, 166 Sandy Loam, and 55 Loam. In the 286 samples of granite of the acidic crystalline rock, there are 100 Ferralsols, 93 Cambisols, and 93 Leptosols, with textures of 143 Loamy Clay, 86 Sandy Loam, and 57 Loam. In the 772 samples of basalt of the basal crystalline rock, there are 300 Nitisols, 200 Cambisols, and 272 Ferralsols, with textures of 300 Loamy Clay, 200 Loam, and 272 Sandy Loam. In the 338 samples of purple rock, there are 160 Regosols, 90 Cambisols, and 88 Leptosols, with textures of 135 Sandy Loam, 118 Loamy Clay Loam, and 85 Silt Loam. In the 800 carbonate rock samples, there are 400 Leptosols, 300 Luvisols, and 200 Cambisols, with textures of 270 Sandy Loam, 300 Loamy Clay Loam, and 230 Loam.

The digestion procedures of soil samples were conducted followed by method 3050B (USEPA, 1996). Each powdered soil sample was digested with a mixture of HNO_3 and H_2O_2. According to the GB/T 17138-1997 [39], the concentrations of Cu and Zn were measured using an atomic absorption spectrophotometer (AA-6880, Shimadzu Corporation, Shanghai, China). Based on the GB/T 17141-1997 [40], the concentrations of Pb and Cd were also measured using the atomic absorption spectrophotometer (AA-6880, Shimadzu Corporation, Shanghai, China). Additionally, the concentration of As was analyzed using a hydride generation atomic fluorescence spectrophotometer (AFS-230E, Beijing Haiguang Instrument, Beijing, China).

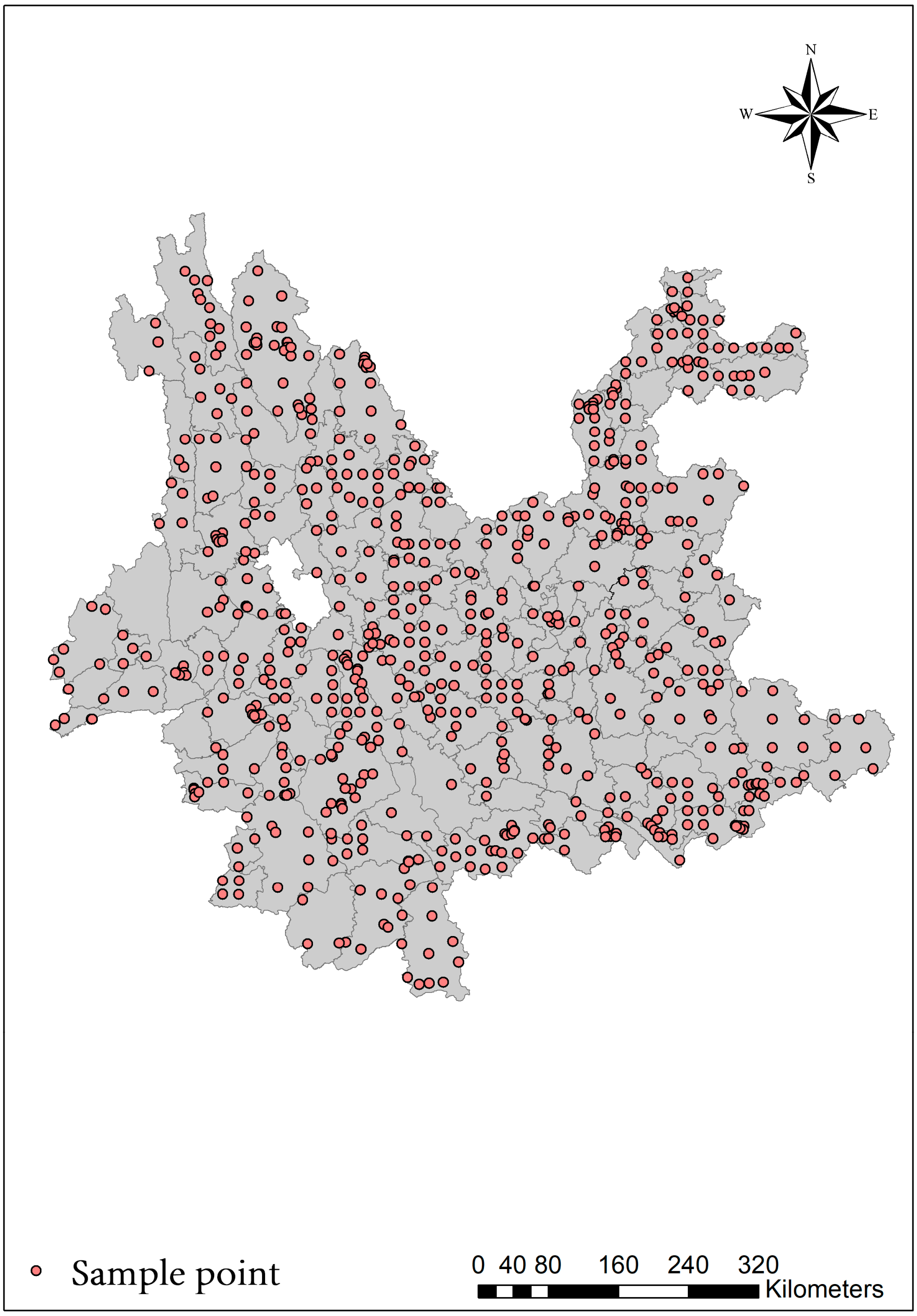

Figure 1. Sampling point distribution map.

2.3. Geo-Accumulation Index

This study used the geo-accumulation index to evaluate the accumulation of heavy metals (Cd, Pb, Cu, Zn, and As) in the soil of the study area. The formula is as follows:

$$I_{geo} = \log_2[C_n/1.5B_n]$$

where C_n, is the concentration of element n in the sample; B_n is the background concentration for Yunnan Province; 1.5 is a correction factor used to account for variations in sedimentation characteristics, rock geology, and other influences.

The higher the geo-accumulation index, the greater the accumulation of heavy metals in the soil, which also indicates a higher risk to the environment and human health. Generally, when the geo-accumulation index exceeds 1, it suggests that the soil has been polluted by heavy metals to varying degrees. The geo-accumulation index has seven levels, with pollution severity corresponding to the levels as shown in Table 1 [41].

Table 1. Igeo pollution level assessment.

Class	Igeo	Contamination Level
0	Igeo $\leq$ 0	Uncontaminated
1	0 < Igeo $\leq$ 1	Lightly contaminated
2	1 < Igeo $\leq$ 2	Moderately contaminated
3	2 < Igeo $\leq$ 3	Moderately contaminated to heavily contaminated
4	3 < Igeo $\leq$ 4	Heavily contaminated
5	4 < Igeo $\leq$ 5	Heavily contaminated to extremely contaminated
6	Igeo > 5	Extremely contaminated

2.4. Data Processing

As shown in Table 2, this study will compare experimental soil data with background values and risk screening for soil heavy metals in Yunnan Province, discussing the pollution status of heavy metal content in the region. Soil data will be organized using Microsoft Excel 2021, while visualizations will be created using Origin 2018. Relevant background value and risk screening value data, etc. [42], are shown below.

Table 2. Soil background values and risk screening values for heavy metals on agricultural land.

Contaminating Element	Background Values for Yunnan Province	Heavy Metal Risk Screening Values for Agricultural Land	Soil Background Values for China	PTE-MPC
Cd	0.218	0.3	0.097	0.6
Pb	40.6	90	26	350
Cu	46.3	50	22.6	100
Zn	89.7	200	74.2	300
As	18.4	40	11.2	20

PTE-MPC: maximum permissible concentrations. Units: mg/kg.

3. Results and Analyses

3.1. Heavy Metal Contamination Status of Soils of Different Arable Lands

3.1.1. Mudstone Type of Metamorphic Rocks

As shown in Figure 2, the soils in the study area of argillaceous rocks from metamorphic rocks are generally polluted, with Cd being the most serious pollutant. For As, 21.74% of the data exceed the heavy metal risk screening value for agricultural land, while 52.17% of the data exceed the background value for soils in Yunnan Province. Although As pollution poses a low threat to agricultural land, it shows high enrichment. The concentrations of Pb, Cu, and Zn exceed the soil background values for Yunnan Province, but their impact on pollution in agricultural land is minimal. However, Pb, Cu, and Zn enrichment is present in the cultivated land.

3.1.2. Mudstone Types

As shown in Figure 3, there is no As pollution in the argillaceous rock study area, with levels below both the background value and the risk control value, indicating no As contamination in this region. None of the Pb samples exceed the risk control value, and only 10.53% of the samples exceed the background value, suggesting that while there is a pollution risk from Pb in the argillaceous rocks, its impact on agricultural land is minimal. Both Zn and Cu levels are higher than the background value, indicating Zn and Cu pollution in the study area. Cd pollution is significantly more severe than that of other heavy metals, exceeding both the background and screening values, posing a high pollution risk.

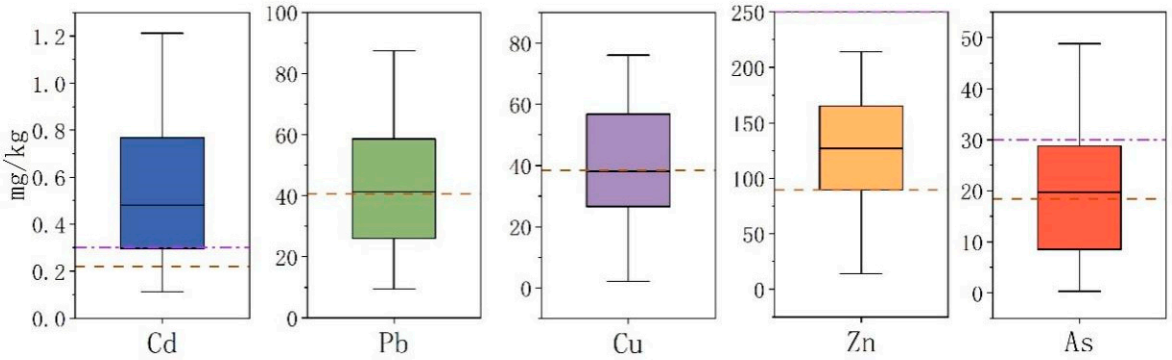

Figure 2. Box plots of heavy metals in soils of mudstone type of metamorphic rocks areas (in the boxplot of PETs content in soil, the red dashed line represents the background value, while the purple dotted line indicates the risk screening value).

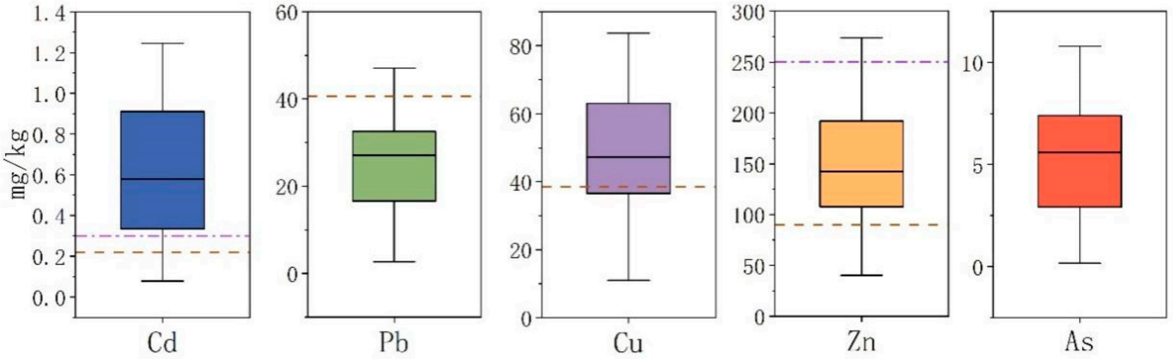

Figure 3. Box plots of heavy metals in soils of mudstone areas (in the boxplot of PETs content in soil, the red dashed line represents the background value, while the purple dotted line indicates the risk screening value).

3.1.3. Quartzites

As shown in Figure 4, the levels of heavy metal pollution of five heavy metal species in the study area of quartz plagioclase are small (Cd, Pb, Cu, Zn and As are present at values 17.75%, 4.71%, 13.41%, 12.32% and 1.45% are higher than the background value), and none of the Pb or As samples were present at values higher than the risk screening value, which indicates that the heavy metals Pb and As in quartz plagioclase can be assigned to the low pollution level with little effect on crops, but they show enrichment in the soil and risk. The Cd pollution in the quartzite rock type is serious compared to the other four kinds of pollution, and there is a risk.

3.1.4. Granites of the Acid Crystalline Rock Type

As shown in Figure 5, the values of As, Pb, Zn and Cu in the study area are higher than the background value and there is a risk of contamination; only 10.14%, 6.29%, 10.49% and 6.64% of the sample points show values higher than the risk screening value, suggesting less contamination into the arable land. The content of the element Cd is higher than the background value as well as the risk screening value, which indicates that there is a problem of Cd contamination in the agricultural soils in the study area, and there is a problem of contamination.

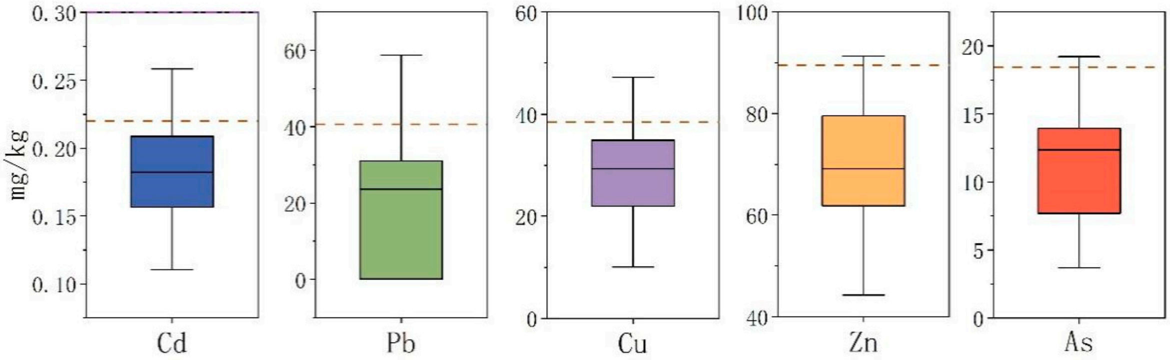

Figure 4. Box plots of heavy metals in soils in quartzite rocky areas (in the boxplot of PETs content in soil, the red dashed line represents the background value).

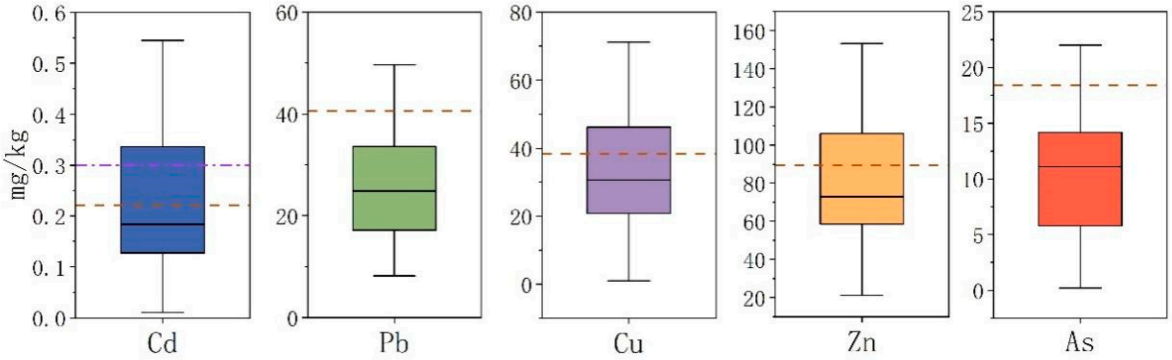

Figure 5. Box plots of heavy metals in soils of granites of the acid crystalline rock type (in the boxplot of PETs content in soil, the red dashed line represents the background value, while the purple dotted line indicates the risk screening value).

3.1.5. Basalt of the Basic Crystalline Rock Type

The area shown in Figure 6 has a mild level of soil pollution, with the average concentrations of five heavy metals in all soil samples being below their corresponding background values. The concentrations of As (0.78%), Cu (8.55%), Pb (5.18%), and Cd (10.10%) in some samples exceeded their respective background values. The exceedance points primarily originate from arable land near mining areas or may result from the improper use of fertilizers and pesticides; however, most sources should be attributed to natural geological origins. It cannot be directly concluded from the data whether the pollution sources lean more towards natural causes or human activities, and further investigations and analyses of the data are needed.

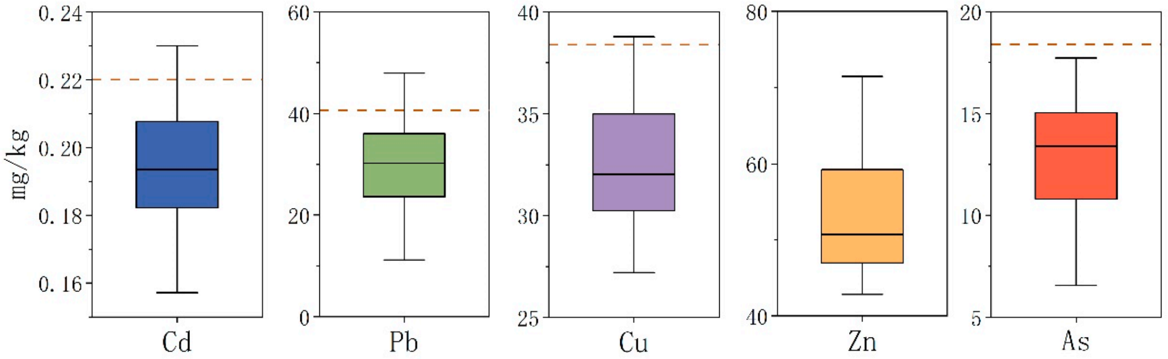

Figure 6. Box plots of soil heavy metals in basaltic areas of basaltic crystalline rock types (in the boxplot of PETs content in soil, the red dashed line represents the background value).

3.1.6. Purple Rocks

As shown in Figure 7, the values of Cd and Cu in the purple rocky arable soil are higher than the background value of Yunnan Province, and the number of sample points is high, with values exceeding the farmland risk screening values of 56.21% and 25.44% for the existence of heavy metal contamination, suggesting the need for strengthened monitoring measures. Secondly, the value of Zn is also higher than the background value of Yunnan Province, but 5.62% of the points show values higher than the heavy metal risk screening value of agricultural land. In the arable soil there is a Zn enrichment phenomenon, but the pollution of agricultural land is low, caused by point source pollution in some parts of the arable land. The levels of Pb and As pollution are significantly lower than the levels of the other three elements, and did not exceed the heavy metal risk screening value of agricultural land, indicating that Pb and As are present in the soil. The contents of Pb and As were significantly lower than the other three elements, and did not exceed the screening value of heavy metal risk in agricultural land, indicating that Pb and As were enriched in the soil.

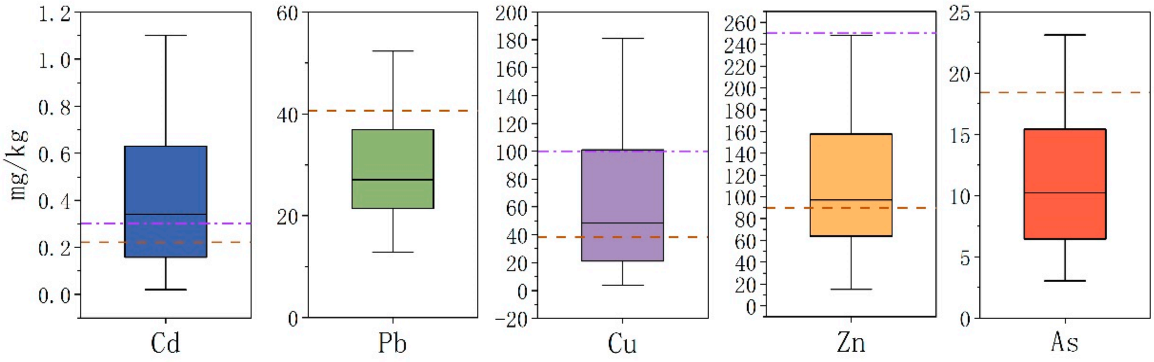

Figure 7. Box plot of soil heavy metals in purple rocky areas (In the boxplot of PETs content in soil, the red dashed line represents the background value, while the purple dotted line indicates the risk screening value).

3.1.7. Carbonate Rocks

As shown in Figure 8, the As and Pb contents of carbonate rock in the cultivated land are higher than the background value of Yunnan Province, indicating that the carbonate matrix differentiation of As and Pb elements are enriched in the soil. The levels of Zn and Cu are higher than the background value of Yunnan Province with a high number of samples, but compared with the risk control value of agricultural land, only 12.13% and 18.5% of the sample points have heavy metal Zn and Cu pollution, which necessitates control measures. The problem of the content of heavy metal Cd exceeding the standard is serious in the carbonate rock type, and is higher than the background value of Yunnan Province and higher than the risk screening value of heavy metal in agricultural land, indicating that the Cd element is enriched in soil by the presence of a soil-forming parent material, and the enriched Cd element will also pollute the agricultural land.

3.2. Risk Evaluation of Heavy Metals in Soils of Arable Land with Different Parent Material

3.2.1. Evaluation of Soil Heavy Metal Risk in the Area of Mudstone Type of Metamorphic Rock

The mean value of each element is ranked Cd (0.49) > Zn (−0.21) > Cu (−0.66) > Pb (−0.80) > As (−0.84). The median and mean values of the accumulation index of the five soil heavy metals Cd in the mudstone area of metamorphic rocks ranged from 0 to 1, and the soil pollution level was 1, indicating mild−moderate pollution; the median and mean values of the accumulation index of the heavy metals Pb, Cu, Zn, and As in the mudstone area of metamorphic rocks were all <0, and the soil pollution level was 0, which belonged to the non-pollution category. Based on the calculation of the mean value, it was evaluated that the soil of the mudstone type of metamorphic rocks was non-polluted. According to the samples of individual points, the Cd (30.43%), Pb (76.09%), Cu (76.09%), Zn (52.52%) and As (69.57%) soil contamination levels were 0, which means no pollution; Cd (34.78%), Pb (19.57%), Cu (21.74%), Zn (36.96%) and As (26.09%) showed soil contamination levels of 1, indicating no to moderate contamination; and a small proportion of Cd (34.78%), Pb (1.32%), Cu (0.66%), Zn (1.97%) and As (1.32%) samples showed a soil contamination level of 2, indicating moderate contamination.

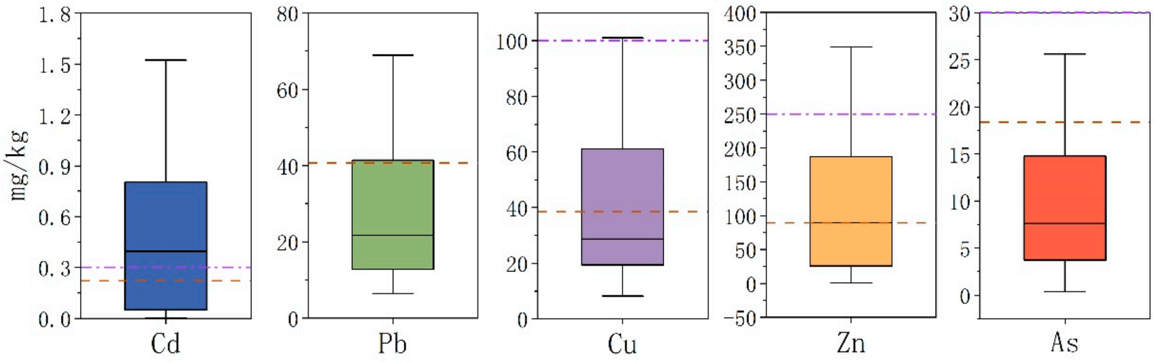

Figure 8. Box plots of heavy metals in carbonatitic soils (in the boxplot of PETs content in soil, the red dashed line represents the background value, while the purple dotted line indicates the risk screening value).

As shown in violin Figure 9, each element can be found in polluted spots; the distribution density of Cd is concentrated near 1, indicating that most of the spots of Cd exist in level 1 or 2 of medium pollution or light–medium pollution. The distribution density areas of Pb, Cu, Zn and As are mainly concentrated at 0 or below 0, which suggests light–medium pollution or no pollution. This indicates that the overall Cd contamination of arable soils in the study area of the mudstone type of metamorphic rocks is greater than that of the other elements, with Cd causing more contamination and a high risk of contamination, and the other four causing lower contamination, with only a small amount of contamination and a low risk of contamination.

3.2.2. Soil Heavy Metal Risk Evaluation in Mudstone Type Areas

Cd (0.59) > Zn (−0.21) > Cu (−0.35) > Pb (−1.41) > As (−2.68). The median and mean values of the accumulation indices of the soil heavy metal Cd in the mudstone type were between 0 and 1, and the soil pollution level was 1, which suggests mildly–moderately polluted; the mean values of the accumulation indices of the heavy metal Zn in the mudstone type were <0, and the soil pollution level was 0, which is non-polluted; however, the median values were between 0 and 1, and the soil pollution level was 1, which suggests mildly–moderately polluted, and the accumulation indices of heavy metals Pb, Cu and As in the mudstone type were <0, and the soil pollution level was 1, which suggests slightly–moderately polluted. Pb, Cu, and As land accumulation index median and mean values were <0 and the soil pollution level was 0, suggesting no pollution. Based on the calculation of the mean value, the soil in the mudstone area was evaluated as non-polluted. According to the samples of individual points, the soil pollution levels of Cd (23.68%), Pb (100%), Cu (68.42%), Zn (39.47%), and As (100%) were classed as 0, which means no pollution; the soil pollution levels of Cd (39.47%), Cu (28.95%), and Zn (47.37%) were classed as 1, which means no pollution to medium pollution; Cd (36.84%), Cu (2.63%) and Zn (13.16%), showed soil pollution levels of 2, indicating medium pollution.

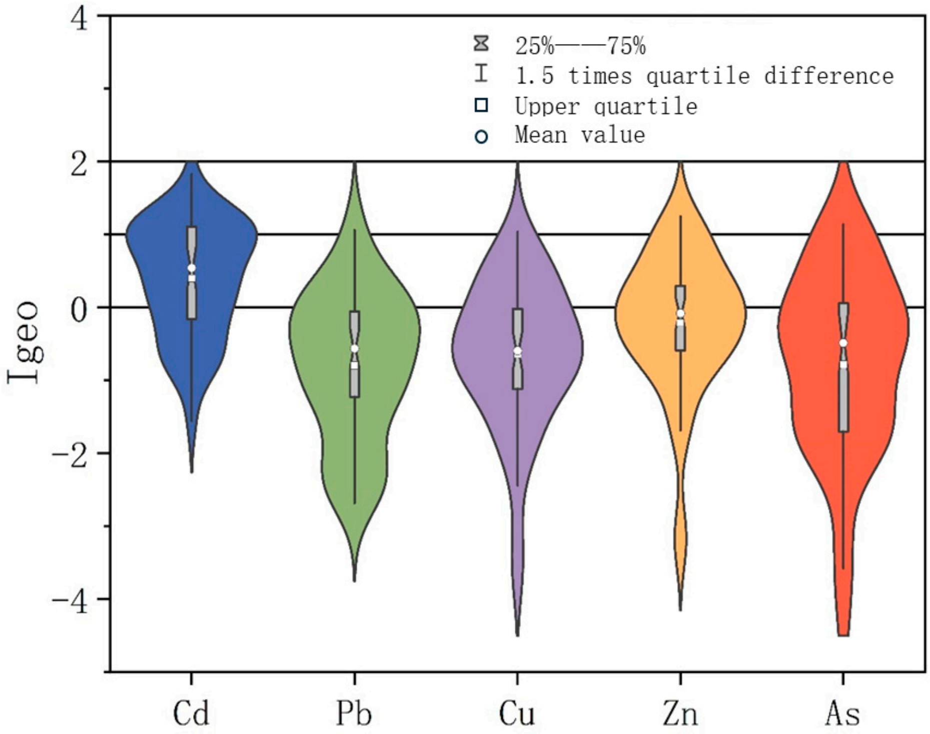

Figure 9. Igeo violin diagram of mudstone classes of metamorphic rocks.

As shown in violin Figure 10, the distribution density of Cd is concentrated between 1 and 2, indicating that most of the points of Cd belong to level 2 pollution, which is medium pollution; the distribution density of Zn is mainly concentrated in the middle of 0 to 1, suggesting level 1 pollution, which is light–medium pollution. The distribution density areas of Pb, Cu and As are mainly concentrated in 0 or below 0, suggesting no pollution or light–medium pollution. But Cd Zn showed high pollution points, greater than 2, suggesting medium-intensity pollution. There is no risk of contamination of heavy metals in most of the arable soils in the study area of mudstone type, but there is contamination of Cd and Zn.

3.2.3. Soil Heavy Metal Risk Evaluation in Quartzite Areas

Cd (−0.72) > Zn (−0.86) > Cu (−0.90) > As (−2.37) > Pb (−4.07). The median and mean values of the accumulation index of heavy metals Cd, Pb, Cu, Zn and As were <0. The soil pollution level was 0, suggesting non-polluted. Based on the calculation of the mean value, it was evaluated that the soil in the quartzite rock type area was non-polluted. According to the samples of individual points, the soil pollution levels of Cd (85.14%), Pb (97.83%), Cu (91.49%), Zn (92.03%) and As (100%) samples were all grade 0, indicating no pollution; the soil pollution levels of Cd (6.70%), Pb (2.17%), Cu (4.89%) and Zn (7.61%) samples were 1, indicating light–moderate contamination; the soil contamination levels of a small portion of the Cd (8.15%), Cu (3.26%) and Zn (0.36%) samples were 2, indicating moderate contamination.

As shown in violin Figure 11, Cd, Pb, Cu and Zn elements were present in medium or medium–strong pollution sites, but the distribution densities of Cd, Pb, Cu, Zn and As were mainly concentrated below 0, suggesting no pollution. This indicates that the overall Cd, Pb, Cu, Zn and As pollution levels in the study area of quartzites were low, and that this is a low-risk area, but there are still some points with risks that need to be paid attention to in order to manage them.

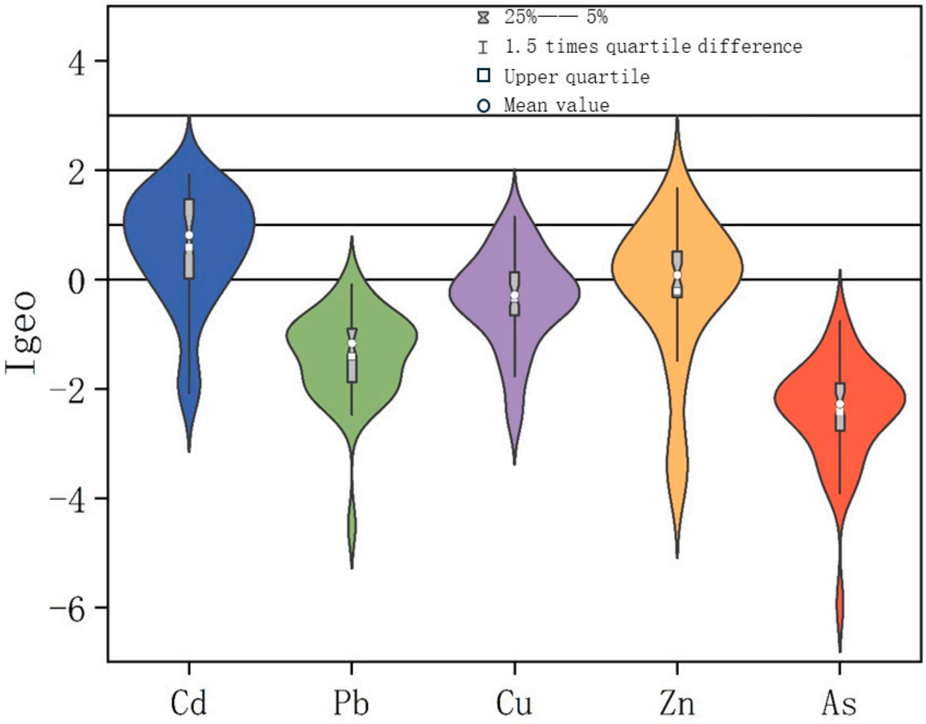

Figure 10. Igeo violin diagram of mudstone class.

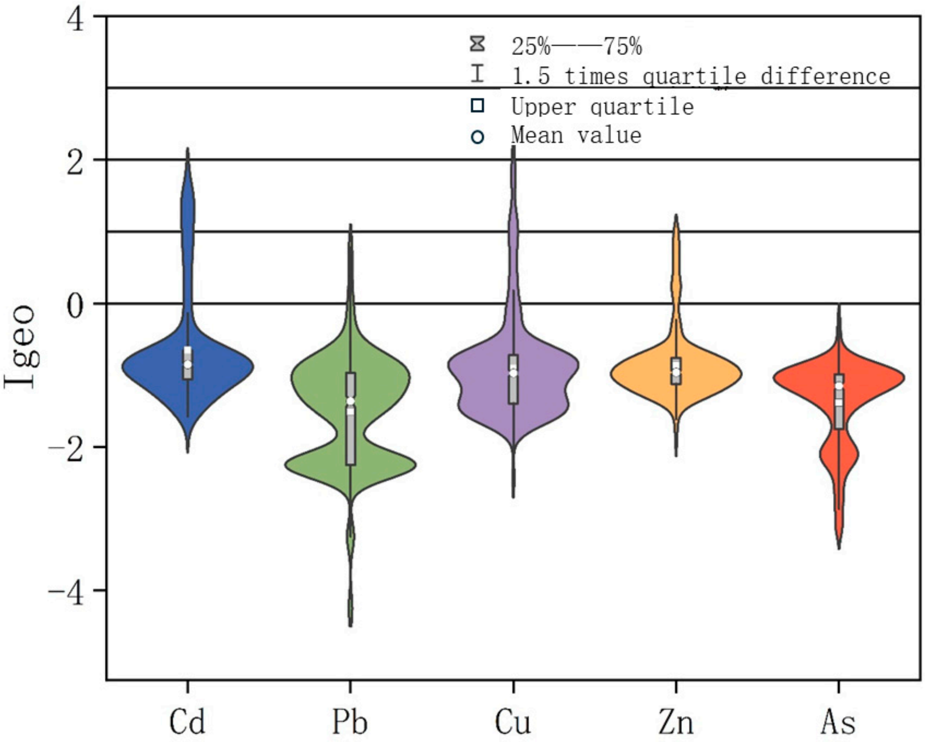

Figure 11. Igeo violin diagram of quartzite rock type.

3.2.4. Soil Heavy Metal Risk Evaluation in Granite of the Acidic Crystalline Rock Type

Zn (−0.77) > Cu (−1.02) > Cd (−1.05) > Pb (−1.22) > As (−1.67). The median and mean values of the ground cumulative index of heavy metals Cd, Pb, Cu, Zn, and As in the granite of acidic crystalline rock type were <0, and the soil pollution level was 0, suggesting non-polluted. Based on the calculation of the mean value, it was evaluated that the soil in the granite area of acidic crystalline rock type was non-polluted. According to the samples from individual points, Cd (75.09%), Pb (89.53%), Cu (85.56%), Zn (79.06%) As (88.09%) showed soil contamination levels of 0, which means no pollution; Cd (13.36%), Pb (4.33%), Cu (8.30%), Zn (13.72%) and As (11.55%) samples have a soil contamination level of 1, indicating light–moderate contamination; and a small proportion of Cd (11.55%), Pb (6.14%), Cu (6.14%), Zn (7.22%), and As (0.36%) samples have a soil contamination level of 2, indicating moderate contamination.

As shown in violin Figure 12, Cd, Pb, Cu, Zn and As have two levels of medium pollution; the second distribution density of Cd, Pb, Cu and Zn is concentrated near the middle of the range 1–2, which indicates that some of the Cd points have one or two levels of pollution, medium pollution or light–medium pollution; the main distribution densities of Cd, Pb, Cu, Zn and As are mainly concentrated below 0, which is no pollution. In the acidic crystalline rock granite study area as a whole, one can see Cd, Pb, Cu, Zn and As pollution, but the level of pollution is low, most of the arable soil shows no pollution risk, and a small part of the arable soil pollution is serious.

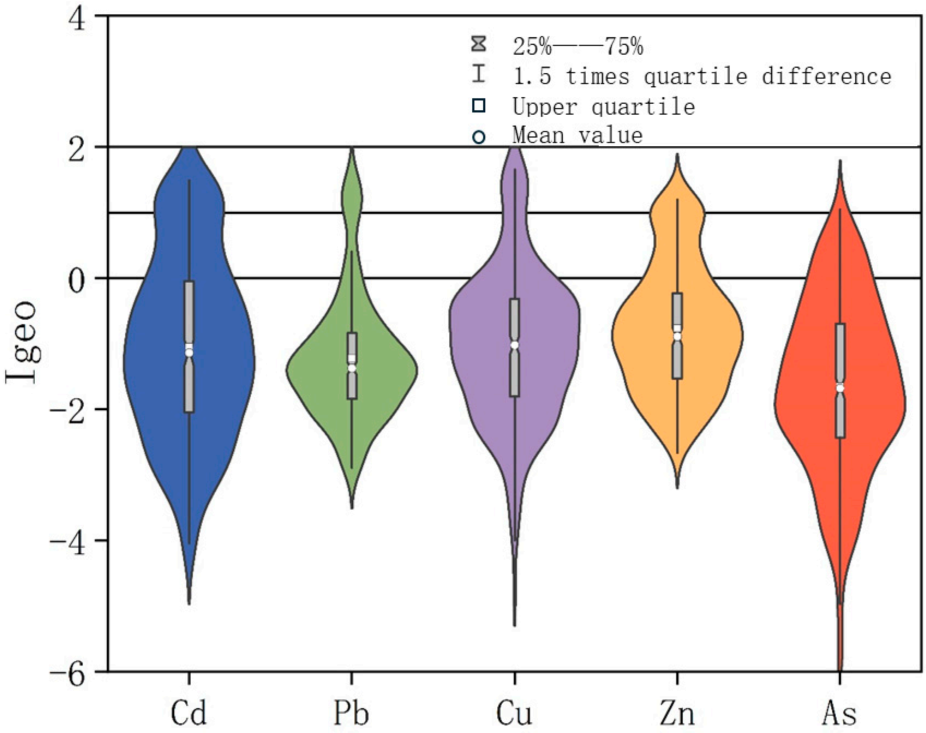

Figure 12. Igeo violin diagram of granite of the acidic crystalline rock type.

3.2.5. Soil Heavy Metal Risk Evaluation in Basalt Areas of Basal Crystalline Rock Types

Cd (−0.62) > Cu (−0.79) > Pb (−1.07) > Zn (−1.20) > As (−1.27). The median and mean values of the ground cumulative index of heavy metals Cd, Pb, Cu, Zn, and As in the basalt of basal crystalline rock type were <0, and the soil pollution level was 0, which suggests non-pollution. Based on the calculation of the mean value, the soil in the basalt area of the basal crystalline rock type was evaluated as non-polluted. According to the samples of individual points, Cd (91.19%), Pb (97.41%), Cu (94.95%), Zn (93.13%) and As (99.74%) samples showed soil pollution levels of 0, which means no pollution; Cd (4.27%), Pb (1.55%), Cu (2.72%), Zn (4.79%) and As (0.26%) samples showed a soil contamination level of 1, indicating light–moderate contamination; a small proportion of Cd (3.11%), Pb (1.04%), Cu (2.33%) and Zn (2.07%) samples showed a soil contamination level of 2, indicating moderate contamination.

As shown in violin Figure 13, the main distribution densities of Cd, Pb, Cu, Zn and As are concentrated below 0, suggesting non-pollution, but there are pollution problems in some sample points of Cd, Pb, Cu and Zn, and the pollution level of Cd reaches level 3, which suggests medium–strong pollution, and some sample points of Pb, Cu, and Zn are in the range of 1–2, suggesting medium pollution. The basalt study area of basaltic crystalline rocks has low levels of Cd, Pb, Cu, Zn and As pollution, but there are points with higher pollution, which need to be screened to find the polluted areas and to treat the pollution in arable soils.

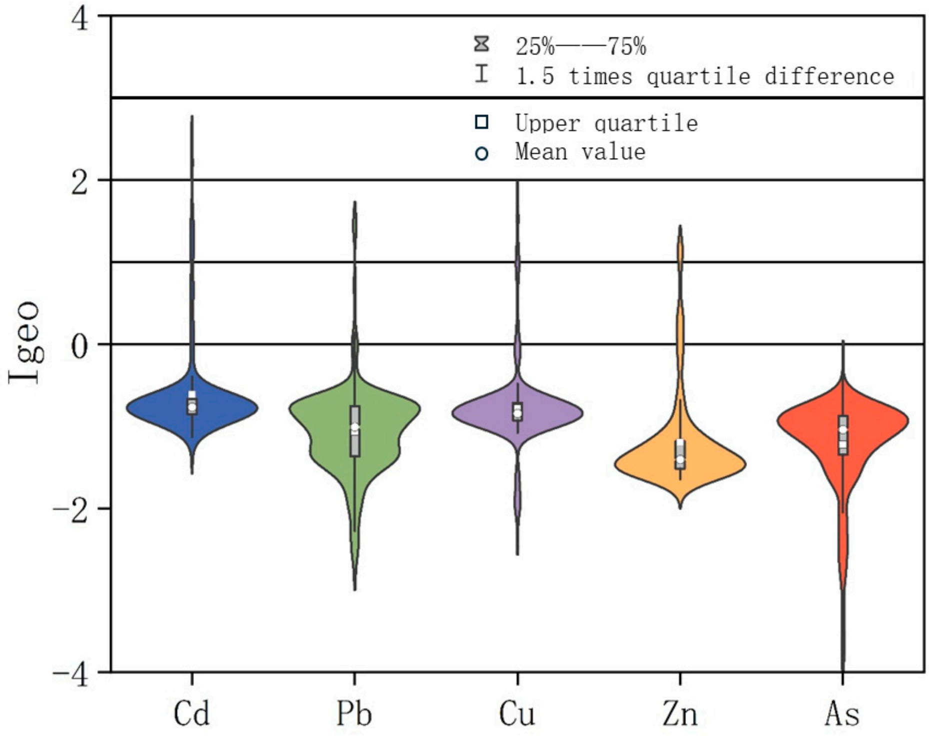

Figure 13. Igeo violin diagram of basalt areas of basal crystalline rock types.

3.2.6. Soil Heavy Metal Risk Evaluation in Purple Rocky Areas

Cd (−0.10) > Cu (−0.57) > Zn (−0.84) > Pb (−1.17) > As (−1.42). The mean values of the accumulation index of heavy metal Zn in purple rock types were all <0, and the soil pollution level was 0, indicating non-polluted; however, the median values were between 0 and 1, and the soil pollution level was 1, suggesting mildly–moderately polluted. The median and the mean values of the accumulation indexes of heavy metal Pb, Cu, Zn, and As in purple rock types were all <0, and the soil pollution level was 0, suggesting non-polluted. Based on the calculation of the mean value, the soil in the study area was evaluated as non-polluted. According to the samples of individual points, Cd (47.63), Pb (94.08%), Cu (54.44%), Zn (66.86%) and As (92.90%) soil pollution levels were 0, which means no pollution; Cd (29.29%), Pb (4.44%), Cu (25.74%), Zn (28.11%) and As (4.44%) showed soil contamination levels of 1, indicating no to moderate contamination; a small proportion of Cd (17.16%), Pb (0.59%), Cu (18.34%), Zn (5.03%) and As (2.66%) samples had a soil contamination level of 2, indicating moderate contamination.

As shown in violin Figure 14, the main distribution densities of Cd and Cu were mainly concentrated in the vicinity of 1, indicating that most of the points of Cd can be assigned to level 1 or 2, suggesting light–medium pollution or medium pollution. The presence of Zn at a level 1–2 suggests medium pollution, but the distribution density is mainly concentrated around 0 or so, suggesting a low level of pollution. The Pb and As distribution density areas are mainly concentrated around 0 or less, suggesting no pollution. The purple rock type study area contained a high level of heavy metal pollution; here, Cd and Cu elements exist in some sample points at levels higher than 3, up to level 4 (suggesting strong pollution); Pb, Zn and As are also present at greater than two points, at level 3, suggesting medium–strong pollution. It is necessary to find the area with the highest value after screening to manage the pollution of arable soil.

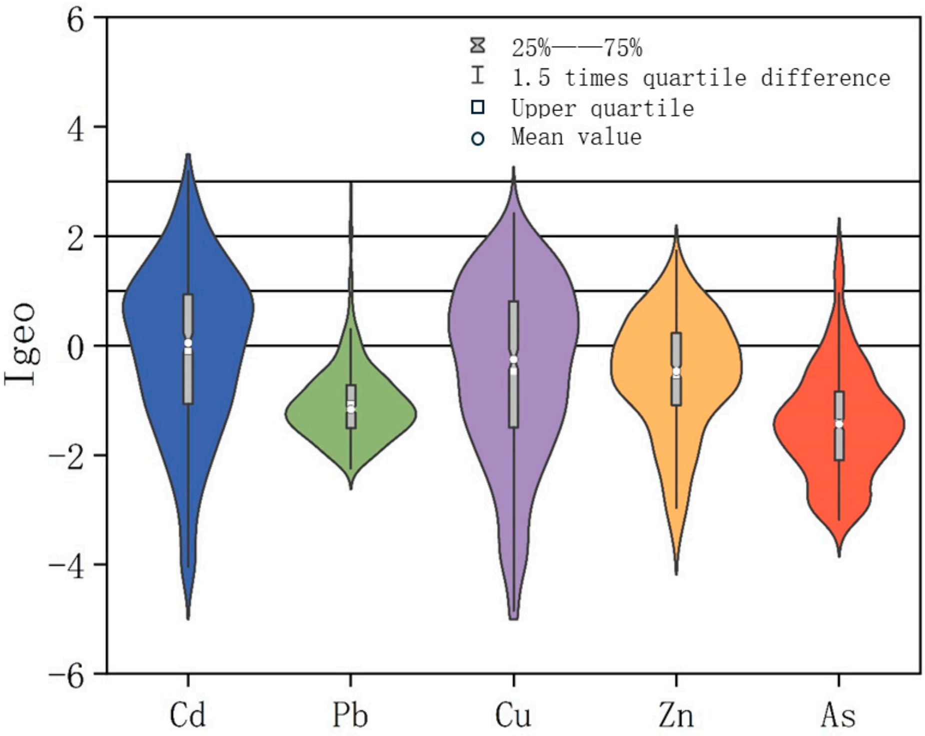

Figure 14. Igeo violin diagram of purple rocks.

3.2.7. Soil Heavy Metal Risk Evaluation in Carbonate Rock Type Areas

Cd (−1.28) > Zn (−1.43) > Cu (2.43) > Pb (−4.43) > As (−5.11). The average median and mean Igeo of five samples of Cd in the mudstone area of metamorphic rocks were <1, and the soil pollution level was 1, suggesting the area was mildly–moderately polluted, and the average median and mean Igeo of Pb, Cu, Zn, and As in the mudstone area of metamorphic rocks were <0, with a soil pollution level of 0, suggesting non-polluted. Overall, the soil in the mudstone area of metamorphic rocks was non-polluted. According to the samples of individual points, Cd (53.67%), Pb (87.11%), Cu (76.94%), Zn (69.18%) and As (91.51%) showed soil pollution levels of 0, which means no pollution; Cd (20.23%), Pb (7.55%), Cu (14.78%), Zn (18.03%) and As (6.39%) showed soil contamination levels of 1, indicating light–moderate contamination; a small proportion of Cd (15.93%), Pb (4.61%), Cu (7.86%), Zn (10.38%) and As (1.89%) samples showed a soil contamination level of 2, indicating moderate contamination.

As shown in violin Figure 15, for Cd, Pb, Cu, Zn and As, there were points of high pollution. The distribution densities of Cd and Zn were mainly concentrated in the vicinity of 1, indicating that for Cd and Zn, some points belonged to level 1 or 2 pollution, indicating medium pollution or light–medium pollution; however, the level for the Cd was greater than 5, suggesting level 6 or very serious pollution, and the level for the Zn was greater than 3, indicating level 4 level or strong pollution. The main distribution densities of Pb, Cu and As were mainly concentrated below 0, which indicates non-polluted, and some points were mildly–moderately polluted or moderately polluted. In the carbonate rock-like study area as a whole, there was Cd, Pb, Cu, Zn and As pollution; the Cd pollution was extremely serious, and experiments must be performed to find the high-pollution areas, and to determine the course of treatment.

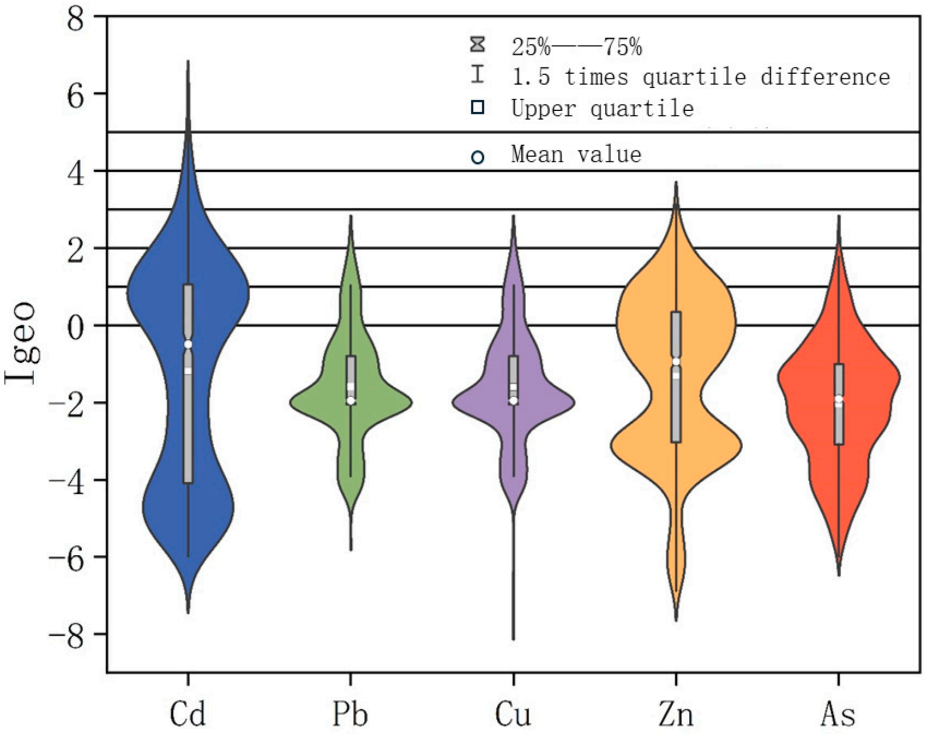

Figure 15. Igeo violin diagram of carbonate rock type.

4. Discussion

4.1. Differences in Heavy Metal Content in Soils from Different Parent Materials

This study reveals that the heavy metal contents in soils developed from different lithologies show significant variations. The influence of parent material on soil composition was here highlighted. Apart from the high average concentration of Cd across the seven types of parent materials, the average concentration of As in metamorphosed mudstone areas was also elevated, with some samples exceeding the background values. In mudstone rock areas, the average concentrations of Zn and Cu were higher than the background values, while the average concentrations of As and Pb were relatively lower. In quartzite rock regions, the overall average concentration of heavy metals was low, although Pb and As slightly exceeded the background values. In the granite of the acidic crystalline rock regions, the average concentrations of As, Pb, Zn, and Cu were relatively high. In the basalt of the basal crystalline rock regions, the average concentrations of heavy metals were generally below the background values. In purple rock areas, the average concentrations of Cu and Zn were high, and in carbonate rock regions, Zn and Cu also showed higher average concentrations.

The parent material serves as the foundation for soil formation, and the contents of heavy metals in soil largely depend on the elemental composition of the parent rock [43–45], consistent with numerous other studies [46–49]. The higher the elemental content in the parent rock, the higher the corresponding elemental content in the soil derived from it. Zhang et al. [50], in their analysis of the relationship between the background values of 13 elements in Tibetan soils and their parent materials, equally confirmed the above view. Wei Xiao feng et al. [51], through their analysis of soils from different parent materials in mineral resource areas, found that the average contents of Cr, Cu, and Ni in medium–basic amphibolite and gneiss metamorphic rock parent materials are 1–2 times higher than those in other parent materials. Tang Shiqi et al. [52], in their study of farmland soils in carbonate rock areas, found that the Cd and As contents exceeded the agricultural land pollution risk control values by 18.52% and 2.92%, respectively. These findings indicate a close correlation between the elemental composition of parent rock and that of the soil, reinforcing the view that lithology plays a crucial role in determining soil heavy metal content. This influence, extending beyond localized regions, underscores the universal role of the parent rock in shaping soil chemical properties.

4.2. Heavy Metal Pollution and Risk Assessment

The farmland areas developed from the seven types of parent materials in this study are generally in a state of mild pollution, with significant differences in heavy metal pollution across different soil parent materials. In the metamorphosed mudstone areas, Cd pollution was the most severe, while As slightly exceeded the background values but remained at a relatively light pollution level. In muddy rock areas, Zn and Cu showed significant pollution, and Cd exceeded the standards considerably. In quartzite rock areas, overall pollution was low, but Cd stood out as a more prominent pollutant. In granite of the acidic crystalline rock areas, Cd exceeded both background and screening values, indicating significant pollution. In basalt of the basal crystalline rock areas, heavy metal pollution was minor, and point-source pollution may be related to mining or agricultural activities. In purple rock areas, the exceedance of Cd and Cu was seen to be more frequent, necessitating increased monitoring. In carbonate rock areas, Zn and Cu pollution was notable, and Cd exceeded standards significantly, with parent material weathering being the main source of pollution. The heavy metal pollution patterns in different parent materials observed in this study are consistent with previous research findings [53,54]. Analyses of the five heavy metals revealed that Cd has the highest number of pollution points and the most severe pollution level, while As showed the fewest pollution points and the lightest pollution degree. Overall, the heavy metal pollution in farmlands was relatively mild, but Cd data show that some areas still exhibit significant pollution issues. In certain farmland soils, heavy metal accumulation, especially Cd, is particularly prominent.

Furthermore, apart from isolated point-source pollution, the accumulation of heavy metals in diffuse pollution is likely related to parent material weathering and geological processes. This highlights the critical role of parent materials in the migration and accumulation of pollutants. To better understand the heavy metal pollution in farmlands, further analyses of the pollution sources within the context of the seven parent materials are necessary.

5. Conclusions

This study demonstrates significant differences in the heavy metal contents and pollution levels across soils developed from different lithologies. Cd showed the highest concentration among the seven parent materials, while As exceeded the background values in metamorphic mudstone areas. The contents of Zn and Cu were higher than the background values in muddy rock areas. In quartzite rock areas, overall concentrations were low, though Pb and As were slightly elevated. Granite areas showed higher concentrations of As, Pb, Zn, and Cu, whereas basalt areas showed generally lower concentrations. Cd and Cu exceedances were particularly severe in purple rock and carbonate rock areas, with parent material weathering being the main source of pollution.

Overall, the study area showed mild contamination, with Cd pollution being the most severe in metamorphic mudstone regions, while other parent materials exhibited varying degrees of contamination. Among the five analyzed elements, Cd showed the highest level of pollution, indicating significant contamination, followed by Zn, which showed moderate pollution. The other three elements exhibited lower levels of contamination. Cd showed the highest number of polluted sites, while As showed the fewest. The accumulation of heavy metals was notably significant, warranting further investigation into pollution sources to optimize remediation strategies. Future research should focus on identifying soil heavy metal pollution sources in different parent material contexts to improve management strategies. Additionally, the significant differences in heavy metal contents among soils derived from different parent rocks, and the correlation between these factors, also warrant attention.

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