Heavy Metal Content, Distribution, Sources, and Ecological Risk of Benggang Soils in Southwestern Fujian (Postprint)

Authors: Jiang Chao, Chen Zhibiao, Chen Zhiqiang, Zhao Jitao

Date: 2017-11-06T00:00:00+00:00

Abstract

Two typical collapsing gullies and a nearby non-collapsing-gully slope (control area) were selected within the Huangnikeng collapsing gully group in Changting County, Fujian Province. Sixty-three soil samples from 0–20 cm depth were collected and analyzed for Cu, Zn, Ni, Pb, Cr, As, and Cd contents. Correlation analysis and principal component analysis were employed to identify heavy metal sources, and the Hakanson potential ecological risk index method was applied to assess the potential ecological risk of heavy metals in the study area, using the Fujian Province background values and the national secondary standard as references. The results showed that the order of soil heavy metal contents in the study area from high to low was Zn (105.56 $\text{mg}\cdot\text{kg}^{1}$) > Pb (67.21 $\text{mg}\cdot\text{kg}^{1}$) > As (61.47 $\text{mg}\cdot\text{kg}^{1}$) > Cu (22.33 $\text{mg}\cdot\text{kg}^{1}$) > Cr (17.12 $\text{mg}\cdot\text{kg}^{1}$) > Ni (5.24 $\text{mg}\cdot\text{kg}^{1}$) > Cd (0.80 $\text{mg}\cdot\text{kg}^{1}$). The contents of Pb and Cd exhibited the pattern of collapsing gully area > control area, while the contents of Cu, Zn, Ni, Cr, and As showed the opposite pattern. The average values of Zn, Pb, As, and Cd in Collapsing Gully No. 1 were 1.12, 2.82, 8.68, and 13.33 times the Fujian Province background values, respectively; those in Collapsing Gully No. 2 were 1.11, 1.36, 11.22, and 16.67 times the background values, respectively; and those in the control area were 1.58, 1.60, 5.14, and 14.44 times the background values, respectively. Comparison with the national soil environmental quality secondary standard revealed that the average As contents in the collapsing gully area and control area exceeded the standard by 1.92 and 2.70 times, respectively, and the average Cd contents exceeded the standard by 2.31 and 2.60 times, respectively. From the catchment slope to the end of the gully channel, the contents of Pb, Zn, and Cd in the collapsing gully area showed an increasing trend, Cu and Cr contents remained relatively stable, and Ni content decreased. From the upper to lower slope positions, the contents of Cu, Zn, Ni, Cr, and Cd in the control area showed an increasing trend, while Pb content decreased slightly. The distribution of As content in the study area showed no significant change. Cu, Ni, and Cr mainly originated from parent material; Zn primarily originated from livestock and poultry farming; the main sources of Cd and As included bedrock weathering and rare earth mining; and Pb mainly originated from composite pollution sources such as bedrock mineralization, coal combustion, and vehicle exhaust emissions. When using the Fujian Province background values as reference, the potential ecological risk coefficient for Cd reached "extremely high risk," As was "considerable risk," and the others were "slight risk." When using the national secondary standard as reference, Cd was classified as "considerable risk" and the others as "slight risk." The potential ecological risk index (Ri) exhibited the pattern of Collapsing Gully No. 2 > control area > Collapsing Gully No. 1. The pollution of Cd and As in the study area has become relatively serious, and corresponding safety precautions should be taken.

Full Text

Content, Distribution, Source and Ecological Risk of Heavy Metals in Soils of Benggang Areas in Southwest Fujian

JIANG Chao[1,2,3], CHEN Zhibiao[1,2,3], CHEN Zhiqiang[1,2,3], ZHAO Jitao[1,2]** (1. College of Geographical Sciences, Fujian Normal University, Fuzhou 350007, China; 2. Key Laboratory for Subtropical Mountain Ecology, Ministry of Science and Technology and Fujian Province, Fuzhou 350007, China; 3. Institute of Geography, Fujian Normal University, Fuzhou 350007, China)

Abstract

Sixty-three surface (0–20 cm) soil samples were collected from two typical Benggang areas (BG1 and BG2) in the Huangnikeng Benggang Group and an adjacent hillside without Benggang erosion (CK) in Changting County, southwestern Fujian Province. The contents of seven heavy metals (Cu, Zn, Ni, Pb, Cr, As, Cd) were measured, and their sources were identified through correlation analysis and principal component analysis. The potential ecological risks were assessed using the Hakanson potential ecological risk index method, with reference to both the soil background values of Fujian Province and the second-class standard of national soil environmental quality.

The results indicated that the average heavy metal concentrations in the study area followed the descending order: Zn (105.56 mg · kg ^{1}) > Pb (67.21 mg · kg ^{1}) > As (61.47 mg · kg ^{1}) > Cu (22.33 mg · kg ^{1}) > Cr (17.12 mg · kg ^{1}) > Ni (5.24 mg · kg ^{1}) > Cd (0.80 mg · kg ^{1}). The contents of Pb and Cd were higher in the Benggang areas than in the control area, while Cu, Zn, Ni, Cr, and As showed the opposite pattern. In BG1, the average contents of Zn, Pb, As, and Cd were 1.12, 2.82, 8.68, and 13.33 times the Fujian provincial background values, respectively; in BG2, they were 1.11, 1.36, 11.22, and 16.67 times; and in CK, they were 1.58, 1.60, 5.14, and 14.44 times. Compared with the national second-class standard (GB15618—1995), As concentrations exceeded the standard by 1.92 times in Benggang areas and 2.70 times in the control area, while Cd exceeded the standard by 2.31 and 2.60 times, respectively.

From the water-collecting slope to the channel outlet, Pb, Zn, and Cd contents in Benggang areas showed increasing trends, Cu and Cr remained relatively stable, and Ni decreased. In the control area, Cu, Zn, Ni, Cr, and Cd increased from the upper to lower slope positions, while Pb decreased slightly. As showed no clear spatial pattern. Source analysis revealed that Cu, Ni, and Cr primarily originated from parent materials; Zn mainly came from livestock breeding; Cd and As were associated with both bedrock weathering and rare earth mining activities; and Pb was attributed to composite pollution sources including bedrock mineralization, coal combustion, and vehicle exhaust emissions.

Using Fujian background values as reference, Cd posed an "extremely strong risk" and As a "strong risk," while other metals presented "slight risk." Using the national second-class standard, Cd showed "strong risk" and others "slight risk." The potential ecological risk index (Ri) followed the order: BG2 > CK > BG1. The study area faces severe Cd and As contamination, requiring appropriate safety measures.

Keywords: Water and soil erosion; Benggang; Soil heavy metal; Potential ecological risk

---

Introduction

Benggang, referred to as the "ecological ulcer" of southern red soil erosion regions in China, represents a unique erosion form resulting from the combined action of water and gravity, where soil layers and even weathering crusts are stripped and collapsed. A Benggang system comprises several components: a water-collecting slope (the catchment area behind the Benggang wall), a collapsing wall (where collapse occurs), a colluvial deposit (formed by accumulated fallen materials), a channel, and an alluvial fan (the mudflow area at the channel outlet) [1-3]. Benggang is widely distributed in low-altitude hilly areas of the Yangtze River Basin, Pearl River Basin, and coastal river basins in southeast China. There are over 239,000 Benggang sites with collapse areas 60 m^2, covering approximately 1,200 km^2 with an annual erosion volume exceeding 60 million tons and an average erosion modulus reaching 59,000 t · km ^{2} · a ^{1} [4].

Benggang erosion is characterized by rapid development, strong suddenness, large erosion modulus, severe hazards, loose and infertile soil, strong acidity, and difficulty in afforestation. Statistics show that from 1949 to 2005, Benggang erosion nationwide resulted in 3,600 km^2 of farmland buried by sand, destroyed 52,100 houses, 36,000 km of roads, over 10,000 bridges, 8,947 reservoirs, and 73,000 ponds, causing direct economic losses of 32.8 billion yuan and affecting 9.17 million people [5]. Consequently, Benggang erosion poses significant threats to regional ecological security, food security, flood control safety, and human settlement safety, severely constraining local socio-economic sustainable development.

As a uniquely Chinese term, Benggang shares similarities with "Badland" geomorphology—characterized by dense gullies and fragmented surfaces—distributed in the Mediterranean Pyrenees, Negev Desert, and Apennine Peninsula [6–8]. Both feature mixed water-gravity erosion processes, destroyed rock structures, reduced stability, varied surface morphology, and alluvial-colluvial deposits at lower positions. Soils exhibit extremely low organic matter content, scarce mineral nutrients, and sparse vegetation. Benggang research offers global comparability and serves as a typical case study for subtropical humid regions.

Soil, as an active interface for material cycling and energy flow in terrestrial ecosystems, represents both a final sink for heavy metals and an important medium for their migration to the atmosphere, water bodies, and organisms [9]. Heavy metals entering soils through bedrock mineralization, rainfall, dust deposition, and anthropogenic activities persist for long periods, are difficult for microorganisms to degrade, and can accumulate continuously in organisms through the food chain, ultimately threatening human health. Currently, soil heavy metal pollution has become a global research hotspot in environmental science [10–12]. However, existing studies have primarily focused on mining areas [10,13], urban environments [14–15], farmland [16–17], water bodies [18–19], and coastal zones [20–21], with limited research on heavy metal pollution characteristics and influencing factors in granite-derived Benggang erosion areas. Meanwhile, since Zeng Zhaoxuan et al. [22] first introduced the concept of "Benggang" into geomorphology over 30 years ago, research has mainly emphasized erosion processes, mechanisms, and disaster prevention [3–5,23–27], while studies on the ecological environmental effects of Benggang erosion, particularly whether intense erosion processes cause heavy metal redistribution and ecological risks, remain relatively weak.

Therefore, this study selected two typical Benggang sites within the Huangnikeng Benggang Group in Changting County, southwestern Fujian Province, using an adjacent non-eroded hillside as a control area. Based on measurements of Cu, Zn, Ni, Pb, Cr, As, and Cd contents in 63 soil samples, we analyzed the distribution characteristics of heavy metals in different Benggang positions, explored interactions among heavy metals and their influencing factors, and evaluated potential ecological risks using the potential ecological risk index method. The aim was to reveal heavy metal pollution characteristics in Benggang erosion areas and provide theoretical basis for Benggang control and ecological restoration.

1. Materials and Methods

1.1 Study Area Overview

Changting County is located in southwestern Fujian Province, characterized by a mid-subtropical monsoon climate with an average annual temperature of 18.5°C (extreme minimum -4.2°C, maximum 39.5°C), average annual precipitation of 1,710 mm, average annual evaporation of 1,403 mm, and a frost-free period of 260 days. The county contains 3,583 Benggang sites (13.77% of Fujian’ s total), with an erosion area of 7.28 km^2 (11.36% of the provincial total), a Benggang density of 1.16 sites · km ^{2}, and an annual erosion volume exceeding 30,000 tons. The Huangnikeng Benggang Group (25°31 49 N, 116°16 52 E) is located approximately 20 km southwest of Zhutian Town in Changting County and about 1 km west of Niukengtou Village along Provincial Highway 205. This group comprises 34 Benggang sites covering approximately 37,500 m^2, with a main channel length of 200.34 m and width ranging 4.87-12.10 m.

This study selected two adjacent Benggang sites with identical parent rock and similar topographic conditions, plus a natural slope without Benggang erosion as a control:

Benggang 1 (BG1): Water-collecting slope at 359 m elevation, 18° gradient, aspect 18° west of south, collapsing wall height 9.43 m, width 3.55-5.09 m, channel length 13.83 m, width 2.20-4.50 m, area 542 m^2. Surface soil was reddish-brown with visible white coarse quartz grains, forming micro-columns about 1 cm high, covered by 2 mm physical crusts, with vegetation coverage of only 2%.

Benggang 2 (BG2): Located approximately 15 m southwest of BG1, water-collecting slope at 318 m elevation, 15° gradient, aspect 26° east of south, collapsing wall height 6.30 m, width 2.70-3.42 m, channel length 16.48 m, width 0.71-1.54 m, area 146 m^2, with vegetation coverage exceeding 90% and 5-10 cm litter cover in the channel.

Control area (CK): Located approximately 100 m southwest of BG1 and BG2, at 323 m elevation, 8° gradient, aspect 24° east of south, slope length 22.78 m, width 4.86-5.20 m, with better vegetation conditions than Benggang areas.

The study area’ s tree species included only *Pinus massoniana* and *Cunninghamia lanceolata*. Shrubs comprised *Baeckea frutescens*, *Ilex pubescens*, *Rhaphiolepis indica*, *Adinandra millettii*, *Syzygium buxifolium*, *Lespedeza bicolor*, *Liquidambar formosana*, *Camellia oleifera*, and *Schima superba*. Herbaceous species were mainly *Miscanthus floridulus* and *Dicranopteris dichotoma*. Soils were eroded red soils derived from granite weathering.

1.2 Sample Collection and Processing

Sampling points were designated as S1, S2, S3, S4, S5, S6, and S7. In Benggang areas, these represented: water-collecting slope (S1), top of collapsing wall (S2), middle of collapsing wall (S3), bottom of collapsing wall (S4), upper colluvial deposit (S5), lower colluvial deposit (S6), and channel outlet (S7). In the control area, points were spaced approximately 4 m apart (calculated based on total collapsing wall and main channel length). At each point, surface soil (0-20 cm) was collected perpendicular to the ground surface using a bamboo shovel. Five subsamples were mixed to form one composite sample of approximately 1 kg. Three replicates were collected at each point (left, middle, and right ends at the same contour), totaling 63 samples. Replicate samples were thoroughly mixed, and approximately 0.5 kg was taken using the quartering method, placed in polyethylene bags, labeled, and temporarily stored in an incubator. To avoid rainfall effects on surface soil heavy metal content [28], sampling was conducted during a rainless period (July 1-15, 2014).

1.3 Sample Testing

1.3.1 Soil Heavy Metal Content Heavy metal analysis employed hot plate digestion [29]: accurately weighed samples (40.0±0.5 mg) were placed in Teflon digestion vessels, mixed with 2 mL of acid mixture (HF:HNO =3:1), and heated at 150°C for 12 h. After cooling, 0.25 mL HClO was added, evaporated to near dryness at 150°C, then redissolved with 2 mL ultrapure water and 1 mL HNO at 150°C for 12 h. The solution was diluted to 40 mL with ultrapure water for analysis. To prevent secondary contamination, all glassware and digestion vessels were soaked in 5% HNO for 24 h, rinsed, and dried before use. All reagents were analytical grade, and water was 18.2 MΩ ultrapure water. Heavy metal contents (Cu, Zn, Ni, Pb, Cr, As, Cd) were determined using an X-Serie ICP-MS (USA) with parallel test RSD% <5%. National standard materials (GBW 07405 yellow-red soil and GBW 07407 latosol) were used for monitoring and correction, with deviations between measured and certified values within 10%. Online dual internal standards of 5 g · L^{1} In and Re were used during analysis, achieving recoveries of 85-115%, meeting the U.S. EPA standard of 80-120%. All analyses were completed at the Key Laboratory for Subtropical Mountain Ecology, Fujian Normal University.

1.3.2 Soil Basic Physico-Chemical Properties Soil physico-chemical properties were measured using conventional methods. Total carbon and nitrogen were determined using an Elementar Vario MAX analyzer (Germany). Total phosphorus, available phosphorus, and available nitrogen (ammonium + nitrate) were measured using a Skalar san++ continuous flow analyzer (Netherlands). Total potassium and available potassium were determined by flame photometry. Soil bulk density and moisture content were measured using a ring knife-aluminum box method. Particle composition was analyzed using a SEDIMAT4-12 particle size system (Germany). pH was measured using a portable pH meter (STARTER 300). Basic physico-chemical properties are shown in .

1.4 Data Processing and Potential Ecological Risk Assessment

1.4.1 Data Processing Data were organized using Microsoft Excel 2003. SPSS was used for one-way ANOVA with LSD test (=0.05) for significance testing. Pearson correlation analysis examined relationships between heavy metals and soil physico-chemical properties. Figures were prepared using Origin 8.0.

1.4.2 Potential Ecological Risk The Hakanson potential ecological risk index method [30] (Ri) was used to assess heavy metal hazards. This method quantitatively evaluates potential ecological risks in soils and sediments by integrating environmental effects and toxicological parameters, reflecting both single-element hazards and combined pollution effects. It has been widely applied in heavy metal risk assessment [10,17,19]. The formulas are:

$$E_r^i = T_r^i \times \frac{C_j^i}{C_k^i}$$

$$R_i = \sum_{i=1}^{n} E_r^i$$

where C_j^i is the measured content of heavy metal i, C_k^i is the reference value, and T_r^i is the toxic response coefficient. Following Hakanson [30] and Xu Zhengqi et al. [31], toxic response coefficients were: Cd(30), As(10), Pb=Cu=Ni(5), Cr(2), Zn(1). E_r^i is the single-element potential ecological risk coefficient, and R_i is the potential ecological risk index. Following Li Yimeng et al. [14], classification standards were: E_r^i <30 = "slight risk", 30 E_r^i<60 = "medium risk", 60 E_r^i<120 = "strong risk", 120 E_r^i<240 = "very strong risk", E_r^i 240 = "extremely strong risk"; R_i<70 = "slight risk", 70 R_i<140 = "medium risk", 140 R_i<280 = "strong risk", R_i 280 = "extremely strong risk". To reflect differences under different reference values, both Fujian provincial soil background values [32] and national second-class soil environmental quality standards [33] were used as references.

2. Results

2.1 Characteristics of Soil Heavy Metal Contents

As shown in , heavy metal concentrations varied across the study area, following the descending order: Zn (105.56 mg·kg^{1}) > Pb (67.21 mg·kg^{1}) > As (61.47 mg·kg^{1}) > Cu (22.33 mg·kg^{1}) > Cr (17.12 mg·kg^{1}) > Ni (5.24 mg·kg^{1}) > Cd (0.80 mg·kg^{1}). Average concentrations in BG1 were: Cu 12.37, Zn 93.34, Ni 4.49, Pb 98.39, Cr 7.59, As 50.16, and Cd 0.72 mg·kg^{1}. In BG2, they were: Cu 12.01, Zn 92.08, Ni 4.55, Pb 47.35, Cr 11.12, As 64.85, and Cd 0.90 mg·kg^{1}. In CK, they were: Cu 42.62, Zn 131.26, Ni 8.61, Pb 55.89, Cr 32.66, As 69.39, and Cd 0.78 mg·kg^{1}. CK values were 3.45, 1.41, 1.92, 0.57, 4.30, 1.38, and 1.08 times those in BG1, and 3.55, 1.43, 1.89, 1.18, 2.93, 1.07, and 0.87 times those in BG2, respectively. Except for Pb in BG1 and Cd in BG2, CK heavy metal contents were significantly higher than in Benggang areas, indicating that Benggang erosion can reduce soil heavy metal contents, with reduction magnitudes following the order: Cu Cr > Ni > Zn > As > Cd > Pb.

Except for Cu, Ni, and Cr (with CK Cu exceeding Fujian background values), average Zn, Pb, As, and Cd contents in BG1 were 1.12, 2.82, 8.68, and 13.33 times the Fujian background values, respectively; in BG2 they were 1.11, 1.36, 11.22, and 16.67 times; and in CK they were 1.58, 1.60, 5.14, and 14.44 times. Compared with the national second-class standard (GB15618—1995), maximum values of Cu and Zn in CK exceeded the standard, while average As contents exceeded the standard by 1.92 times in Benggang areas and 2.70 times in CK, and average Cd contents exceeded by 2.31 and 2.60 times, respectively.

The coefficient of variation (CV) reflects data dispersion and spatial heterogeneity. In Benggang areas, Pb showed the highest CV (54.06%), followed by Cd (44.44%), while other elements ranged 15.09-34.07%. In CK, Cu, Cr, Zn, and Pb had relatively high CVs (46.72%, 32.55%, 31.48%, and 20.16%, respectively), with other elements below 20%. Across the entire study area, CVs followed the order: Cu (82.49%) > Cr (75.06%) > Pb (50.05%) > Ni (41.60%) > Cd (37.50%) > Zn (31.69%) > As (22.40%).

2.2 Spatial Distribution Characteristics of Soil Heavy Metals

Heavy metal distribution patterns varied across the study area ([Figure 1: see original paper]). Along the sequence from water-collecting slope, top of collapsing wall, middle of collapsing wall, bottom of collapsing wall, upper colluvial deposit, lower colluvial deposit to channel outlet, Benggang areas showed stable Cu and Cr contents, increasing Zn and Cd, decreasing Ni, slightly decreasing Pb at colluvial deposits but generally increasing overall. In CK, most heavy metals (Cu, Zn, Ni, Cr, Cd) increased from upper to lower slope positions, while Pb decreased slightly. As showed fluctuating patterns without clear spatial trends. Overall, except for Pb and As, heavy metal contents in Benggang systems showed strong stability across different positions with small spatial variations.

2.3 Source Analysis of Soil Heavy Metals

2.3.1 Correlation Analysis Correlation analysis among heavy metals helps identify their sources [9,34-36]. As shown in , strong correlations existed among Cu, Zn, Ni, and Cr, with correlation coefficients of Cu-Zn (0.806), Cu-Ni (0.775), Cu-Cr (0.946), Zn-Cr (0.737), and Ni-Cr (0.659), suggesting common sources. Pb, As, and Cd showed distinct correlation patterns: Pb-Cr was significantly negatively correlated (r = -0.318), indicating different sources; As-Cu (0.385), As-Zn (0.317), and As-Cr (0.434) were significantly or extremely significantly positively correlated, while As-Pb was extremely significantly negatively correlated (r = -0.369), suggesting mixed influences on As; Cd-Zn was significantly positively correlated (r = 0.268), with no correlations with other elements, suggesting external sources for Cd.

Compared with local zonal vegetation soils of *Castanopsis carlesii* forests [37], the study area showed higher pH and bulk density but lower organic matter, total nitrogen, total phosphorus, and total potassium, indicating obvious erosion characteristics (see). Soil physico-chemical properties significantly affect heavy metal ecological activity, toxicity, and environmental mobility [36,38]. Correlation analysis with soil properties () revealed that Cu and Cr were extremely significantly positively correlated with organic matter, total nitrogen, total phosphorus, and available potassium, and significantly negatively correlated with pH, bulk density, and total potassium. Zn showed similar correlations with soil properties as Cu and Cr, except for no correlation with available potassium. Ni was extremely significantly correlated with total phosphorus and available potassium. Pb showed extremely significant positive correlations with pH, bulk density, and available phosphorus, but extremely significant negative correlations with organic matter and total nitrogen, and significant negative correlations with total phosphorus and available potassium (opposite to Cu and Cr). As was extremely significantly positively correlated with organic matter, total nitrogen, and total phosphorus (though with low coefficients of 0.465, 0.378, and 0.376, respectively) and extremely significantly negatively correlated with pH and bulk density. Cd was only correlated with total potassium (R = -0.254*).

2.3.2 Principal Component Analysis To accurately parse heavy metal sources, principal component analysis was performed on 15 indicators of heavy metals and physico-chemical properties (). KMO and Bartlett's test values were 0.683 and 0, respectively, confirming suitability for PCA. After varimax rotation, the first seven principal components explained 87.42% of total variance, capturing most information. PC1 explained 23.51% of variance with loadings of Cu (0.982), Ni (0.788), and Cr (0.890). Given that average contents of Cu, Ni, and Cr were significantly lower than Fujian background values (except CK Cu), PC1 was identified as a "natural source factor." PC3 explained 12.58% of variance with Zn loading of 0.807, suggesting livestock breeding as the source based on correlation analysis. PC5 explained 8.28% of variance, primarily representing Cd (loading 0.939). PC7 explained 8.86% of variance with As loading of 0.934. Cd and As sources were likely related to both parent materials and rare earth mining activities in the county. Pb was distributed across multiple components, suggesting composite pollution from bedrock weathering, residential coal combustion, and vehicle exhaust/tire wear from nearby Provincial Highway 205. Only total phosphorus showed significant loading in PC1, indicating that Benggang erosion mainly affects soil physico-chemical properties rather than heavy metal distribution.

2.4 Potential Ecological Risk of Soil Heavy Metals

Single-element potential ecological risk coefficients are presented in . Using Fujian background values as reference, average risk coefficients followed the order: Cd > As > Pb > Cu > Ni > Zn > Cr. Cd posed the most severe risk (“extremely strong risk”), As showed “strong risk,” while others were “slight risk.” Using the national second-class standard, the order was Cd > As > Cu > Pb > Ni > Zn > Cr, with Cd at “strong risk” and others “slight risk.”

As shown in [Figure 2: see original paper], potential ecological risk indices (Ri) followed the order: BG2 > CK > BG1. Using Fujian background values, average Ri was 570.24 (“extremely strong risk”); using the national standard, average Ri was 105.53 (“medium risk”). Overall, soil heavy metal pollution in the study area poses certain potential risks, with Ri generally increasing from water-collecting slope to channel outlet in Benggang areas under both reference systems.

3. Discussion and Conclusions

This study demonstrated that Pb and Cd contents were higher in Benggang areas than in CK, while Cu, Zn, Ni, Cr, As, and Cd showed the opposite pattern. Zn, Pb, As, and Cd exhibited obvious local enrichment and point source pollution trends, with Zn, Pb, and Cd contents generally higher than those in China’ s farmland soils [39], consistent with findings by Wang et al. [10,40], Li et al. [41], and Wang et al. [42]. This may be related to the granite-weathered red soil environment and agricultural/livestock activities in western Fujian and southern Jiangxi [17]. Average Pb, As, and Cd contents approached or exceeded those in major Chinese urban soils [14], while CK Cu was slightly higher than urban soils and Benggang Cu was less than half of urban levels. All samples showed Zn, Ni, and Cr contents far below urban soil levels, indicating minimal industrial impact and distinct differences from urban soil pollution characteristics.

The Benggang erosion process can be summarized as: under alternating water and gravity actions, original slope soils collapse to form the collapsing wall, fallen materials accumulate at the wall base to form colluvial deposits, which are then partially transported and deposited in the channel or carried to the channel outlet and downstream farmland to form alluvial fans. Liu et al. [26] monitored Benggang erosion in Guangdong using 3D laser scanning from 2011-2013 and found that erosion mainly occurred at the collapsing wall, colluvial deposits, and their lateral areas, consistent with this study’ s heavy metal distribution patterns showing general increases from water-collecting slope to channel outlet. Additionally, no obvious differences in heavy metal spatial distribution were observed between Benggang sites with different vegetation coverage, and spatial variations of Cu, Zn, Ni, and Cr were relatively small across different Benggang positions, while Pb, As, and Cd showed larger variations. This suggests that Benggang erosion may be an important cause of heavy metal spatial heterogeneity, potentially influenced by external pollution sources.

Correlation and principal component analyses, combined with spatial distribution characteristics, revealed strong coupling among Cu-Ni-Cr, suggesting origins from parent material weathering. Zn, as an important component of livestock feed additives used for disease reduction and growth promotion, is poorly utilized by animals and mostly excreted in manure, increasing soil Zn content [43-45]. Local residents raise pigs, chickens, and ducks year-round, indicating livestock breeding as a Zn source. Cd and As contents far exceeded Fujian background values, suggesting sources including: (1) parent materials; and (2) rare earth mining. Changting County is a enriched region for new ion-adsorption rare earth elements in southern China. Since the 1990s, escalating rare earth prices have intensified mining activities, potentially affecting Cd and As inputs to soils [41-42]. Pb showed extremely significant negative correlation with organic matter, indicating high Pb content in parent materials, while residential coal combustion and vehicle exhaust/tire wear dust from nearby Provincial Highway 205 also contributed through atmospheric (dry) and rainfall (wet) deposition.

Single-element risk coefficients showed that As and Cd contents were relatively high with large toxic response coefficients (10 and 30, respectively), making their risk coefficients far exceed those of other elements. Consequently, Ri values largely depended on As and Cd pollution status. Ri distribution increased from upstream to downstream areas, consistent with erosion processes. Due to Fujian' s extremely low Cd background value (0.054 mg · kg ^{1}) and low As background (5.78 mg · kg ^{1}), their risk coefficients were much higher than when using the national standard. Overall, Cd and As pollution has become prominent and warrants serious attention from authorities. Furthermore, Benggang erosion showed no obvious mitigation effect on the main pollutants As and Cd, with small Ri differences between Benggang and control slopes, indicating persistently high potential ecological risks. Regional planting practices, mining activities, transportation, and waste discharge from humans and livestock all constitute effective pathways for external heavy metal input to soils, requiring further research on source identification in agricultural areas.

References

[1] Liu X L, Zhang D L, Jia Y Y. Soil physical properties of collapsing hill and gully and their indications for soil erosion: An example of Liantanggang collapsing hill and gully in Wuhua County of Guangdong[J]. Advances in Earth Science, 2013, 28(7): 802-811

[2] Sheng J A, Liao A Z. Erosion control in South China[J]. CATENA, 1997, 29(2): 211-221

[3] Luk S H, Yao Q Y, Gao J Q, et al. Environmental analysis of soil erosion in Guangdong Province: A Deqing case study[J]. CATENA, 1997, 29(2): 97-113

[4] Liang Y, Ning D H, Pan X Z, et al. The characteristics of Benggang erosion and its control in red region of southern China[J]. Soil and Water Conservation

in China, 2009(1): 31-34

[5] Jiang F S, Huang Y H, Wang M K, et al. Effects of rainfall intensity and slope gradient on steep colluvial deposit erosion in Southeast China[J]. Soil Science Society of America Journal, 2014, 78(5): 1741-1752

[6] Bryan R B, Yair A. Badland Geomorphology and Piping[M]. Norwich: Geo Books, 1982: 3-24

[7] Gallart F, Marignani M, Pérez-Gallego N, et al. Thirty years of studies on badlands, from physical to vegetational approaches. A succinct review[J]. CATENA, 2013, 106: 4-11

[8] Vergari F, Seta M D, Monte M D, et al. Badlands denudation "hot spots" : The role of parent material properties on geomorphic processes in 20-years monitored sites of Southern Tuscany (Italy)[J]. CATENA, 2013, 106: 31-41

[9] Dai B, Lv J S, Zhan J C, et al. Assessment of sources, spatial distribution and ecological risk of heavy metals in soils in a typical industry-based city of Shandong Province, eastern China[J]. Environmental Science, 2015, 36(2): 507-515

[10] Wang F, Huang Y Z, Wang X L, et al. Ecological risk assessment of heavy metals in surrounding soils of tungsten ores: Comparison of different evaluation methods[J]. Environmental Chemistry, 2015, 34(2): 225-233

[11] Rodríguez Martín J A, Ramos-Miras J J, Boluda R, et al. Spatial relations of heavy metals in arable and greenhouse soils of a Mediterranean environment region (Spain)[J]. Geoderma, 2013, 200/201: 180-188

[12] Alary C, Demougeot-Renard H. Factorial kriging analysis as a tool for explaining the complex spatial distribution of metals in sediments[J]. Environmental Science & Technology, 2010, 44(2): 593-599

[13] Huang X J, Jiang C S, Hao Q J. Assessment of heavy metal pollutions in soils and bioaccumulation of heavy metals by plants in Rongxi Manganese mineland of Chongqing[J]. Acta Ecologica Sinica, 2014, 34(15): 4201-4211

[14] Li Y M, Ma J H, Liu D X, et al. Assessment of heavy metal pollution and potential ecological risks of urban soils in Kaifeng City, China[J]. Environmental Science, 2015, 36(3): 1037-1044

[15] Chen T B, Zheng Y M, Lei M, et al. Assessment of heavy metal pollution in surface soils of urban parks in Beijing, China[J]. Chemosphere, 2005, 60(4): 542-551

[16] Li M S, Tong L J. Specificity and ecological risk of heavy metal pollution in Liaoning sewage irrigation district[J]. Chinese Journal of Eco-Agriculture, 2008, 16(6): 1517-1522

[17] Jiang R, Lv Y Z, Shen S Y. Assessment of heavy metal content and pollution in organic and conventional farming soils in North China[J]. Chinese Journal of

Eco-Agriculture, 2015, 23(7): 877-885

[18] Yu X, An Y L, Wu Q X. Pollution characteristics and ecological risk assessment of heavy metals in the sediments of Chishui River[J]. Acta Scientiae Circumstantiae, 2015, 35(5): 1435-1443

[19] Cheng X, Wang R L, Wang J L, et al. Potential ecological risks assessment of heavy metals in the reservoir sediment of the western Haihe River basin[J]. Chinese Journal of Applied Ecology, 2015, 26(5): 1495-1500

[20] Yu R L, Hu G R, Zhao J X, et al. Distribution, transfer and stock of heavy metals in *Kandelia candel* mangrove situated in Quanzhou bay wetland, southeast coast of China[J]. Environmental Chemistry, 2013, 32(1): 125-131

[21] Li Y H, Yuan J J, Chen H Y, et al. The distribution characteristics of Cu, Zn, Pb and N, P, K in the several plants on coast of Quanzhou Bay[J]. Chinese Journal of Eco-Agriculture, 2008, 16(3): 630-634

[22] Zeng Z X, Huang S M. Physical Geography in China: Geomorphology[M]. Beijing: Science Press, 1980: 32-36

[23] Woo M K, Fang G X, diCenzo P D. The role of vegetation in the retardation of rill erosion[J]. CATENA, 1997, 29(2): 161-176

[24] diCenzo P D, Luk S H. Gully erosion and sediment transport in a small subtropical catchment, South China[J]. CATENA, 1997, 29(2): 191-210

[25] Lam K C, Leung Y F, Yao Q Y. Nutrient fluxes in the Shenchong Basin, Deqing County, South China[J]. CATENA, 1997, 29(2): 191-210

[26] Liu X L, Zhang D L. Study on erosion process of collapsing hill and gully by three-dimensional monitoring: An example of Liantanggang in Wuhua County of Guangdong Province[J]. Journal of Soil and Water Conservation, 2015, 29(1): 26-31

[27] Chen Z B, Zhu H J, Liu Q, et al. Slump gully characteristic of small watershed of Genxi River and its control measures[J]. Journal of Natural Disasters, 2006, 15(5): 83-88

[28] Tao Q, Yao J, He S F, et al. Migration and transformation characteristics of heavy metals with surface runoff under different rainfall intensities in contaminated soil[J]. Journal of Soil and Water Conservation, 2015, 29(2): 65-68

[29] Zhang K, Yang X, Wu Y J, et al. Pollution characteristics and ecological risk assessment of heavy metals in surface sediments in Changsha-Zhuzhou-Xiangtan reach, Xiang Jiang River, China[J]. Journal of Agricultural Resources and Environment, 2015, 32(1): 60-65

[30] Hakanson L. An ecological risk index for aquatic pollution control. A sedimentological approach[J]. Water Research, 1980, 14(8): 975-1001

[31] Xu Z Q, Ni S J, Tuo X G, et al. Calculation of heavy metal' s toxicity coefficient in the evaluation of potential ecological risk index[J]. Environmental Science & Technology, 2008, 31(2): 112-115

[32] Chen Z J, Chen C X, Liu Y Q, et al. Study on soil environmental background values in Fujian Province[J]. Environmental Science, 1992, 13(4): 70-75

[33] State Environmental Protection Administration of China, General Administration of Quality Supervision, Inspection and Quarantine of China. GB15618—1995 Environmental Quality Standard for Soil[S]. Beijing: China Standard Press, 1995

[34] Ye C, Li S Y, Zhang Q F. Sources and assessment of heavy metal contamination in water-level fluctuation zone of the Three Gorges Reservoir, China[J]. Chinese Journal of Eco-Agriculture, 2011, 19(1): 146-149

[35] Muyessar T, Jilili A, Jiang F Q. Distribution characteristics of soil heavy metal content in northern slope of Tianshan Mountains and its source explanation[J]. Chinese Journal of Eco-Agriculture, 2013, 21(7): 883-890

[36] Ning X B, Xiang W H, Fang X, et al. Heavy metal concentrations and pollution assessment of limestone forests in Huaxi District, Guiyang City[J]. Acta Ecologica Sinica, 2009, 29(4): 2169-2177

[37] Ren W L, Guo J F, Wu B B, et al. Decomposition dynamics of leaf litter in logging residue of a secondary *Castanopsis carlesii* plantation and its chemical composition changes[J]. Chinese Journal of Applied Ecology, 2015, 26(4): 1077-1082

[38] Sun J W, Huang Y Z, Shi M C, et al. Research progress on biotoxicity of heavy metals in soil[J]. Acta Ecologica Sinica, 2008, 28(6): 2861-2869

[39] Zhang X M, Zhang X Y, Zhong T Y, et al. Spatial distribution and accumulation of heavy metal in arable land soil of China[J]. Environmental Science, 2014, 35(2): 692-703

[40] Wang F, Huang Y Z, Wang X L, et al. Ecological risk assessment of heavy metals in surrounding soils of a copper smelting plant in Jiangxi Province[J]. Environmental Chemistry, 2014, 33(7): 1066-1074

[41] Li X F, Chen Z B, Chen Z Q, et al. Concentrations and health risk assessment of heavy metals in soil and vegetables from REEs mining area, Fujian Province[J]. Journal of Soil and Water Conservation, 2013, 27(1): 146-151

[42] Wang Y S, Hou X L, Wu P F, et al. Characteristics and evaluation of heavy metal pollution in deserted land-area left-over by the rare earth mining in Changting, Fujian[J]. Journal of Safety and Environment, 2014, 14(4): 259-262

[43] Jiang P, Jin S Y, Hao X Z, et al. Distribution characteristics of heavy metals in feeds, pig manures, soils and vegetables[J]. Journal of Agro-environment Science, 2010, 29(5): 942-947

[44] Meng X H, Zhang J B, Li P, et al. Summary of livestock environmental pollution and environmental management policies[J]. Journal of Ecology and Rural Environment, 2014, 30(1): 1-8

[45] Liu K L, Li D M, Huang Q H, et al. Ecological benefits and environmental carrying capacities of red paddy field subjected to long-term pig manure amendments[J]. Scientia Agricultura Sinica, 2014, 47(2): 303-313

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

Source: ChinaXiv —Machine translation. Verify with original.