ASSESSMENT OF PLANT DIVERSITY IN HEAVY METAL-POLLUTED AREAS OF THE XIKUANGSHAN MINING REGION, HUNAN PROVINCE

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(Received 25th Jul 2025; accepted 10th Nov 2025)

Abstract. Taking plant communities in heavy metal-polluted areas as the research subject, this study analyzed the species composition, diversity, and dominant species differences in plant communities within the Xikuangshan heavy metal-polluted area using the typical sampling method. The results indicated that in the heavy metal-polluted area, Gramineae and Compositae were the dominant families, comprising 8 genera and 9 species, and 8 genera and 11 species, respectively. Herbaceous plants dominated the plant communities in the heavy metal-polluted area, accounting for 70.77% of the total. The number of plant families in lightly, moderately, and heavily polluted areas significantly decreased with increasing pollution levels, and monotypic families and monospecific genera became increasingly scarce. The 54 genera of seed plants in the area could be classified into 11 distribution types, with the pantropical and cosmopolitan distribution types containing the largest number of genera, accounting for 42.59% and 24.07%, respectively, indicating distinct tropical characteristics. The Margalef richness index, Shannon-Wiener diversity index, and Pielou evenness index of plant communities in lightly, moderately, and heavily polluted areas showed no significant differences with increasing pollution levels. The β-diversity results revealed a certain negative correlation between the degree of heavy metal pollution and plant community species similarity; the greater the change in pollution level, the lower the community similarity. The findings of this study provide a theoretical basis for formulating science-based restoration and protection strategies in the region.

Keywords: *Xikuangshan, heavy metal pollution, ecological risk index, plant community, plant diversity*

Introduction

Plant diversity encompasses both the number of species within a community and the evenness of individual distribution among those species. It reflects variations in structural types, species composition, and habitat conditions within plant communities. High plant diversity means a large number of species and an even distribution of individuals, whereas low diversity indicates fewer species and uneven distribution. The relationship between plant diversity and environmental factors is highly significant (Liu et al., 2019; Tan et al., 2019). Investigating the impact of environmental factors on plant diversity is crucial for understanding the patterns of plant diversity variation. Among these factors, heavy metals pose a significant threat due to their concealed nature, resistance to degradation, and tendency to accumulate, as they can become toxic to the soil-plant system when present above certain thresholds (Xiao et al., 2004). Such toxicity can alter plant community structure and reduce biodiversity (Ren et al., 2015). Heavy metal-contaminated areas often exhibit fewer species, simplified community

DOI: http://dx.doi.org/10.15666/aeer/2401_137151

structures, and overall lower species diversity (Li et al., 2014; Fu et al., 2017). For example, Belykh et al. (2015) reported reduced plant diversity at heavily polluted sites compared to less contaminated areas, indicating that heavy metal pollution degrades plant habitats and reduces plant diversity. Similarly, Pastor and Hernández (2012), through regular soil monitoring in landfill discharge zones, found that rising heavy metal levels hinder vegetation recovery and disrupt natural succession. While numerous studies have explored the characteristics of plant diversity in heavy metal-polluted areas, the relationship between gradient changes in heavy metal pollution and plant diversity still requires further investigation.

Xikuangshan in Hunan, China, is the world's largest antimony mining area and is often referred to as the 'Antimony Capital of the World.' Long-term unregulated mining and smelting activities in the area have severely contaminated the soil with heavy metals like antimony, arsenic, cadmium, and lead (Ku et al., 2015). The Hakanson potential ecological risk index classifies this location as a high-risk zone due to heavy metal pollution (Fu, 2015). Li et al. (2010) studied the plant community in the Xikuangshan antimony mining area and found that the vegetation is predominantly herbaceous, with relatively few shrubs and low overall species diversity. Their study concluded that heavy metal pollution significantly elevates local ecological risk and poses a substantial constraint on vegetation restoration in the area. In recent years, several studies have examined the characteristics of heavy metal accumulation in native plants in Xikuangshan (Xue et al., 2014; Fu et al., 2016), identified hyperaccumulator species (Guo et al., 2019), and investigated the spatial distribution and migration patterns of heavy metals in the mining area (Li et al., 2017). Many scholars have subsequently carried out investigations on antimony pollution in soil, solid waste, and organisms in mining areas. However, research on plant diversity remains limited. To address this gap, the present study focuses on plant communities across areas with varying levels of heavy metal pollution in Xikuangshan. By analyzing species composition, diversity patterns, and trends along a heavy metal gradient, this research is beneficial for identifying super-enriched antimony plants in antimony mining areas and provides a theoretical foundation for plant diversity conservation, vegetation restoration, and ecological rehabilitation in the Xikuangshan region.

Study area and methods

Overview of the study area

Xikuangshan is located in the Mining Township of Lengshuijiang City, in northern Hunan Province, China. The region features a landscape of intersecting valleys, dominated by mountains, hills, and river valleys. The primary water systems include the Lianxi and Qingfeng Rivers, along with smaller tributaries such as the Xuanshan River, Choupi Stream, Feishuiyan River, and Batang Mountain Stream, which are all part of the Zi River watershed. The region experiences a subtropical humid monsoon climate, characterized by distinct seasons and mild temperatures, with an average temperature of 16–17°C. Xikuangshan is rich in antimony, lead, and other nonferrous metal resources. Its antimony reserves represent approximately 30% of the global total, making it one of the world's most significant antimony mining sites. Ecologically, Xikuangshan falls within the subtropical evergreen broad-leaved forest zone, with native vegetation consisting of evergreen broad-leaved forests and mixed evergreen-deciduous broad-leaved forests. However, decades of intensive mining and smelting have severely degraded the natural habitat. Herbaceous plant communities and sparse shrublands have largely replaced the original vegetation, resulting in reduced species diversity. Consequently, vegetation restoration has become a central focus of ecological rehabilitation efforts in the Xikuangshan region.

Research methods

Pollution level classification

The Hakanson potential ecological risk index method (Hakanson, 1980) was employed to classify heavy metal pollution into three levels: light, moderate, and severe, as shown in *Table 1*.

Table 1. *Classification of heavy metal contamination*

Potential ecological risk index	Range	Level
RI	$2000 < RI$	LL
	$2000 \leq RI \leq 6000$	ML
	$6000 \leq RI$	SL

LL, ML, and SL indicate light level, moderate level, and severe level, respectively

We selected this method for its comprehensive evaluation approach, which assesses several indicators such as soil heavy metal content, toxicity levels, and pollution levels. It also accounts for the synergistic effects of multiple elements and the environmental sensitivity to heavy metal contamination. The calculation formula is as follows:

$$E_r^i = T_r^i \times \frac{C_{surface}^i}{C_n^i} \tag{Eq.1}$$

$$RI = \sum E_r^i \tag{Eq.2}$$

where $C^i_{surface}$ represents the measured concentration of the i-th heavy metal, C^i_n denotes the reference value for the i-th heavy metal, and T^i_r indicates the toxic response coefficient of the i-th heavy metal.

Quadrat sampling

From July to August 2019, we conducted quadrat surveys in heavy metal-contaminated areas of Xikuangshan using a representative sampling approach. Based on the potential ecological risk index, three pollution-level zones (light, moderate, and severe) were identified, with ten quadrats established in each zone. The quadrats were randomly placed, with herbaceous plants sampled in 1 m × 1 m quadrats, shrubs in 4 m × 4 m, and trees in 10 m *10 m. Sampling sites were located near mining areas, factories, and slag disposal zones, within the coordinates 27°44′24″-27°48′39″N and 111°27′26″-111°31′24″E. Survey forms entailed detailed information on each quadrat, including its number, GPS coordinates, elevation, surrounding environmental conditions, and plant species data (height, abundance, and coverage).

Species identification and classification

Plant species were identified using authoritative references such as the *Flora of China* (Flora of China Editorial Committee, 1959-2004) and *Higher Plants of China in Color* (Editorial Committee of the Color Illustrations of Higher Plants in China, 2016). Floristic regionalization followed the classification system outlined in *Phytogeography and Vegetation Geography of China* (Chen, 2015).

Data collection and analysis

After identifying and classifying the plants in each quadrat, we analyzed the composition of plant communities in the contaminated areas. Species dominance was determined using the Importance Value (IV), with the species exhibiting the highest IV in each community designated as the dominant species. Data integration and calculations were performed using Excel 2010. One-way analysis of variance (ANOVA) was conducted in SPSS 17.0, using Duncan's method to assess significant differences in plant diversity indices across the three pollution levels.

Calculation formula:

Margalef species richness index:

$$E = (S-1)/\ln N \tag{Eq.3}$$

Shannon-Wiener diversity index:

$$H = -\sum P_i \ln P_i \tag{Eq.4}$$

Pielou evenness index:

$$J_{sw} = (-\sum P_i \ln P_i)/\ln S \tag{Eq.5}$$

In the formula, S represents the total number of plant species in the quadrat, N denotes the sum of individuals for all species in the quadrat, and Pi indicates the ratio of individuals of species i to the total number of individuals of all species (Qian and Ma, 1994).

Sorensen similarity coefficient:

$$C_s = 2j/(a+b) \tag{Eq.6}$$

where j signifies the number of common species between two compared communities, while a and b reflect the number of species found in each community (Chen et al., 2009).

$$\text{Importance Value (IV)} = \text{Relative Density} + \text{Relative Abundance} + \text{Relative Frequency} \tag{Eq.7}$$

Results and analysis

Species composition and floristic elements in heavy metal-polluted areas

The survey identified 65 vascular plant species, belonging to 31 families and 56 genera, across 30 quadrats in heavy metal-polluted areas. Dicotyledons accounted for 24 families, 42 genera, and 48 species; monocotyledons for 5 families, 12 genera, and 15 species; and pteridophytes for 2 families, 2 genera, and 2 species. Asteraceae (8 genera, 11 species) and Poaceae (8 genera, 9 species) families were the most dominant, comprising 16.92% and 13.84% of the total species, respectively. Nine families (Asteraceae, Poaceae, Fabaceae, Urticaceae, Polygonaceae, Convolvulaceae, Rosaceae, Solanaceae, and Amaranthaceae) had at least two genera each, which together represented 29.03% of all families. In contrast, 22 monotypic families were recorded, including Chenopodiaceae, Cyperaceae, Dioscoreaceae, Phytolaccaceae, Valerianaceae, Menispermaceae, Vitaceae, Alangiaceae, Loganiaceae, Commelinaceae, Euphorbiaceae, Typhaceae, Cucurbitaceae, Papaveraceae, Pteridaceae, Anacardiaceae, Symplocaceae, Araliaceae, Equisetaceae, Moraceae, Verbenaceae, and Staphyleaceae. These monotypic families represented 70.96% of the total families and accounted for 39.28% of the total genera and 38.46% of the total species. The polluted area exhibited low species diversity, with a predominance of monotypic genera and species. The life forms identified included herbs (46 species), lianas (7 species), shrubs (10 species), and trees (2 species). Herbs were the most common life form (70.77%), with only one tree species, *Aralia chinensis* (Chinese angelica tree), recorded.

According to China's floristic regionalization, Xikuangshan in central Hunan belongs to the Sino-Japanese Forest Subregion of the East Asian Floristic Region. The analysis of 54 seed plant genera revealed 11 distribution types (*Table 2*), each with distinct floristic variations. Pantropical elements accounted for 42.59%, while word-wide spread elements accounted for 24.07%. The remaining nine types each contained ≤ 3 genera, making up the remaining 44.44%. The predominance of pantropical elements indicates a strong tropical affinity, consistent with the region's geographical location.

Table 2. *Genus count for the eleven distribution types of spermatophytes in heavy metal-contaminated areas*

Distribution type	Genus	Rate
Word-wide spread	13	24.07
Pantropic	23	42.59
Old World Tropic	1	1.85
Tropical Asia & Tropical Australasia Oceania	2	3.7
Tropical Asia & Tropical Africa	2	3.57
Tropical Asia	2	3.7
North Temperate	2	3.7
East Asia & North America Disjuncted	2	3.7
Old World Temperate	2	3.7
Temperate Asia	3	5.56
East Asia	2	3.7

Plant species composition in different pollution-level zones

The investigation of plant communities in areas with varying levels of heavy metal pollution revealed a notable decline in species richness with increasing pollution (*Table 3*). The lightly polluted area recorded 39 plant species, representing 24 families and 38 genera. The moderately polluted area had 30 species from 17 families and 28 genera, while the severely polluted area contained only 26 species from 10 families and

25 genera. This decline in species number indicates that heavy metal pollution inhibits plant diversity and reduces species richness. We recorded 19 monotypic families in the lightly polluted area, representing 79.16% of the total number of families. The most species-rich families were Asteraceae (6 species, 15.38%) and Poaceae (5 species, 12.82%). In the moderately polluted area, aside from Asteraceae (8 species) and Poaceae (7 species), the remaining 15 families were monotypic or monogeneric, making up 88.23% of the families. In the severely polluted area, only four monotypic families (Cyperaceae, Chenopodiaceae, Equisetaceae, and Loganiaceae) were observed, comprising 40% of the families, while the other six families contained two or more species. Asteraceae remained dominant (7 species, 26.92%) in this area, followed by Poaceae (4 species, 15.38%). These findings suggest that as pollution intensifies, the number of monotypic (or monogeneric) plant families declines, while the proportion of families with multiple species (or genera) increases. Six plant species (*Erigeron annuus, Bidens pilosa, Lagedium sibiricum, Miscanthus sinensis, Boehmeria nivea, and Buddleja lindleyana*) were present across all pollution levels, indicating their ecological resilience and adaptability in heavy metal-polluted environments.

Table 3. *Summary of plant families, genera, and species recorded across different levels of heavy metal pollution*

Classes	Contamination level					
	LL		ML		SL	
	Number	Ratio	Number	Ration	Number	Ration
Families	24	77.42%	17	54.83%	10	32.25%
Genera	38	67.86%	28	50%	25	44.64%
Species	39	60%	30	46.15%	26	40%

LL, ML, and SL indicate light level, moderate level, and severe level, respectively

Furthermore, the composition of plant life-forms varied significantly with pollution levels (*Table 4*). The richness of plant life-forms decreased in the following order: lightly polluted (4 types) > moderately polluted (3 types) > severely polluted (2 types). As heavy metal pollution intensified, the proportion of herbaceous plants increased, while the presence of vines and shrubs gradually declined. Trees were found only in the lightly polluted area (see *Table 4*). Based on the natural succession process of plant communities, the vegetation in the studied area is in the early stages of ecological recovery. Heavy metal pollution has hindered the natural succession of plant communities, resulting in a simplified structure of life-forms in more contaminated areas.

Table 4. *Plant life-form statistics across different levels of heavy metal pollution*

Contamination level	Life-form							
	Herbaceous		Vines		Shrub		Arbor	
	Number	Ratio	Number	Ratio	Number	Ratio	Number	Ratio
LL	24	61.54%	4	10.25%	9	25.64%	2	2.56%
ML	24	80%	3	10%	3	10%	—	—
SL	24	92.31%	—	—	2	7.69%	—	—

LL, ML, and SL indicate light level, moderate level, and severe level, respectively.

DOI: http://dx.doi.org/10.15666/aeer/2401_137151

Plant diversity across different pollution levels

α-Diversity analysis

α-Diversity is the diversity of species within a single, specific habitat or ecosystem. It is a measure of local diversity, focusing on the number of species (species richness) and their relative abundance (species evenness) in one particular site. We assessed α-diversity across areas with different levels of heavy metal pollution using three indices: the Margalef richness index, Shannon-Wiener diversity index, and Pielou evenness index. The results showed that the Margalef richness index decreased with increasing potential ecological risk index, following the order: lightly polluted > moderately polluted > severely polluted (1.019 > 0.992 > 0.759). In contrast, both the Shannon-Wiener diversity index and Pielou evenness index showed a different pattern: moderately polluted > severely polluted > lightly polluted (Shannon-Wiener: 1.468 > 1.212 > 1.064; Pielou: 1.003 > 0.759 > 0.717). However, none of the indices showed statistically significant differences among the three pollution levels ($p > 0.05$; *Fig. 1*). Overall, the diversity indices revealed a general decline in plant diversity with increasing pollution severity, suggesting that heavy metal pollution exerts an inhibitory effect on plant diversity, with more severe pollution associated with reduced diversity levels. Interestingly, although the lightly polluted area had a higher species richness, it showed lower Shannon-Wiener and Pielou indices compared to the moderately polluted area, indicating a less even species distribution. This suggests that the plant community in the moderately polluted area had a more uniform species composition.

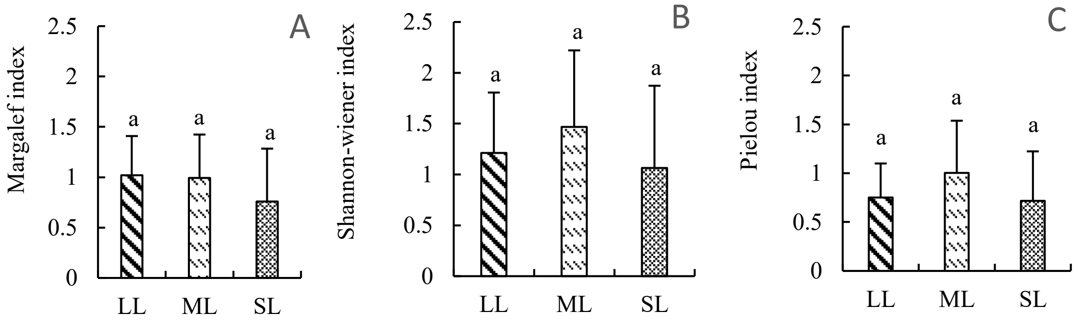

Figure 1. *(A-C) Variation of plant diversity indices under different levels of heavy metal contamination. Same letters indicate no significant differences (p > 0.05). LL, ML, and SL indicate light level, moderate level, and severe level, respectively*

β-Diversity analysis

β-diversity is a measure of the change in species composition between different habitats or ecosystems. It quantifies the "species turnover" along an environmental gradient or between different geographical areas. High beta diversity means the communities are very different from each other. We used the Sorensen similarity index to assess species similarity among plant communities across different levels of heavy metal pollution, analyzing the relationship between pollution gradients and β-diversity. The results showed that similarity coefficients followed the order: (severely & moderately polluted) > (moderately & lightly polluted) > (severely & lightly polluted) (*Table 5*). The Potential Ecological Risk Index (PERI) is a methodology developed to evaluate the comprehensive risk of heavy metal pollution in sediments or soils. It assesses the potential biological and ecological impact of multiple contaminants simultaneously. Correlating these values with differences in potential ecological risk indices (ΔRI) between pollution levels revealed an inverse relationship between plant community β-diversity (similarity) and the magnitude of heavy metal pollution gradient variation. Increased pollution gradients led to decreased similarity and higher β-diversity. When two locations exhibit high similarity but significantly differ in their Potential Ecological Risk Index, it indicates an anomaly in environmental health that would otherwise be expected to be comparable. This suggests that the high-risk area may be experiencing ecological stress, such as pollution or degradation, warranting heightened attention. The pollution gradient difference between moderately and severely polluted areas (ΔRI = 19852) exceeded that between lightly and moderately polluted areas (ΔRI = 10065). However, their community similarity coefficient (50%) was higher than that between lightly and moderately polluted areas (34.78%). This suggests that beyond a certain pollution threshold, plant communities in heavily contaminated environments tend to exhibit higher species similarity.

Table 5. *Sorenson similarity coefficients under different contamination levels*

Contamination level	**Number of species**	**Number of common species**			**Similarity coefficient (%)**			**Difference value of RI**		
		LL	**ML**	**SL**	**LL**	**ML**	**SL**	**LL**	**ML**	**SL**
LL	39	—	—	—	—	—	—	—	—	—
ML	30	12	—	—	34.78	—	—	10065	—	—
SL	26	10	14	—	30.76	50	—	29917	19852	—

LL, ML, and SL indicate light level, moderate level, and severe level, respectively

Analysis of dominant species across heavy metal-polluted areas

Dominant species play a crucial role in shaping plant community structure due to their high abundance, coverage, and biomass, and are generally less influenced by the presence of other species. In heavy metal-polluted environments, dominant species often demonstrate high resistance, tolerance, or absorption capacity towards heavy metals, serving as the primary constructive species. In this study, dominant species were identified based on importance values (IV), with the species having the highest IV in each quadrat considered dominant. The Importance Value (IV) is a compound metric used in plant ecology to quantify the overall ecological significance of a species within a community. Instead of relying on just one measure (like abundance), it combines several key factors into a single number, providing a more holistic view of a species' role. The findings revealed that 19 dominant species from 18 genera and 8 families were present in the communities across 30 quadrats (*Table 6*). The Poaceae and Asteraceae families have the most dominant species, accounting for 36.84% and 26.31%, respectively. *Glycine soja*, *Arthraxon hispidus*, and *Cynodon dactylon* were found exclusively in lightly polluted areas, demonstrating their low dominance and limited ecological adaptability in heavy metal-polluted environments. *Artemisia carvifolia*, *Miscanthus sinensis*, and *Equisetum hyemale* were dominant in both lightly and severely polluted areas, suggesting strong ecological adaptability across pollution gradients. *Polygonum posumbu and Fagopyrum dibotrys* emerged as dominant species in severely polluted areas, implying that members of the Polygonaceae family may possess notable heavy metal accumulation or tolerance capabilities.

Table 6. *Dominant species across different contamination levels*

	Plots	Dominant species	Genera	Family	IV
LL	1	*Artemisia carvifolia*	Artemisia	Compositae	101.49
	2	*Miscanthus sinensis*	Miscanthus	Poaceae	109.18
	3	*Glycine soja*	Glycine	Leguminosae	64.96
	4	*Arthraxon hispidus*	Arthraxon	Poaceae	130.38
	5	*Pteridium aquilinum*	Pteridium	Pteridiaceae	104.20
	6	*Equisetum ramosissi*	Equisetum	Equisetaceae	109.31
	7	*Cynodon dactylon*	Cynodon	Poaceae	123.63
	8	*Bidens pilosa*	Bidens	Compositae	147.87
	9	*Miscanthus sinensis*	Miscanthus	Poaceae	130.27
	10	*Cynodon dactylon*	Cynodon	Poaceae	165.01
ML	11	*Bidens pilosa*	Bidens	Compositae	73.06
	12	*Imperata cylindrica*	Imperata	Poaceae	182.04
	13	*Cayratia japonica*	Cayratia	Vitaceae	81.05
	14	*Eleusine indica*	Eleusine	Poaceae	86.43
	15	*Pteridium aquilinum*	Pteridium	Pteridiaceae	155.85
	16	*Paspalum paspaloides*	Paspalum	Poaceae	174.01
	17	*Setaria glauca*	Setaria	Poaceae	72.88
	18	*Macleaya cordata*	Macleaya	Papaveraceae	58.80
	19	*Boehmeria nivea*	Boehmeria	Urticaceae	64.14
	20	*Paspalum paspaloides*	Paspalum	Poaceae	102.92
SL	21	*Polygonum posumbu*	Polygonum	Compositae	99.47
	22	*Artemisia argyi*	Artemisia	Compositae	127.17
	23	*Pilea pumila*	Pilea	Urticaceae	103.94
	24	*Paspalum paspaloides*	Paspalum	Poaceae	202.31
	25	*Artemisia carvifolia*	Artemisia	Compositae	90.23
	26	*Alternanthera philoxeroides*	Alternanthera	Amaranthaceae	128.71
	27	*Fagopyrum dibotrys*	Fagopyrum	Polygonaceae	202.28
	28	*Miscanthus sinensis*	Miscanthus	Poaceae	121.37
	29	*Equisetum ramosissimum*	Equisetum	Equisetaceae	163.19
	30	*Miscanthus sinensis*	Miscanthus	Poaceae	125.03

LL, ML, and SL indicate light level, moderate level, and severe level, respectively

The importance value (IV) reflects a species' dominance within the community (Song, 2001). Comparing the maximum IV of dominant species across different pollution levels revealed that these values increased with pollution intensity, peaking at 202.31 in severely polluted areas (*Fig. 2*). The trend suggests that when pollution levels rise, so do the importance values of dominant species, resulting in increased dominance.

Discussion

Species composition in heavy metal-polluted areas

Survey results show that 65 vascular plant species, representing 31 families and 56 genera, were recorded across the 30 quadrats in the study area. This species richness is significantly lower than that of the Daxiong Mountain National Forest Park in Loudi City, which hosts 1286 vascular plant species, including 68 ferns from 30 families and 48 genera, and 1218 seed plants from 166 families and 668 genera (Zhang, 2018). These findings suggest that long-term environmental pollution and ecological imbalance induced by mining, smelting, and other anthropogenic activities have significantly impaired the vegetation system of the mining area. Under typical geomorphological conditions, natural vegetation succession progresses through six stages: herbaceous community, shrub-grass community, shrub community, shrub thicket, shrub-tree transition, and arborescent community (Wen et al., 2015). This reflects a dynamic progression from lower to higher stages, and vegetation restoration follows a similar pattern.

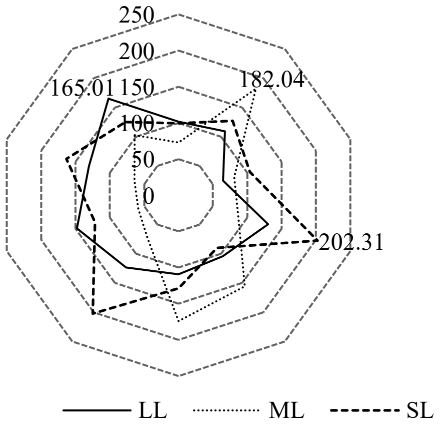

__Figure 2.__ Comparison of maximum importance value (IV) of dominant species under varying pollution levels. LL, ML, and SL indicate light level, moderate level, and severe level, respectively

The absolute dominance of herbaceous plants in natural communities indicates that vegetation restoration in mining areas remains at an early successional stage, manifested by the increasing number of herbaceous species (Gai et al., 2009). Our results about the current characteristics of plant communities in the Xikuangshan mining area align with this pattern. We also observed that as heavy metal pollution intensifies, plant community structure becomes simplified, and herbaceous species dominate. This suggests that heavy metal pollution is hindering vegetation succession, limiting the development of more complex plant communities. Therefore, a clear relationship exists between vegetation restoration progress, successional community dynamics, and pollution intensity. To facilitate vegetation restoration and enhance species diversity in mining areas, it is essential to control and remediate heavy metal pollution to prevent further ecological deterioration.

Impact of heavy metal pollution on plant diversity

Our study confirms that heavy metal pollution significantly suppresses plant diversity, with fewer species recorded in more polluted areas, which is consistent with the findings of Hu (2010). As pollution intensity increases, the number of plant families, genera, and species declines, along with overall species richness. This supports the conclusion that heavy metal pollution levels directly affect community diversity.

Plant diversity is determined not only by the number of species within a community, but also by the evenness of individual species distribution. Interestingly, although the moderately polluted area had fewer plant species than the lightly polluted area, it exhibited slightly higher Shannon-Wiener and Pielou evenness indices. This possibly reflects a more uniform species distribution within the moderately polluted community, potentially due to the stable growth and even distribution of dominant or hyperaccumulator plants within the community. In contrast, the severely polluted area exhibited the lowest diversity metrics, demonstrating that heavy metal pollution is a significant factor contributing to reduced plant diversity.

Su et al. (2018) discovered that the Shannon-Wiener diversity and Pielou evenness indices of grassland plants in the Tejinhan Mountain Nature Reserve (altitude range: 900-1440 m) showed no significant correlation with altitude gradients above 1100 m. Similarly, Gao et al. (2009) reported that herbaceous layer plant diversity in Mengshan Mountain, Shandong Province, did not follow a consistent variation pattern across different altitude zones. One-way ANOVA revealed that heavy metal pollution gradients had no statistically significant impact on plant α-diversity. The lack of significance may result from confounding factors such as topography, slope, or sampling error, or from the ecological characteristics of the Xikuangshan mining area itself. We can think of two potential explanations for this phenomenon. The Xikuangshan mining area exhibits extremely high potential ecological risk indices for heavy metals (Wang et al., 2010; Zhuo et al., 2019), forming a high-risk zone with plant communities characterized by a few dominant or hyperaccumulator species. Such community homogenization across pollution gradients may explain the lack of significant diversity differences. Dominant species such as *Paspalum distichum* and *Cynodon dactylon* frequently form mono-dominant communities across various pollution levels. Individual species are distributed unevenly within such communities, resulting in generally low diversity indices, which also contribute to the insignificant diversity variations among pollution gradients.

When environmental gradients exhibit significant variation, the number of shared species between communities decreases, resulting in higher β-diversity (Wang et al., 2000). Our analysis revealed a negative correlation between heavy metal pollution gradients and plant community similarity, indicating that greater variation in pollution levels corresponds to lower community similarity among plant communities. When pollution levels act as a gradient of environmental factors, β-diversity undergoes significant changes. Thus, heavy metal pollution is a major contributor to anthropogenically driven habitat heterogeneity, influencing species turnover. Notably, even when the potential ecological risk index exceeds 10,000, community similarity between moderately and heavily polluted zones remains as high as 50%. Drastic changes in soil conditions likely eliminate species with low heavy metal resistance, while natural selection favors the establishment of dominant species and hyperaccumulators. These species, though limited in number, maintain stable populations across pollution gradients, contributing to high inter-community similarity in severely polluted zones. In summary, variations in heavy metal pollution gradients influence both plant distribution and community similarity. However, in severely polluted environments, plant communities exhibit relatively high interspecific similarity.

Besides, in heavy metal-polluted areas, environmental factors such as slope, soil texture, and moisture interact synergistically with pollution to collectively shape species distribution and diversity. Steep slopes, coarse soil texture, and low moisture levels contribute to physical stressors such as erosion risks, poor water and nutrient retention, and drought conditions. The superposition of these multiple stressors collectively filters out all but a few robust species (e.g., plants from the Poaceae and Asteraceae families) capable of simultaneously tolerating both pollution and harsh physical conditions, leading to an overall reduction in diversity.

Heavy metal pollution and community-dominant species

Xu et al. (2015) observed that dominant species composition varies with elevation in the water-level fluctuation zone of the Xiangxi River in the Three Gorges Reservoir area, with the species exhibiting distinct spatial aggregation patterns. Similarly, in this study, dominant species differed markedly across pollution levels, reflecting varying ecological adaptability to heavy metal-stress environments. For example, *Glycine soja*, *Arthraxon hispidus*, and *Cynodon dactylon* were confined to lightly polluted zones, while *Paspalum distichum and Fagopyrum dibotrys* thrived in severely polluted habitats. Species like *Miscanthus sinensis* and *Artemisia carvifolia* were found across various pollution intensities, highlighting interspecific differences in heavy metal tolerance. These variations likely arise from species-specific physiological mechanisms of heavy metal resistance. Within the Urticaceae family, *Boehmeria nivea* and *Pilea pumila* emerged as dominant species in moderately and severely polluted areas, respectively. Likewise, members of the Polygonaceae, such as *Polygonum posumbu and Fagopyrum dibotrys*) dominated in the severely polluted zones. These findings highlight significant variability in heavy metal resistance across plant families and genera. Analysis of species importance values revealed that key species become increasingly dominant at higher pollution levels, likely because intensified contamination promotes the formation of mono-dominant communities through the high aggregation of hyperaccumulators with large populations. Luo et al. (2007) demonstrated that dominant plants in mining areas typically exhibit rapid growth, high abundance, and strong community-forming tendencies. Similarly, Zhang et al. (2015) observed that in rocky desertification zones, only a few highly adaptable species survive, resulting in pronounced ecological dominance. These patterns are consistent with our findings in the Xikuangshan mining area, where dominant species with high importance values are likely hyperaccumulators with strong resistance to heavy metals. Such species are ideal candidates for phytoremediation and offer significant ecological and environmental benefits for the rehabilitation of contaminated lands.

Conclusions

Heavy metal pollution is a significant factor leading to the low plant diversity and slow vegetation recovery in the Xikuangshan mining area. In the heavy metal-polluted areas of Xikuangshan, the Margalef richness index, Shannon-Wiener diversity index, Pielou evenness index, and the number of families, genera, and species of plant communities generally exhibited a declining trend as pollution intensified. There is a certain negative correlation between the magnitude of the heavy metal pollution gradient and community similarity—the greater the gradient change, the lower the community similarity. Between the moderately and severely polluted areas based on the potential ecological risk index, the species similarity of plant communities was the highest. Heavy metal pollution is an important ecological factor influencing the similarity of plant communities in the polluted areas of Xikuangshan. The dominant species in the plant communities of the heavy metal-polluted areas in Xikuangshan are primarily from the Poaceae and Asteraceae families. However, the dominant species in plant communities across different pollution levels clearly differ, reflecting the varying ecological adaptability of different plants to heavy metal-polluted environments. Given that the importance value of dominant species increases with rising pollution levels and their dominance becomes more pronounced, the importance value can be considered a key indicator for selecting hyperaccumulators and identifying pioneer plants.

Acknowledgements. We are deeply grateful to Professor Peng Youlin from Hunan University of Arts and Science for his expert guidance and invaluable assistance in plant identification. We also extend our sincere thanks to Zhang Xin, Yuan Hui, and Ouyang Tianlai from Hunan University of Humanities, Science and Technology for their contributions to the field surveys.

Funding. The work was supported by the National Natural Science Foundation of China (41907037); the “Biodiversity Conservation and Ecological Simulation” Innovation Team of Hunan Universities (201937924).

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