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Effects of Vegetation Pattern and Spontaneous Succession on Remediation of Potential Toxic Metal-Polluted Soil in Mine Dumps

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Abstract: The ecological rehabilitation of potential toxic metal-contaminated soils in sites disturbed by mining has been a great challenge in recent decades. Phytoremediation is one of the most widely promoted renovation methods due to its environmental friendliness and low cost. However, there is a lack of in situ investigation on the influence of vegetation pattern and spontaneous succession on the rehabilitation of potential toxic metal-polluted soil. To clarify how the vegetation pattern in the early stage of restoration and the spontaneous succession influence the remediation of the soil, we investigated a metal mining dump in Sichuan, China, by field investigation and laboratory analysis. We determined the plant growth, soil fertility, and the capacity of potential toxic metals (PTMs) in metal mining soil under different initial vegetation patterns for different years to understand the role of vegetation pattern and spontaneous succession in PTM pollution phytoremediation projects. The results show that: (1) Phytoremediation with a simple initial vegetation pattern (RP rehabilitative plant pattern) which involves two rehabilitation plants, *Agave sisalana* and *Neyraudia reynaudiana*, achieves a PTM pollution index that is 9.28% lower than that obtained with the complex vegetation pattern (RP&LP rehabilitation plants mixed with local plants pattern), 21.86% lower in the soil fertility index, and 73.69% lower in the biodiversity index; (2) The phytoremediation with the 10-year RP&LP pattern was associated with a PTM pollution index that was 4.04% higher than that for the 17-year RP&LP pattern, a soil fertility index that was 4.48% lower, and a biodiversity index that was 12.49% lower. During the process of vegetation succession, if accumulator plants face inhibition of growth or retreat, the reclamation rate will decrease. The vegetation patterns influence the effect of phytoremediation. Spontaneous vegetation succession will cause the phytoremediation process to deviate from the intended target. Therefore, according to the goal of vegetation restoration, choosing a suitable vegetation pattern is the main premise to ensure the effect of phytoremediation. The indispensable manipulation of succession is significant during the succession series, and more attention should be paid to the rehabilitative plants to ensure the stable effect of reclamation. The results obtained in this study could provide a guideline for the in situ remediation of PTM-polluted soil in China.

Keywords: phytoremediation; vegetation pattern; spontaneous succession; mine dump; potential toxic metals

1. Introduction

The large amount of potential toxic metals present in the tailings of metal mines is an important source of potential toxic metal pollution in soil [1–4]. Among the approaches used for the restoration of PTM-contaminated soils, phytoremediation technologies have drawn considerable attention [5–7].

The phytoremediation of PTM pollution from mining is widely employed around the world since it is a low-cost method of environmental protection. Although phytoremediation has many advantages, there are also many limitations to its effective implementation [8–11]. Rehabilitation plant species play the key role in reclamation projects, particularly the high accumulation plants which still have different definitions [12]. In the future, genetics may be used to produce new high accumulation plants [13]. These plants can absorb potential toxic metals in soil and thus reduce the negative effects on ecosystem health [2,14]. New efficient metal high accumulation plants are being explored for applications in phytoremediation and phytomining. Molecular tools are being used to better understand the mechanisms of metal uptake, translocation, sequestration, and tolerance in plants [13,15]. These efforts can also promote the development of agromining and phytomining [16–18]. However, these projects can have unintended effects. For example, soil fertility can decline after phytoremediation. This was observed in the jarrah (*Eucalyptus marginata*) forest of southwestern Western Australia [19]. After restoration, the area displayed reduced biological activity, pH, and organic carbon levels [20–22]. Another troubling aspect is that fertilizer application is required to increase the concentrations of N, P, and K to initiate the restoration process [22–24].

During spontaneous succession, the effect of potential toxic metal remediation changes with the changes in vegetation structure and function. Mining operations create extremely broad ecological gradients, and therefore the natural rehabilitative plant communities should have relatively high abundance indices [25,26]. However, the structure and function of plantations are highly simplified in some project sites [26]. This leads to doubt regarding the resilience of these simplified forests to environmental change (e.g., drought, invasive species, pests, and diseases) and their capacity to deliver anticipated ecosystem services (e.g., nutrient cycling, erosion control, shelter, and food resources for wildlife) [27].

Due to the important role that vegetation patterns play in the progression of soil erosion [28], an increasing number of studies have been conducted to examine the relationship between vegetation patterns and soil erosion [29]. Plant diversity [30] and soil fertility [31] are influenced by vegetation patterns.

There are few studies on the interactions between vegetation patterns and spontaneous succession regarding their effect on the remediation of soil potential toxic metal concentrations. To fill this knowledge gap, we investigated plant biodiversity, soil fertility, and the potential toxic metal content in the soil of reclaimed potential toxic metal mining sites under different vegetation patterns, i.e., rehabilitative plant (RP) and rehabilitative plant and local plant (RP&LP), for project durations of 10 years and 17 years. Our goal was to reveal the influence of vegetation pattern and natural succession on potential toxic metal rehabilitation.

2. Materials and Methods

2.1. Study Area

The study sites are located in Panzhihua City, Sichuan Province, China. The sites fall within the range of 101°44′20″–101°47′08″ longitude, 26°35′35″–26°37′15″ latitude. Due to the low altitude and the influence of surrounding high terrain, the four seasons are not distinguishable; however, the dry season and the rainy season are clearly distinguishable with high insolation. The environment of Panzhihua has a huge impact on the middle and lower reaches of the Changjiang River. The Yalong River and the Jinsha River merge into the Changjiang River at Panzhihua.

The study area possesses the third largest vanadium-titanium magnetite resource in the world and has been plagued by potential toxic metal pollution for a long time. Due to the serious damage of stripped land surface and fallen vegetation, ecological rehabilitation work has been conducted for many years. The sampling regions are shown in Figure 1.

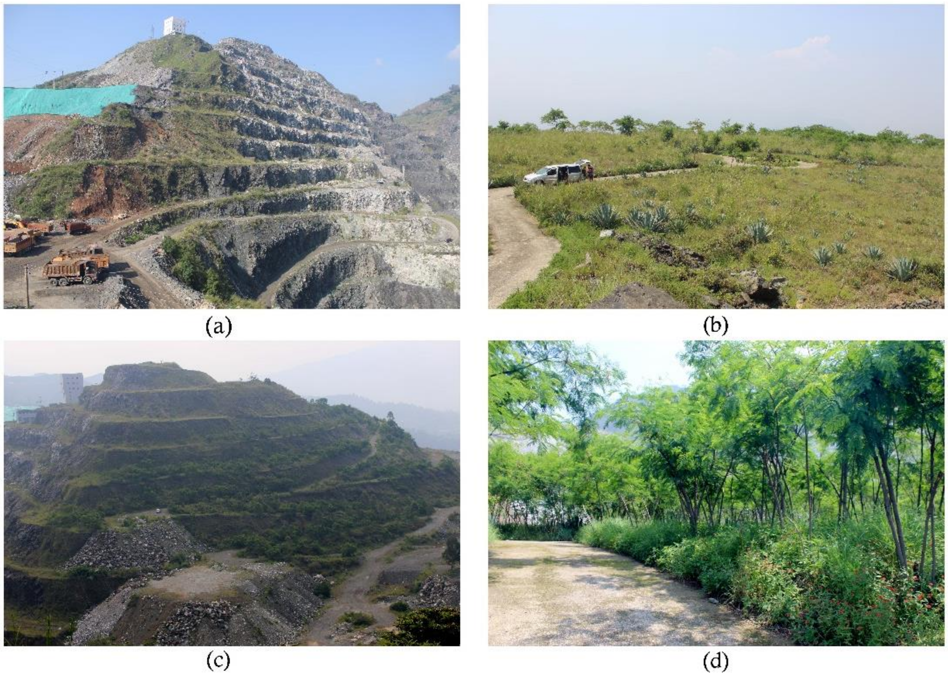

Figure 1. Views of the sampling regions. (**a**) Metal mining and dump. (**b**) The rehabilitative plant (RP) site restored for 10 years. (**c**) The rehabilitative plant and local plant (RP&LP) site restored for 17 years. (**d**) The RP&LP site restored for 10 years.

In this study, there were five study sites. Three of the sites had been under reclamation for 10 years, and the other two had been under reclamation for 17 years. The characteristics of each site are shown in Table 1. The vegetation restoration uses engineering methods to prevent landslides and plant in situ able plants. Due to a change in government planning, there are two different vegetation restoration patterns in the region. As a result, different restoration effects have appeared.

Table 1. Basic information about the sampling area.

Time	Vegetation Pattern	Characteristic
10-year dump	RP&LP (rehabilitative plant and local plant)	To ensure that the restoration effects of the landscape and the recovery of potential toxic metals are completed simultaneously, rehabilitative plants and native plants are cultivated in the area.
	RP (rehabilitative plant)	Only vegetation for restoration.
	LP (local plant)	There is no mining disturbance in the native plant natural growth area.
17-year dump	RP&LP (rehabilitative plant and local plant)	In the early stage, plants were only planted for restoration. The natural invasion of native plants resulted in succession.
	LP (local plant)	There is no mining disturbance in the native plant natural growth area.

2.2. Data Collection

2.2.1. Ground Vegetation Surveys

Open-pit mine dump sites caused the complete destruction of the vegetation due to surface mining. The study sites have the same initial state. Due to differences in human planning, two different vegetation patterns were used to remediate the dumps. We selected sites with a uniform distribution of vegetation within the study area and set quadrants with dimensions of 4 m × 4 m to identify plant species, conduct abundance counts, and measure plant heights [32].

2.2.2. Soil Fertility

The tested soil was collected from the upper 0–20 cm of the soil of the recovery area [32]. Soil samples were air-dried, sieved through a 2-mm mesh, and then stored in plastic bags at 4 °C before analysis [32]. We determined the organic carbon content via potassium dichromate oxidation and external heating; total nitrogen content by a semimicro Kjeldahl method; and total phosphorus and total potassium via inductively coupled plasma-mass spectrometry (ICP-MS) with HF-$HClO_4$-HNO_3, that is, near-total digestion in a mixture of HNO_3, $HClO_4$, and HF.

2.2.3. Levels of Potential Toxic Metals in Soil

The tested soil was collected from the upper 0–20 cm of the soil of the recovery area. Concentrations of soil potential toxic metals were tested using an Agilent 7700X ICP-MS (Agilent Technologies, Santa Clara, CA, USA) with HF-$HClO_4$-HNO_3. Three replicate experiments were performed for each test [33].

2.3. Data Analysis

2.3.1. Diversity

The species diversity index reflects the abundance and uniformity of the species in the community. We utilized Hill's diversity number to compare the diversity of species in the study areas [34]:

$$D_A = \sum_{i=1}^{S} \left(\frac{N_i}{N}\right)^{\frac{1}{1-A}} \tag{1}$$

where A is the study area acreage, S is the number of species, and N is the total number of individual species

2.3.2. Potential Toxic Metal Pollution Index

In this study, a comprehensive evaluation of potential toxic metal pollutants is accomplished with the Nemero comprehensive index. The Nemero index [35] is developed by incorporating single-factor indices; it is a kind of multi-factor environmental quality index which can give consideration to extreme values. The single-factor portion can be expressed as:

$$P_i = \frac{C_i}{S_i} \tag{2}$$

where P_i is the single pollution index of the element i pollutants, C_i is the actual measured value of the pollutant, and S_i is the soil environmental quality standard of the element i pollutants. The comprehensive index can be expressed as:

$$P_S = \sqrt{\frac{\overline{P_i}^2 + P_{i\,max}^2}{2}} \tag{3}$$

where P_s is the soil comprehensive pollution index, $\overline{P_i}$ is the average value of single pollution index, and $P_{i\,max}$ is the maximum single pollution index.

According to the Chinese Environmental Quality Standard for Soils (GB 15618-1995), the acceptable concentrations (in mg/kg) are 100 for Cu, 1.5 for Mn, 0.3 for Cd, 200 for Cr, 100 for Ni, 250 for Zn, 120 for Pb; 40 for As, and 2000 for Fe [36].

2.3.3. Soil Property Index

We evaluate the soil fertility with the improved Nemero index. Soil pH, organic matter, total nitrogen, total phosphorus, total potassium, available nitrogen, available phosphorus, and available potassium were selected for this analysis. The above indicators of soil fertility cannot be combined via simple addition. First, the data are standardized to eliminate the dimensional differences among the parameters:

$$Pi = Ci/Xa\ (Pi \leq 1);\ \text{if}\ Ci \leq Xa \quad (4)$$

$$Pi = 1 + (Ci - Xa)/(Xc - Xa)\ (1 < Pi \leq 2);\ \text{if}\ Xa < Ci \leq Xc \quad (5)$$

$$Pi = 2 + (Ci - Xc)/(Xp - Xc)\ (2 < Pi \leq 3);\ \text{if}\ Xc < Ci \leq Xp \quad (6)$$

$$Pi = 3;\ \text{if}\ Ci > Xp \quad (7)$$

where *Pi* is the separate fertility index, *Ci* is the measured value, and *Xa*, *Xc*, and *Xp* are the classification criteria of each soil property in Table 2.

Table 2. The classification criteria of each soil property.

Soil Property	pH	pH	TN	TP	TK	AN	AP	AK	SOM
	>7.0	<7.0		g/kg			mg/kg		g/kg
Xa	9	4.5	0.75	0.7	10	60	5	50	10
Xc	8	5.5	1.00	1.5	15	90	10	100	20
Xp	7	6.5	1.50	2.0	20	150	20	150	30

Notes: TN is total nitrogen; TP is total phosphorus; TK is total potassium; AN is alkaline nitrogen; AP is available phosphorus; AK is available potassium; and SOM is soil organic matter.

After the standardization of the above formula, the soil fertility indices of each single item are obtained.

The above formula is used to calculate the fertility index of each single value; however, the single indices are insufficient for evaluating the overall soil fertility. Therefore, the improved Nemero comprehensive index method is used to calculate the comprehensive fertility index. It can be expressed as:

$$P_S = \frac{\sqrt{P_{\text{i avg}}^2 + P_{\text{i min}}^2}}{2} \cdot \left(\frac{n-1}{n}\right) \quad (8)$$

where P_s is the comprehensive soil fertility index, $P_{\text{i avg}}$ is the average value of the separate fertility indices, $P_{\text{i min}}$ is the minimum value among the separate fertility indices, and n is the number of evaluation factors.

In order reflect the fact that lower index values indicate lower soil fertility as well as the minimum factor law of plant growth, we replace $P_{\text{i max}}$ in the original Nemero formula with $P_{\text{i min}}$. We add the correction term $(n - 1)/n$ to reflect credibility, i.e., higher reliability with greater numbers of the soil properties considered (n).

2.3.4. Statistical Analysis

The *t*-test was used to assess significant differences in the soil fertility and soil potential toxic metal content between the RP&LP and the LP at 17 years, the RP&LP at 10 years and 17 years, and the LP at 10 years and at 17 years. One-way analysis of variance (ANOVA) with Duncan multiple comparisons was carried out to evaluate significant differences among the RP&LP, RP and LP at the 10-year period. All statistical analyses were conducted using SPSS 22.0 (IBM Institute, Armonk, NC, USA) with a significance threshold of $p < 0.05$.

3. Results

3.1. Growth Situation and Diversity of Two Vegetation Patterns with Different Durations

The plant species, plant height, number of stems and diversity index under two vegetation patterns with different durations are shown in Table 3.

Table 3. Plant species, growth situation and diversity index of each study site.

Years	Vegetation Pattern	Species	Height (cm)	Number of Stems	Diversity Index
10	RP&LP	*Agave sisalana*	57.83 ± 7.87	5	8.06
		Neyraudia reynaudiana	109.17 ± 10.72	11	
		Taxus chinensis	380.00 ± 18.83	4	
		Artemisia argyi	75.83 ± 6.11	4	
		Zinnia elegans	54.67 ± 5.34	10	
		Amaranthus viridis	57.62 ± 11.15	3	
		Stipa capillata	44.33 ± 3.66	3	
	RP	*Agave sisalana*	96.80 ± 3.41	6	2.12
		Neyraudia reynaudiana	157.00 ± 3.87	18	
	LP	*Neyraudia reynaudiana*	90.00 ± 3.85	5	3.23
		Artemisia argyi	69.00 ± 3.61	3	
		Zinnia elegans	50.00 ± 8.12	4	
17	RP&LP	*Agave sisalana*	43.00 ± 4.79	3	9.21
		Neyraudia reynaudiana	97.75 ± 10.28	6	
		Taxus chinensis	563.50 ± 65.82	4	
		Artemisia argyi	121.25 ± 11.12	5	
		Zinnia elegans	35.00 ± 4.89	7	
		Lespedeza bicolor	111.50 ± 11.98	4	
		Patrinia scabiosaelia	36.20 ± 8.70	5	
		Lantana camara	54.00 ± 10.71	3	
	LP	*Artemisia argyi*	53.25 ± 6.68	4	2.09
		Zinnia elegans	42.00 ± 11.79	4	

Note: results are expressed as means ± SD (standard deviation).

There were seven plant species in the 10-year RP&LP area, with two unique species, namely *Amaranthus viridis* and *Stipa capillata*. The 10-year RP area has two species of remediation plants and the 10-year LP site has three species. The main rehabilitation plants *Agave sisalana* and *Neyraudia reynaudiana* appear in artificial remediation areas. Eight plants were found in the 17-year RP&LP, five of which were also found in the 10-year RP. *Lespedeza bicolor*, *Patrinia scabiosaelia*, and *Lantana camara* were only found in the 17-year RP&LP. There are two species of plants in the 17-year LP area.

The species *Agave sisalana* and *Neyraudia reynaudiana* appeared in the 10-year RP&LP, 10-year LP, and 17-year RP&LP as high accumulation plants; however, the growth of plants in these three areas is different. *Agave sisalana* plants exhibited the best growth in the 10-year LP site, with an average plant height of 96.8 cm and number of plants per unit square of 6. In the 10-year RP&LP, the average plant height is 57.83 cm and the number of plants per unit square is 5. In the 17-year RP&LP, the average plant height is 43 cm and the number of plants per unit square is 3. *Neyraudia reynaudiana* also exhibited the best growth in the 10-year LP, with an average plant height of 157 cm and number of plants per unit square of 18. In the 10-year RP&LP, the average plant height of *Neyraudia reynaudiana* is 109.17 cm and the number of plants per unit square is 11. In the 17-year RP&LP, the average plant height of *Neyraudia reynaudiana* is 97.75 cm and the number of plants per unit square is 6.

By visual observation, it was determined that there is no obvious difference between the 10-year RP&LP and the 17-year RP&LP. However, the diversity index of the 17-year RP&LP (9.21) is 14.74% higher than that of the 10-year RP&LP (8.06). Species distributions are determined by plant traits and interactions with other species [37] and many invasive species likely fill the same ecological niche as native species [38].

3.2. Soil Fertility Changes

Table 4 shows the soil fertility differences in different vegetation patterns but at same restoration age. The soil fertility index also is shown in Table 4.

From Table 4, we can find that (1) the nutrients in the top 15–20 cm of soil at the five study sites were all low due to the local geological conditions and the restoration project. (2) In the 10-year rehabilitation areas, the soil fertility at the RP&LP site (index = 0.64) was 27.12% higher than in the RP site (0.50) but equal to that at the LP site. The significant differences between the RP&LP site and the LP site were in SOM, TP, AN, AP, AK and pH, while the significant differences between the RP site and LP site were in SOM, TN, TP, TK, AN, AK and pH; however, the significant differences between the RP&LP site and RP site were in SOM, TN, TK, AP, AK, and pH. (3) In the 17-year rehabilitation areas, the soil fertility in the RP&LP site (0.67) was 7.88% lower than that in the LP site (0.73), with significant differences in TN, TK, AN, and AK.

The significant differences in the RP&LP sites between 17- and 10-year rehabilitation were in SOM, TP, AN, AK, while the significant differences between the 10-year LP site and the 17-year LP were in SOM, TP, AP, indicating that the soil fertility slowly increased as the rehabilitation time increased; however, it did not reach the level of the surrounding undisturbed mining areas.

In general, the value of SOM, AK, and pH varied significantly in10-year rehabilitation area, with the value of SOM increased significantly in the RP&LP site, the AK value increased significantly at the PR site and the pH in the LP area increased significantly, respectively. In the 17-year rehabilitation areas, the value of TN, TK, AN, and AK changed significantly.

Table 4. Soil fertility and soil fertility indices.

Years of Rehabilitation	10 Years			17 Years	
Vegetation Pattern	RP&LP	RP	LP	RP&LP	LP
SOM (g/kg)	22.9 ± 1.25cB	4.83 ± 0.33a	10.76 ± 1.25bA	14.44 ± 0.90aA	18.95 ± 1.28aB
TN (mg/kg)	1468.57 ± 50.21bA	270.00 ± 10.29a	1103.33 ± 48.33bA	861.25 ± 32.21aA	1265.00 ± 45.13bA
TP (mg/kg)	1155.71 ± 33.11aA	1083.00 ± 58.32a	3036.67 ± 45.26bA	3842.50 ± 98.24aB	4320.00 ± 98.32aB
TK (mg/kg)	2754.29 ± 31.32bA	1150.00 ± 33.33a	2303.33 ± 46.01bA	1633.75 ± 68.32aA	2405.00 ± 56.22bA
AN (mg/kg)	47.84 ± 4.11aA	42.67 ± 3.34a	60.60 ± 4.18bA	73.26 ± 8.92bB	60.64 ± 8.26aA
AP (mg/kg)	8.16 ± 1.26bA	3.14 ± 0.27a	3.76 ± 0.52aA	9.71 ± 0.32aA	8.33 ± 0.90aB
AK (mg/kg)	112.00 ± 4.21aA	203.63 ± 25.23c	158.52 ± 9.40bA	174.05 ± 10.12bB	129.90 ± 10.12aA
pH	7.61 ± 0.96aB	7.68 ± 0.66b	7.85 ± 0.61cA	7.54 ± 0.33aA	7.24 ± 0.19aA
soil fertility index	0.64	0.50	0.63	0.67	0.73

Notes: TN is total nitrogen; TP is total phosphorus; TK is total potassium; AN is alkaline nitrogen; AP is available phosphorus; AK is available potassium; and SOM is soil organic matter. Results are expressed as means ± SD. Different lowercase letters in the same row indicate significant differences between vegetation patterns within the same rehabilitation time; while different uppercase letters in the same row indicate significant differences between the same vegetation pattern in different rehabilitation times, at $p < 0.05$.

3.3. Potential Toxic Metal Pollution Remediation

Table 5 summarizes the PTM pollution indices in the study areas. The Nemero indices indicate that there was a 3.33% improvement compared the LP site with the RP&LP site after 10 years of rehabilitation, and the improvement was more significant after 17 years of rehabilitation.

In the 10-year rehabilitation areas, the significant differences between the RP&LP site and the RP site were in Cu, Cd, Cr, Ni, Zn, Pb, As, and Fe, and the significant differences between the RP&LP site and the LP site were in Cd, Cr, Ni, Zn, and Pb, while the significant differences between the RP site and the LP site were in Zn, Pb, As, and Fe.

In the 17-year rehabilitation areas, the significant differences between RP&LP site and the LP site were in Cu and Ni.

The significant differences between 10-year RP&LP and 17-year RP&LP sites were in Cr and Ni, while the significant differences between 10-year LP and 17-year LP sites were in Cu, Cd, Ni, Pb and As.

In conclusion, in the 10-year rehabilitation areas, the content of Pb and Zn varied significantly, the content of Zn had a significant repair effect in the RP area. In the 17-year rehabilitation area, the content of Cu and Ni varied significantly, and the repair effect of Ni was significant.

Table 5. Soil potential toxic metal content and pollution indices.

Years of Rehabilitation	10 Years			17 Years	
Vegetation Pattern	RP&LP	RP	LP	RP&LP	LP
Cu (mg/kg)	306.50 ± 59.32bA	191.24 ± 8.25a	223.57 ± 18.33abB	225.72 ± 18.14bA	134.72 ± 10.24aA
Mn (mg/kg)	1863.90 ± 87.47aA	1691.21 ± 51.21a	1802.06 ± 51.15aA	1791.77 ± 34.97aA	1685.50 ± 58.27aA
Cd (mg/kg)	0.31 ± 0.01bA	0.11 ± 0.12a	0.12 ± 0.01aA	0.21 ± 0.01aA	0.20 ± 0.01aB
Cr (mg/kg)	494.50 ± 41.21bB	19.70 ± 2.14a	69.17 ± 5.23aA	78.41 ± 3.24aA	76.75 ± 5.21aA
Ni (mg/kg)	353.00 ± 51.24bB	13.55 ± 1.89a	21.30 ± 0.12aA	77.58 ± 4.54aA	133.80 ± 7.25bB
Zn (mg/kg)	133.29 ± 10.21cA	97.05 ± 7.24a	117.67 ± 10.26bA	146.55 ± 8.21aA	112.30 ± 9.22aA
Pb (mg/kg)	9.70 ± 1.25bA	1.86 ± 0.21a	15.37 ± 1.90cB	8.21 ± 1.02aA	6.76 ± 0.57aA
As (mg/kg)	1.45 ± 0.17bA	0.77 ± 0.01a	1.54 ± 0.22bB	1.13 ± 0.90aA	1.02 ± 0.21aA
Fe (g/kg)	117.36 ± 12.15bA	86.63 ± 5.54a	108.86 ± 8.54bA	102.67 ± 7.25aA	121.63 ± 9.21aA
Pollution index	884.68	802.56	855.25	850.35	800.02

Note: Results are expressed as means ± SD. Different lowercase letters in the same row indicate significant differences between vegetation patterns within the same rehabilitation time; while different uppercase letters in the same row indicate significant differences between the same vegetation pattern in different rehabilitation times, at $p < 0.05$.

4. Discussion

4.1. Effect of Vegetation Pattern on Remediation Efficiency of Soil Potential Toxic Metals

Vegetation pattern has an important influence on ecosystem rehabilitation [39]. Distinct spatial patterns consisting of vegetated patches alternating with areas of bare soil have been described for savanna ecosystems worldwide [40,41]. When such patterns are generated by the patchy distribution of woody plants, both facilitation and competition may be operating [42]. The consequences of land use are affected by vegetation pattern. This is particularly evident in agricultural lands. The vegetation pattern will determine the migration and diffusion processes of soil potential toxic metals. Only a few vegetation pattern indices can comprehensively predict the degree of potential toxic metal pollution in soils. The correlation between some vegetation pattern indices and the degree of comprehensive potential toxic metal pollution is weak, and some relationships cannot be reasonably explained. Vegetation pattern is not the dominant factor for predicting the comprehensive pollution due to potential toxic metals [43–45]. Different initial vegetation patterns determined by the restoration target will influence the soil restoration effect. In this study, there are two species of rehabilitation plant in the 10-year RP site. However, the competition between the species is weak due to the absence of tall trees in the area and the absence of other thriving plants. Therefore, both potential toxic metal rehabilitation plants thrive. The plant height and vegetation density are higher than at the other sites, and the effect of potential toxic metal rehabilitation is also superior. In the 10-year RP&LP site, the growth of other landscape plants impacts the restoration plants and reduces the rate of remediation. Therefore, the growth and quantity of remediation vegetation affects the potential toxic metal remediation of soil in the two different vegetation patterns investigated in this study. Moreover, vegetation pattern affects the surface runoff and influences the soil erosion [46]. After years of developing sloping farmland, the rainfall receptivity and soil microbial community diversity of the farmland could be effectively improved [47].

In the process of phytoremediation, biomass accumulation due to vegetation photosynthesis increases [48]. Abandoned agricultural fields may lead to land degradation and desertification; however, vegetation succession will alter the resilience and response of the ecosystem [49]. When abandoned land is changed to other land use patterns under succession, soil properties also change [50–52].

The revegetation of mine dumps is very difficult and requires human participation due to the infertile conditions [53]. The restoration technique for mine dumps involves covering the soil and then planting vegetation. Species with a high tolerance for or absorption of potential toxic metals are generally planted to ensure that plants can survive in areas with high levels of potential toxic metals. In the process of plant growth, plants will continually absorb potential toxic metal pollutants in the soil through the roots. This helps reduce the concentration of soil potential toxic metals. In the first 10 years of recovery, the growth of the above-ground part of the plant increases the biomass of the surface and the elongation of the root system absorbs deeper potential toxic metal contaminants. Therefore, the concentration of potential toxic metal contaminants in soil decreases rapidly. With the growth of surface plants, the level of soil humus increases, soil fertility increases, and new succession plants begin to appear. After the invasion of the successional plants, the growth of potential toxic metal remediating plants is inhibited. Species richness usually increases as succession progresses [54].

In ecosystems that have been strongly transformed by humans, particularly where hydrological conditions have been disturbed, the rate of successional processes increases. This leads to quicker encroachment and development of plant communities, which causes local extinction of specialized; light-demanding plant species by shading [55,56]. Invasive plant species can have catastrophic impacts on ecosystem services, such as reduced habitat quality, decreased stream water flow, and lower vegetation cover and diversity. For example, plant succession on saline-alkali land will affect the chemical properties of soil, thus affecting the diversity and community composition of soil rhizosphere microorganisms [57]. Most invasive alien plants affect local biodiversity and ecosystem functions [58].

4.2. Research Limitation and Future Work

The restoration of soil quality after soil degradation due to unsustainable land use is vital for maintaining or improving ecosystem services for future generations [59–61]. However, succession generally requires long time periods to affect ecological changes [62] and identifying plant community change requires that the underlying ecological variation be defined and encompassed in replicate regions throughout the study area [63]. To understand plant community dynamics in diverse and dynamic ecosystems, long-term monitoring is required to generate robust datasets across plant community types [64]. Monitoring functional groups and species of interest over time is a common method used to track succession, especially in areas affected by biological plant invaders [65].

In remediation projects, fertile soil mixed with fragmented rocks is transported to form large-scale dumps [66]. The natural succession process of both soil and vegetation in these areas requires a significant amount of time, during which the dumps are exposed to wind and water erosion processes [67]. In this harsh environment, ecological rehabilitation needs to consider the restoration of potential-toxic-metal-polluted soil and the reconstruction of plant communities. The plant pattern determines the initial number of PTM restoration plants in the plant community, and the process of plant succession affects the growth of potential toxic metal restoration plants. It is important to mention that revegetation, particularly in the context of metal-polluted soils in mining areas, is critical to promoting soil microbial life, which in turn will enhance the phytoremediation process [68]. Phytoremediation projects for potential toxic metal contaminated soils should set clear objectives and plan for future land development. Vegetation community succession is an inevitable process of community development [69]. However, spontaneous community succession may inhibit the growth of potential toxic metal remediation plants or even remove them from the community. Manual intervention is particularly important when plant succession deviates from the preset target [70,71].

5. Conclusions

Phytoremediation is the preferred method of the remediation of soil pollution from potential toxic metal mines. However, the relationships between vegetation patterns, natural succession, and potential toxic metal restoration efficacy have not received in-depth study. In this study, field surveys and laboratory tests were conducted to analyze potential toxic metal content, soil fertility, and surface vegetation diversity under reclamation projects with different vegetation patterns and spontaneous succession. The results show that the simple initial vegetation pattern with low vegetation diversity exhibited a superior remediation effect for potential toxic metals, but that the soil fertility reclamation effect was inferior. Spontaneous vegetation succession will reduce the rate of potential toxic metal remediation and will cause the phytoremediation process to deviate from the intended target. In the early stage of phytoremediation, the target should be accurately positioned and the balance between PTM reclamation and soil fertility recovery should be considered. It is important to select the appropriate initial vegetation pattern. Meanwhile, spontaneous vegetation succession is unavoidable in long-term phytoremediation projects. Therefore, it requires long-term monitoring and improvement of management to ensure that the succession will not disturb the effect of soil remediation. Appropriate human intervention against natural succession at appropriate times will ensure stable and efficient soil remediation.

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