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Alleviation of heavy metal stress and enhanced plant complex functional restoration in abandoned Pb–Zn mining areas by the nurse plant *Coriaria nepalensis*

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Heavy metal pollution caused by mining has been a topic of concern globally because it threatens ecological functions and human health. Nearly all current remediation strategies take into account only such short-term issues as how to reduce or stabilize the content of heavy metals in soil, how to reduce the toxicity of heavy metals, and how to preserve water, soil and nutrients. However, little attention is paid to such long-term issues as whether plants can survive, whether communities can be stabilized, and whether ecosystem functions can be restored. Therefore, improving plant diversity and community stability are key aspects of improved mine restoration. To explore the possibility of reconstructing plant complexes in mining areas, the local nurse plant *Coriaria nepalensis* was selected as the research object for a study in the Huize Pb–Zn mining area of southwest China. *C. nepalensis* could increase the contents of nutrient elements (C, N, and P), reduce the contents of heavy metals (Mn, Cu, Zn, Cd, and Pb), and strengthen the plant complex functions (diversity, functional traits, and complex biomass) in its root zone. In general, *C. nepalensis* can form fertility islands (survival islands) in mining areas, which facilitate the colonization and success of additional less stress-resistant species. We propose *C. nepalensis* as a key species for use in restoration based on its ability to restore ecosystem functions under extremely stressful conditions. We encourage combination of *C. nepalensis* with other nurse plants to reinforce the rehabilitation of ecosystem functions.

KEYWORDS

heavy metal, plant diversity, structural equation model, functional trait, complex biomass, functional diversity, nutrient element

Highlights

- *Coriaria nepalensis* formed fertility islands (survival islands) in abandoned Pb–Zn mining areas.
- *Coriaria nepalensis* increased the contents of nutrient elements (C, N, and P) in its root zone.
- *Coriaria nepalensis* reduced the contents of heavy metals (Mn, Cu, Zn, Cd, and Pb) in its root zone.
- *Coriaria nepalensis* strengthened the plant complex functions (diversity, functional traits, and complex biomass) in its root zone.
- *Coriaria nepalensis* weakened the toxicity of heavy metals and the intensity of competition among plants.

Introduction

The mining of metals creates abandoned land featuring severe abiotic stresses imposed by high concentrations of trace elements, high conductivity, physical and chemical instability, and scant soil (Coelho et al., 2011; Li et al., 2022). In addition, overexploitation has caused tremendous harm to biodiversity and ecosystems (i.e., land and food security, soil quality, water quality, vegetation, and ecosystem services; Hossain et al., 2013; Gosain et al., 2015; Haddaway et al., 2019). Furthermore, heavy metals diffuse along with runoff, thus threatening the soil health and production of humans (Yang et al., 2012; Wang et al., 2020). Excessive exposure to heavy metals is associated with a variety of ailments (Munford et al., 2020). More importantly, land pollution and degradation caused by mining as well as by other anthropogenic activities have expanded worldwide, and the ecological restoration of abandoned lands has become an urgent environmental problem (Ilunga et al., 2015; Liu and Liu, 2020).

The current techniques for rehabilitation of abandoned mining areas may be divided into three categories: physical/mechanical, chemical, and biological methods. The physical/mechanical remediation method is based on earthworks and strives to return the post-mining land to its previous state using practices such as tilling, classifying, leveling, and topsoil replacement (Seenivasan et al., 2015). However, this method is expensive, and it is only suitable for economically developed areas (Festin et al., 2019). The chemical method involves removing excess heavy metals and hazardous chemicals from the soil and adjusting the soil pH (Mensah, 2015). However, chemical reagents are costly, require a vast group of professional technicians, and cause secondary pollution to the soil, so they cannot be utilized on a broad scale (Wu et al., 2010). Biological methods take advantage of the extraction or purifying functions of organisms. The most commonly used biological method is phytoextraction (Bolan et al., 2011), which reduces contamination levels in soil by extracting, translocating, and immobilizing heavy metals through hyperaccumulator plants. Compared to the two aforementioned techniques, phytoextraction has the advantages of *in situ* remediation, low cost, environmental friendliness, and suitability for large polluted areas (Teixeira et al., 2011). However, although phytoextraction has been touted as a viable method for treating abandoned mining areas, few studies have demonstrated that planting hyperaccumulative plants for mine waste restoration can produce a long-term plant community (Wu et al., 2013; Li and Huang, 2015).Overall, nearly all of these remediation strategies take into account only such short-term issues as how to reduce or stabilize the content of heavy metals in soil, how to reduce the toxicity of heavy metals, and how to preserve water, soil and nutrients. However, little attention is paid to such long-term issues as whether plants can survive, whether communities can be stabilized, and whether ecosystem functions can be restored.

Developing methods to establish stable plant complexes (patches) and prevent the spread of pollution is essential for mine restoration (Köbel et al., 2021; Zeidler et al., 2021). Several studies (Wang et al., 2014b; Jia et al., 2020; Bateman et al., 2021) have revealed that transplanting dominant plants to form new plant complexes may produce a series of benefits to ecosystem functions during mining area rehabilitation, but this process requires sustained professional program management, and the plant complexes cannot develop through succession. In other words, selection of spontaneous plant species is the key to successful restoration of mined land (Loreau and de Mazancourt, 2013). The ideal characteristics for species selection are an ability to establish and grow rapidly on barren substrates (Martínez-Fernández et al., 2011). Pioneer plant species, although very effective at colonizing a barren environment, do not necessarily promote the establishment of other plant species or improve soil conditions (Lei and Duan, 2008; Parraga-Aguado et al., 2013). Nurse plant species are stress-resistant plants that can thrive in difficult conditions (e.g., severely polluted soil, degraded soil, drought, and extreme cold) and establish small islands around their habitats, allowing less stress-tolerant plants to survive and develop beneath their canopies in harsh conditions with abiotic pressures (Padilla and Pugnaire, 2006; Saikia and Khan, 2012; Wang et al., 2014a). Hooper et al. (2005) suggested that necessary ecosystem functions should be promoted by selecting and combining nurse plant species, facilitating the establishment of other plant species and ultimately promoting plant–soil feedbacks. It is critical to search for native nurse plant species and research their roles (including high accumulation of soil organic carbon and nutrients, reducing soil metal concentrations, and improving community stability) in the establishment of plant patches, which are important for the recovery of abandoned mining areas.

According to reports, the total area of land resources lost by mining in the world has exceeded 20 million ha (Liu et al., 2018). In China, more than 118,000 mines are in operation, and the total volume of mine waste produced since 2009 has surpassed 10 billion tons (Pan et al., 2014). There are currently about 12,000 tailings ponds, which cover a significant area of land, including land in agricultural and forest regions (Yin et al., 2011). Uncontrolled mining has wreaked damage on local soil resources and polluted the ecosystem (Risueno et al., 2020b). The Huize Pb–Zn Mining District (Yunnan Province) has been an important metalliferous area in southwestern China since the Ming Dynasty, and conventional smelting processes have resulted in heavy metal contamination of the surrounding soil (Li et al., 2019). We discovered the nurse plant *Coriaria nepalensis* Wall. (Coriariaceae) (Awasthi et al., 2022a), which may help to alleviate the heavy metal pollution problem in this mining area. *C. nepalensis* is a common native shrub species of Yunnan Province that grows between 1200 and 2500 m a.s.l. (Awasthi et al., 2022b). A previous study (Mourya et al., 2019) showed that *C. nepalensis* could accumulate nutrients and thus aid the colonization of additional plants and contribute to the recovery of degraded forest ecosystems in the central Himalaya. To explore the role of *C. nepalensis* in the abandoned land in the Pb–Zn mining area, we established sample sites at three distinct locations in the mine. More specifically, we assessed the impacts of *C. nepalensis* on soil fertility, heavy metal concentration, plant diversity, functional diversity, and community productivity; analyzed whether *C. nepalensis* can form “survival islands” under extreme conditions; and explored the mechanisms by which *C. nepalensis* influences soil properties and plant complexes. Our results provide information that is useful for restoring polluted and degraded areas, such as tailings, abandoned mines, and quarries, under the same climatic and geographical conditions as exist in this study area.

Materials and methods

Description of the study area

The Huize Pb–Zn Mining District (NE Yunnan Province, China; 26°63′ N, 103°71′ E), with total confirmed mineral deposits of more than 1.52 million tons and a vast resource area of approximately 74,000 ha, is located at the southwest end of the Yangzi Platform (Zhou et al., 2018). The research area (town of Kuangshan) is located in the northeastern portion of Huize County, which has a typical subtropical plateau monsoon climate with a mean annual temperature of 12.5°C, mean elevation of 2,200 m, mean annual sunlight of 2,100 h, and mean annual rainfall of 820 mm (data from China’s National Meteorological Information Center for the years 1990 to 2015). The natural soil type is brown or yellow-brown loam, and the natural vegetation is dominated by Pinus yunnanensis and Populus yunnanensis. The study area and sampling locations are shown in **Figure 1** and **Table 1**.

Experimental design

This study was conducted in the summer of July to December 2021 at the Pb–Zn mining area and laboratory. Based

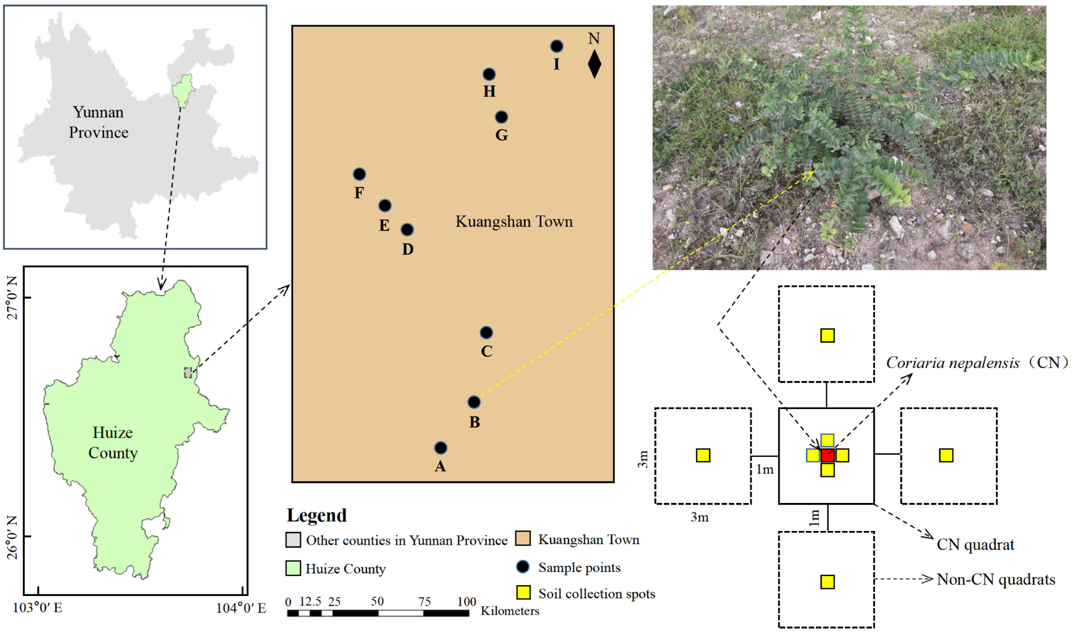

FIGURE 1
Overview of the research area, sampling points, and soil collection spots.

TABLE 1 Main characteristics of the research area.

Sample points	Elevation	Slope	Slope aspect
A	2484.5 m	19°	South 146°
B	2500.2 m	15°	Southeast 147°
C	2498.5 m	17°	South 157°
D	2540.2 m	19°	South 166°
E	2510.4 m	18°	South 164°
F	2493.7 m	19°	Northeast 146°
G	2505.4 m	20°	Southeast 140°
H	2482.6 m	19°	South 150°
I	2459.6 m	12°	North 150°

on the locations of the major mine pits, we selected three sample regions (three replicates per sample region; **Table 1**) for collecting data. The three sample regions were all located on naturally restored mining terraces and separated from each other by more than 500 m. In each replicate, we chose *C. nepalensis* as the central point and established a 3 m × 3 m quadrat (CN quadrat) around it. Because of the large spatial heterogeneity of plant survival in the study area, four additional 3 m × 3 m quadrats (Non-CN quadrats) were established in all four major cardinal directions as control quadrats (all at a distance of 1 m from the CN quadrat) to represent the real situation as much as possible (Nyenda et al., 2020). In each plot, three plants were harvested to determine the related plant indicators (Functional traits and Biomass). Soil collection spots were arranged in all four major directions of the CN quadrat and at the central location of each Non-CN quadrat. The detailed layout of the sample points is shown in **Figure 1**.

Plant sampling and handling

We established a total of 45 quadrats for plant sample collection. In each quadrat, whole plants of selected individuals were harvested, shaken, placed in envelopes, and labeled. A metal frame with dimensions of 1 m × 1 m with 100 equally distributed grids (10 cm × 10 cm) was constructed above the canopy in each quadrat during cover measurement (Wang et al., 2018). We ensured that all plants collected had healthy root systems and no leaf chlorosis. The whole plants were carefully washed three times with tap water, rinsed with deionized water, and then height and root length were measured. Next, the samples were dried at 105°C for 30 min, then at 65°C for 48 h, and weighed to determine their biomass. A list of the native plants harvested is provided in **Table 2**.

Diversity index calculation

Complex biomass (CB), plant species richness (Simpson index, D, and Shannon–Wiener index, H), and Pielou evenness (J) indices were measured. The calculation methods are as follows:

Simpson index (D) $= 1 - \sum_{1}^{S} Pi^2$, (1) (Tang et al., 2020)

Shannon-Wiener index (H) $= -\sum_{i=1}^{S} Piln\ Pi$, (2) (Tang et al., 2020)

Pielou evenness index (J) $= \frac{H}{\ln S}$, (3) (Tang et al., 2020)

Complex biomass (CB) $= \sum_{1}^{S} XN$, (4) (Tang et al., 2020)

where S is the number of species in a quadrat, N is total number of individuals of each species in a quadrat, Pi is the ratio

TABLE 2 Native plant species collected in the study.

Family	Species	Life form	Root system
Asteraceae	*Erigeron canadensis* L.	Annual Herb	Taproot
	Sonchus oleraceus L.	Annual Herb	Taproot
	Bidens pilosa L.	Annual Herb	Taproot
	Erigeron annuus (L.) Pers.	Annual Herb	Taproot
	Artemisia japonica Thunb.	Perennial Herb	Taproot
	Taraxacum mongolicum Hand.-Mazz.	Perennial Herb	Taproot
	Artemisia lavandulifolia DC.	Perennial Herb	Taproot
	Leontopodium leontopodioides Beauv.	Perennial Herb	Taproot
Poaceae	*Setaria viridis* Beauv.	Annual Grass	Fibrous root
	Cynodon dactylon (L.) Pers.	Perennial Grass	Fibrous root
	Imperata cylindrica (L.) Beauv.	Perennial Grass	Fibrous root
	Miscanthus sinensis Anderss.	Perennial Grass	Fibrous root
Fabaceae	*Lotus corniculatus* Linn.	Perennial Herb	Taproot
	Trifolium repens Linn.	Perennial Herb	Taproot
Commelinaceae	*Commelina communis* L.	Annual Herb	Adventitious root
Polygonaceae	*Oxyria sinensis* Hemsl.	Perennial Herb	Taproot
Lamiaceae	*Clinopodium chinense* Benth.	Perennial Herb	Adventitious root
Violaceae	*Viola philippica*	Perennial Herb	Taproot
Cyperaceae	*Cyperus rotundus* L.	Perennial Grass	Fibrous root
Ericaceae	*Vaccinium fragile* Franch.	Perennial Shrub	Taproot

of the number of species i to the total number of individuals in a quadrat, and X is average biomass per species in a quadrat.

Five key survival functional traits (plant height, root length, cover, life form, and root system) known to be associated with the settlement of extreme habitats were selected for analysis. After dividing the functional traits into 11 categories, we computed multi-trait functional indices, including the functional richness index (FRic), functional evenness index (FEve), functional divergence index (FDiv), functional dispersion index (FDis), and Rao's quadratic entropy index (RaoQ) using the "FD" package in R (Laliberté and Legendre, 2010). FRic is the area of functional trait space occupied by the organism in a community. FEve reflects the uniformity of distribution of functional traits in the ecological space within the community. FDiv indicates the difference in characteristic values of organisms in a community. FDis describes the mean distance in functional trait space for each species from the centroid of all species in an assemblage and reflects niche differentiation and resource competition of organisms within the community. RaoQ integrates the information of species richness and functional characteristics differences between species pairs and mainly calculates the variation in distance between species (Laliberté and Legendre, 2010).

Soil sampling and determination

We collected 72 soil samples (0–30 cm), which were analyzed for soil bulk density (SBD), pH, soil organic matter content (SOM), total nitrogen content (TN), total phosphorus content (TP), and soil heavy metal content (SHM). After removing stones and plant roots, the soil samples were air dried, ground to a fine powder, and then passed separately through 2 mm, 1 mm, and 0.25 mm sieves. SBD was measured using soil cores (volume of 100 cm^3) and the volume ring technique (Li et al., 2016). Soil pH was determined using a water–soil ratio of 5:1 in an aqueous suspension. SOM was analyzed by the oxidation method, using $K_2Cr_2O_7$–H_2SO_4 followed by titration with $FeSO_4$ (Wu et al., 2015). Soil TN was analyzed using a Foss Kjeltec analyzer and the acid digestion method, respectively (Hu et al., 2018). To determine SHM, soil samples (0.5 g) were digested in HNO_3:$HClO_4$ (5:1, v/v) at 240°C for 4 h, filtered and diluted into 50 mL volumetric flasks with distilled water, and then the contents of Mn, Cu, Zn, Cd, and Pb in the extracts were measured *via* flame atomic absorption spectrophotometer (Agilent, 240 FS).

Quality assurance and statistical analyses

All indicator analyses were performed in triplicate, and the analytical values were calibrated using blank controls. The relative standard deviation of the three replicate measurements, except for blanks, was fixed at no more than 5%. Glassware was soaked in HCl (10% v/v) for 24 h and then rinsed with deionized water. Two continuous calibration standards (CCV) were tested for every 10 samples (5% of samples), and the calibration curve was linear with a regression coefficient (r)2 > 0.990. More

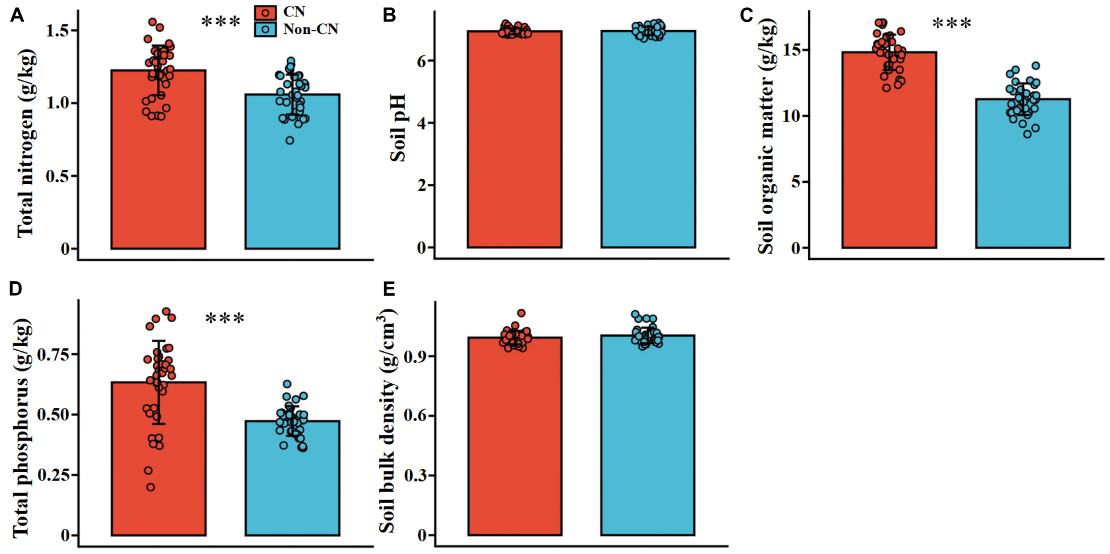

FIGURE 2
Total nitrogen **(A)**, soil pH **(B)**, soil organic matter **(C)**, total phosphorus **(D)**, and soil bulk density **(E)** in the presence (CN) or absence (Non-CN) of *C. nepalensis* in sample regions ($n = 36$). *** ($p \leq 0.001$) indicate significant differences between CN and Non-CN.

TABLE 3 Effects of presence or absence of *C. nepalensis* (CN/Non-CN) on total nitrogen (TN), soil pH (pH), soil organic matter (SOM), total phosphorus (TP), soil bulk density (SBD), and soil heavy metal contents (Mn, Cu, Cd, Zn, and Pb).

Factor	CN/Non-CN		Factor	CN/Non-CN	
	F	*P*		F	*P*
TN	20.706	**<0.001**	pH	0.134	0.716
SOM	141.881	**<0.001**	TP	27.887	**<0.001**
SBD	1.399	0.241	Mn	22.616	**<0.001**
Cu	36.804	**<0.001**	Cd	29.686	**<0.001**
Zn	31.650	**<0.001**	Pb	50.401	**<0.001**

The bold indicates highly significant differences.

importantly, quality assurance and quality control procedures were performed using the reference material GBW07405 (soil) received from the National Research Center for Reference Materials (Beijing, China).

Because of the imbalance between the datasets of plant communities of Non-CN and CN, new data were generated using the SMOTE algorithm to obtain balance (Chawla et al., 2002; Hong et al., 2021). The SMOTE algorithm was executed in R software with the "UBL" package (Branco et al., 2016). One-way analysis of variance (ANOVA) was used to assess the effects of the presence or absence of *C. nepalensis* on soil properties and plant complex characteristics. The Pearson correlation approach was utilized to examine the relationships between soil and plant complexes among the CN and Non-CN quadrats. A structural equation model (SEM) was constructed using the lavaan package in R (Rosseel, 2012), and the model parameter estimation method was based on the maximum likelihood method. The SEM was established to estimate the contribution rate and path of the primary influencing factor in the presence of *C. nepalensis*. All of the above statistical tests and illustrations drawn were executed in R version 4.1.3 or 4.2.0 (R Core Team, 2018).

Results

Effects of *Coriaria nepalensis* on soil properties and heavy metal contents

Soil TN ($F = 20.706$, $p < 0.001$), TP ($F = 27.887$, $p < 0.001$), and SOM ($F = 141.881$, $p < 0.001$) were significantly promoted in each sample region when *C. nepalensis* was present (**Figure 2** and **Table 3**). In addition, the concentrations of Mn ($F = 22.616$, $p < 0.001$), Cu ($F = 36.804$, $p < 0.001$), Cd ($F = 29.686$, $p < 0.001$), Zn ($F = 31.650$, $p < 0.001$), and Pb ($F = 50.401$, $p < 0.001$) in soil were higher in the Non-CN quadrats than in the CN quadrats (**Figure 3** and **Table 3**). The presence or absence of *C. nepalensis* did not affect SBD ($F = 1.399$, $p < 0.001$) or pH ($F = 0.134$, $p < 0.001$) across the sample regions (**Figure 2** and **Table 3**). In summary, the main functions of *C. nepalensis* in the mining areas were to enhance soil fertility and reduce the contents of heavy metals in soil without changing the soil's physical structure or acidity and alkalinity.

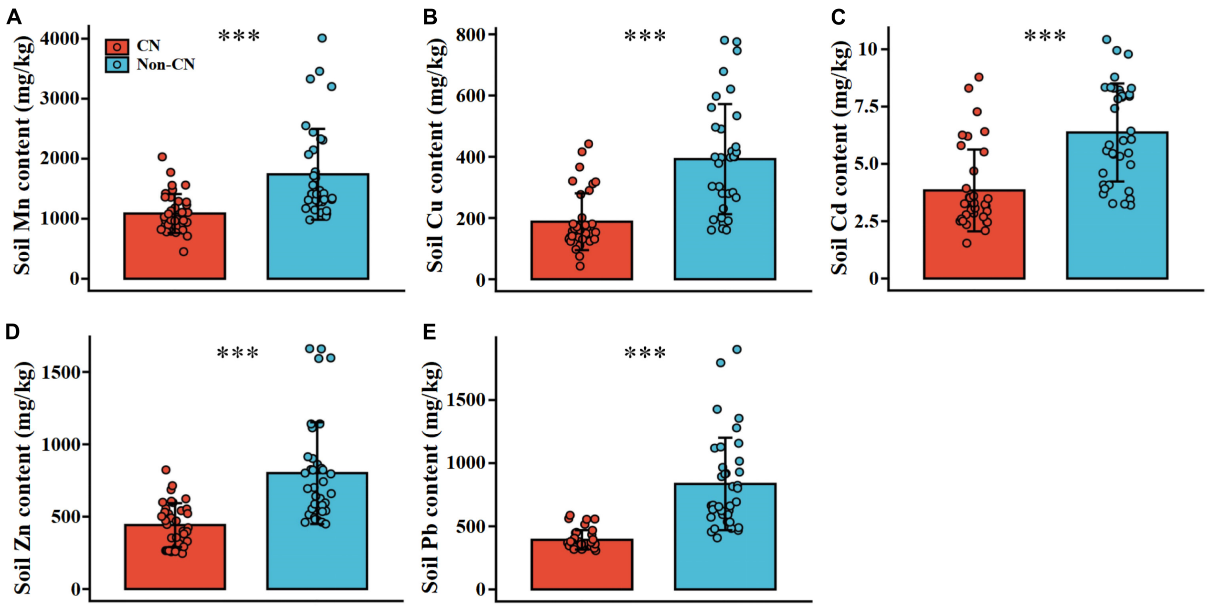

FIGURE 3
Soil contents of Mn **(A)**, Cu **(B)**, Cd **(C)**, Zn **(D)**, and Pb **(E)** in the presence (CN) or absence (Non-CN) of *C. nepalensis* in sample regions ($n = 36$). *** ($p \leq 0.001$) indicate significant differences between CN and Non-CN.

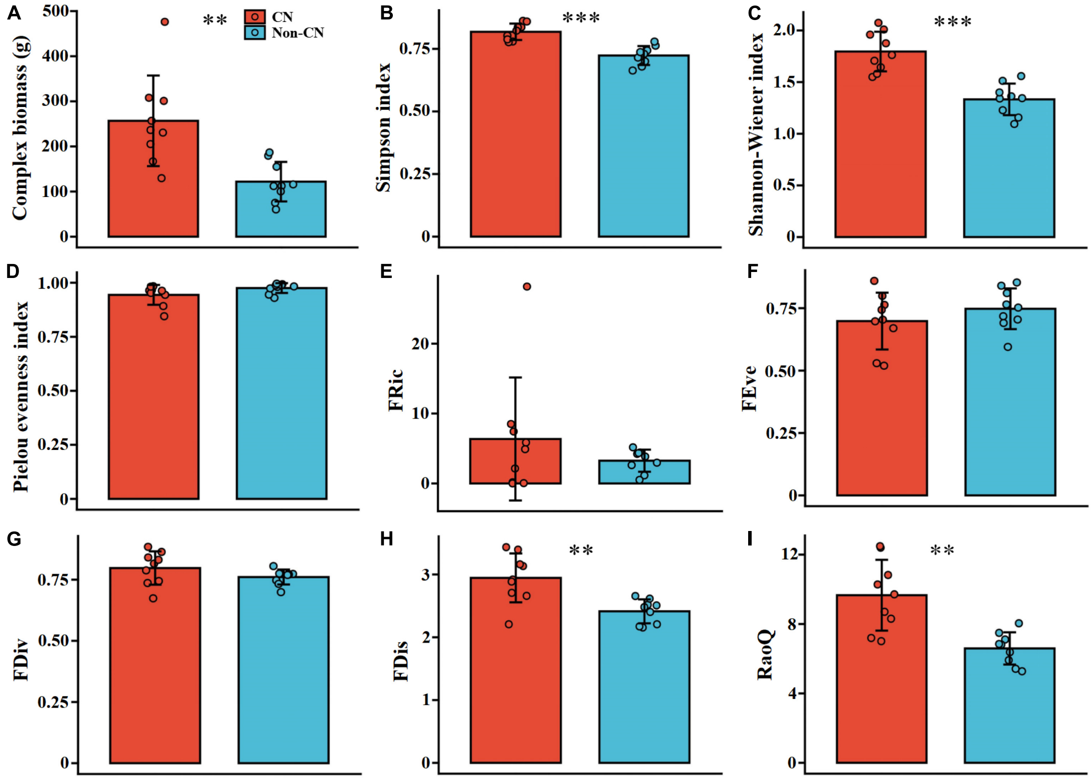

FIGURE 4

Complex biomass **(A)**, Simpson index **(B)**, Shannon−Wiener index **(C)**, Pielou evenness index **(D)**, functional richness index **(E)**, functional evenness index **(F)**, functional divergence index **(G)**, functional dispersion index **(H)**, and Rao's quadratic entropy index **(I)** in the presence (CN) or absence (Non-CN) of *C. nepalensis* in sample regions ($n = 9$). Asterisks indicate significant differences between CN and Non-CN: ** ($0.001 < p \leq 0.01$), *** ($p \leq 0.001$).

TABLE 4 Effects of presence or absence of *C. nepalensis* (CN/Non-CN) on complex biomass (CB), Simpson index (D), Shannon−Wiener index (H), Pielou evenness index (J), functional richness index (FRic), functional evenness index (FEve), functional divergence index (FDiv), functional dispersion index (FDis), and Rao's quadratic entropy index (RaoQ).

Factor	CN/Non-CN		Factor	CN/Non-CN	
	F	*P*		F	*P*
CB	13.642	**0.002**	D	32.210	**<0.001**
H	31.967	**<0.001**	J	3.420	0.083
FRic	1.086	0.313	FEve	1.114	0.307
FDiv	2.176	0.160	FDis	13.564	**0.002**
RaoQ	16.833	**0.001**			

The bold indicates highly significant differences.

Effects of *Coriaria nepalensis* on diversity, function, and biomass of plant complexes

CB ($F = 13.642$, $p = 0.002$), D ($F = 32.210$, $p < 0.001$), H ($F = 31.967$, $p < 0.001$), FDis ($F = 13.564$, $p = 0.002$), and RaoQ ($F = 16.833$, $p = 0.001$) were remarkably larger in the CN quadrats than the Non-CN quadrats (Figure 4 and Table 4). There were no significant differences related to the presence or absence of *C. nepalensis* for J ($F = 3.420$, $p = 0.083$), FRic ($F = 1.086$, $p = 0.313$), FEve ($F = 1.114$, $p = 0.307$), and FDiv ($F = 2.176$, $p = 0.160$) (Figure 4 and Table 4). The emergence of *C. nepalensis* changed the relationships among species, provided more living space for plants in different niches, increased species diversity, and increased functional diversity and community productivity, thus enhancing the stability of the mining ecosystem.

Relationships among soil and plant complex characteristics in the presence and absence of *Coriaria nepalensis*

This research focused on the relationships between indicators with a correlation coefficient greater than 0.3 (Figure 5). In the CN quadrats, TN was positively related to H, FRic, FEve, and CB. H and CB entirely had a positive correlation with FRic and FEve, respectively. FDis was positively associated

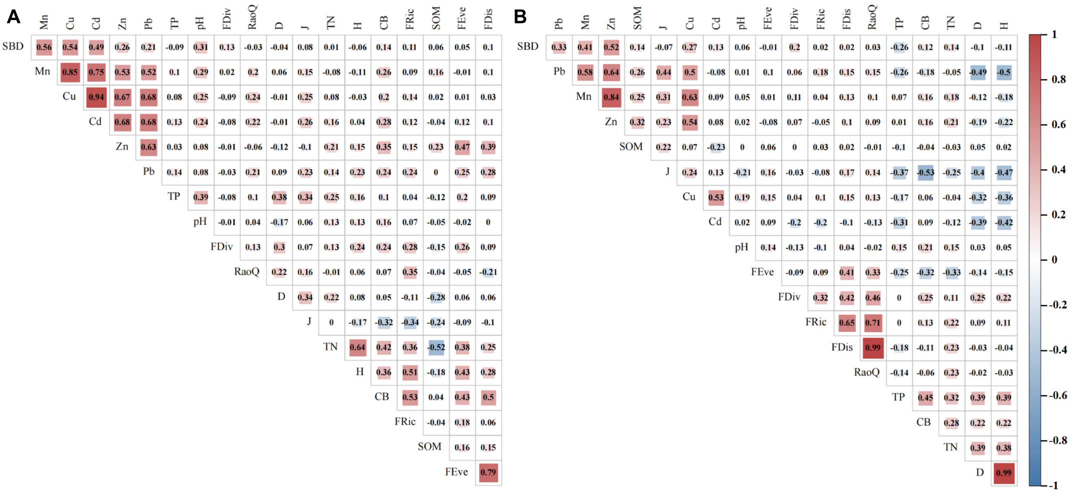

FIGURE 5

Pearson correlation coefficients of total nitrogen (TN), total phosphorus (TP), soil organic matter (SOM), soil bulk density (SBD), pH, soil heavy metal contents (Mn, Cu, Zn, Cd, and Pb), complex biomass (CB), Simpson index (D), Shannon–Wiener index (H), Pielou evenness index (J), functional richness index (FRic), functional evenness index (FEve), functional divergence index (FDiv), functional dispersion index (FDis), and Rao's quadratic entropy index (RaoQ) in sample regions. **(A)** Indicates presence of *C. nepalensis* (CN), and **(B)** Indicates absence of *C. nepalensis* (Non-CN).

with Zn, CB, and FEve. SBD was positively and strongly related to Mn, Cu, and Cd. Mn, Cu, Cd, Zn, and Pb were positively associated with each other. In the Non-CN quadrats, D and H were negatively and strongly related to Pb, Cu, and Cd, and there were positive correlations among FRic, FEve, FDiv, FDis, and RaoQ. Strong positive correlations were observed among the Pb, Zn, Cu, and Mn contents in the soil. In addition, Pb, Zn, and Mn were positively associated with SBD. Therefore, in the study area, the presence of *C. nepalensis* allowed for better contact between the plant complex and the soil, increased the nitrogen content in the soil, and weakened the toxic effects of heavy metals on plants.

Structural equation model of *Coriaria nepalensis* stabilization of plant complexes

According to **Figure 5A**, the presence of *C. nepalensis* changed the plant–soil feedback, which might directly or indirectly affect complex biomass. Therefore, SEM was used to explore the key factors affecting complex biomass (**Figure 6**). The Non-CN quadrats were used as controls. In the CN quadrats, the effects could be divided into three main paths: (i) FDis → CB ($\lambda = 0.47$), (ii) FRic → CB ($\lambda = 0.52$), and (iii) TN → H ($\lambda = 0.64$) → FRic ($\lambda = 0.54$) → CB ($\lambda = 0.52$). In the Non-CN quadrats, there were two major paths: (i) TN → H ($\lambda = 0.38$) and (ii) FDis → FRic ($\lambda = 0.66$). When *C. nepalensis* was present, FRic and FDis were direct factors affecting the biomass of the community, while TN and H were indirect factors. When *C. nepalensis* was not present, the soil nitrogen content affected plant richness, and the differences in plant characters was the factor maintaining the functional richness. Overall, nitrogen may be the main limiting factor of plant colonization and survival in the mining ecosystem.

Discussion

Influence of *Coriaria nepalensis* on soil properties

Our findings indicate that there was large spatial heterogeneity of relevant soil indicators in the study area, which was due to the different timings, methods, and intensities of mining (Shi et al., 2022). To verify the role of *C. nepalensis* in the restoration process of abandoned Pb–Zn mining areas, we tested whether it could positively modify soil properties. When *C. nepalensis* was present, soil TN, TP, and organic matter increased significantly, while SHM contents decreased dramatically (**Figures 2**, **3** and **Table 3**). *C. nepalensis* is a non-legume actinorhizal N-fixing species with root nodules (Yan et al., 2017), and the arbuscular mycorrhizal fungi in concert with nodulating bacteria in its roots effectively fix nitrogen from the soil and air (Tiwari et al., 2003; Manral et al., 2022). Fang et al. (2008) and Awasthi et al. (2022c) proved that *C. nepalensis* was more important as a nitrogen source than grass or ferns in studies of artificial forests and natural forests on upland sites in Southwest China and Northeast India.

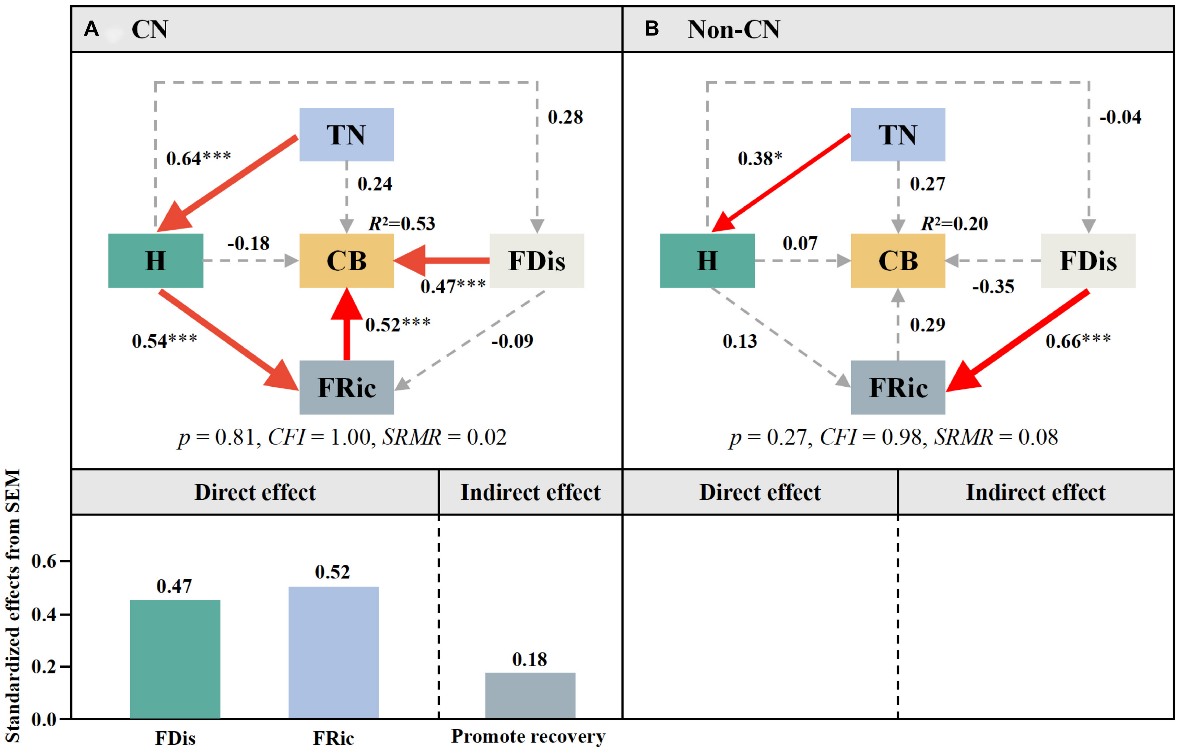

FIGURE 6
Effects of *C. nepalensis* from SEM. Total nitrogen content (TN), complex biomass (CB), Shannon−Wiener index (H), functional richness index (FRic), and functional dispersion index (FDis). Path coefficients are adjacent to arrows. Red lines indicate significant positive pathways. Asterisks indicate significant differences between CN **(A)** and Non-CN **(B)**: * ($0.01 < p < 0.05$), *** ($p \leq 0.001$).

This is the reason for the significant increase in nitrogen in the microenvironment around *C. nepalensis*. The accumulation, decay, and decomposition of litter are the main reasons for the increase in soil organic matter. Using ^{15}N isotope tracing, Wang et al. (2021) found that an increase in nitrogen significantly enhanced ecosystem function in a subtropical forest in China. Mineral-bound phosphorus is the main form of phosphorus present in nature. However, nitrogen enrichment can promote the dissolution of recalcitrant mineral-bound phosphorus into available phosphorus, thus increasing the phosphorus content of the soil (Wang et al., 2022). Cao et al. (2017) dried, ground, sieved, distilled, and filtered *C. nepalensis* plant material to produce plant washing agents and suggested that they had excellent removal effects for Pb, Zn, and Cd in soil. Therefore, *C. nepalensis* can secrete substances capable of removing heavy metal elements, reducing the contents of heavy metals around its roots.

The presence of *C. nepalensis* did not change the acidity and alkalinity of the soil but did increase the correlation between heavy metal elements and SBD (**Figure 5**). The development of vegetation in mining areas alters the soil porosity, which is an important driving factor for strengthening the relationship with heavy metals (Ciarkowska, 2017). The main reasons for the change in the relationship with heavy metal elements are that an increase in nutrient elements can promote the accumulation of heavy metal elements in plants, nutrient elements can form insoluble salts that directly absorb surface heavy metal ions or induce and enhance their adsorption by soil, and nutrient element ions can precipitate with heavy metal ions (Baragano et al., 2021). *C. nepalensis* roots may secrete a variety of cell-active substances, which may regulate soil nutrient elements and heavy metal elements. More attention should be given to this topic in future research.

Effect of *Coriaria nepalensis* on plant complexes

Our research showed that the presence of *C. nepalensis* facilitated the maintenance of more species and increased high-level niche differentiation, resulting in larger complex biomass (**Figure 4** and **Table 4**), which is consistent with research on phosphorus-rich soil (Yan et al., 2017) and hillsides with serious surface erosion. *C. nepalensis* had a strong promoting effect in the harsh environment, in which the α-diversity and biomass of herbs growing under the canopy of *C. nepalensis* were significantly higher than those of herbs growing in open air (Joshi et al., 2001). Moreover, in the highly degraded forests in the Indian central Himalaya, some research (Kumar and Ram, 2005; Mourya et al., 2019) has demonstrated that *C. nepalensis* helps restore original vegetation composition by triggering forest renewal.

Traditional ecological theory suggests that the abiotic component of the species niche is the sole determinant of species establishment and growth under extreme conditions. However, this view ignores the interactions between organisms that may realign the species' fundamental niche, resulting in a final ecological niche filtered through abiotic and biotic effects (Navarro-Cano et al., 2018). The use of inter-plant facilitation to construct plant patches as a means of mine rehabilitation is an emerging direction of research in the field of ecology (Wang et al., 2014b). Field surveys performed to select nurse species that are resistant and can facilitate the colonization and survival of other plants are a critical step toward this restoration approach. Therefore, studying the effects of nurse plants on plant diversity, complex biomass, and soil properties is essential for mining area restoration.

Effect of *Coriaria nepalensis* on changing plant–soil feedbacks

Soil and plants, as the basic structural units of the ecosystem, play an important role in the ecological restoration of mining areas, and there are complicated interactions between them (Li et al., 2021). In this research, when *C. nepalensis* was not present, the strong toxicity of heavy metals led to lower plant diversity and more intense competition among species (**Figure 5B**). However, when *C. nepalensis* was present, the opposite occurred. TN was positively related to H, FRic, FEve, and CB (**Figure 5A**). According to structural equation modeling (**Figure 6**), the presence of *C. nepalensis* increased the nitrogen content in the soil, promoted increases in complex biomass and niche complementarity, and enhanced the adaptability of auxiliary species to heavy metal pollution. In abandoned Pb–Zn mining areas, the contents of nutrient elements in the soil matrix are a key factor that restricts plant colonization (Cross et al., 2021a). Cross et al. (2021b) suggested that the germination of seeds, survival of seedlings, and growth of plants are positively correlated with the nitrogen in the soil, which indicates that nitrogen (available N; Li and Liber, 2018) is the decisive factor limiting vegetation restoration in mining areas. Many ecological studies (Perroni-Ventura et al., 2010; Huang et al., 2012) have defined fertility islands as areas of trees or shrubs (usually nitrogen-fixing plants) under abiotic stress, and the areas beneath these canopies have higher concentrations of nitrogen and organic matter than areas outside of the canopies. Such fertility islands, also known as survival islands, can promote improvement of the local soil matrix and form stable vegetation patches (Perroni-Ventura et al., 2010). Compared to adjacent bare land, it can create better resource pools and physical and chemical properties in or near the rhizosphere (Nyenda et al., 2020). In summary, *C. nepalensis* is a nurse plant that can form fertility islands in extreme habitats.

Rich species and functional traits greatly promote the amount of community biomass and the stability of the ecosystem (Qiu and Cardinale, 2020). The diversity of plants depends on the feedbacks in the ecosystem and the complementarity among species, and these accumulate over time (Reich et al., 2012). The plant patches (survival islands) in the mining area provide a basis for a community of highly diverse species with redundant functions and the development of a more stable ecosystem over time. Furthermore, Risueno et al. (2020a) suggested that plant patches have a positive effect on soil microorganisms, stimulating them to enhance the biogeochemical cycle. Thus, *C. nepalensis* can greatly facilitate vegetation restoration and control of heavy metal pollution in mining areas.

Beyond discovering the functions and roles of *C. nepalensis* in difficult habitats, it is important to determine why *C. nepalensis* aids the settlement of other species and to define the relevant ecological principle, which we did not consider. Xu et al. (2020) identified and explained the formation mechanism of the relationship between leguminous plants and their neighbors in 11 large forest plots (16–60 ha) around the world. They pointed out that this relationship is an atypical "altruism" and that its essence is still "egoism." In extreme cases, there is almost no competition for nitrogen resources between nitrogen-fixing plants and their neighbors. These plants pass through stages of first being "selfish," then "beneficial to others," and finally to a state of mutual benefit and harmonious coexistence.

We hope that future researchers give more attention to the roles of other nurse plants in abandoned mining area land when conducting field investigations. The best way to rehabilitate is to adapt to the local conditions and allow nature to develop.

Conclusion

In the course of natural succession of abandoned land in the mining area, nurse plants contribute to the formation of fertility islands (survival island), which is beneficial for other plants to colonize, survive and grow. This is essential for promoting community reconstruction, as confirmed by this study on the positive impact of *Coriaria nepalensis* as a nurse plant on soil properties, such as increasing the content of nutrient elements and reducing the content of heavy metals in the soil, and on plant patch formation, such as increasing the patch biomass and reducing the intensity of interspecific competition. Therefore, it is suggested that future research can be focused on exploring the law of natural succession followed by the nurse plants in mining areas.

Data availability statement

The original contributions presented in this study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

X-QY: conceptualization, methodology, software, writing – original draft, visualization, and investigation. Z-LG: investigation and software. C-QD: methodology, validation, revision, review and editing, supervision, and funding acquisition. JY, HT, and L-YL: investigation. TL and C-EL: methodology. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Publisher's note

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