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Coupling relationship between soil properties and plant diversity under different ecological restoration patterns in the abandoned coal mine area of southern China

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Abstract

Understanding the effects of ecological restoration in abandoned coal mine on soil and plant is important to improve the knowledge of ecosystems evolution and facilitate taking appropriate ecological restoration management practices. This study aims to evaluate the coupling relationship between plant diversity and soil properties after ecological restoration in abandoned coal mine area. The plant diversity and soil properties were investigated in four sites of different ecological restoration patterns in Fengcheng county, a typical coal- rich area in the history of southern China. The results indicated that: 1) the PSR (*Pinus massoniana* and *Schima superba gardn* restoration) site had higher Shannon-Wiener index and Simpson index values than PR (*Pinus massoniana* restoration) site, and in herb layer, the plant diversity was significantly higher than other layers; 2) in the PSR site, the soil properties were improved more notably than that of PR and NR (nature restoration) sites, and the plant diversity were also better than PR site; 3) Clay, SOM (soil organic matter), and MBC (microbial biomass carbon) made a great contribution to the plant diversity. It was concluded ecological restoration patterns had significant effects on soil nutrient content and plant diversity, and there exists evident coupling relationship between plant diversity and soil properties. This study has important effects of ecological restoration and management in abandoned coal mine area.

Keywords: Ecological restoration, Plant diversity, Soil properties, Vegetation configuration, Abandoned coal mine area

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1 Introduction

Coal is one of the three primary energy resource in the world, and the exploited of coal accounts for one-third of the world's energy consumption (Gao et al., 2021). China is the largest country of coal production, and coal is also the mainly energy resource in the nation’s energy supply, such as power fuel and to generate electricity, and its dominance will continue for a long time (Ruan et al., 2022; Wu et al., 2020b; Yuan et al., 2022). Coal mining activities cause environmental damage, such as landscape fragmentation, species loss, vegetation elimination, soil degradation (Babí Almenar et al., 2019; Liu et al., 2019; Yang et al., 2022). Moreover, underground coal mining may cause land subsidence and produce large quantities of mine waste, having a irreversible damage to ecosystem development (Du et al., 2021; Lechner et al., 2016; Xu et al., 2023). The ecological environment background conditions of coal mine areas are always very poor, due to coal excavation, coal washing and coal gangue disposal, seriously threatening the safety of people and property (Ahirwal and Maiti, 2018). In China, coal resource utilization has recently increased rapidly due to the long-term dependence of the economic development (Xie et al., 2023). The area destroyed by mining activities has increased to 120,000 km^2 in 2020, and the number of abandoned coal mines was more than 12,000 (Wang et al., 2022). Furthermore, in 2022, abandoned mines account for 30.35% of the mine development area, and only 4.64% has been restored (Lyu et al., 2022). Therefore, the implementation of ecological restoration in abandoned coal mine area is expecially urgent. Ecological restoration is a main measure to maintain the stability of the ecosystem, and how to scientifically and effectively conducted ecological restoration has been highly valued by many researches (Ismaeel and Ali, 2020). The United Nations General Assembly proclaimed a ten-year plan on ecosystem restoration to facilitate the restoration of damaged ecosystems (UNEP, 2019), and the “13th Five-Year Plan (2016–2020)” in China has given priority to ecological restoration of mining areas..

Recently, many studies on ecological restoration of abandoned coal mine area have concentrated ecological restoration measures to improve soil properties, restore ecosystem structure and function, and improve biodiversity (Chen et al., 2020; Du et al., 2021). Vegetation restoration plays an important role in improving soil quality and restoring other ecological services in abandoned coal mine area (Chen et al., 2020; Kaiser-Bunbury et al., 2017; Lu et al., 2022). Additionally, vegetation restoration is not only low costs and environment friendly, but also bring aesthetic value and produce social economic benefits (Pathak S et al., 2020; Sun et al., 2021).

Re-vegetation can improve the soil structure and property (Zhao et al., 2022a). Appropriate vegetation restoration projects can significantly improve soil nutrient and activity (Yuan et al., 2018; Deng et al., 2018b). It is well know that soil properties are conducive to the maintenance of plant diversity (Gong et al., 2019). Some researches reported that soil nutrients, soil pH, soil water content (SWC), and soil bulk density (SBD) had significant effect on plant diversity (Damgaard et al., 2013; Yan et al., 2015). Soil pH can change soil enzyme activity and nutrient, thus affecting plant diversity (Cambrollé et al., 2014). SWC and SBD plays a key role in soil hydrological processes, and the improvement of which is beneficial to improving ecosystem productivity and plant diversity (Boluwade and Madramootoo, 2016; Katherine et al., 2010). Soil nitrogen (N) and phosphorus (P) affect plant diversity by limiting the growth of vegetation, whereas soil organic matter (SOM) is significantly correlated with available nitrogen (AN) and available phosphorus (AP) (Chen et al., 2019; Liu et al., 2021). Previous researches reported that soil heterogeneity and nutrients was thought to improve diversity and spatial heterogeneity of plant communities (Schweiger et al., 2016). Meanwhile, vegetation restoration can improve soil nutrient availability, and improve ecosystem productivity (Bakker et al., 2019; Chen et al., 2019). However, the influential mechanisms of soil properties on plant diversity are complex, and few studies are available for it (Lü et al., 2019; Wu et al., 2019).

Plant diversity is one of the most important feature in biodiversity, which can describe the structural complexity of plant community (Sun et al., 2019). Plant diversity can be measured through the metrics of Margalef index (M), Simpson index (H), Shannon-Wiener index (D), and Pielou index (J) (Bennett et al., 2006). Current researches on the coupling relationship between soil properties and plant diversity always concentrate on forest rather than coal mine restoration area. How soil properties affect plant diversity, and their interactions under different vegetation configuration are still needed to be studied. Therefore, the research of coupling relationship between soil properties and plant diversity under different ecological restoration patterns plays an important role in providing theoretical guidance for abandoned coal mine restoration.

In this study, we analyze the effects of different vegetation restoration patterns on plant diversity and soil property, as well as the relationship between them in abandoned coal mine area. The aims of this study are to: 1) evaluate the change trend of soil properties and plant diversity in abandoned coal mine under different vegetation restoration patterns, 2) discover the relationship between soil properties and plant diversity, 3) determine impacting fators of soil properites and plant diversity from plant community's point of view. It is expected to better understand the ecosystem process happened in abandoned coal mine area for better ecological restoration benefits.

2 Materials and methods

2.1 Study sites

The study was carried out in the abandoned coal mines of Liushe, Shanxi and Longxi coal mine area (115°48′30″~115°57′30″ E, 27°56′00″~27°59′30″ N), located in Fengcheng county, Jiangxi province, China (**Fig.1**). The altitude ranges from 45 to 75 m, with an average of 60 m. The study sites are suitable for the growth of broadleaved forest and subtropical coniferous forest species, such as *Pinus massoniana, Cunninghamia lanceolata.* and *Schima superba gardn.* The shrubs in the study area are mainly *Osmanthus fragrans var.semperflorens, Photinia* × *fraseri Dress, Camellia japonica L,* and *Lagerstroemia indica L.,* and the herbs are *Cynodon dactylon L., Setaria viridis L., Dendranthema indicum,* and *Poa annua L.*

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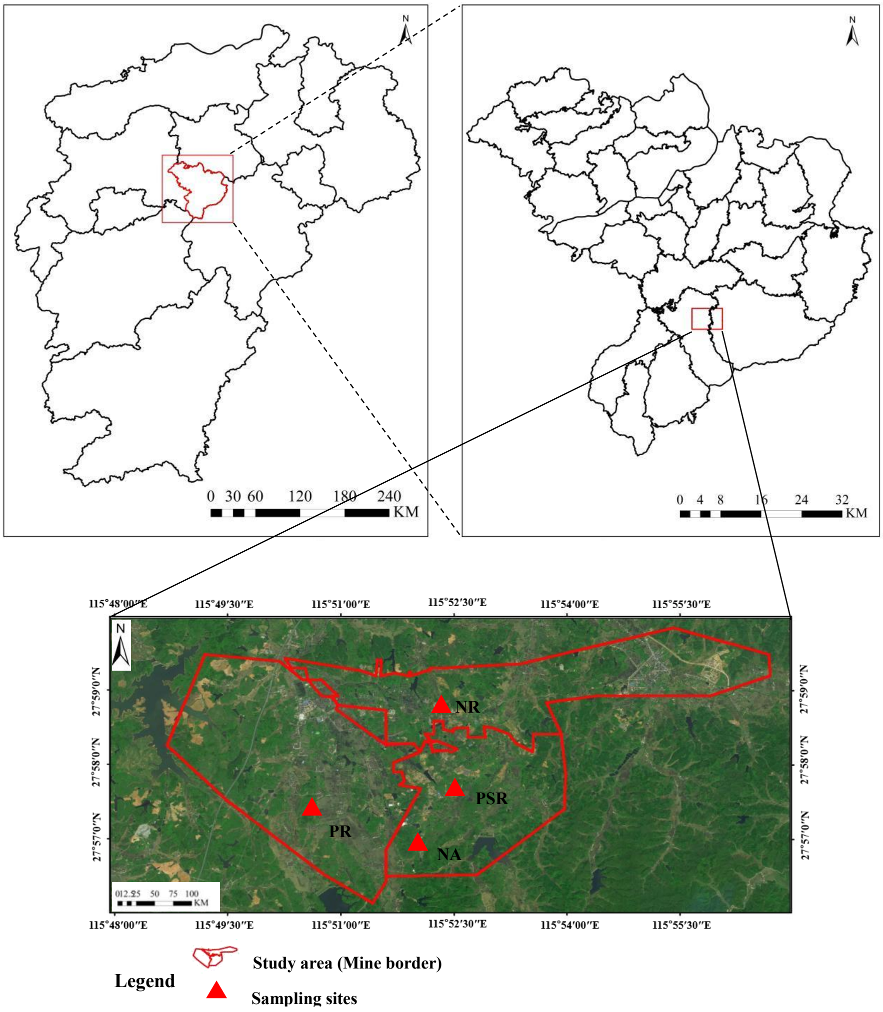

Fig. 1 Location of study sites in the south of Fengcheng County, Jiangxi, China (from Bigemap and http://bnr.jiangxi.gov.cn/col/col45382/index.html).

2.2 Sites selection, plant investigation and soil sampling

The *Pinus massoniana* and *Schima superba gardn* were important for re-vegetation and afforestation on abandoned coal mine area due to its strong adaptability (Pietrzykowski, 2014), and were native dominant plant species in south China. Based on the environment factors, ecological restoration patterns, and the scope of coal mine, we selected the ecological restoration areas with different restoration patterns of the same vegetation restoration year in abandoned coal mining areas. Four typical sites of different ecological restoration patterns were selected: PR (*Pinus massoniana* restoration), PSR (*Pinus massoniana* and *Schima superba gardn* restoration), NR (nature restoration), and NA (nature undisturbed area) as a control **(Table 1**). For each ecological restoration pattern, considering both the location and slope, we choose two sample sites in the study area, and randomly established five plots in each site. The latitude, longitude, altitude and dominant species were recorded in each study sites. We made ground vegetation inv to collect data on plant diversity in June 2022. The investigation sites were depended on the plant community size,10 m × 10 m quadrat were selected in ten study sites as arbor layer, ten 5 m × 5 m quadrat were mechanically arranged as shrub layer squares in the arbor quadrat, and one 1 m × 1 m herb layer quadrat was set in the center of each shrub quadrat. We recorded the species name, quantities of trees, height, the branch diameter and coverage of arbor layers, names, heights, the number of shrubs. In the herb layer, species name, average coverage and average height of each species occurring were recorded.

Considering the characteristics of soil properties in the top layer, each soil profile was sampled for every 10 cm by auger from three layers: 0-10 cm, 10-20 cm, and 20-30 cm. Soil samples (8-10) were collected along an S-shaped pattern from each study site, and a total of 100 soil samples were collected for soil properties determination. At each sampling site, approximately 0.5-1 kg of soil sample was selected according to the quartet method after removing plant roots, stones, weeds and litter. After air-drying, the collected soil samples were crushed, and passed through a sieve. Finally, the physical and chemical properties of soil were determined.

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Table 1 Information on the five study sites

Types	Altitude (m)	Longitude	Latitude	Restoration years	Dominant species
PR	68.23	115°50′36″	27°57′21″	10	*Pinus massoniana, Camellia japonica L., Photinia × fraseri Dress*
PSR	75.44	115°52′35″	27°57′38″	10	*Pinus massoniana, Schima superba gardn, Photinia × fraseri Dress*
NR	65.37	115°52′16″	27°58′48″	10	*Pinus massoniana, Cunninghamia lanceolata, Camellia japonica L., Pyracantha fortuneana*
NA	46.54	115°52′15″	27°56′42″	>20	*Cunninghamia lanceolata, Schima superba gardn, Osmanthus fragrans var. Semperflorens, Photinia × fraseri Dress*

2.3 Plant diversity analysis and soil properties measurement

The importance value (IV) and plant diversity index of different plant layers were calculated through the plant investigation data. IV is an essential species diversity index and the IV value can directly indicate the relative importance of plant species in a community (Zhang et al., 2011). In this study, the plant diversity index H, D, J, and M were calculated to describe the plant diversity in different ecological restoration patterns area (Kumar et al., 2015; Zhou et al., 2016). The calculation methods were as follows:

Important value (IV) = (Relative density + Relative frequency + Relative coverage) /3 (1)

where the relative density is the density of a species / sum of the densities of all species; the relative frequency is the frequency of a species / sum of the frequencies of all species; the relative coverage is the plant coverage of a species / sum of plant coverage of all species.

Shannon–Wiener diversity index (H):

$$H = -\sum_{i=1}^{S} P_i \ln P_i \qquad (2)$$

Simpson diversity index (D):

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$$D = 1 - \sum_{i=1}^{S} P_i^2 \tag{3}$$

Pielou evenness index (J):

$$J = H / \ln S \tag{4}$$

Margalef richness index (M):

$$M = (S - 1) / \ln N \tag{5}$$

where P_i is the ratio of the number of individuals, i is the base of the logarithm, $P_i = n_i/n$ and i=1, 2, 3,…n_i, of species i in the sample to the total number of individuals, n, of the species in the sample, S is the number of species in the sample quadrat, and N is the number of all plants in the sample quadrat.

SBD and SWC were determined separately by the stainless-steel cylinder and gravimetric method, and the soil mechanical composition (clay/silt/sand) was measured using the dry sieving method. Soil pH was measured using a water–soil ratio of 2.5:1.0 and the potentiometric method. SOM was measured by the $K_2Cr_2O_7$ oxidation-external heating method. The contents of soil AN was measured by NaOH hydrolysis proliferation by the alkalihydrolysis method, AP was measured using the molybdenum-antimony colorimetric method and AK was measured by flame atomic absorption spectrophotometry method (Liao et al., 2014). The contents of soil microbial biomass carbon (MBC) and soil microbial biomass nitrogen (MBN) were determined by the chloroform fumigation extraction method (Dong et al., 2018).

2.4. Statistical analysis

One-way analysis of variance (ANOVA) was used to analyze the significance of the difference among soil properties in different ecological restoration patterns and different soil layers at a significance level of $P < 0.05$. Statistical analysis was performed using SPSS 26 (IBM SPSS Statistics 26). Person's correlation coefficient was used to quantify the relationship between soil properties and species diversity. The corresponding relationships between soil properties and species diversity were quantified and the ordination map was drawn using redundancy analysis (RDA) by the Canoco 5.0, and Origin 2019 was used to draw the graphs.

3 Results

3.1 Plant diversity and community composition under different ecological restoration patterns

The composition of the plant communities in each study area were shown in **Table 2**. In the sample plots, a total of 21 families, 29 genera, and 31 species were observed. A total of 24 species appeared in the NA site, and the dominant species in arbor layer were *Cunninghamia lanceolata* and *Schima superba gardn*, the dominant species in shrub layer were *Osmanthus fragrans var. Semperflorens*, *Photinia* × *fraseri Dress,* the dominant species in herb layer were *Setaria viridis L.*, *Dendranthema indicum*, *Poa annua L.*, and *Miscanthus*. Under the PR site, the number of plant species was 19, *Pinus massoniana* was the dominant species in arbor layer, and the shrub layer mainly contain *Photinia* × *fraseri Dress* and *Camellia japonica L.*, the dominant species in herb layer were *Cynodon dactylon L.*, *Setaria viridis L.*, *Poa annua L.*, *Clover*. There were 24 species in the PSR site, *Pinus massoniana* and *Schima superba gardn* were re-vegetation plant species in arbor layer, the dominant species in shrub layer were *Photinia* × *fraseri Dress*, *Camellia japonica L.*, and *Pyracantha fortuneana*, and the herb layer mainly contain *Cynodon dactylon L.*, *Dendranthema indicum*, *Poa annua L*, *Clover*. Under the NR site, the number of plant species was 27, and the dominant species in arbor layer were *Pinus massoniana* and *Cunninghamia lanceolata*, the shrub layer and herb layer had the most abundant in all treatments, including *Osmanthus fragrans var. Semperflorens*, *Osmanthus fragrans cv.tbubergii*, *Camellia japonica L.*, *Pyracantha fortuneana*, *Cynodon dactylon L.*, *Dendranthema indicum, Poa annua L.*, *Clove, Miscanthus*.

The plant diversity index H (**Fig. 2a**) and D (**Fig. 2b**) values did not differ significantly among the 4 study sites, while they had significant difference ($P < 0.05$) in the 3 forest layers. The NR site had higher D and H values than PR site and PSR site, and the order of them was: NR>NA>PSR>PR. In the four study sites, there were significantly higher diversity for herbs layer than for arbors and shrubs layers. The plant diversity index J values had no significant differences among the 4 study sites and 3 forest layers (**Fig. 2c**). It reached the highest in the PR site shrub layer, with the lowest value observed in the NA site herb layer. As it was seen in **Fig. 2d**, The plant diversity index M had significant difference ($P < 0.05$) in different ecological restoration patterns, and the highest value was appeared in NR site while the lowest value was in PR site. The shrub layer showed the lowest Margalef richness index (M) value in PSR, NR and NA site, and the order of them was: NR>NA>PSR. However, in the PR site, there was the highest value in shrub layer and the lowest value in herb layer. Overall, the plant diversity was slightly higher in the NR and NA site than those in PR and PSR sites. The results indicated that re-vegetation restoration community led to lower plant diversity than natural succession community did.

Table 2 The composition of plant communities under different ecological restoration patterns.

Layer	Family	Genus	Species	Importance value			
				PR	PSR	NR	NA
Arbor layer	Pinaceae	Pinus	*Pinus massoniana*	0.66	0.31	0.17	0.11
	Pinaceae	Pseudolarix	*Pseudolarix amabilis*	0.1	0.13	0.13	0.12
	Cupressaceae	Sabina mill.	*Sabina chinensis*	0.05	0.06	0.12	-
	Taxodiaceae	Cunninghamia	*Cunninghamia lanceolata*	0.12	0.12	0.21	0.18
	Salicaceae	Salix	*Salix matsudana*	0.04	-	0.08	0.10
	Lauraceae	Cinnamomum	*Cinnamomum camphora*	-	0.05	0.10	0.07
	Scrophulariaceae	Paulownia	*Paulownia*	-	0.06	-	0.06
	Leguminosae sp.	Robinia L.	*Robinia pseudoacacia L.*	0.03	-	0.05	0.08
	Elaeocarpaceae	Elaeocarpus	*Elaeocarpus decipiens*	-	-	0.03	0.07
	Theaceae	Schima reinw.	*Schima superba gardn*	-	0.27	-	0.21
Shrub layer	Osmanthus fragrans	Osmanthus	*Osmanthus fragrans var. semperflorens*	0.14	0.06	0.12	0.32
	Rosaceae	Photinia Lindl.	*Photinia × fraseri Dress*	0.25	0.23	0.08	0.21
	Osmanthus fragrans	Osmanthus Lour.	*Osmanthus fragrans cv.tbubergii*	0.1	0.12	0.15	-
	Theaceae Mirb.	Camellia L.	*Camellia japonica L.*	0.37	0.16	0.23	0.18
	Rosaceae	Rose L.	*Rosa chinensis*	-	0.13	0.06	-
	Rosaceae	Pyracantha	*Pyracantha fortuneana*	0.06	0.15	0.17	0.14
	Theaceae Mirb.	Camellia L.	*Camellia oleifera abel.*	0.08	-	0.05	-
	LYTHRACEAE	Lagerstroemia L.	*Lagerstroemia indica L.*	-	0.12	0.08	0.16
	Malvaceae	Hibiscus L.	*Hibiscus mutabilis L.*	-	0.03	0.06	-
Herb layer	Gramineae	Cynodon dactylon	*Cynodon dactylon L.*	0.23	0.27	0.13	0.05
	Gramineae	Setaria beauv.	*Setaria viridis L.*	0.12	0.09	0.06	0.19
	Asteraceae	Dendranthema	*Dendranthema indicum*	0.08	0.11	0.10	0.22
	Poaceae	Poa L.	*Poa annua L.*	0.21	0.23	0.11	0.15
	Compositae	Artemisia	*Artemisia hedinii*	-	0.04	0.08	0.10
	Leguminosae sp.	Trifolium	*Clover*	0.16	0.11	0.16	-
	Poaceae	Miscanthus	*Miscanthus*	0.05	0.04	0.10	0.17
	Poaceae	Lolium	*Lolium perenne L.*	-	0.06	0.06	0.03
	Poaceae	Zoysia	*Zoysia japonica Steud*	-	-	0.08	0.02
	Poaceae	Buchloe engelm.	*Buchloe dactyloides*	-	0.05	-	0.05
	Poaceae	Eremochloa Buse	*Eremochloa ophiuroides*	0.07	-	0.07	-
	Poaceae	Zoysia	*Zoysia pacifica goudswaard*	0.08	-	0.05	0.02

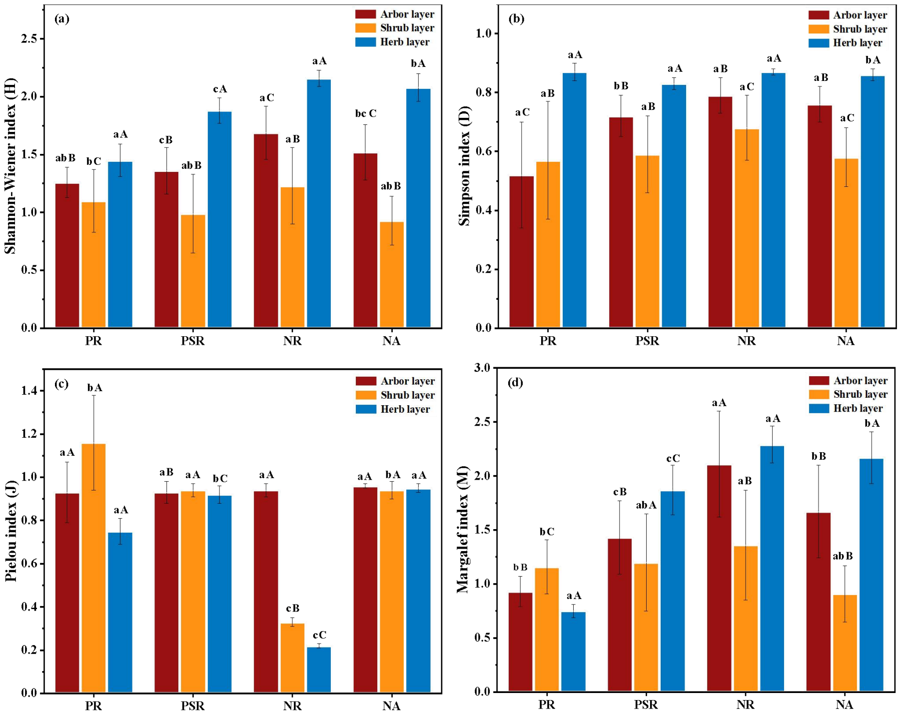


Fig. 2 Diversity indices of different ecological restoration patterns in the 4 study sites ; (a) Shannon-Wiener index (H), (b) Simpson index (D), (c) Pielou index (J), (d) Margalef index (M). Different lowercase letters indicate significant difference under ecological restoration years (one-way ANOVA, $P < 0.05$). Different uppercase letters indicate significant difference among different soil depths at the same sites (one-way ANOVA, $P < 0.05$).

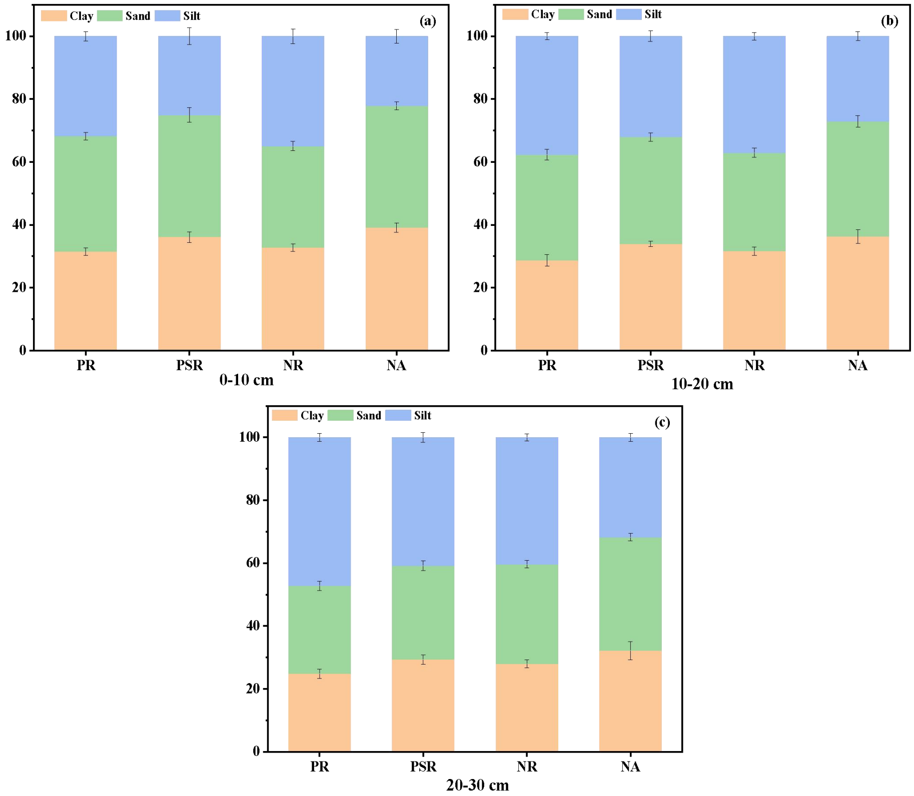
3.2 Soil properties under different ecological restoration patterns

Fig. 3 showed the soil mechanical composition for different ecological restoration patterns. The PSR site and the NA site had a similar soil texture, which were significantly better ($P < 0.05$) than other ecological restoration patterns, indicating that if the time of the mixed vegetation restoration is more than 10 years, the soil mechanical composition was close to the nature undisturbed area. The clay content in PSR site was 17.1% and 7.6 % higher than that in PR and NR site,respectively, but at the same time, the sand content in PSR site was 34.6% and 29.3% lower than that in PR and NR site. The clay and sand contents increased slowly with the increasing of soil depth, but the silt content had a opposite trend. PR site was significantly higher ($P < 0.05$) than the other sites in terms of silt content in the 20-30 cm soil layer, and PSR site was significantly higher than the other sites on sand content in the 0-10cm soil layer. In **Fig. 4a**, SBD was shown significantly lower ($P < 0.05$) in the PSR site than that in the PR and NR sites. Moreover, with the increase of soil depth, the SBD values showed an upward trend in all the 4 study sites . The NA site had the lowest SBD value in the 0-10 cm soil layer. In **Fig. 4b**, NA and PR sites were seen higher SWC value than the other study sites on the 0-10 soil layer. Moreover, the PSR site was seen to be significantly higher ($P < 0.05$) than the other study sites on the 20-30 cm soil layer and the NR site showed lowest SWC on the 0-10 cm soil layer. PR and PSR site were seen lower pH value than the other study sites on all the soil layers (**Fig. 4c**).Specifically, except for NA site the highest pH value on 10-20 cm soil layer, PS, PSR, and NR sites had the highest pH value on 20-30 cm soil layer. Furthermore, NA PS, PSR, and NR sites had the lowest value on the 0-10 soil layer, and the highest pH value was seen in NR site on the 20-30 cm soil layer in all the 4 study sites. The results indicated that PSR site had better physical properties.

Fig. 5 showed the effects of different ecological restoration patterns on soil chemical properties. In **Fig. 5a**, PSR site was significantly higher ($P < 0.05$) than that of the other study sites and exhibited the highest SOM value. Additionally, the SOM had a decrease trend with the increase of soil depth except PR site, and the lowest SOM was seen in NR site 20-30 cm soil layer, which was 0.4 time of the highest value in PSR site 0-10 cm soil layer. As it was seen in **Fig. 5b**, AK showed significant difference in PR, PSR and NR sites, and PSR site was significantly higher ($P < 0.05$) than that of PR and NR sites, but PR and NA site had no significant difference, and NA site showed the highest AK value. Meanwhile, similar to SOM, AK value decreased with the increasing of soil depth, and NR site was seen significantly lower AK on 20-30 cm soil layer. Similar to AK, PSR site was seen higher AP value than that of PR and NR sites, and NA site showed the highest AP value on 0-10 cm soil layer (**Fig. 5c**). On 20-30 cm soil depth, there was no significant difference between

PSR, NR, and NA sites, and NR site had the lowest AP value. In **Fig. 5d**, AN showed significant difference in the 4 study sites, with the highest value observed in NA site and the lowest value in NR site. In the PR and NR site, the lowest AN value appeared on 10-20 cm soil layer, while PSR and NR site observed the lowest value on 20-30 cm soil layer. The results indicated that PSR site can significantly improve the chemical properties.

Soil microbial properties of different ecological restoration patterns were showed in **Fig. 6**. The MBC in PR, PSR, NR, and NA sites had significant difference, and the MBC values in PR and PSR sites were significantly ($p < 0.05$) higher than that in NR site (**Fig. 6a**). Meanwhile the MBC did not differ significantly among all soil layers in each study sites. The MBC value decreased slowly with the increasing of soil depth, and the lowest MBC value was seen in NR site 20-30 cm soil layer. In **Fig. 6b**, the MBN was significantly higher in PSR site than that in PR and NR sites, and the MBN value decreased as follows: NA>PSR>PR>NA. Additionally, in PR and NR site, the MBN value was decrease with the increasing of soil depth, while the highest MBN value in PSR site and the lowest value in NA site were observed on 10-20 cm soil layer.



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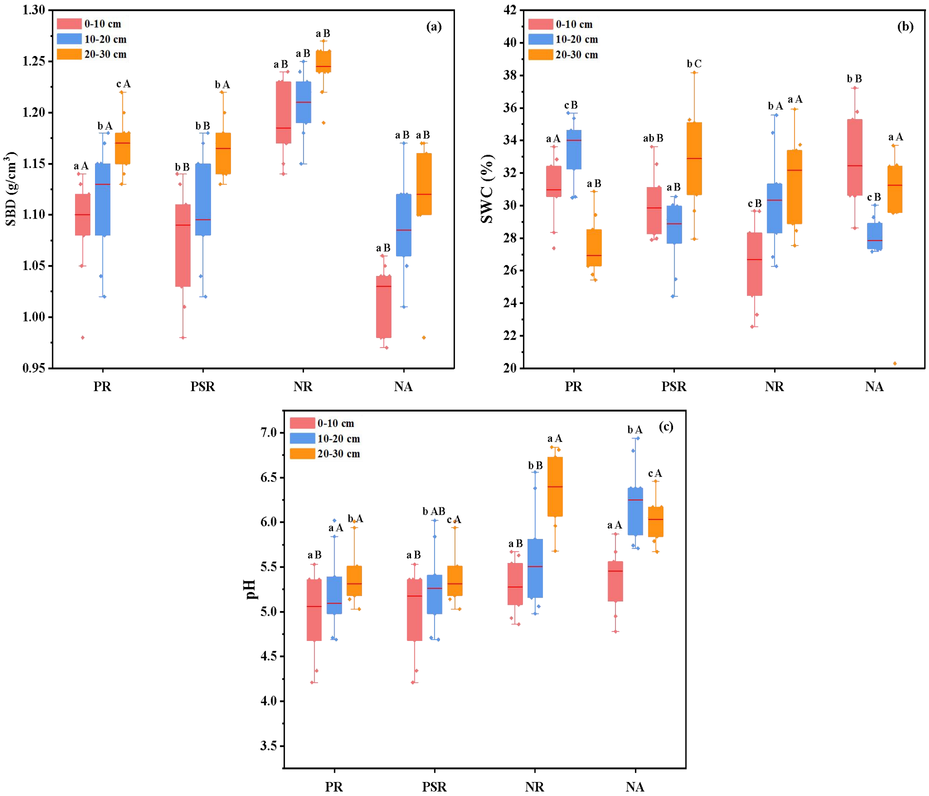

Fig. 4 Soil physical indicators of different ecological restoration patterns in the 4 study sites on different soil layers. (a) SBD; (b) SWC; (c) pH.

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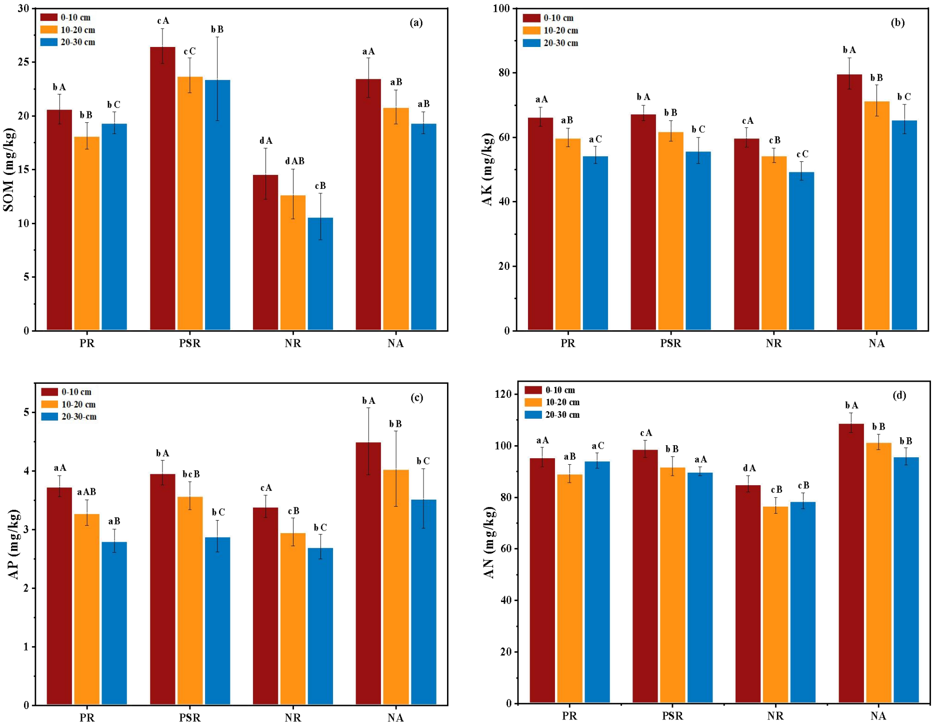

Fig. 5 Soil chemical indicators of different ecological restoration patterns in the 4 study sites on different soil layers. (a) SOM ; (b) AK ; (c) AP; (d) AN.

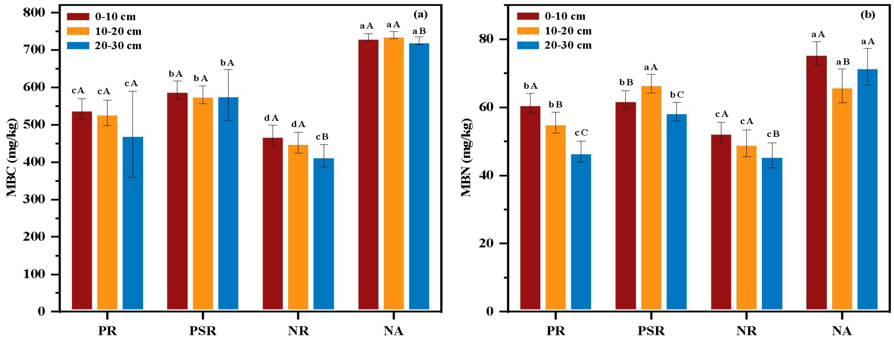

Fig. 6 Soil microbial properties of different ecological restoration patterns in the 4 study sites on different soil layers. (a) MBC and (b) MBN.

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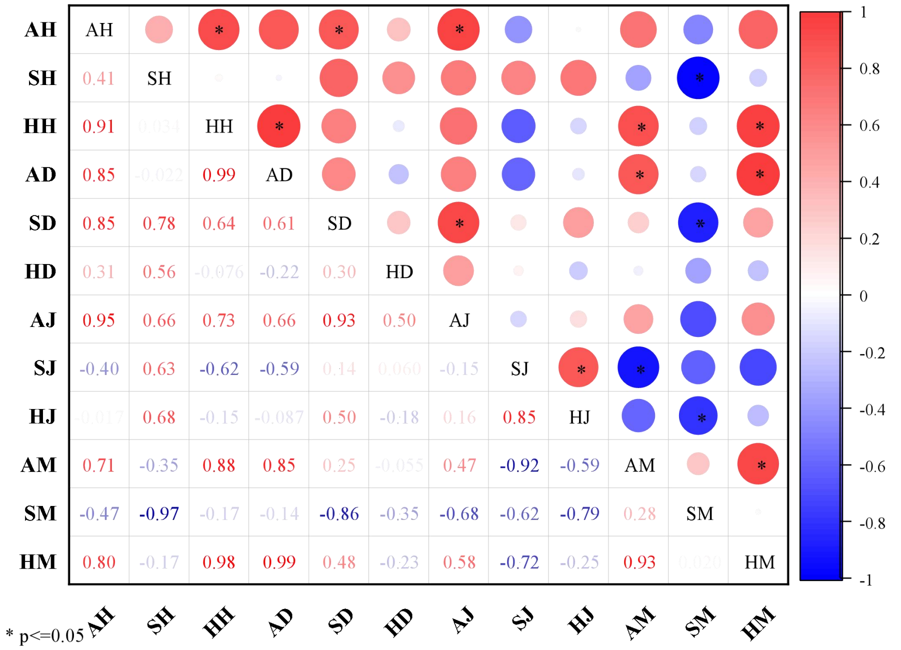
3.3 Coupling relationship between plant diversity and soil properties

The correlation matrix and the corresponding significance level of the 4 plant diversity indexes in 3 different forest layers (arbor layer Shannon-Wiener index (AH), shrub layer Shannon-Wiener index (SH), herb layer Shannon-Wiener index (HH), arbor layer Simpson index (AD), shrub layer Simpson index (SD), herb layer Simpson index (HD), arbor layer Pielou index (AJ), shrub layer Pielou index (SJ), herb layer Pielou index (HJ), arbor layer Margalef index (AM),shrub layer Margalef index (SM), herb layer Margalef index (HM)) were shown in **Fig. 7**. For Shannon-Wiener index, AH had a significant positive relationship with HH ($R^2 = 0.91$, $P < 0.05$), while AH and SH, HH and SH had no significant correlation ($R^2 = 0.41$, $P > 0.05$; $R^2 = 0$, $P > 0.05$, respectively). For Simpson index, there was significant positive relationship between AD and HD ($R^2 = 0.61$, $P < 0.05$), while AD and HD, SD and HD had no significant correlation ($R^2 = -0.22$, $P > 0.05$; $R^2 = 0.33$, $P > 0.05$, respectively). For Pielou index, there was no significant correlation between AJ and HJ, SJ and HJ ($R^2 = 0.16$, $P > 0.05$; $R^2 = -0.15$, $P > 0.05$, respectively), SJ had a significant positive relationship with HJ ($R^2 = 0.85$, $P < 0.05$). For Margalef index, AM demonstrated a significant positive relationship with HM ($R^2 = 0.93$, $P < 0.05$), while AM and SM, HM and SM had no significant correlation ($R^2 = 0.28$, $P > 0.05$; $R^2 = 0$, $P > 0.05$, respectively). In order to eliminate redundancy, the significantly correlated indices in each plant diversity indexes were eliminated in this study. Finally, the HS, HH, AD, HD, AJ, SJ, SM, and AM were screened out.

Similarly, we analyzed the correlation and significance of main soil properties. It can be found from **Fig. 8** that in the soil physical properties, the mechanical composition were significantly correlated with each other, and the coefficient was more than 0.8 at the 0.01 significance level. SWC, SBD, and pH were not seen significant correlation in this study. For soil chemical properties, SOM, AK, AP and AN all had a significant positive relationship with each other. For soil microbial properties, there was positive significant correlation between MBC and MBN ($R^2 = 0.93$, $P < 0.01$). Finally, the six soil properties (Clay, SBD, SWC, pH, SOM, and MBC) were screened out.

We calculated the correlation coefficients between the remaining plant diversity indexes (HS, HH, AD, HD, AJ, SJ, SM, AM) and soil properties (Clay, SBD, SWC, pH, SOM, MBC) in different soil depths to reveal the effects of plant diversity on soil properties of ecological restoration area (**Fig. 9**). The SH and SJ had a negative relationship with clay, SOM, and MBC, but had a positive relationship with SBD. Meanwhile, the correlation coefficient had a decreased trend with the increase of soil depth. While the SM had a positive relationship with clay, SOM, and MBC. Especially, on the 0-10 cm soil layer, the correlation among SH, SJ, and SM, and clay, SWC, SOM, and MBC became more significant. It indicated that the Shannon-Wiener index, Pielou index, and Margalef index in shrub layer significantly affected the topsoil properties. AD and AM had a significant negative relationship with SWC and pH on 10-20 cm soil layer, and had a significant positive relationship with clay on the 0-30 cm soil layer. SBD was positively correlated with AJ while SOM showed a negative correlated with AJ on all the soil layers. This result indicated that the plant diversity indexes in arbor layer had great contribution to the soil properties. Under each soil depths, HH had a significant positive relationship with clay, while a negative correlation with SWC and pH. And there were significant negative correlations between the HD and the SOM. The above analysis results indicated that the plant diversity of all layers had a deep impact on soil properties.



	AH	SH	HH	AD	SD	HD	AJ	SJ	HJ	AM	SM	HM
AH	AH		*		*		*					
SH	0.41	SH									*	
HH	0.91	0.034	HH	*						*		*
AD	0.85	-0.022	0.99	AD						*		*
SD	0.85	0.78	0.64	0.61	SD		*				*	
HD	0.31	0.56	-0.076	-0.22	0.30	HD						
AJ	0.95	0.66	0.73	0.66	0.93	0.50	AJ					
SJ	-0.40	0.63	-0.62	-0.59	0.14	0.060	-0.15	SJ	*	*		
HJ	-0.017	0.68	-0.15	-0.087	0.50	-0.18	0.16	0.85	HJ		*	
AM	0.71	-0.35	0.88	0.85	0.25	-0.055	0.47	-0.92	-0.59	AM		*
SM	-0.47	-0.97	-0.17	-0.14	-0.86	-0.35	-0.68	-0.62	-0.79	0.28	SM	
HM	0.80	-0.17	0.98	0.99	0.48	-0.23	0.58	-0.72	-0.25	0.93	0.020	HM

Fig. 7 Correlation analysis of plant diversity indexes. AH: arbor layer Shannon-Wiener index, SH: shrub layer Shannon-Wiener index, HH: herb layer Shannon-Wiener index, AD:arbor layer Simpson index, SD: shrub layer Simpson index, HD: herb layer Simpson index, AJ: arbor layer Pielou index, SJ: shrub layer Pielou index, HJ: herb layer Pielou index, AM: arbor layer Margalef index, SM: shrub layer Margalef index, HM: herb layer Margalef index. *, significance at $P < 0.05$ level.

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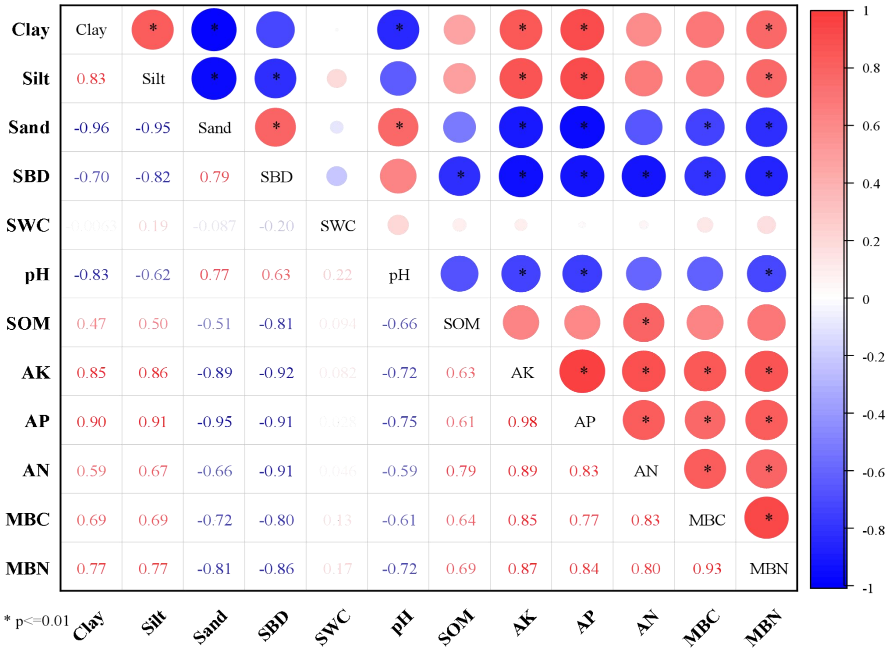

Fig. 8 Correlation analysis of main soil properties. Indicated values represent the correlation coefficients. The red color indicates a positive correlation, and the blue color indicates a negative correlation, *, significance at P < 0.01 level.

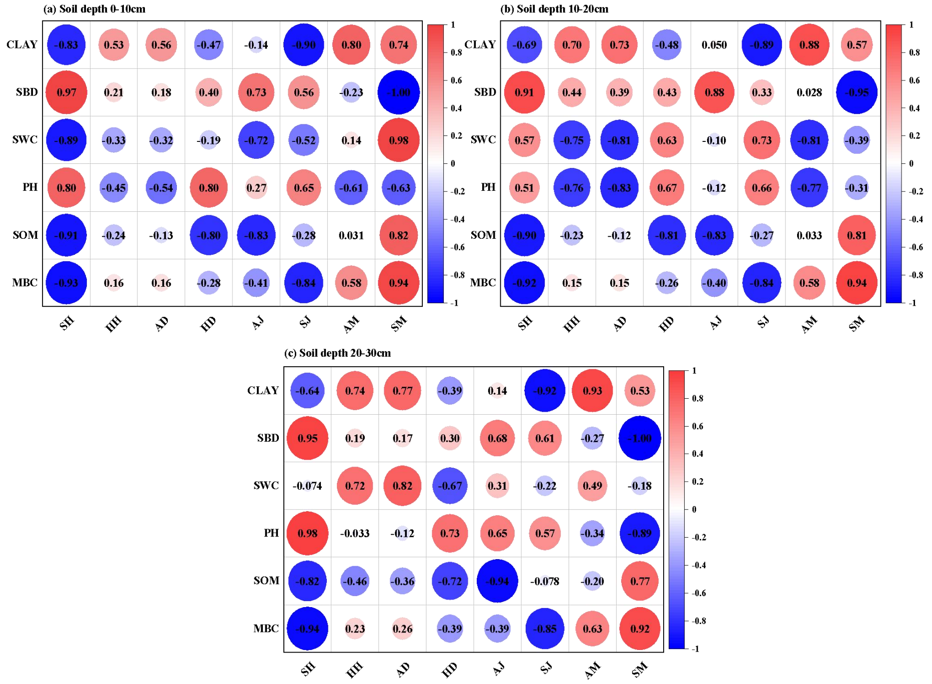

Fig. 9 Correlation coefficients between soil properties and plant diversity indexes of different ecological restoration patterns sites at different soil depth layers. (a) 0-10 cm soil layer; (b) 10-20 cm soil layer; (c) 20-30 cm soil layer.

In order to deeply discover how plant diversity and soil property affect plant community, RDA model was used to analyze the corresponding relationships of soil properties in different soil depth layers and plant diversity of all layers (**Fig. 10**, **Table 3**).. The results indicated that species composition was significantly affected soil properties on different soil depth layers. Clay, SOM, and MBC made a great contribution to the plant diversity. They were the most important explanatory variables in the RDA developed to explain plant diversity. In particular, Clay had substantially greater explanatory power for plant diversity than other soil properties, indicating that soil physical property mechanical composition can explain plant diversity patterns better.

Table 3 Soil properties explanatory variables and contributions to the vegetation composition.

Index	Soil depth (cm)	Explains %	Contribution %	F	P
Clay	0-10	26.6	58.1	13.7	0.002^{**}
	10-20	29.2	58.5	15.7	0.002^{**}
	20-30	25.2	54	12.8	0.002^{**}
SOM	0-10	11.5	25.2	6.9	0.002^{**}
	10-20	8.4	16.9	5	0.002^{**}
	20-30	8.5	18.3	4.8	0.002^{**}
MBC	0-10	4.1	8.9	2.5	0.044^{*}
	10-20	6.6	13.2	4.2	0.006^{**}
	20-30	6.7	14.3	4	0.01^{**}
pH	0-10	2.2	4.7	1.4	0.226
	10-20	3	6	2	0.084
	20-30	3.2	6.8	2	0.082
SBD	0-10	0.6	1.3	0.4	0.848
	10-20	1.7	3.5	1.1	0.322
	20-30	1.6	3.4	1	0.392
SWC	0-10	0.8	1.7	0.5	0.78
	10-20	1	2	0.7	0.616
	20-30	1.5	3.1	0.9	0.45

Notes, $^{**}P < 0.01$

$^{*}P < 0.05$

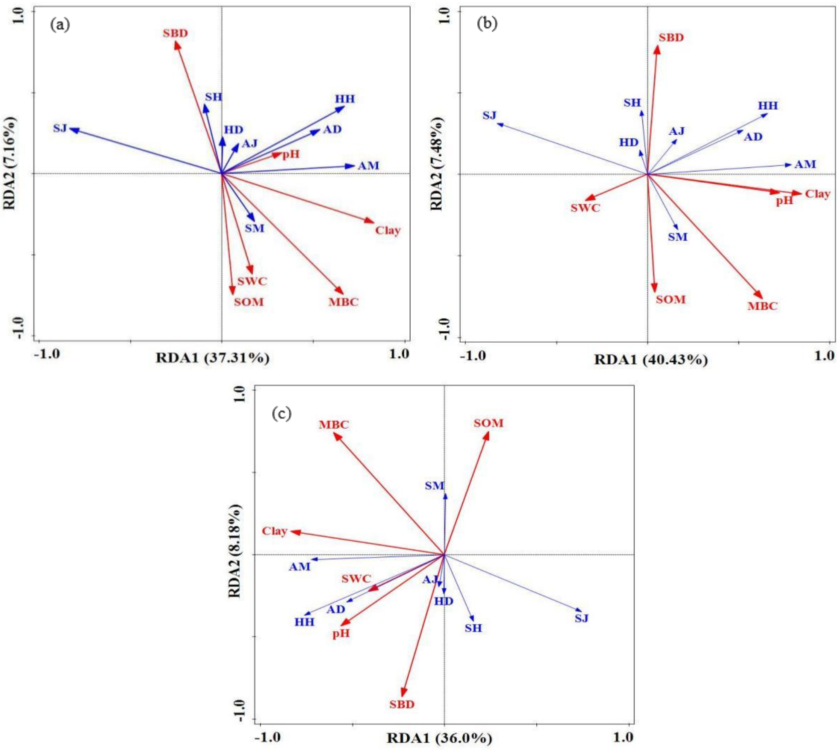

Fig. 10 Redundancy analysis of soil l properties and plant diversity indexes of tree, shrub and herb layers at at different soil depth layers. (a) 0-10 cm soil layer; (b) 10-20 cm soil layer; (c) 20-30 cm soil layer.

4 Discussion

4.1 Plant diversity in different ecological restoration patterns

The improvement of the ecosystem services and functions can be reflected through the changes in plant diversity (Xu et al., 2022b). Furthermore, the plant diversity index H, D, J, and M could quantification the plant community composition and diversity (Zhu et al., 2017). In this study, the plant diversity index H, D, J, and M in the different ecological restoration patterns were gradually close to the NA site, indicating that re-vegetation is beneficial to reestablish plant community and restore plant diversity in abandoned mines, which was similar to other studies (Zhang et al., 2023). However, high plant diversity index did not mean stable community (Wang et al., 2019). Compared to the M, D and H (Jiang et al., 2022; Wang et al., 2019), the J

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in the plant communities can also help maintain the community stability (Zhang et al., 2023). In this study, the plant diversity index M, D and H were higher in the NR site than those in other sites. The PSR site showed similar plant diversity index with NA site and lower than NR site (**Fig. 2**), which indicated that although the plant diversity was lower, the the community structure was more stable (Thomas S et al., 2007). The *Pinus massoniana* was native dominant economic forest in south China, and was often used in vegetation ecological restoration projects in post-mining areas due to the characteristics of evergreen (Zhao et al., 2021). Re-vegetation in abandoned area using *Pinus massoniana* mixed with other plant species was more conducive to improve soil properties and structure (Dou et al., 2013; Wang et al., 2023). In this study, the plant diversity index (**Fig. 2**) in PSR site which was re-vegetation by *Pinus massoniana* mixed with *Schima superba gardn*, was much higher than the re-vegetation only by *Pinus massoniana* in PR site, indicating that ecological restoration patterns of mixed vegetation was more effective in promoting the re-vegetation process of plant diversity. The results also indicated that for the abandoned coal mine area vegetation ecological restoration, planting dominant plants mixed with other vegetation was a suitable measure to efficiently rebuilt ecological functions in abandoned coal mine area. Therefore, identification of dominant plants in re-vegetation is of great importance for the species selection in abandoned coal mine area.

4.2 Soil properties in different ecological restoration patterns

The vegetation restoration was a effective measurement in improvement of soil properties and had a significant effect in the ecological restoration of abandoned coal mine areas (Bi et al., 2021). In this study, soil properties in most of study sites were significantly improved, indicating that soil nutrient content improved significantly with the process of vegetation restoration (Deng et al., 2018a). The changes in plant diversity resulted in the efficient utilization of soil nutrients, and increased soil productivity (Deng et al., 2018b; Wu et al., 2020a). Furthermore, different vegetation types can affect soil properties through the nutrient release of litter and plant roots, therefore had significant differences in soil quality (Danise et al., 2021; Yu et al., 2018). In this study, significant change was also observed in soil mechanical composition. In the NSR site, the clay and sand contents were higher than those in PR and NR sites (**Fig. 3**), but the silt was lower, indicating that mixed vegetation restoration can improve soil particles and prevent the loss of soil nutrients (Gao and Huang, 2020). SBD played an important role in soil development by affecting water infiltration, plant growth, and nutrient utilization (Mora and Lázaro, 2014; Salazar et al., 2009). In this study, PSR and NA sites showed lower SBD than other sites, and with the increase of soil depth, SBD had a increase trend (**Fig. 4**). The lower SBD mainly due to the growth of plant root systems can help to improve the compactness of soil (Yan et al., 2019), and the decomposition of litter improve the topsoil structure (Freschet et al., 2013). Meanwhile, the soil pH in PR and PSR sites was significantly lower than that in other sites. This is because the increase of organic acid produced by the the decomposition of conifer litter from *Pinus massoniana* (Vittori Antisari et al., 2011). The lower pH and SBD in restoration area could in turn accelerated vegetation succession.

Studies have reported that SOM was the basis for other soil properties, and vegetation restoration can promote the SOM input and significantly improve the soil nutrient availability (Bakker et al., 2019; Deng et al., 2017; Jia et al., 2017). In PSR site, SOM was significantly higher than that of PR and NR sites, indicating slow decomposition of litter and absorption of soil nutrient of *Pinus massoniana* needles (Ali et al., 2019; Chen and Cao, 2014). The plant root exudate and litter provided carbon sources to soil, and with vegetation succession, the plant root exudate and litter can promote the increase of SOM (Bu et al., 2018; Zhu et al., 2010). Therefore, in the *Pinus massoniana* restoration area, the withered pine needles covered on the surface soil layer caused litter decomposition slowly, and thus *Pinus massoniana* species restoration should mix with broad-leaved species. Our results also showed that in the vertical soil profile of different study sites, the SOM in the topsoil was significantly higher than that on other soil layers (**Fig. 5**), because of the promotion of nutrient absorption of the dense roots on soil surface (Liu et al., 2020). In our study,

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the SWC in NR site was lower than that of other sites because of the lower SOM. High SOM was conductive to improve SWC, because SOM can improve plant root growth and water absorption, therefore enhance water retention (de Oliveira Garcia et al., 2018). SWC and soil nutrients were important indicators in evaluating the effects of vegetation restoration and soil quality (Liu et al., 2022). Studies have shown that the SOM played an important role in AN and AP, because SOM increased soil microbial activity, and enhanced soil nitrogen (N) and phosphorus (P) mineralization (Chen et al., 2019). Our results showed that in the vertical soil profile of different study sites, AK, AN, and AP had a downward trend (**Fig. 5**), this is probably because of soil leaching characteristics and changes in the soil microbial and biomass (Zhao et al., 2022a). In addition, deeper soil obtains limited nutrients from the decomposition of litter, resulting in higher nutrients in topsoil layer (Zhao et al., 2022b).

Soil microbial biomass mainly include MBC and MBN, which can impact the cycling of SOM and soil nutrients (Yang et al., 2010). Our results showed that the MBC and the MBN in PSR site were significantly higher than that in PR and NR sites (**Fig. 6**). Compared to the *Pinus massoniana* forest, *Pinus massoniana* species mixed with broad-leaved species forest decomposed litter more effectively, and had higher effectiveness of microbial substrate. Furthermore, there was more supported microbial groups and quantities in the *Pinus massoniana* species mixed with broad-leaved species forest than *Pinus massoniana* forest, resulted in lower MBC and MBN contents in the PR site.

4.3 Coupling relationship between plant diversity and soil properties

It was well known that plant diversity was strongly related to soil properties, which can determine the distribution of plant species (Wang et al., 2018). Our results indicated that the relationship between plant diversity and soil properties in different layers was significant, and the correlation trend on 10-20 cm soil layer was stronger than that on other layers (**Fig. 9**). The main reason was that the litter decomposition and roots activity provided nutrients, soil-vegetation ecosystem had feedback mechanisms between soil and vegetation, and they can interact with each other (Li et al., 2021). SOM was an important factor in plant diversity to sustain the function of plant growth (Kooch et al., 2020). In this study, SOM was negatively correlated with the Shannon-Wiener index, Simpson index, and Pielou index but negatively correlated with Margalef index. On one hand, under the condition of poor soil nutrients, vegetation improved the growth through the increase of water availability and degree of mineralization, while sufficient soil nutrients can also improve the growth of vegetation (Petersen et al., 2015). On the other, the soil microbial activity can promote SOM accumulation, resulted in increased plant pathogen attack, deterioration plant living environment (Bongiorno et al., 2019; Hagen-Thorn et al., 2004). Therefore, only optimum soil nutrient conditions can improve plant diversity. Our results indicated that SBD was positively correlated with the Shannon-Wiener index, Simpson index, and Pielou index but negatively correlated with Margalef index, while SWC was positively correlated with plant diversity in the surface soil layer, indicating that SBD was significantly affect the plant diversity. SBD and SWC played an important role in soil hydrological processes (Katherine et al., 2010), and affected the geochemical cycle of plants and microorganisms (Vereecken et al., 2014). Studies have reported that soil pH decrease resulted in the degradation of plant diversity (Xu et al., 2022a; Xue et al., 2019). However, although the decrease of soil pH had a negative effect on plant growth, it provided more space for increasing plant diversity (Zhao et al., 2022b). This indicated that species composition led to changes in community environment, resulted in complex interaction among plant and soil and resources for plant growth, which might diminish the importance of soil properties on plant diversity (Härdtle et al., 2003; Pérez-Bejarano et al., 2008). Therefore, the plant growth in abandoned coal mine was not only a process of plant adaptation to soil nutrients, but also the interaction of plant growth and soil properties. In summary, mixed coniferous with broad-leaved forests can improve SBD and SWC better, and is beneficial to improve soil nutrient conditions, which plays an important role in the enhancement of soil ecosystem functions in abandoned coal mine area.

Based on the current situation of China, ecological restoration such as planting trees, tillage or grass on rights sites should be a good choice for abandoned mines restoration. The goal of ecological restoration in abandoned coal mine area was to create an healthy ecosystem of harmonious coexistence between human and nature. Therefore, a vegetation configuration that mixed coniferous and broad-leaved vegetation was worthy of consideration. This is not only beneficial to improve soil properties, but also increases plant diversity and enhance soil ecosystem functions.

5 Conclusion

The ecological restoration of abandoned mining area should pay attention to the enhancement of soil ecosystem functions and achieving sustainable development. The vegetation configuration of ecological restoration plays a crucial role in accomplishing these goals. Our study showed that 1) there was significant differences in plant diversity and ecological restoration patterns. The PSR site had higher Shannon-Wiener index and Simpson index values than PR site did, and the plant diversity of herb layer was significantly improved than that of the arbor and shrub layers. The plant diversity was slightly higher in the NR and NA site than those of PR and PSR sites. 2) Ecological restoration patterns had a significant effect on the soil properties, and SBD, SWC, SOM, and MBC also significantly affected plant diversity. 3) Identification of dominant plants in re-vegetation is of great importance for the species selection in abandoned coal mine area. 4) It was recommend that vegetation configuration was of great significance in improving soil properties and increasing plant diversity, vegetation restoration of mixed coniferous with broad-leaved forests should be paid enough attention to abandoned coal mines ecological restoration.

Declaration of competing interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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Author contribution:

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Data Availability Statement

The data presented in this study are available in this manuscript.

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