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Evaluation of coupling coordination relationship between different habitat materials and vegetation system in the engineering disturbed area

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In order to explore the coupling coordination relationship between habitat materials and vegetation system in the engineering disturbed area, six different vegetation restoration patterns in Xiangjiaba engineering disturbed region were utilized as research objects. An evaluation system of 14 habitat materials indicators and 10 vegetation indicators was established. The weight of each indicator was determined by Principal Component Analysis (PCA), and the interrelationship between habitat material and vegetation system was investigated using the Partial Least Square Path model (PLS-PM). Finally, a model for the degree of coupling coordination between habitat materials and vegetation system under different vegetation restoration modes was constructed. The results showed that: 1) habitat materials and vegetation system are closely related, and the habitat materials have a stronger impact on ecosystem restoration. Artificial vegetation restoration technologies can effectively improve soil conditions in engineering disturbed areas, allowing for vegetation restoration in a healthy environment. 2) Under different vegetation restoration patterns, the habitat materials and vegetation coupling coordination index of natural forest plots, frame beam filling soil plots, thick layer base material spraying plots, guest external soil spray seeding plots, vegetation concrete plots, and abandon slag slope plots was 0.767, 0.673, 0.669, 0.625, 0.557, and 0.400, respectively. The development of habitat materials and vegetation in guest external soil spray seeding plots was of a synchronous type. The vegetation development lagged behind habitat materials in thick layer base material spraying plots, vegetation concrete plots, and abandon slag slope plots, while habitat materials lagged behind vegetation development in natural forest plots, frame beam filling soil plots. The model for the degree of coupling coordination between habitat materials and vegetation constructed in this study can serve as a scientific reference for evaluating the impact of ecological restoration engineering in other similar projects.

KEYWORDS

engineering disturbance area, habitat materials and vegetation system, coupling coordination, evaluation model, ecological restoration

Introduction

The Chinese infrastructure industry is experiencing rapid growth. Engineering construction alters the surface structure on a massive scale and causes vegetation damage, causing the environment to be severely disrupted (Chen et al., 2019; Cui et al., 2020; Bai et al., 2021; Kong D. L. et al., 2021). In this context, vegetation ecological restoration technology arose, combining the safety of traditional slope treatment methods with vegetation reconstruction ecology. It has since become widely utilized and developed (Yang et al., 2015; Zhao et al., 2017). In vegetation ecological restoration techniques, habitat materials are employed to form a soil environment that is favorable for the growth of plants. The characteristics and succession process of vegetation communities, soil quality of habitat materials often have a direct impact on its benefits after the adoption of vegetation ecological restoration technique (Zhou et al., 2017; Bai et al., 2020). Meanwhile, vegetation and habitat materials interact with each other, as vegetation needs the soil of habitat materials for growth and soil fertility of habitat materials is also changed by vegetation. Therefore, the focus of research for vegetation restoration has shifted from soil quality assessments of habitat materials and simple vegetation diversity alone to the investigation of the vegetation-soil system coupling relationship (Jiang et al., 2010; Du et al., 2013; Bai et al., 2019; Cui et al., 2022).

Yan et al., applied the “spatio-temporal substitution approach” to investigate the law of synergistic succession of vegetation and soil in sample plots with different vegetation restoration patterns. In this field, it has been discovered that soil bulk density, organic matter, and water content could be employed as characteristic indexes of soil development, and various vegetation metrics revealed different synergistic laws in vegetation community succession and soil formation (Yan 2012). Xue et al., constructed a vegetation-soil coupling model for multiple highway slope protection modes based on grey correlation degree. The findings demonstrated that soil physical and chemical parameters accounted for the most variation in vegetation. The soil slope has a higher coupling coordination degree than the rock slope (Xue et al., 2016). Yin et al., discovered various degrees of correlation between different vegetation types and soil properties, and there was a substantial correlation between species diversity of herbaceous plants and soil water content, phosphatase activity, and protease activity. While there was a substantial correlation between species diversity of woody plants and soil total phosphorus level and protease activity. We should pay attention to dynamic changes in the vegetation regeneration of rock slopes and Proposing control methods (Yin et al., 2012). Through research of the relationship between vegetation and soil features in 20 typical slope protection plots, Zhang et al. discovered that the vegetation restoration effect of soil slopes and the coordinated development between vegetation and soil are both better than those of rock slopes (Zhang H. F. et al., 2013). It is clear that vegetation and soil have a complicated and nonlinear dynamic coupling connection, and the interaction and organic combination of the vegetation system and the soil system results in the establishment of a sustainable vegetation restoration system (Wang et al., 2021; Jiao et al., 2005; Zhou et al., 2016). Due to the clear spatial heterogeneity of vegetation and soil features, the investigation of the soil-vegetation coupling connection of vegetation restoration in a specific area is the premise and basis for the evaluation and regulation guidance of targeted vegetation restoration effects.

The vegetation system and habitat materials system are important subsystems in vegetation ecological restoration, and their coupling and coordination directly affect the effect of vegetation ecological restoration. The soil quality of the habitat materials and vegetation restoration have received the majority of attention in recent years in academic studies on the ecological environment of Xiangjiaba Hydropower Station, but there has been a dearth of research on the coupling relationship between habitat materials and vegetation system (Zeng et al., 2009; Zhao et al., 2020). As a result, this paper takes representative sample plots under different vegetation restoration patterns in the disturbed area of Xiangjiaba Hydropower Station as the research object, and the vegetation-soil coupling coordination model is constructed based on the systematic analysis of vegetation and soil characteristics under different vegetation restoration models, combined with the coupling coordination degree correction model. The goal of this study is to provide a scientific reference for revealing the interaction between habitat materials and vegetation in a disturbed area, as well as a theoretical foundation for enhancing the scientific management level of similar vegetation ecological restoration projects.

Materials and methods

Overview of the research area

The right bank of the dam site of Xiangjiaba Hydropower Station is located in Shuifu County, Yunnan Province, and the

TABLE 1 Basic situation of sample plots.

Sample	Dominant species	Geographic coordinates	Altitude (m)	Slope (°)	Slope property	Vegetation restoration time
A1	*Pennisetum alopecuroides (L.) Spreng*	N28°38′15.75″ E104°24′51.74″	328.5	63	Excavated slope	2004.12
A2	*Imperata cylindrica (L.) Beauv*	N28°38′23.65″ E104°24′42.08″	288.9	40	Abandoned slag slope	2004.11
A3	*Leucaena leucocephala (Lam.) de Wit*	N28°38′21.99″ E104°26′16.22″	388.9	51	Excavated slope	2004.12
A4	*Lagerstroemia indica L*	N28°39′00.30″ E104°23′40.28″	473.9	30	Excavated slope	2005.06
A5	*Setaria viridis (L.) Beauv*	N28°38′59.45″ E104°24′10.14″	520.5	42	Abandoned slag slope	
A6	*Alnus cremastogyne Burk*	N28°39′07.14″ E104°23′38.82″	502.4	45		

left bank is located in Yibin County, Sichuan Province. It has a subtropical monsoon climate with an average annual temperature of 18°C. The reservoir region and adjacent counties have a maximum frost-free duration of 320 days and a minimum of 266 days. The annual average precipitation is 1030.5 mm, the annual average evaporation is 1001.1 mm, and the relative humidity ranges from 74% to 83%. In the project region, the soil layer is generally thin, the texture is harsh, and the organic matter level is low. Soil erosion is particularly severe in the project location, which is a crucial erosion control area in the Yangtze River's upper reaches. The slope area of the real construction disturbance area accounts for more than 50 percent of the overall construction area at Xiangjiaba Hydropower Station. The disturbed area's slope vegetation types include primarily shrubs and grasses, with more dryland agriculture vegetation, artificial greening ornamental vegetation, and commercial fruit trees, and less forest vegetation (Ye, 2016; Xu et al., 2017).

In the disturbed area of the Xiangjiaba Hydropower Station project, different vegetation restoration method sample plots were selected for vegetation survey and soil sampling. This survey included six sample plots: vegetation concrete plots (A1), frame beam filling soil plots (A2), thick layer base material spraying plots (A3), guest external soil spray seeding plots (A4), abandon slag slope plots (A5), and natural forest plots (A6). The project's disturbed area was mostly formed in 2004, and the artificial vegetation restoration patterns were mostly implemented between November 2004 and June 2005. To avoid the effects of rainfall and other climatic conditions on soil parameters, the sampling period should include at least 1 week without rain, and the sampling work should be performed during that time. Table 1 depicts the basic circumstances of each plot.

Investigation and analysis of vegetation

The vegetation community study was conducted in all plots using a combination of field survey and quadrat sampling method. According to the type of vegetation, 5 m × 5 m quadrats of tree and shrub layer or 1 m × 1 m quadrats of herb layer was built up in each sample plot, and the sample was repeated 5 times (Zhang and Shangguan, 2016). The total vegetation coverage, plant name, split coverage, average height, number of plants were recorded, and the species diversity index, richness index, and evenness index were calculated by the following equation in Table 2 (Xia 2010).

Collection and analysis of soil samples

Three soil repeated sampling plots were set up in each sample plot at the same time as the vegetation research, and soil samples were collected by circular knife method and bisect method. Because the overlaying soil layer in the vegetation restoration sample was roughly 10 cm thick, soils within 0–10 cm of the soil surface layer were obtained from each plot, sealed, and returned to the laboratory after debris removal (Li et al., 2018). Each soil sample was split into two parts: one was air-dried, crushed, and screened (2 mm pore size) for physical and chemical analysis, while the other was kept fresh in a refrigerator at 4°C as soon as feasible for biological features examination.

Physical and chemical indicators of habitat materials mainly include

Water content, organic matter, available nitrogen, total phosphorus, accessible phosphorus, and available potassium. The drying method was used to measure water content, the potassium dichromate volumetric method was used to estimate

TABLE 2 Formula used to calculate vegetation community diversity index.

Vegetation community diversity index		Formula
The species diversity index of vegetation community	*Shannon-Wiener* diversity index (*SW*)	$SW = -\sum_{i=1}^{S} P_i \ln P_i$
	Simpson diversity index (*SP*)	$SP = 1 - \sum_{i=1}^{S} (P_i)^2$
	McIntosh diversity index (*MI*)	$MI = \frac{N - \sqrt{\sum_{i=1}^{S} (N_i)^2}}{N - \sqrt{N}}$
The species richness index of vegetation community	*Margalef* richness index (*MA*)	$MA = (S - 1)/\ln N$
	Menhinick richness index (*ME*)	$ME = S/\sqrt{N}$
	Monk richness index (*MO*)	$MO = S/N$
The species evenness index of vegetation community	*Pielou* evenness index (J_{SW})	$J_{SW} = SW/\ln S$
	Alatato evenness index (J_A)	$J_A = \frac{(\sum_{i=1}^{S} (P_i)^2) - 1}{exp(SW) - 1}$
	Simpson evenness index (J_S)	$J_S = \frac{SP}{1 - 1/S}$

organic matter. The available nitrogen, total phosphorus, available phosphorus, and available potassium were determined by Spectrophotometer method based on the modified Berthelot reaction with an Skalar San++ continuously flowing autoanalyzer (Bao 2000; Chen 2005; Zhang et al., 2006; Zhang 2007; Zhang, 2011).

Biological indicators of habitat materials mainly include

Urease, neutral phosphatase, sucrase, polyphenol oxidase, microbial biomass nitrogen, microbial biomass phosphorus, and microbial diversity. The indophenol colorimetry method was used to measure urease, while the disodium phenyl phosphate method was used to determine neutral phosphatase, sucrase was determined by DNS (3,5-dinitrosalicylic acid) method, and polyphenol oxidase was determined by pyrogallol colorimetry. The chloroform fumigation method was used to evaluate the nitrogen, and phosphorus content of microbial biomass (Shen 1998; Chen 2005). The average color change rate per well (AWCD) was utilized to reflect the metabolic level of microorganisms to a single carbon source, and the BIOLOG-ECO microplate method was employed to quantify microbial diversity. 10 sugars, 7 carboxylic acids, 6 amino acids, 4 poly polymers, 2 phenols, and 2 amines are among the carbon sources of BIOLOG-ECO microplates employed in this work, for a total of 31 carbon sources (Choi and Dobbs 1999; Zhang W. et al., 2013; Xiang et al., 2014).

Coupling model construction

Highly sensitive evaluation index reflecting the effect of vegetation restoration in the Xiangjiaba Project's affected region was developed. The vegetation integrated subsystem includes 10 indicators such as vegetation coverage (CO), Species diversity index [*Shannon-Wiener* diversity index (*SW*), *McIntosh* diversity index (*MI*), and *Simpson* diversity index (*SP*)], richness index [*Margalef* richness index (*MA*), *Menhinick* richness index (*ME*), and *Monk* richness index (*MO*)], and evenness index (*Simpson* evenness index (J_S), *Pielou* evenness index (J_{SW}) and *Alatato* evenness index (J_A). The habitat materials integrated subsystem includes 14 indicators such as water content (WAT), organic matter (SOM), available nitrogen (AN), total phosphorus (TP), available phosphorus (AP), available potassium (AK), urease (URE), neutral phosphatase (NEP), sucrase (INV), polyphenoloxidase (PPO), microbial biomass nitrogen (MBN), microbial biomass phosphorus (MBP), microbial entropy (qMBC), AWCD. Because different indexes have varying dimensions and magnitudes, the range standardization method is used to standardize the data, and the principal component analysis method is utilized to estimate each index's weight (Xie et al., 2017; Zheng and Yang, 2022). Figure 1 depicts the weight findings for each index.

The coupling degree (C) is a useful metric to qualitatively evaluate the degree of interaction between systems or elements. Other domestic researchers have conducted extensive research on coupling degree, believing that the value of coupling degree is 0–1, with the value being closer to 1 when the coordination among the system's elements is stronger and closer to 0 when the coordination is weaker (Peng et al., 2011; Zhang H. F. et al., 2013; Zhang Y. et al., 2013; Luo et al., 2018; Li et al., 2019). The coupling degree can only represent the strength and size of the system's interaction, and it can't fully reflect the overall synergistic effect between systems or between elements within the system. A habitat materials and vegetation system coupling coordination model after vegetation restoration in the disturbed area of Xiangjiaba Project was constructed with reference to the coupling model in physics and Wang Shujia's

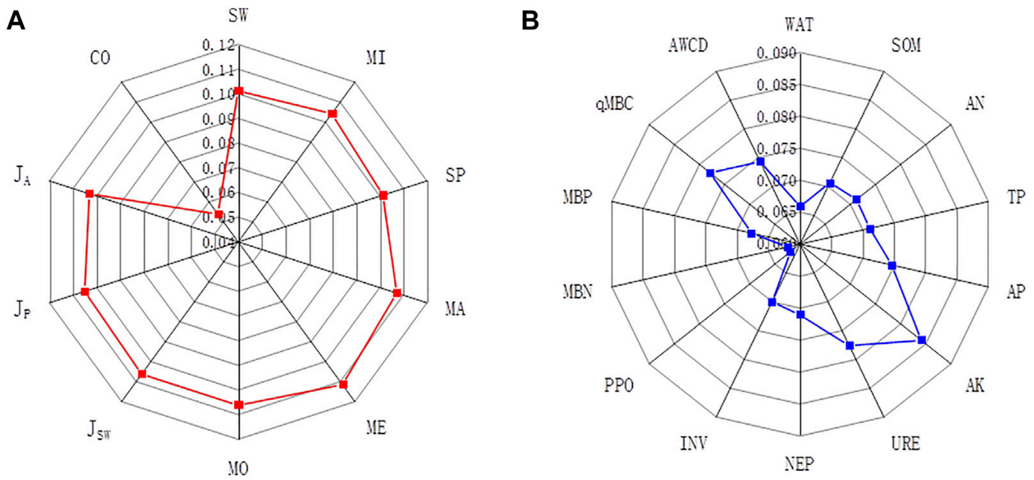

FIGURE 1
Radar map of coupling coordination index and weight between vegetation system **(A)** and soil system **(B)**.

modification of the domestic coupling model in order to more objectively and accurately reflect the coupling and coordination relationship between habitat materials and vegetation system in the process of vegetation restoration in the study area (Liu and Song 2005; Wang et al., 2021). The following is the calculating formula:

$$C = \frac{2\sqrt{\delta}}{1+\delta} \quad (2-1)$$

$$\delta = \frac{min[S(x), P(x)]}{max[S(x), P(x)]} \subset [0, 1] \quad (2-2)$$

$$P(x) = \sum_{i=1}^{p} a_i x_i \quad (2-3)$$

$$\mathrm{S}(\mathrm{x}) = \sum_{j=1}^{q} b_j x_j \quad (2-4)$$

In the formula: C is the coupling degree of the habitat materials and vegetation system, $0 \le C \le 1$. a_i and b_j are the weights of the i habitat material indicator and j vegetation indicator, x_i and x_j are the standardized values of the i habitat material indicator and j vegetation indicator, *S(x)* is the habitat materials comprehensive evaluation function, and *P(x)* is the vegetation comprehensive evaluation function. The coupling coordination degree of the habitat materials and vegetation system was evaluated in order to further evaluate the overall "synergistic" effect of habitat materials and vegetation subsystems in the evaluation of ecological restoration effect, and to avoid the error caused by only relying on the evaluation of coupling degree. The following is the calculating formula:

$$C_d = \sqrt{C \times T} \quad (2-5)$$

$$T = \alpha S(x) + \beta P(x) \quad (2-6)$$

In the formula: C_d is the coupling coordination degree of habitat materials and vegetation system, $0 \le C_d \le 1$. The closer the C_d value is to 1, the closer it is to the high-quality coupling coordination state between habitat materials and vegetation system; T is the comprehensive coordination index of habitat materials and vegetation system; α and β are the contribution rates of habitat materials and vegetation subsystems. In the process of vegetation restoration in the disturbed area, habitat materials and vegetation subsystems influence and depend on each other, and the importance coefficients of ecological restoration are the same for both, so α and β take the average value of 0.5.

If *P(x)/S(x)* is greater than 1, the growth and development of vegetation is faster than that of habitat material; if *P(x)/S(x)* is less than 1, the growth and development of vegetation is slower than that of habitat material, and vegetation does not make full use of habitat materials fertility resources; and the closer the ratio is to 1, the more synchronous and coordinated the succession between them tends to develop (Luo et al., 2018). In summary, the coordinated evaluation criteria of habitat materials and vegetation system coupling for ecological restoration in the disturbed area of Xiangjiaba project are established as shown in Table 3.

Data processing and analysis

The data were subjected to a general statistical analysis using the programs SPSS and Excel, which were created by IBM Corporation and Microsoft Corporation, respectively. SmartPLS and RStudio tools, created by SmartPLS GmbH and RStudio, respectively, were used to analyze the partial least

TABLE 3 Classification of habitat materials and vegetation system coupling coordination types.

Habitat materials and vegetation system coupling coordination degree	Coordination state	$P(x)/S(x)$	Coupling coordination type
$0.00 < Cd \le 0.20$	Low-level coordination (LC)	$P(x)/S(x) > 1.2$	LC- habitat materials lag
		$0.8 \le P(x)/S(x) \le 1.2$	LC- habitat materials and vegetation system balance
		$P(x)/S(x) < 0.8$	LC-Vegetation lag
$0.20 < Cd \le 0.40$	Primary coordination (PC)	$P(x)/S(x) > 1.2$	PC- habitat materials lag
		$0.8 \le P(x)/S(x) \le 1.2$	PC- habitat materials and vegetation system balance
		$P(x)/S(x) < 0.8$	PC-Vegetation lag
$0.40 < Cd \le 0.60$	Intermediate coordination (IC)	$P(x)/S(x) > 1.2$	IC- habitat materials lag
		$0.8 \le P(x)/S(x) \le 1.2$	IC- habitat materials and vegetation system balance
		$P(x)/S(x) < 0.8$	IC-Vegetation lag
$0.60 < Cd \le 0.80$	Advanced coordination (AC)	$P(x)/S(x) > 1.2$	AC- habitat materials lag
		$0.8 \le P(x)/S(x) \le 1.2$	AC- habitat materials and vegetation system balance
		$P(x)/S(x) < 0.8$	AC-Vegetation lag
$0.80 < Cd \le 1.0$	Superior coordination (SC)	$P(x)/S(x) > 1.2$	SC- habitat materials lag
		$0.8 \le P(x)/S(x) \le 1.2$	SC- habitat materials and vegetation system balance
		$P(x)/S(x) < 0.8$	SC-Vegetation lag

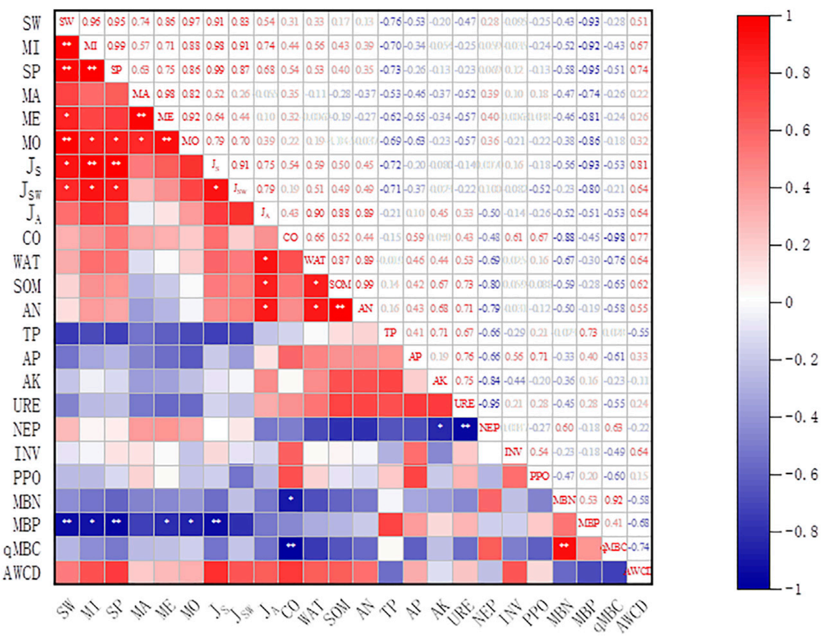

FIGURE 2
Correlation between indicators of habitat materials and vegetation system under different vegetation restoration models. Notes: * indicates significant correlation ($p < 0.05$), and ** indicates highly significant correlation ($p < 0.01$).

square path model (PLS-PM). SmartPLS and SPSS were used to evaluate the relationships between the indicators; Origin was used to depict the relationships between the vegetation and soil systems; and Canoco was used to process the weights between the indicators and the BIOLOG data using Principal Component Analysis (PCA). Software called Origin and Canoco were created by OriginLab Inc. and Microcomputer Power Inc.

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TABLE 4 Coupling coordination of habitat materials and vegetation system in different areas.

Sample plot	*P(x)*	*S(x)*	*P(x)/S(x)*	*C*	C_d	Coupling coordination type
A1	0.1611	0.5981	0.2694	0.8177	0.5572	IC-Vegetation lag
A2	0.7101	0.2885	2.4614	0.9065	0.6728	AC- habitat materials lag
A3	0.3280	0.6092	0.5383	0.9539	0.6686	AC-Vegetation lag
A4	0.3572	0.4279	0.8346	0.9959	0.6253	AC- Vegetation and habitat materials balance
A5	0.0815	0.3129	0.2605	0.8099	0.3996	LC-Vegetation lag
A6	0.9028	0.3828	2.3586	0.9145	0.7667	AC- habitat materials lag

Results

Analysis of correlation between vegetation and habitat materials indicators

The examination of the correlation between the aforesaid indicators (Figure 2) revealed that the vegetation system and the habitat materials system had varying degrees of correlation discrepancies. Vegetation cover and microbial biomass carbon showed highly significant negative correlation, and it showed significant negative correlation with microbial biomass nitrogen. The water content, organic matter, and available nitrogen all demonstrated a strong positive association with Alatato evenness index. The microbial biomass phosphorus showed highly significant negative correlation with Shannon-Wiener diversity index, Simpson diversity index, Simpson evenness index, and it showed significant negative correlation with McIntosh diversity index, Menhinick richness index, and Monk richness index. Many indexes in the vegetation integrated subsystem had a substantial negative correlation with the level of microbial biomass phosphorus, indicating that improving the transformation ability of microorganisms to phosphorus would impede the development of vegetation community variety.

Analysis of habitat materials and vegetation system coupling coordination characteristics of different vegetation restoration patterns

The coupling coordination degree is a numerical index that describes the degree of interdependence between the system's constituents (Pu et al., 2021; Nan et al., 2021; Xu et al., 2016). The coupling coordination degree of habitat materials and vegetation system can scientifically and precisely depict the relative development levels and interactions of the two systems. In the disturbed area of the Xiangjiaba Project, the calculation results of habitat materials comprehensive evaluation index, vegetation comprehensive evaluation index, habitat materials and vegetation system coupling degree, and habitat materials and vegetation system coupling coordination degree of 6 different vegetation restoration models were shown in Table 4. The vegetation comprehensive assessment index was ranked A6 > A2 > A4 > A3 > A1 > A5, while the habitat materials comprehensive evaluation index was ranked A3 > A1 > A4 > A6 > A6 > A5 > A2. The coupling degree of habitat materials and vegetation system varied from 0.8099 to 0.9959, with A4 > A3 > A6 > A2 > A1 > A5 as the order of coupling degree. The change of coupling coordination degree was 0.3996–0.7667, with A6 > A2 > A3 > A4 > A1 > A5. The findings reveal that the comprehensive assessment index and coupling coordination features of habitat materials and vegetation system in the disturbed region change significantly with the difference in vegetation restoration model, and the overall coordination type is better than abandoned land.

Analysis on influencing factors of habitat materials and vegetation system coupling coordination

Partial least squares path model (PLS-PM) is a comprehensive analysis model for analyzing multivariable causal relationships. This model can not only handle the problem of indicator multicollinearity, but also calculate the direct and indirect effects of various variables on response variables. 25 observation variables were selected to construct PLS-PM in order to study the relationship between vegetation community characteristics and physical and chemical properties of habitat materials under different vegetation restoration patterns, as shown in Figure 3. The R^2 of the vegetation system is 0.832, the R^2 of the habitat materials system is 0.959, and the R^2 of the habitat materials and vegetation coupling coordination system is 0.838, all of which are more than 0.6 in the PLS-PM calculation. As a result, the dependent variables in this model are effectively explained by the independent variables. The number of external models loads of observed variables greater than 0.7 under each latent variable is 76%, which is within an acceptable range, indicating that the characteristic index used is appropriate for evaluating the habitat materials and vegetation system coupling coordination model

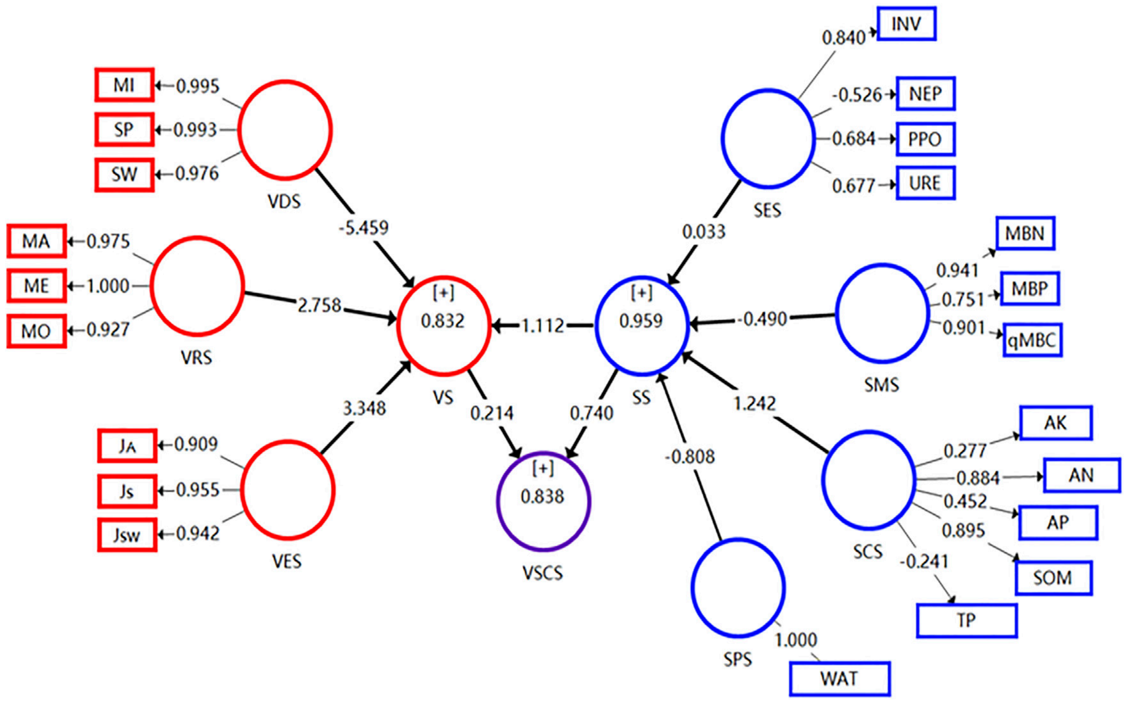

FIGURE 3
PLS-PM analysis map under different vegetation restoration models. Notes: VDS: vegetation diversity subsystem; VRS: vegetation richness subsystem; VES: vegetation uniformity subsystem; VS: total vegetation system; SS: habitat materials total system; SES: habitat materials enzyme subsystem; SMS: habitat materials microorganism subsystem; SCS: habitat materials chemistry subsystem; SPS: habitat materials physics subsystem; VSCS: habitat materials and vegetation system coupling coordination system.

(Qi and Kong 2017; Yang et al., 2017; Kim et al., 2021; Kong W. B. et al., 2021; Ma et al., 2021; Zhao et al., 2022).

When the vegetation system and the habitat materials system act on the coupling coordination system, the influence of the habitat materials system on the overall coupling coordination system was higher than that of the vegetation system, as determined by decomposing the direct effect, indirect effect, and total effect among the latent variables and analyzing the relationship between the latent variables and their influence on the habitat materials and vegetation system. The reason for the follow-up analysis could be that the vegetation in the disturbed area has been severely damaged, and the vegetation community has not evolved to the top community after some degree of ecological restoration, so the vegetation system's influence on the coupling coordination system is weaker than the habitat materials system's during the same time period.

The path coefficients of the habitat materials physics and chemistry subsystems were −0.808 and 1.242, respectively, both of which were greater than 0.7 and had a large direct influence on the habitat materials system, followed by the indirect coefficient of the habitat materials microorganism subsystem, which calculated as −0.490, and the path coefficient of the habitat materials enzyme subsystem was 0.033, which had the least direct effect on the habitat materials system. However, enzymes indirectly affect the habitat materials system throughout the ecological cycle by changing the transformation of nutrient content in habitat materials chemistry and habitat materials microbial indices. The content of microbial carbon, microbial nitrogen and microbial phosphorus can also indirectly reflect the nutrient content of the habitat materials. The path coefficients of the diversity subsystem, evenness subsystem, and richness subsystem in the vegetation system were −5.495, 3.348, and 2.758, respectively, all greater than 0.7, showing that they have a significant impact on the vegetation system. The diversity index, evenness index, and richness index are chosen to better intuitively describe the vegetative system. In the early stages of vegetation restoration, we should focus on factors that directly affect the habitat materials system, such as water content and available nutrients in habitat materials, while in the middle and later stages of vegetation restoration, we should focus on the content of enzymes and the influence of microbial carbon, microbial nitrogen and microbial phosphorus on the nutrient content of the habitat materials, in order to achieve better ecological restoration results.

Discussion

The structure and components of vegetation community will gradually become stable during the process of vegetation community succession due to intraspecific and interspecific competition (Zhang et al., 2015). Because they are not disturbed by external disturbances, natural forest plots are more likely to form a stable structure with trees and shrubs as dominating species in this study than other plots, which is consistent with He et al.'s studies on *southern hemlock* (He et al., 2010). The niche dynamics of a *Pinus massoniana* plantation were studied by Li et al.(2021) who found that as the community matures, the interaction among species becomes more stable, niche differentiation increases, the niche overlap index falls, and the struggle between species is waning. As a result, it is assumed that the intense succession stage in the early stage of vegetation development in natural forest sample plots has ended, and the succession trend has begun to slow down. However, the early succession stage consumes a lot of nutrients in the habitat materials and vegetation system, and the content of organic matter in the original soil in the Xiangjiaba area is generally low, and soil erosion in the project site is more serious, so the soil is difficult to work with. This is consistent with the results of Xu et al. on the current status of soil lag in *Caragana* and grassland ditches caused by intense succession (Xu et al., 2016).

The *P(x)* value of abandon slag slope was significantly lower than that of other plots, because the dominant species were mostly annual or perennial grass like *Setaria viridis (L.) Beauv*. after the primary stage of secondary succession, with a single vegetation type, low species richness, low utilization of habitat materials nutrients by vegetation, and an unstable community as a whole. Those indicated that the coupled habitat materials and vegetation system was in a weakened state and the vegetation lags behind, which is consistent with Jian et al.'s result on the quantitative classification and structure of grassland communities in small watersheds of the loess hilly region (Jian et al., 2022). Although the soil quality and vegetation coverage of the thick layer base material spraying plots were improved over the abandoned area, the *Medicago sativa L., Festuca elata Keng ex E. Alexeev,* and *Cynodon dactylon (L.) Pers.* sown in the early stages of restoration entirely withdrew from the succession sequence due to the invasion of *Leucaena leucocephala (Lam.)*. The important value of *Leucaena leucocephala (Lam.)* in the sample plot was 57.14%, which was significantly greater than that of other linked species, indicating that there was a single dominant population of *Leucaena leucocephala (Lam.)* (Zhao et al., 2021). The invasion of foreign species diminishes the complexity of the vegetation community structure, which is harmful to the ecological community's stability (Xia 2010). As a result, vegetation development continues to lag behind habitat materials.

Prior research on the early succession process and community stability on the disturbed slope of Xiangjiaba Hydropower Station discovered that the multi-level structure of tree, shrub, grass, and vine was beneficial to community stability (Xu et al., 2016). The vegetation communities of vegetation concrete technical plots and frame beam filling soil plots both evolved from the initial configuration of pure herbs to a multi-layer community structure of herb-shrub-vine combination after more than 10 years of succession, but the coupling state of habitat materials and vegetation system has changed. The frame beam filling soil plots used a lot of habitat materials nutrients in the early stages of community secondary succession, and the sampling period was concentrated in August during the summer, when the demand for habitat materials nutrients in the multi-level community of tree, shrub, herb and vine was significantly higher than other periods. Because the humus created by falling leaves and litter, as well as other nutrients given by the external environment, was less, the habitat materials system was generally barren at this time, causing the habitat materials system to lag behind. During the initial species allocation, the vegetation concrete plots added organic materials and organic fertilizers. Although habitat materials fertility was rapidly depleted during the early stages of vegetation succession, there is still a surplus in the overall fertility following the establishment of a stable structure, indicating that the sample plot is experiencing vegetation lag (Xia 2010). The original establishment of the vegetation community in the guest external soil spray seeding plots was still dominated by *Lagerstroemia indica L.* after a period of secondary succession, while the *Cynodon dactylon (L.) Pers.* was completely destroyed. In comparison to other restoration models, the guest external soil spray seeding plots had a balanced habitat materials and vegetation system development, indicating that the vegetation system composed of woody plants like *Lagerstroemia indica L.* and herbaceous plants like *Imperata cylindrica (L.) Beauv.* and *Diplopterygium glaucum (Thunberg ex Houttuyn) Nakai* had the best coordination with the habitat materials system. To some extent, habitat materials fertility regulation and restoration species selection based on local conditions can encourage the joint development of plants and habitat materials.

To summarize, the four restoration plots chosen in the project's disturbed area are in a state of coordinated development, indicating that various habitat materials and vegetation systems are in the process of transitioning to high-quality and coordinated development at this time, and significant ecological restoration progress has been made. However, there is still much room for improvement in maintaining balanced habitat materials and vegetation development. The development and succession of vegetation communities will be aided by improved habitat materials' soil quality during the ecological restoration and vegetation reconstruction process.

Simultaneously, as natural succession progresses, the vegetation community will have a greater level of community structure, which will be more favourable to the accumulation of organic matter and improve habitat materials' soil quality progressively (Han et al., 2010; Yang et al., 2018; Hu et al., 2021). As a result, when selecting an ecological restoration method, it is necessary to tailor measures to local conditions in order to improve not only the coupling and coordination relationship between vegetation growth and the habitat materials environment, but also to promote their common development and increase the ecological benefits of vegetation restoration.

Conclusion

Habitat materials variables play a bigger role in the habitat materials and vegetation coupling coordination system. The correlation between the system indicators were significantly varied, and organic matter, water content, available nitrogen, AWCD, microbial biomass phosphorus and microbial biomass nitrogen were among the habitat materials system indicators that had substantial effects on vegetation community succession and growth.

The growth of habitat materials and vegetation system coupling and coordination in the four artificial vegetation restoration patterns is varied after vegetation restoration, and the ecological restoration effect of them is impressive when compared to abandon slag slope plots. The natural forest sample plot has the highest habitat materials and vegetation system coupling coordination index, whereas frame beam filling soil plots, thick layer base material spraying plots and guest external soil spray seeding plots are all well-coordinated. The distinction lies in the balanced state of habitat materials and vegetation system development in the secondary classification, and the vegetation concrete plots are the intermediate coordinated state vegetation lag type.

To achieve sustainable development, species should be selected from multiple niches as much as possible for sample sites with lagging vegetation. In addition, in subsequent monitoring, alien species invasion should be avoided. According to the results of the PLS-PM analysis, the amounts of organic matter, available nitrogen, and available phosphorus can be suitably raised in the lagging sample plots to improve the habitat materials lag.

Data availability statement

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

Author contributions

BZ conceived and designed the experiment. RG and BZ contributed to the writing of the first draft, review and editing. YS, XH, and YW conduct data analysis, LZ, DX, and WX provided conceptual advice for the experimental program. All authors contributed critically to the drafts and gave final approval for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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