forests

MDPI

Article

The Coupling Relationship between Herb Communities and Soil in a Coal Mine Reclamation Area after Different Years of Restoration

Rui Gao [1], Ning Ai [1,2,*], Guangquan Liu [2], Changhai Liu [1], Fangfang Qiang [1], Zhiyong Zhang [1], Ting Xiang [1] and Kaixuan Zang [1]

1 College of Life Science, Yan'an University/Shaanxi Engineering and Technological Research Center for Conversation and Utilization of Regional Biological Resources, Yan'an 716000, China
2 China Institute of Water Resources and Hydropower Research, Beijing 100038, China
* Correspondence: aining@yau.edu.cn

Abstract: In a complete organic ecosystem restoration in mining areas, soil and vegetation complement and influence each other. It is of great significance to evaluate the ecological restoration effect on and ecosystem stability of the mining area, with the coupling and coordinating relationship between herb community and soil physicochemical properties after land reclamation. Therefore, this study takes Juxinlong Coal Mine in Dongsheng District of Ordos City, Inner Mongolia Autonomous Region as the study area. The understory herbaceous plant community and soil factors with restoration time of 3 to 7 years were selected as the research objects. In addition, artificial grassland and natural restoration grassland were used as controls to investigate the species composition of herbaceous communities and soil physicochemical properties in different sites. The grey relational coupling model was adopted not only to study the relationship between herb community and soil factors but also to explore the coupling mechanism between herb community and soils' physicochemical properties. The results included: (1) 51 herbaceous plants were investigated in the study area, among which Gramineae, Compositae, Leguminosae, and Chenopodiaceae were the primary ones, accounting for 70% of the total. (2) With the increase of restoration years, the diversity indices of understory herbaceous plants generally showed an increasing trend, but the diversity indices of understory herbaceous plants with different restoration years was smaller than that of artificial grassland. (3) The results of grey correlation analysis showed that the diversity of herbaceous plant community in the study area was closely related to soils' available nitrogen and water content. (4) The degree of coupling and coordinating between the diversity of herbaceous plants and soils in the study area presented a trend of first increasing then decreasing during the accumulating restoration years. Among them, the degree of coupling between the diversity of understory herbaceous plants and soil system in the 5-year restoration's sample plot (0.73) was found to be the highest, which was classified as medium coordination. The lowest coupling degree of herb diversity and soils was identified in the artificial grassland (0.51), which was light incoordination. Therefore, it is suggested that the control of water and nitrogen resources should be strengthened, the herbaceous vegetation should be reasonably selected, and the artificial tending should be carried out in the later stage of understory herbaceous vegetation construction in the study area to better promote the vegetation construction in the mining area.

Keywords: mining area; understory herbs; species diversity; coupling coordination

Citation: Gao, R.; Ai, N.; Liu, G.; Liu, C.; Qiang, F.; Zhang, Z.; Xiang, T.; Zang, K. The Coupling Relationship between Herb Communities and Soil in a Coal Mine Reclamation Area after Different Years of Restoration. *Forests* **2022**, *13*, 1481. https://doi.org/10.3390/f13091481

Academic Editor: Venceslas Goudiaby

Received: 24 August 2022
Accepted: 10 September 2022
Published: 14 September 2022

1. Introduction

Coal resources are one of the leading energy sources for industrial consumption in China and play an essential role in China's economic development [1]. Uncalculated coal-mining activities have caused severe environmental pollution and ecological damage, changes in soil structures and functions [2,3], soil quality decline, biodiversity losses, and vegetation reductions, which have become problems that need to be solved for the sustainable development of these mining areas [4,5]. Existing studies have already shown that vegetation restoration was the most direct and effective way to improve the ecological environment of mining areas [6–8]. Vegetation restoration has been widely used to address the ecological environmental problems in mining areas and to promote their developments with the advantages of low cost, strong applicability and sustainability [9,10]. Land reclamation is an effective way to solve the conflict between coal mining and land resources mitigation, and alleviate the contradiction between people and land in mining areas. The restoration of soil fertility is the focus of land reclamation and ecological restoration in abandoned mining areas [11]. In the ecosystem of a mining area, soil and vegetation are two interdependent factors. Vegetation succession affects soil development, and soil nutrients restrict plant growth; thus, soil and vegetation complement and influence each other [12,13]. Scientific and reasonable vegetation restoration can effectively solve soil and water loss, biodiversity loss, and other ecological environmental problems, and can improve soil fertility, and form a positive interaction with the soil ecosystem. At present, many scholars often use a coupling coordination model to quantitatively evaluate the relationship between soil and vegetation [14], and the strength and synergistic effect of soil-vegetation interaction are reflected by two indicators: coupling degree and coupling coordination degree [15–17]. Luo et al. [18] found that the coupling degree and coupling coordination degree of the vegetation-soil system in different periods of vegetation restoration of artificial *Haloxylon ammodendron* were not in one-to-one correspondence. Peng et al. [19] also found that the coupling degree and coupling coordination degree of different returning farmland to forests and grasslands in karst peaks and depressions are not in one-to-one correspondence, and the positions of the comprehensive indices of vegetation and soil in the overall model are not completely consistent. Therefore, studying the coupling relationship between vegetation and soil poses significantly theoretical and practical significances for revealing the directions of vegetation community's succession and vegetation construction in mining ecosystems.

Plant community is the product of the interaction between plants and the environment. With the change of species diversity, vegetation community succession from pioneer stage to relatively stable stage. In the process of ecosystem restoration, the dynamic pattern of community succession responds to the changes of community environment and biodiversity [20]. As an essential part of vegetation system in a mining area, the herb layer plays a significant role in water and soil conservation, biodiversity protection, the ecosystem's function maintenance, succession and development [21]. Herbaceous plants affect the stability of ecosystems by occupying ecological niches in the community, and their biodiversity variations are also critical indicators to measure both the structures and functions of forest communities. Liu et al. [22] found that using shade-tolerant herbaceous plants in the forest-grass composite ecosystem could effectively reduce soil erosion. Thomaes et al. [23] have shown that species-rich understory herbs were more conducive to the restoration of forest systems. Wei et al. [24] discovered that understory plant diversity was positively correlated with soil microenvironment. Species diversity is the foundation of ecological function, and it represents the community structure, organization level, development, stability, and habitat condition [25]. The herb layer species occupy a dominant position in the entire community richness [26], restricts the ecosystem nutrient cycle, habitat heterogeneity, such as ecological process, and also affects the tree seedling survival, development and growth [27]. Therefore, it is of great value to study the composition and diversity of understory herbaceous community in mining area for the regulation and management of an artificial forest ecosystem.

Inner Mongolia Autonomous Region has been an important coal mine region in China. Since the implementation of reclamation policy in its mining areas, the vegetation coverage there has increased significantly. At present, the research on vegetation reclamation in coal mining areas mainly focuses on "soil quality" [28–30], "water and soil conservation" [31–33] and "biodiversity" [34–36], etc. However, there has been little research on the coupling relationship between understory herbaceous community and soils after different restoration years in the mining area. Therefore, in this study, understory herbaceous plant communities and soil factors with restoration of 3–7 years in the reclamation area of Juxinlong Coal Mine were taken as the research objects, while artificially and naturally restored grasslands were taken as the controls to clarify species composition and diversity of understory herbaceous plants with different restoration years. Then, the grey correlation coupling model method was used to analyze the coupling degree of herbaceous plant community and soil factors in the study area, so as to clarify the coupling coordination degree of the understory herbaceous plant community and soil after land reclamation in the mining area, and finally provide scientific basis and data support for vegetation configuration and tree species selection in the ecological restoration and reconstruction of mining areas in the study area and similar areas.

2. Materials and Methods

2.1. Overview of the Study Area

The study area is located at Juxinlong Coal Mine (110°4′2″ E, 39°54′16″ N) in Ordos City, Inner Mongolia Autonomous Region. Its average altitude is about 1360 m, the terrain is flat, the climate type is temperate continental climate, and the frost-free period was about 135 days. Rainfall varies greatly every year, with an average annual volume of about 400 mm, mainly concentrated in July to September. Since 2011, the mining area has undergone land reclamation work in the mining areas. At present, there have already been shrubs like *Hippophae rhamnoidoes* and *Tamarix chinensis*, as well as *Achnatherum splendens*, *Leymus chinensis* (Trin.) Tzvel., and *Calamagrostis epigeios* (L.) Roth and other shrub-grass-dominated vegetation communities.

2.2. Plot Setting and Sample Collection

Through on-the-spot investigations and explorations in the study area, the understory herbaceous plants' communities with different restoration years (3 years, 4 years, 5 years, 6 years and 7 years) were selected as the research object (Figure 1), and the adjacent naturally restored grasslands and artificially restored grasslands were used together as the control group. Three plots of 10 m × 10 m were set up in the distribution area of the under-forest herb community with each restoration period, and five 1 m × 1 m herb samples were set up in each plot by the diagonal method, with each plot being investigated and recorded. Information and indicators included the number of herb species, height, and coverage within the quadrat. In each plot, along the diagonal, we set three soil profiles with a depth of 1 m, used a ring knife to collect soil samples, removed surface litter, and divided them into 5 layers vertically downward from the surface, namely 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, 80–100 cm. Three ring knives were set up for each layer of the same section to be repeated for later determination and calculation of soil physical properties. Meanwhile, the soil samples collected from each layer of the profile were put into Ziplock bags and brought back to the laboratory for natural air-drying and sieving before their chemical indices determination. Sample plot information is listed in Table 1.

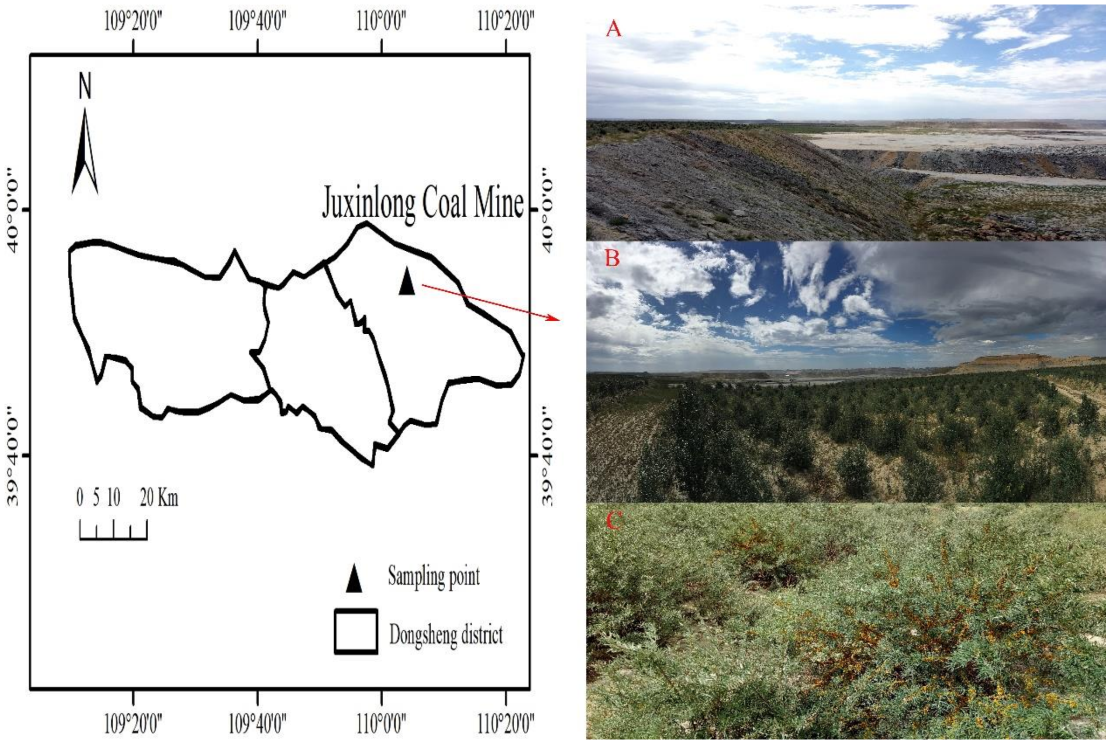

Figure 1. Sample plot map. Note: In Figure 1, (**A**) is the overview map of the mine site before restoration measures, (**B**) indicates the overview map of the mine site after the implementation of vegetation restoration measures, and (**C**) is the overview map of the sea buckthorn sample plot in mining area.

Table 1. Basic information of sample land.

Sample Code	Plot Type	Restore Year	Altitude (m)	Plant Spacing × Row Spacing (m)	Base Diamete (cm)	Height (cm)
R7	Macro-fruit seabuckthorn	7	1350	2 m × 3 m	4.2 ± 0.15	168 ± 3.84
R6	Macro-fruit seabuckthorn	6	1320	2 m × 3 m	5.2 ± 0.19	190 ± 3.55
R5	Macro-fruit seabuckthorn	5	1370	2 m × 3 m	3.8 ± 0.29	167 ± 2.92
R4	Macro-fruit seabuckthorn	4	1390	2 m × 3 m	4.1 ± 0.13	163 ± 2.18
R3	Macro-fruit seabuckthorn	3	1390	2 m × 3 m	3.0 ± 0.11	126 ± 2.3
NG	Natural restoration grassland	7	1390	/	/	/
AG	Artificial grassland	7	1390	/	/	/

2.3. Determination of Soil Samples' Properties

The drying method was applied to measure the natural Soil Water Content (SWC). The "ring-cutting and water immersion" method was used to measure and calculate the soil bulk density (BD), total porosity (TCP), saturation moisture content (SMC) and capillary water-holding capacity (CWHC) [37]. Soil particle size was identified by BT-9300 S laser analyzer for particle size distribution (soils' particle size classification was based on the American soil texture classification standard). The pH value was determined using the PHS-320 high-precision intelligent acidity gauge, at the water-soil ratio of 2.5:1. Soil electric conductivity was measured by DDS-608 multi-functional conductivity meter, and the water-soil ratio was set to 5:1. The potassium dichromate oxidation process combined with the heating method was adopted to measure the Soil Organic Carbon (SOC). Available Nitrogen (AN) was determined via the alkaline hydrolysis—diffusion absorption method, Available Phosphorus (AP) was identified using the molybdenum antimony anti-colorimetric method, and Available potassium (AK) by the flame photometer method. Total Nitrogen (TN) was measured using the kjeldah method. Total Phosphorus (TP) was identified based on the sodium hydroxide melting-molybdenum antimony colorimetric method [38].

2.4. Calculation of Herb Diversity

α-diversity indices mainly focus on the number of species in local uniform habitats, so they are also known as the diversity of native habitats. They are widely used in plant community research. Margalef index, Simpson dominance index, Shannon-Wiener diversity index and Pielou evenness index are calculated to characterize the richness, dominance, diversity, and evenness index of species community composition. Therefore, in this study, Margalef index, Pielou index, Simpson index, and Shannon-Wiener index were used to calculate the diversity of herbaceous communities after different restoration years in the study area.

Important value (P_i): P_i= (Relative density + Relative height + Relative coverage)/3
Margalef index (D'): $D' = (S - 1) / \ln N$
Pielou index (E): $E = H' / \ln S$
Simpson index (D): $D = 1 - \sum P_i^2$
Shannon-Wiener index (H'): $H' = -\sum P_i \ \ln P_i$

Here, S is the number of species growing in the plot, and N is the sum of the numbers of all individual species.

2.5. Grey Correlation Coupling Analysis

The coupling coordination degree model includes two indices: coupling degree and coupling coordination degree, which can directly reflect the interaction degree and synergistic effect between factors. The coupling analysis of plant diversity and soil factors is carried out by using the grey correlation degree method, and the coupling degree between plants and soil is explored by establishing the grey correlation degree model, system coupling coordination degree evaluation criteria are shown in Table 2. Four plant diversity indices and 15 soil factors were used in this study. Firstly, dimensionless standardization is used to process the data of indicators involved in the measurement, and then the correlation coefficient is calculated according to the following formula [39]:

Table 2. System of ecosystem coupling coordination.

Coupling Degree (C)	**$0 \le C < 0.4$**	**$0.4 \le C < 0.5$**	**$0.5 \le C < 0.6$**	**$0.6 \le C < 0.7$**	**$0.7 \le C < 0.8$**	**$0.8 \le C < 0.9$**	**$0.9 \le C < 1$**
Type of coordination	Serious incoordination	Medium incoordination	Light incoordination	Light coordination	Medium coordination	Favorable coordination	Superior coordination

Note: Data was cited from OECD [40].

(1) Data standardization:

$$x'_i(k) = \frac{x_i(k) - minx_i(k)}{maxx_i(k) - minx_i(k)}$$

(2) Incidence coefficient:

$$\gamma\left(x'_0(k), x'_i(k)\right) = \frac{\Delta x_{min} + \varepsilon \Delta x_{max}}{\Delta x_{0i}(k) + \varepsilon \Delta x_{max}}$$

$$\Delta x_{min} = \underset{\forall j \epsilon i}{min}\,\underset{\forall k}{min} |x'_0(k) - x'_j(k)|$$

$$\Delta x_{max} = \underset{\forall j \epsilon i}{max}\,\underset{\forall k}{max} |x'_0(k) - x'_j(k)|$$

$$\Delta x_{0i}(k) = |x'_0(k) - x'_i(k)|$$

ε is the resolution coefficient, its range is generally $0 < \varepsilon < 1$, and the general value is $\varepsilon = 0.5$.

(3) Calculation of grey correlation degree by equal weight method:

$$\Gamma_{(ij)} = \frac{1}{n}\sum_{k=1}^{n}\gamma\left(x_0'(k), x_i'(k)\right)$$

When 0 < $\Gamma_{(ij)} \leq 0.35$, the correlation degree is weak; when 0.35 < $\Gamma_{(ij)} \leq 0.65$, the correlation degree is medium; when 0.65 < $\Gamma_{(ij)} \leq 0.85$, the correlation degree is strong; when 0.85 < $\Gamma_{(ij)} \leq 1.0$, the correlation degree is significantly strong.

(4) Establishment of coupling model:

$$\begin{cases} d_i = \frac{1}{l}\sum\limits_{j=1}^{l}\Gamma(ij) \quad (i = 1, 2, 3, \ldots l; j = 1, 2, 3, \ldots m) \\ d_j = \frac{1}{m}\sum\limits_{i=1}^{m}\Gamma(ij) \quad (i = 1, 2, 3, \ldots l; j = 1, 2, 3, \ldots m) \end{cases}$$

(5) Coupling analysis:

$$C(k) = \frac{1}{m \times l}\sum_{i=1}^{m}\sum_{j=1}^{l}\gamma\left(x_0'(\mathrm{k}), x_i'(\mathrm{k})\right)$$

Here, *m* is the number of soil indicators, and *l* is the quantity of diversity indicators.

2.6. Data Processing and Analysis Softwares

Excel 2016 was employed to calculate the species diversity indices, grey correlation degree and system coupling/coordination degree, ArcGis 10.3 was used for map of sample area, SPSS for one-way ANOVA and Duncan 's method for multiple comparisons and Origin 2018 was used to draw figures.

3. Results

3.1. Difference Characteristics of Soil Properties

Table 3 exhibits that the soil in the study area was alkaline, and the soil indices showed significant indigenous differences in different places ($p < 0.05$). Soil clay, silt, electrical conductivity, soil organic carbon and available phosphorus content were the highest in the 7-year restoration plots. Soil total porosity, capillary capacity, available nitrogen and total phosphorus content were the highest in the 6-year restoration plots. The contents of soil sand and soil organic carbon were high in the 5-year and 4-year restoration plots, and the soil water content, pH, electrical conductivity, and available potassium were high in the 3-year restoration plots. The soil water content, electrical conductivity and the soil water content in natural restoration grassland were relatively high, the contents of soil sand and soil organic carbon in artificial grassland were high.

Table 3. Soil physical and chemical properties.

	R7	R6	R5	R4	R3	NG	AG
BD (g/cm^3)	1.21 ± 0.03 ^{bc}	1.14 ± 0.06 ^{c}	1.25 ± 0.02 ^{ab}	1.31 ± 0.02 ^{a}	1.15 ± 0.03 ^{c}	1.19 ± 0.02 ^{bc}	1.28 ± 0.02 ^{a}
TCP (%)	40.87 ± 2.8 ^{c}	48.24 ± 0.64 ^{a}	43.48 ± 0.62 ^{bc}	45.04 ± 2.24 ^{ab}	43.12 ± 0.84 ^{bc}	44.5 ± 1.45 ^{bc}	43.19 ± 1.31 ^{bc}
SWC (%)	7.19 ± 0.24 ^{cd}	9.52 ± 0.37 ^{b}	6.34 ± 0.41 ^{d}	8.16 ± 0.37 ^{bc}	12.53 ± 1.42 ^{a}	11.05 ± 0.79 ^{a}	4.43 ± 0.53 ^{e}
SMC (%)	34.47 ± 2.05 ^{d}	42.59 ± 1.47 ^{a}	35.01 ± 0.18 ^{bcd}	34.92 ± 1.92 ^{bcd}	37.81 ± 0.66 ^{b}	37.53 ± 0.58 ^{bc}	34.75 ± 0.89 ^{cd}
CWHC (%)	24.63 ± 0.68 ^{c}	34.62 ± 1.34 ^{a}	24.09 ± 0.72 ^{c}	24.65 ± 1.08 ^{c}	30.52 ± 0.09 ^{b}	30.57 ± 0.56 ^{b}	25.21 ± 0.92 ^{c}
Clay (%)	4.25± 0.32 ^{a}	3.07 ± 0.48 ^{c}	2.31 ± 0.16 ^{d}	2.28 ± 0.14 ^{d}	3.25 ± 0.36 ^{bc}	3.70 ± 0.16 ^{ab}	2.94 ± 0.11 ^{c}

Table 3. *Cont.*

	R7	R6	R5	R4	R3	NG	AG
Silt (%)	68.77± 3.07 [a]	59.41 ± 2.81 [bc]	52.55 ± 5.89 [cd]	48.22 ± 3.64 [d]	62.33 ± 2.76 [ab]	68.45 ± 0.91 [a]	48.02 ± 0.56 [d]
Sand (%)	26.98 ± 3.39 [c]	37.51 ± 3.01 [b]	45.14 ± 6.05 [a]	49.50 ± 3.78 [a]	34.41 ± 3.03 [bc]	27.85 ± 0.75 [c]	48.63 ± 0.7 [a]
pH	7.89 ± 0.03 [b]	7.62 ± 0.1 [cd]	7.62 ± 0.1 [cd]	7.75 ± 0.02 [bcd]	8.4 ± 0.05 [a]	7.82 ± 0.03 [bc]	7.56 ± 0.18 [d]
EC (μS/cm)	142.38 ± 9.66 [a]	98.39 ± 4.62 [bc]	76.34 ± 9.05 [d]	85.41 ± 5.73 [cd]	139.34 ± 11.92 [a]	143.01 ± 15.9 [a]	111.67 ± 1.16 [b]
SOC (g/kg)	7.56 ± 0.59 [a]	2.83 ± 0.89 [b]	6.98 ± 0.38 [a]	6.54 ± 1.2 [a]	3.39 ± 0.71 [b]	7.17 ± 0.8 [a]	6.56 ± 0.09 [a]
AN (mg/kg)	8.33 ± 0.07 [b]	9.83 ± 1.08 [a]	8.47 ± 0.24 [ab]	9.1 ± 1.17 [ab]	7.91 ± 0.33 [b]	3.08 ± 0.08 [c]	3.58 ± 0.27 [c]
AK (mg/kg)	85.13 ± 8.88 [ab]	56.47 ± 23.24 [bcd]	72.73 ± 21.42 [abc]	40.83 ± 8.06 [cd]	98.07 ± 14.59 [a]	39.6 ± 1.19 [d]	42.27 ± 1.39 [cd]
AP (mg/kg)	53.35 ± 5.99 [a]	19.98 ± 12.99 [bc]	9.62 ± 1.49 [d]	6.63 ± 0.64 [d]	17.39 ± 4.54 [bc]	24.46 ± 0.82 [b]	10.99 ± 0.38 [d]
TP (g/kg)	0.34 ± 0.01 [de]	0.66 ± 0.03 [a]	0.54 ± 0.02 [b]	0.44 ± 0.02 [cd]	0.31 ± 0.07 [e]	0.4 ± 0.02 [cd]	0.48 ± 0.05 [bc]

Note: Different lowercase letters indicated that there were significant differences in soil physical and chemical properties between different plots ($p < 0.05$). BD, bulk density; TCP, total porosity; SWC, soil water content; SMC, saturation moisture content; CWHC, capillary water-holding capacity; EC, electric conductivity; SOC, soil organic carbon; AN, available nitrogen; AK, available potassium; AP, available phosphorus; TP, total phosphorus.

3.2. Composition of Understory Herb Community after Different Restoration Years

Table 4 lists 51 species of understory herbaceous plants in the study area, mainly Compositae (32%), Gramineae (20%), Leguminosae (12%) and Chenopodiaceae (6%). The proportion of caryophyllaceae and Labiatae together was 4%. The families of Valerianaceae, Apocynaceae, Amaranthaceae, Brassicaceae, Crassulaceae, Bignoniaceae, Violaceae, Thymelaeaceae, Geraniaceae, Polygonaceae and Chicoryaceae were all single families and single genera, jointly accounting for 2%. With the increase of restoration years, the number of understory herbaceous plants in the study area did not change significantly, while the number of species in various plots was lower than those in naturally and artificially restored grasslands.

Table 4. General situation of herbaceous plant communities under forests with different restoration years.

Restore Year	Species Number	Top Five Importance Values				
7	9	*Leymus chinensis* (Trin.) Tzvel.	*Achnatherum splendens* (Trin.) Nevski	*Calamagrostis epigeios* (L.) Roth	*Cirsium arvense var. integrifolium*	*Phragmites australis* (Cav.) Trin. ex Steud.
		0.2109	0.1606	0.1522	0.1253	0.1164
6	12	*Echinochloa crusgalli* (L.) Beauv.	*Calamagrostis epigeios* (L.) Roth	*Artemisia annua* Linn.	*Dracocephalum moldavica* L.	*Artemisia ordosica* Krasch.
		0.2452	0.1750	0.1574	0.1048	0.0625
5	8	*Leymus chinensis* (Trin.) Tzvel.	*Achnatherum splendens* (Trin.) Nevski	*Calamagrostis epigeios* (L.) Roth	*Artemisia annua* Linn.	*Artemisia ordosica* Krasch.
		0.2762	0.2421	0.2048	0.1328	0.0736
4	9	*Lepidium apetalum* Willd.	*Melilotus officinalis* (L.) Pall.	*Echinochloa crusgalli* (L.) Beauv.	*Incarvillea sinensis* Lam.	*Sonchus oleraceus* L.
		0.2979	0.1459	0.1371	0.1156	0.0805
3	7	*Lepidium apetalum* Willd.	*Melilotus officinalis* (L.) Pall.	*Salsola collina* Pall.	*Oxytropis neimonggolica* C. W. Chang et Y. Z. Zhao	*Setaria viridis* (L.) Beauv.
		0.3493	0.2441	0.1970	0.0718	0.0552
Natural restoration grassland	28	*Artemisia sieversiana* Ehrhart ex Willd.	*Achnatherum splendens* (Trin.) Nevski	*Artemisia gmelinii*	*Cynanchum chinense* R. Br.	*Artemisia capillaris* Thunb.
		0.1035	0.0816	0.0787	0.0787	0.0612
Artificial grassland	32	*Achnatherum splendens* (Trin.) Nevski	*Cynanchum chinense* R. Br.	*Phragmites australis* (Cav.) Trin. ex Steud.	*Artemisia sieversiana* Ehrhart ex Willd.	*Miscanthus sinensis* cv.
		0.1107	0.0794	0.0768	0.0729	0.0677

Note: Numbers in the table represent important values (Pi).

3.3. Diversity Characteristics of Herbaceous Plant Communities after Different Restoration Years

Figure 2 exhibits that with the increase of restoration years, the Margalef index, Simpson index and Shannon-Wiener index of herbaceous plant communities in the study area fluctuated up and down, basically showing a trend of increasing first then decreasing, which were less than those in artificial and natural restoration grasslands. The Pielou index of understory herbs with different restoration years showed a relatively gentle change, and there was no obvious trend change. Among them, the Pielou index of understory herbaceous plants in the 7-year restoration sample site (0.927) was the largest, while the Pielou index of natural restoration grassland (0.474) was the smallest, and their difference was large.

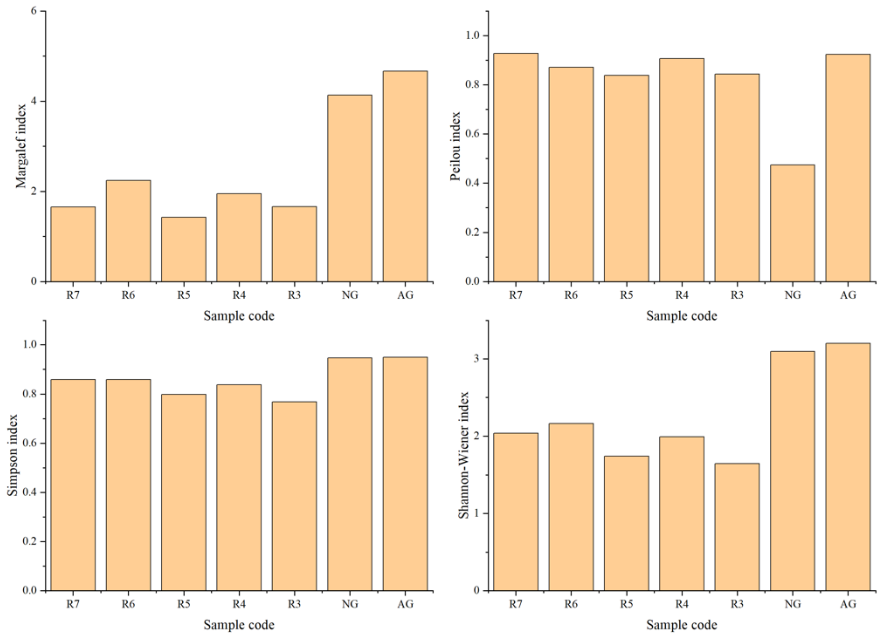

Figure 2. Diversity indices of understory herbaceous plant community in different restoration years.

3.4. Analysis of Grey Correlation between Plant Community Diversity and Soil Factors

Figure 3 shows that the degrees of correlations between herb community diversity indices and soil factors were around 0.50–0.91, with an average value of 0.66, while the general correlation degree was medium or above. Among them, the degree of correlation between Margalef index and available nitrogen (0.91) was the maximum (strong correlation), while that between Margalef index and available potassium (0.56) was the minimum (medium correlation). Pielou index exhibited the highest correlation (strong) with available nitrogen (0.78), and the lowest correlation (medium) with available phosphorus (0.50); Simpson index presented the highest correlation with soil moisture (0.77) (strong), and the lowest correlation with total phosphorus (0.58) (medium). Shannon-Wiener index showed the highest correlation with available nitrogen (0.83) (strong), and the lowest correlation with total phosphorus (0.54) (medium).

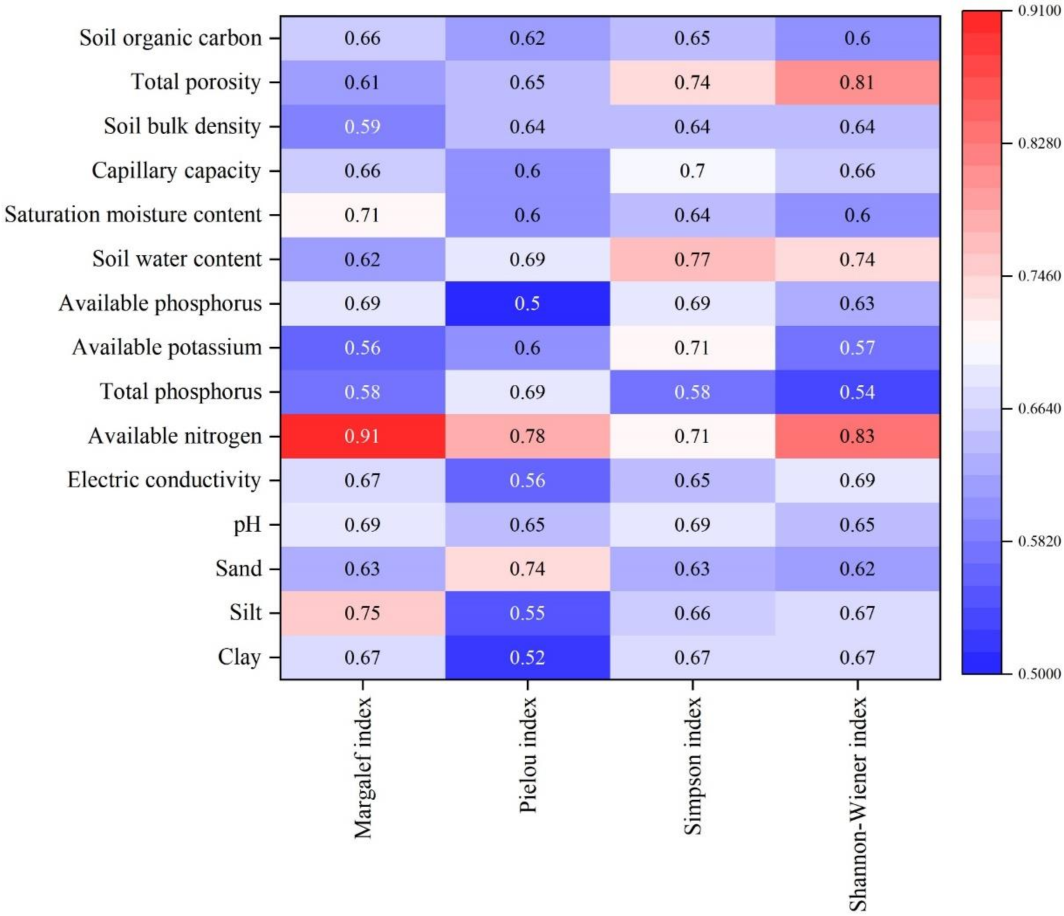

Figure 3. Coupled heat map of herbaceous community diversity and soil.

3.5. Analysis of Coupling/Coordinating between Plant Community Diversity and Soil Factors

It can be seen from Table 5 that the degree of coupling/coordinating between herb community and soil system in each sample plot of the study area ranged from 0.51 to 0.73. The coupling degree between herb community diversity and soil system in the sample plots of 5 and 6 years of restoration was the maximum (0.73), which was a medium coordination. The herb community diversity and soil system in the sample plots of natural restoration grassland after restoration of 3, 4 and 7 years were in a state of light coordination. The coupling degree between plant community diversity and soil system in artificial grassland was the minimum (0.51), which was a light incoordination. With the accumulating restoration years, the coupling degree between herbaceous plant diversity and soil system first increased then decreased.

Table 5. Coordination evaluation model of plant diversity and soil system coupling in different restoration years.

Restore Year	Coupling	Coordination Type
7	0.67	Light coordination
6	0.70	Medium coordination
5	0.73	Medium coordination
4	0.69	Light coordination
3	0.65	Light coordination
Natural restoration grassland	0.65	Light coordination
Artificial grassland	0.51	Light incoordination

4. Discussion

4.1. Analysis of Community Composition and Diversity of Understory Herbaceous Plants in Coal Mines' Reclamation Areas

The understory herbaceous communities in the study area were dominated by Compositae, Gramineae, Leguminosae and Chenopodiaceae, jointly accounting for 70% of the herbaceous species in the study area (Table 4), which was similar to the research results of other scholars. Guo et al. [41] in the study of Antaibao open-pit coal mine found that its reclamation area of artificial forest's herbaceous plant communities were mainly made up of with Gramineae, Compositae and Papillionaceae. Feng et al. [42] also found that Compositae, Leguminosae, Chenopodiaceae, and Gramineae were the dominant groups in the study of compositions of plant community in Ningdong mining area. Wang et al. [43] investigated 44 understory herbaceous plants in the ecological reclamation area of Antaibao opencast coal mine. The dominant families are Gramineae and Compositae. The major reason for this was that these groups of plants possessed a wide niche, drought tolerance, barrenness, strong reproduction and adaptability, with broad universality for dry and windy mining areas [44]. In the meantime, this study also found that understory herbaceous plants were mostly one-year-old ones and few Gramineae/Compositae ones at the early stage of the reclamation. With the accumulating restoration years, perennial herbaceous plants gradually increased, while the proportion of Gramineae and Compositae herbaceous plants occurring together also grew. Gou et al. [45] also found that with the increase of planting years of Caragana korshinskii, the understory herbaceous plants was gradually dominated by perennial herbaceous plants when studying the understory herbaceous plant communities of artificial Caragana korshinskii forests with different planting years in the aeolian sand area of northwestern Shanxi. Hao et al. [46] found that, with the increase of restoration years, the community composition of plants evolved from one-year-old and two-year-old, high density and small individuals to perennial, low density and large individuals. Species diversity is an essential feature of biological communities, and the basis of grassland ecosystem stability [47]. In this study, with the increase of restoration years, the Margalef index, Simpson index and Shannon-Wiener index of herbaceous plant community basically showed a trend of increasing first and then decreasing, which was similar to the results of Zhang et al. [48]. The reason for this may be that, in the early stage of reclamation, the competition of herbaceous plants was less, and the sunshine and nutrients were sufficient, while in the later stage, the community species diversity decreased due to the influence of seabuckthorn forest and herbaceous dominant species. The Pielou index of herbaceous plants under different restoration years showed a relatively gentle change trend, indicating that the community stability was also relatively stable, which was similar to the results of Mao et al. [49]. The Margalef index, Simpson index, and Shannon-Wiener index of understory herbaceous communities after different restoration years were lower than those of artificial grasslands (Figure 1), mainly due to the latter being planted artificially. Accordingly, in vegetation construction, plant species increased, and species distribution uniformity improved.

4.2. Analysis of Coupling between Herb Community and Soil Factors after Different Restoration Years

The correlation between species diversity and soils' physicochemical factors of understory herbaceous plant communities after different restoration years was above the medium degree. Available nitrogen and soil moisture were found to be the main influencing factors of herbaceous plant communities in the study area (Figure 3). Water was verified as the major limiting factor of vegetation growth in arid system. It was also confirmed as the direct source of moisture for vegetation growth and utilization [50,51]. Wang et al. [52] found that soil water content was positively correlated with species diversity. Cui et al. [53] proved that the herb layer maintained strong function of water conservation. Afforestation activities will cause a decrease of soil water content in a certain period. Under this kind of stress, drought-resistant herbaceous plants would occupy numerous niches, consequently inhibiting the seed germination and growth before changing the diversity of understory plant communities [54,55]. Wang et al. [56] found that soil water content had the greatest relative influence on the diversity of herbaceous plants, and showed a negative correlation. The reason for this may be that the local perennial herbaceous plants have drought resistance, and higher water content may cause stress to most herbaceous plants. Huang [57] showed that the water consumption of legume grassland was higher than that of gramineous grassland. Wang [58] found that the influence of growth environment system indices factors on resilience was in the order of soil water content, soil nutrient content, and soil bulk density.

Nitrogen was demonstrated to have changed the competitiveness of individual plants or functional groups [59–61]. Xu et al. [62] found that, in the early stage of ecological restoration, available nitrogen in soil greatly influenced the α diversity indices of understory herbaceous plants. Chen et al. [63] showed that soil available nitrogen content is an important potential factor affecting plant diversity in the herb layer, which is related to the direct use of alkaline hydrolyzed nitrogen by herbs to promote their growth. In addition, some herbaceous plants with higher requirements for water and fertilizer conditions may also be more inclined to distribute in habitats with higher alkaline hydrolysis nitrogen content. Hu et al. [64] discovered that the grass cover under forests was beneficial to increasing the soils' available nitrogen content, and the artificially grass-planting forestland raised this specific content faster than the native one. However, some studies showed that the increase of nitrogen content led to the decrease of species diversity [65], which might be due to the rapid expansion of dominant species because of the addition of soil nitrogen content, inhibition of the growth of other species in reproduction, and promotion of the simplification of community structure [66]. Yuan et al. [67] showed that legumes could effectively improve soil moisture and nitrogen nutrition in the abandoned soil field of the Loess Plateau, which was attributed to the nitrogen fixation function of legumes. Therefore, when the artificial vegetation was restored in this mining area, soils' water and nitrogen contents should both be reasonably regulated to better improve the vegetation community structure in the study area.

Ecosystem stability can control the species diversity. With the accumulation of restoration years, the coupling degree between understory herbaceous plant diversity and soil system increased first, and then decreased (Table 5). This might be due to the understory herbaceous layer at the beginning of the reclamation stage; the vegetation community inflicted a fierce competition for living spaces, waters, nutrients, and other resources. Moreover, there was a phenomenon of plant eliminations, decays, and deaths [68], which lowered the coupling coordination degrees of plants and soils in this stage. In the later stage of artificial restoration, the vegetation could absorb resources more effectively with the gradual stabilization of the feedback mechanism between niche differentiation and soils, while its anti-interference ability and resilience stability to environmental changes have also been effectively improved. The coupling/coordination degree between vegetation and soil was thus classified into the medium coordination stage. However, this study also showed that, after 7 years of restoration, the coupling/coordination degree between herbaceous plant community and soil in the study area turned into a light coordination stage, while the degree also showed a downward trend. This might be caused by the fact that *Hippophae rhamnoides* forest did not have flat stubble after 7 years, which led to the decline of the coupling degree between herbaceous plant community and soil under the forest [69,70]. Zhao et al. [71] found that the herbaceous plant community and soil factors had different trends with the increase of restoration years in the process of restoration of degraded land in Horqin Sandy Land. The vegetation community recovered rapidly in the early stage of restoration, but after 12 years of restoration, the vegetation composition changed significantly. The recovery of soil was relatively slow, and it was not until 20 years after recovery that the content of soil nutrients such as carbon and nitrogen increased significantly. In this study, although the number of species and the diversity indices of herbaceous plants in artificially and naturally restored grasslands were both higher, the adaptability of herbaceous plants planted in artificial grasslands was different due to the interference of human activities. Consequently, the diversity of plants and number of species exceeded the carrying capacity of water and soil in the local ecological environment. However, the naturally restored grassland was caused by native recovery, without manual intervention. Moreover, the vegetation's natural recovery succession process was long, resulting in low coupling between artificially/naturally restored grasslands and soils, which were identified as light incoordination and light coordination. Therefore, in the future, in the ecological restoration process of abandoned mining areas in the study area, appropriate manual interventions should be carried out to control the planting density.

5. Conclusions

This study found 51 species of herbaceous plants in the study area, mainly Compositae, Gramineae, Leguminosae, and Chenopodiaceae. The composition of understory herbaceous communities was similar to that of non-understory herbaceous communities. With the accumulating restoration years, the diversity indices of understory herbaceous plants generally showed an increasing trend, but were less than that in artificial grassland. In this study, the coupling and coordinating degrees between understory herbaceous plant diversity and soils increased first, and then decreased with the accumulating restoration years. The feedback mechanism between herbaceous plant community and soils gradually stabilized, while the light incoordination caused minimal coupling between the vegetation and soils in artificial restoration plots. The correlation between herbaceous plant community's diversity and soil factors was above medium degree, while available nitrogen and soil water content were the key driving factors of herbaceous plant community changes. Therefore, this study suggests that, for this study area, future restoration of artificial vegetation should consider the carrying capacity of local waters and soils, strengthen the regulation of water and nitrogen resources, and conduct appropriate vegetation tending in order to better promote the recovery of vegetation in abandoned mining areas.

Author Contributions: Conceptualization, R.G., N.A., F.Q., Z.Z., T.X. and K.Z.; methodology, R.G., N.A., G.L. and C.L.; writing—original draft preparation, R.G.; writing—review and editing, N.A. and R.G.; supervision, N.A., G.L. and C.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Plan (2016YFC0501602, 2016YFC0501705), China Institute of Water Resources and Hydropower Research (IWHR) Research & Development Support Program (SC0145B012022, SC0202A012018), Ordos Key Water Conservancy Science and Technology Project (2022-2130310-XX), Shaanxi Natural Science Basic Research Project (2021JQ626) and the National Natural Science Foundation of China (32060297, 31370541).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Wang, G.; Xu, Y.; Ren, H. Intelligent and ecological coal mining as well as clean utilization technology in China: Review and prospects. *Int. J. Min. Sci. Technol.* **2019**, *29*, 161–169. [CrossRef]
2. Kent, M.; Coker, P. *Vegetation Description and Analysis, a Practical Approach*; John Wiley & Sons: New York, NY, USA, 1992; p. 319.
3. Lim, B.-S.; Kim, A.R.; Seol, J.; Oh, W.-S.; An, J.-H.; Lim, C.-H.; Lee, C.-S. Effects of Soil Amelioration and Vegetation Introduction on the Restoration of Abandoned Coal Mine Spoils in South Korea. *Forests* **2022**, *13*, 483. [CrossRef]
4. Xiao, W.; Hu, Z.; Fu, Y. Zoning of land reclamation in coal mining area and new progresses for the past 10 years. *Int. J. Coal Sci. Technol.* **2014**, *1*, 177–183. [CrossRef]
5. Sheoran, V.; Sheoran, S.A. Reclamation of abandoned mine land. *J. Min. Metall. A Min.* **2009**, *45*, 13–32.
6. Luna, L.; Pastorelli, R.; Bastida, F.; Hernández, T.; García, C.; Miralles, I.; Solé-Benet, A. The combination of quarry restoration strategies in semiarid climate induces different responses in biochemical and microbiological soil properties. *Appl. Soil Ecol.* **2016**, *107*, 33–47. [CrossRef]

7. Mukhopadhyay, S.; George, J.; Masto, R.E. Changes in polycyclic aromatic hydrocarbons (PAHs) and soil biological parameters in a revegetated coal mine spoil. *Land Degrad. Dev.* **2017**, *28*, 1047–1055. [CrossRef]
8. Zhou, W.; Qian, M.; Wang, S.; Li, S.; Cao, Y. Spatial Distribution and Regulating Factors of Soil Nutrient Stocks in Afforested Dump of Pingshuo Opencast Coalmine, China. *Forests* **2022**, *13*, 345. [CrossRef]
9. Cohen-Fernandez, A.C.; Naeth, M.A. Increasing woody species diversity for sustainable limestone quarry reclamation in Canada. *Sustainability* **2013**, *5*, 1340–1355. [CrossRef]
10. Pathak, S.; Agarwal, A.V.; Pandey, V.C. Phytoremediation—A holistic approach for remediation of heavy metals and metalloids. In *Bioremediation of Pollutants*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 3–16.
11. Li, L.; Li, T.; Meng, H.; Xie, Y.; Zhang, J.; Hong, J. Effects of Seven-Year Fertilization Reclamation on Bacterial Community in a Coal Mining Subsidence Area in Shanxi, China. *Int. J. Environ. Res. Public Health* **2021**, *18*, 12504. [CrossRef]
12. Fan, X.; Guan, Y.; Bai, Z.; Zhou, W.; Zhu, C. Optimization of Reclamation Measures in a Mining Area by Analysis of Variations in Soil Nutrient Grades under Different Types of Land Usage—A Case Study of Pingshuo Coal Mine, China. *Land* **2022**, *11*, 321. [CrossRef]
13. Zhang, Z.; Ai, N.; Liu, G.; Liu, C.; Qiang, F. Soil quality evaluation of various microtopography types at different restoration modes in the loess area of Northern Shaanxi. *Catena* **2021**, *207*, 105633. [CrossRef]
14. Li, X.; Lei, S.; Liu, F.; Wang, W. Analysis of Plant and Soil Restoration Process and Degree of Refuse Dumps in Open-Pit Coal Mining Areas. *Int. J. Environ. Res. Public Health* **2020**, *17*, 1975. [CrossRef] [PubMed]
15. Liu, D.; Yang, Y. Coupling Coordinative Degree of Regional Economy-Tourism-Ecological Environment—A Case Study of Anhui Province. *Resour. Environ. Yangtze Basin* **2011**, *20*, 892–896.
16. Wang, H.; Guo, Y.; Xu, Y.; Qi, W.; Bu, F.; Qi, H. Coupling Relationship between Vegetation and Soil System in Ecological Restoration of Different Stand Types in Jiufeng Mountain. *Ecol. Environ. Sci.* **2021**, *30*, 2309–2316.
17. An, S.; Zhang, S.; Hou, H.; Zhang, Y.; Xu, H.; Liang, J. Coupling Coordination Analysis of the Ecology and Economy in the Yellow River Basin under the Background of High-Quality Development. *Land* **2022**, *11*, 1235. [CrossRef]
18. Luo, Q.; Ning, H.; Chen, Q. Relation between Vegetation and Soil of Haloxylon ammodendron Plantation in the Process of Sand-fixation. *J. Desert Res.* **2018**, *38*, 780–790.
19. Peng, W.; Song, T.; Zeng, F.; Wang, K.; Du, H.; Lu, S. Models of vegetation and soil coupling coordinative degree in grain for green project in depressions between karst hills. *Trans. Chin. Soc. Agric. Eng.* **2011**, *27*, 305–310.
20. Jiyi, Z.; Halin, Z.; Tonghui, Z.; XueYong, Z. Dynamics of species diversity of communities in restoration processes in Horqin Sandy Land. *Acta Phytoecol. Sin.* **2004**, *28*, 86–92. [CrossRef]
21. Nilsson, M.-C.; Wardle, D.A. Understory vegetation as a forest ecosystem driver: Evidence from the northern Swedish boreal forest. *Front. Ecol. Environ.* **2005**, *3*, 421–428. [CrossRef]
22. Liu, Y.-F.; Huang, Z.; Meng, L.-C.; Li, S.-Y.; Wang, Y.-B.; Liu, Y.; López-Vicente, M.; Wu, G.-L. Understory shading exacerbated grassland soil erosion by changing community composition. *Catena* **2022**, *208*, 105771. [CrossRef]
23. Thomaes, A.; de Keersmaeker, L.; Verschelde, P.; Vandekerkhove, K.; Verheyen, K. Tree species determine the colonisation success of forest herbs in post-agricultural forests: Results from a 9 yr introduction experiment. *Biol. Conserv.* **2014**, *169*, 238–247. [CrossRef]
24. Wei, L.; Archaux, F.; Hulin, F.; Bilger, I.; Gosselin, F. Stand attributes or soil micro-environment exert greater influence than management type on understory plant diversity in even-aged oak high forests. *For. Ecol. Manag.* **2020**, *460*, 117897. [CrossRef]
25. Ma, K.; Huang, J.; Yu, S.; Chen, L. Plant Community Diversity in Ongling Mountain, Beijing, China: II. Species Richness, Evenness and Species Diversities. *ACTA Ecol. Sin.* **1995**, *15*, 268–277.
26. Gilliam, F.S. The ecological significance of the herbaceous layer in temperate forest ecosystems. *BioScience* **2007**, *57*, 845–858. [CrossRef]
27. Cook, J.E. Structural effects on understory attributes in second-growth forests of northern Wisconsin, USA. *For. Ecol. Manag.* **2015**, *347*, 188–199. [CrossRef]
28. Sasaki, K.; Shirakura, F.; Mallory, F.F. Woody Plant Communities after 40 Years of Pollution Control and Restoration in Smelter-Denuded Landscapes. *Northeast. Nat.* **2022**, *29*, 82–96. [CrossRef]
29. Sun, H.; Zhang, J.; Wang, R.; Li, Z.; Sun, S.; Qin, G.; Song, Y. Effects of vegetation restoration on soil enzyme activity in copper and coal mining areas. *Environ. Manag.* **2021**, *68*, 366–376. [CrossRef]
30. Guo, D.; Shi, Z.; Li, H.; Bai, Z.; Shao, H. The correlation between eco-restoring modes and soil quality succession during plant re-vegetation in large-scale mining areas. *Pak. J. Bot.* **2020**, *52*, 317–322. [CrossRef]
31. Yuan, Y.; Li, X.; Xiong, D.; Wu, H.; Zhang, S.; Liu, L.; Li, W. Effects of restoration age on water conservation function and soil fertility quality of restored woodlands in phosphate mined-out areas. *Environ. Earth Sci.* **2019**, *78*, 653. [CrossRef]
32. Zhang, L.; Wang, J.; Bai, Z.; Lv, C. Effects of vegetation on runoff and soil erosion on reclaimed land in an opencast coal-mine dump in a loess area. *Catena* **2015**, *128*, 44–53. [CrossRef]
33. Indorante, S.J.; Jansen, I.J.; Boast, C.W. Surface mining and reclamation: Initial changes in soil character. *J. Soil Water Conserv.* **1981**, *36*, 347–351.
34. Qin, Z.; Chen, Q.; Ji, X.; Ming, S.; Du, Q. Biodiversity protection and ecological restoration of Guilin Karst quarry. In *E3S Web of Conferences, 2020*; EDP Sciences: Les Ulis, France, 2020; Volume 194, p. 04025.

35. Vahter, T.; Bueno, C.G.; Davison, J.; Herodes, K.; Hiiesalu, I.; Kasari-Toussaint, L.; Oja, J.; Olsson, P.A.; Sepp, S.K.; Zobel, M. Co-introduction of native mycorrhizal fungi and plant seeds accelerates restoration of post-mining landscapes. *J. Appl. Ecol.* **2020**, *57*, 1741–1751. [CrossRef]
36. Meng, C.; Lanlan, Z.; Zhen, L.; Zhiqing, Z.; Liping, Z.; Yuanfang, H. Effects of regenerated periods and vegetation modes on soil microbial functional diversity in regenerated land of opencast coal mine. *Trans. Chin. Soc. Agric. Eng.* **2019**, *35*, 278–285.
37. Institute of Soil Science, Chinese Academy of Sciences. *Soil Physical Properties Determination Method*; Science Press: Beijing, China, 1978.
38. Bao, S. *Soil Agrochemical Analysis*; China Agriculture Press: Beijing, China, 2000.
39. Wang, Y.; Jiang, Z.; Wang, J. Impact of sloping land conversion program on coupling of agricultural ecological system. *Syst. Eng. Theory Pract.* **2015**, *35*, 3155–3163.
40. Organisation for Economic Co-Operation and Development (OECD). *Environmental Indicators-Development, Measurement and Use*; OECD: Paris, France, 2003.
41. Guo, C.; Zhang, F.; Wang, X.; Lu, N. Effects of meteorology and soil on the herb species diversity in plantations in a reclamation area of coal mine after 6 years. *Environ. Sci. Pollut. Res.* **2020**, *27*, 24231–24241. [CrossRef]
42. Feng, F.; Xu, L.; Gu, Q.; Liu, Y.; Yang, Y.; Liu, R. Characteristics of natural plant community and its relationship with soil physi-chemical properties in Ningdong mining area. *Bullet. Soil Water Conserv.* **2021**, *41*, 48–56.
43. Wang, L.; Guo, D.; Bai, Z.; Shangguan, T. Species composition and spatial pattern of understory herbaceous plants on an ecological rehabilitation site from open coal mining. *Chin. J. Appl. Environ. Biol.* **2012**, *18*, 399–404. [CrossRef]
44. Geng, B.; Wang, S.; Cao, Y.; Guo, C.; Guo, D.; Zhao, B.; Bai, Z. Comparative analysis of vegetation reconstruction characteristics of different years in the reclaimed land of the Pingshuo opencast mining area, Shanxi Province. *Acta Ecol. Sin.* **2022**, *42*, 3400–3419.
45. Gou, Q.; Liu, J.; Wang, G.; Zhao, F. Changes of herbaceous plant composition and niche characteristics in differentaged artificial Caragana korshinskii forest in sandy-hilly region of northwest Shanxi Province, China. *Acta Ecol. Sin.* **2022**, *22*, 1–22.
46. Hao, H.; Liu, Y.; Wang, D.; Yang, Z.; Wu, G. Influence of Restoration on Community Plant Diversity and Spatial Structure of Typical Grasslands. *Acta Agrestia Sin.* **2016**, *24*, 754–759.
47. Nie, Y.; Xu, L.; Xin, X.; Chen, B.; Zhang, B. Effects of fence enclosure on the plant community composition and niche characteristics in a temperate meadow steppe. *Acta Prataculturae Sin.* **2020**, *29*, 11–22.
48. Zhang, Y.; Zhou, Q.; Xu, J.; Wei, M.; Chen, J.; He, W.; Wang, P.; Yan, Z. Effects of Forest Ages on the Diversity of Understory Plants and Soil Seed Bank of Pinus massoniana Plantations. *Ecol. Environ. Sci.* **2021**, *30*, 2121–2129.
49. Mao, Y.; Chen, F.; Guo, Y.; Liu, J.; Jiang, F.; Li, X. Restoration dynamics of understory species diversity in Castanopsis hystrix plantations at different ages. *Chin. J. Appl. Environ. Biol.* **2021**, *27*, 930–937.
50. Wang, C.; Fu, B.; Zhang, L.; Xu, Z. Soil moisture–plant interactions: An ecohydrological review. *J. Soils Sediments* **2019**, *19*, 1–9. [CrossRef]
51. Gao, R.; Ai, N.; Liu, G.; Liu, C.; Zhang, Z. Soil C:N:P Stoichiometric Characteristics and Soil Quality Evaluation under Different Restoration Modes in the Loess Region of Northern Shaanxi Province. *Forests* **2022**, *13*, 913. [CrossRef]
52. Wang, Q.; Quan, Z.; Han, Y.; Fu, M.; Ye, Y. Variation of Vegetation Diversity and Its Soil Relationship with Soil Physical and Chemical Property in Lands of Different Geomorphic Types in Coal Mining Subsidence Area. *Acta Bot. Boreal. Occid. Sin.* **2014**, *34*, 1642–1651.
53. Cui, N.; Zhang, D.; Liu, Y.; Zhang, J.; Ou, J.; Zhang, J.; Chao, D.; Tuowei, J. Plant diversity and soil physicochemical properties under different aged Pinus massoniana plantations. *Chin. J. Ecol.* **2014**, *33*, 2610–2617.
54. Jiao, J.; Zhang, Z.; Bai, W.; Jia, Y.; Wang, N. Assessing the ecological success of restoration by afforestation on the Chinese Loess Plateau. *Restor. Ecol.* **2012**, *20*, 240–249. [CrossRef]
55. Souza, A.F.; Ramos, N.P.; Pizo, M.A.; Hübel, I.; Crossetti, L.O. Afforestation effects on vegetation structure and diversity of grasslands in southern Brazil: The first years. *J. Nat. Conserv.* **2013**, *21*, 56–62. [CrossRef]
56. Wang, H.; Zhang, M.; Nan, H. Abiotic and biotic drivers of species diversity in understory layers of cold temperate coniferous forests in North China. *J. For. Res.* **2019**, *30*, 2213–2225. [CrossRef]
57. Huang, Z. Soil Water Balanc of Typical Artificial and Natural Grasslands in the Semi-Arid Loess Plateau. Master's Thesis, Northwest A&F University, Xianyang, China, 2017.
58. Wang, L. Comprehensive Evaluation of Vegetation Disturbance-Damage-Restoration and Restoration Scheme in Mining Area from the Perspective of Resilience. Ph.D. Thesis, China University of Mining and Technology, Xuzhou, China, 2021.
59. Bobbink, R.; Hicks, K.; Galloway, J.; Spranger, T.; Alkemade, R.; Ashmore, M.; Bustamante, M.; Cinderby, S.; Davidson, E.; Dentener, F. Global assessment of nitrogen deposition effects on terrestrial plant diversity: A synthesis. *Ecol. Appl.* **2010**, *20*, 30–59. [CrossRef] [PubMed]
60. Walter, C.A.; Raiff, D.T.; Burnham, M.B.; Gilliam, F.S.; Adams, M.B.; Peterjohn, W.T. Nitrogen fertilization interacts with light to increase Rubus spp. cover in a temperate forest. *Plant Ecol.* **2016**, *217*, 421–430. [CrossRef]
61. Wu, J.; Liu, W.; Fan, H.; Huang, G.; Wan, S.; Yuan, Y.; Ji, C. Asynchronous responses of soil microbial community and understory plant community to simulated nitrogen deposition in a subtropical forest. *Ecol. Evol.* **2013**, *3*, 3895–3905. [CrossRef] [PubMed]
62. Xu, L.; Feng, F.; Liu, Y.; Yang, Y.; Zheng, W. Relationship between plant species diversity and soil chemical properties in coal gangue dump:early stage of ecological restoration in Lingwu Mining Area. *Coal Sci. Technol.* **2020**, *48*, 97–104.
63. Chen, X.; Li, Y.; Zuo, Y.; Lin, S.; Chu, D.; He, K. Effects of Stand Characteristics and Soil Nutrient Characteristics on Herbaceous Diversity. *Acta Bot. Boreal. Occid. Sin.* **2022**, *42*, 1396–1407.

64. Hu, Y.; Feng, Q.; Yin, X.; Tang, G.; Xu, L.; Li, F.; Peng, H.; Zhang, J. Effects of planting grasses under forests on physical and chemical properties of forest soils in Northern Guangdong. *Chin. J. Grassl.* **2021**, *43*, 58–65.
65. Strengbom, J.; Walheim, M.; Näsholm, T.; Ericson, L. Regional differences in the occurrence of understorey species reflect nitrogen deposition in Swedish forests. *Ambio* **2003**, *32*, 91–97. [CrossRef]
66. Odum, E.P. Productivity and biodiversity: A two-way relationship. *Bull. Ecol. Soc. Am.* **1998**, *79*, 125.
67. Yuan, X.; Gao, Z.; Zhang, X.; Du, J.; Bai, H.; Xu, B. Improved effects of different legume plants on the abandoned soil field in the Loess Plateau. *Sci. Soil Water Conserv.* **2016**, *14*, 121–127.
68. Li, X.; Zhang, M.; Guo, Y.; Li, D.; Deng, Y.; Lu, Z. Relationship Between Understory Plant Diversity and Soil Factors in Coal Mining Subsidence Area. *J. Soil Water Conserv.* **2022**, *36*, 268–276.
69. Bao, Y.; Wang, J.; Sun, D.; Liu, Y. Study on Technology of Stumping and Rejuvenating of Hipplphae Rhamnoides Linn. *Prot. For. Sci. Technol.* **2004**, *3*, 14–20.
70. Li, T.; Li, Y.; Tian, T.; He, B.; Xu, D.; Gao, J.; Li, G. Density dynamics with model adjustments for stump sprouts of *Hippophae rhamnoides subsp. sinensis*. *J. Zhejiang A F Univ.* **2011**, *28*, 713–719.
71. Zhao, X.; Xie, Y.; Ma, X.; Wang, S. Vegetation structure and its relationship with soil physicochemical properties in restoring sandy grassland in Horqin Sandy Land. *J. Desert Res.* **2022**, *42*, 134–141.