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Five Years of Natural Vegetation Recovery in Three Forests of Karst Graben Area and Its Effects on Plant Diversity and Soil Properties

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Abstract: In recent decades, excessive human activities have led to large-scale rocky desertification in karst areas. Vegetation restoration is one of the most important ways to control rocky desertification. In this study, vegetation surveys were conducted on three typical plantations in Jianshui County, Yunnan Province, a typical karst fault basin area, in 2016 and 2021. The plantations were *Pinus massoniana* forest (PM), *Pinus yunnanensis* forest (PY), and mixed forests of *Pinus yunnanensis* and *Quercus variabilis* (MF). Plant diversity and soil nutrients were compared during the five-year period. This paper mainly draws the following results: The plant diversity of PM, PY, and MF increased. With the increase of time, new species appeared in the tree layer, shrub layer, and herb layer of the three forests. Tree species with smaller importance values gradually withdrew from the community. In the tree layer, the Patrick index, Simpson index, and Shannon–Wiener index of the three forests increased significantly. The Pielou index changed from the highest for PM in 2016 to the highest for PY in 2021. In the shrub layer, the Pielou index of the three forests increased. The Patrick index changed from the highest for MF in 2016 to the highest for PY in 2021. There was no significant difference in species diversity index for the herb layer. With the increase of vegetation restoration time, the soil bulk density (BD) of the three forests decreased. There was no significant difference in soil total porosity (TP), soil capillary porosity (CP), and non-capillary porosity (NCP). The pH of PM increased significantly from 5.88~6.24 to 7.24~7.34. The pH of PY decreased significantly ($p < 0.05$). The contents of total nitrogen (TN) and ammonium nitrogen (NH_4^+-N) in PY and MF decreased. The content of nitrate nitrogen (NO_3^--N) in the three forests increased significantly ($p < 0.05$). Total phosphorus (TP) content decreased in PM and MF. The content of available phosphorus (AP) in PM and PY increased. In general, with the increase of vegetation restoration time, plant diversity and soil physical and chemical properties have also been significantly improved. The results can provide important data support for vegetation restoration in karst areas.

Keywords: vegetation restoration; biodiversity; soil nutrients; rocky desertification; karst fault basin

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1. Introduction

The karst area in Southwest China is one of the largest continuous distribution areas of exposed carbonate rocks in the world [1–3]. The ecosystems of karst areas are fragile, and are characterized by barren soil layers, discontinuous soil, fast water leakage, and high levels of rock exposure [4,5]. Unreasonable human activities such as forest destruction in the karst region have led to large-scale rocky desertification in the region, which has had a serious impact on the ecological environment and has constrained the sustainable development of the region [6–9]. Ecological restoration is particularly difficult after vegetation destruction, and vegetation restoration and rehabilitation are an urgent requirement for improving ecological and environmental problems in the region [10]. Species diversity and soil physicochemical properties are important indicators of ecosystem health in the process of vegetation restoration. On the one hand, the increase in the number of species and the enrichment of species can improve the anti-disturbance ability and adaptability of the ecosystem, thus better maintaining the functional integrity and ecological balance [11]. On the other hand, soil texture, organic matter content, soil carbon, nitrogen and phosphorus content, acidity and alkalinity, and other physicochemical properties are also directly related to the nutrient uptake and health status of plants [12–14].

In the process of vegetation restoration, through the introduction of suitable tree species and native plants, plantation forests can rapidly increase vegetation cover, build a multi-level, multi-species ecosystem, and provide suitable habitats and ecological niches for other species [15,16]. This not only helps to recover and protect endangered species, but also promotes the interaction and symbiosis between species, thus enriching the diversity of community species. It has been shown in the Guangxi karst region that plantation forest vegetation restoration significantly increased the α-diversity of soil microorganisms, with particularly significant effects on bacterial abundance and fungal abundance [17]. Other scholars found that karst plant diversity showed an increasing trend of species diversity with vegetation restoration through the study of Maolan National Nature Reserve in Guizhou [18]. With the restoration of vegetation, community stratification and community structure became more obvious and complete, and the quantitative characteristics of plant communities were also significantly improved [19]. Additionally, vegetation restoration can significantly increase the organic carbon, nitrogen, and phosphorus content of soil by increasing vegetation cover, reducing soil erosion, and improving soil structure, and it also helps to restore the fertility of the soil [20–22]. The results of some scholars who studied the effects of vegetation restoration on the physicochemical properties of soils in the tropical karst region of southwestern China showed that vegetation restoration can effectively improve the content of total nitrogen and total phosphorus, which is conducive to the rapid restoration of vegetation in the Nonggang National Nature Reserve [23]. Some scholars have also studied the changes of soil K, N, and P after forest restoration in Shilin Stone Forest Geographical Park in Yunnan, and found that total nitrogen, available nitrogen, and total phosphorus contents increased in the 0–100 cm soil layer during the vegetation restoration process from grass to shrub [24]. In summary, studies have provided a preliminary understanding of the trends in species diversity and soil physico-chemical properties in karst areas as a result of vegetation restoration. However, due to the diversity of karst landscapes, the results of different studies are not consistent, and more in-depth studies should be conducted on typical regions to provide theoretical support.

In this study, Jianshui County, Yunnan Province, a typical karstic faulted basin area, was taken as the study area. PM, PY, and MF were used as the study objects to carry out the investigation of species diversity and the study of soil properties. This study aimed to (1) to analyze the differences in community structure and species diversity of different forests at different stages of restoration, and (2) to investigate the effects of different stages of restoration on the physicochemical properties of soils in different forests. The aim is to provide a scientific basis for revegetation of karst areas and restoration of damaged ecosystems.

2. Materials and Methods

2.1. Study Area

The study area was located in Jianshui County, Yunnan Province (102°33′–103°11′ E, 23°12′–24°10′ N), on the southern edge of Yunnan Guizhou Plateau. The landscape is typical of a karstic faulted basin area. The climate belongs to a subtropical climate, with sufficient sunlight and long frost-free period. Rainfall distribution is extremely uneven. Seasonal drought often occurs in this area. The altitude is 2515 m. The annual average temperature in this area is 18.9 °C, the annual average precipitation is 600~800 mm, and the rainfall from May to October accounts for 80.23% of the annual rainfall. Evaporation is 2311.19 mm, which is 2.7 times the total rainfall. The dominant vegetation type is evergreen deciduous broad-leaved mixed forest. The main trees include *Pinus massoniana*, *Pinus yunnanensis*, *Cyclobalanopsis glauca*, *Quercus variabilis*, *Puccinella*, and *Zelkova*. Shrubs include *Myrsine africana*, *Nitraria tangutorum*, *Dodonaea viscosa*, *Lindera communis* etc. Herbs mainly include *Eulaliopsis binata*, *Trifolium repens*, *Arthraxon hispidus*, *Heteropogon contortus*, *Magnolia liliiflora*, *Oplismenus undulatifolius*, etc.

2.2. Sample Plot Setting, Plant Investigation and Sample Collection

Different forests with similar altitude, slope, parent rock, soil type, and typical representative were selected as research plots (Table 1). The forests were *Pinus yunnanensis* forest, *Pinus massoniana* forest, and *Pinus yunnanensis* and *Quercus variabilis* mixed forest, which were established in 2002. Comprehensive vegetation surveys were conducted in 2016 and 2021. Four 20 m × 20 m tree samples, five 5 m× 5 m shrub samples, and nine 1 m × 1 m herb samples were selected for investigation in each sample plot, totaling 12 tree, 15 shrub, and 27 herb samples. Tree survey indicators included species name, diameter at breast height (DBH), height, and crown width and coordinates were recorded in the tree layer. The height, number of plants, basal diameter, crown width, and total coverage of each quadrat were recorded in the shrub layer (DBH ≤ 1 cm). Abundance, average height, species coverage, and total coverage were recorded in the herb layer. Meanwhile, environmental factors such as geographic location, elevation, slope, slope direction, soil type, and rock bareness were recorded, as well as height, cover, and dominant species at each level of the community.

Table 1. Basic information on geographical and vegetation characteristics of different study areas.

Vegetation Types	Geographic Location	Mother Rock	Soil Type	Elevation (m)	Slope Direction	Slope (°)
PM	102°57.3284′ 23°42.6571′	Limestone	Brown calcareous soil	1480	South	11°
PY	23°40.4983′ 102°46.6766′	Limestone	Red calcareous soil	1560	Northeast	16°
MF	102°45.6766′ 23°40.4651′	Limestone	Brown calcareous soil	1607	Southwest	33.6°

Note: PM: Pinus massoniana forest; PY: Pinus yunnanensis forest; MF: mixed forest of Pinus yunnanensis and Quercus variabilis.

Soil sampling and vegetation surveys were carried out simultaneously. Before sampling, the litter on the surface of the soil was removed. Stratified sampling was carried out at 0–10 cm, 10–20 cm, and 20–30 cm in this study. Soil sample collection is divided into two parts. One part is to use a ring knife to collect the undisturbed soil of each soil layer for the determination of soil physical properties. The other part is based on the five-point sampling method, using a soil drill from the ground down through the three layers of sampling, for a total of 90 soil samples. The same layer of soil was uniformly mixed into one soil sample and marked for the determination of soil chemical properties. After the mixed soil sample was naturally air-dried, it was passed through a 2 mm sieve for subsequent determination.

2.3. Data Analysis Methods

The calculation formula of species importance value (IV) of plants in tree layer, shrub layer, and herb layer are as follows:

$$\mathrm{IV(Tree, Shrub)} = (\mathrm{RA} + \mathrm{RD} + \mathrm{RF})/3 \tag{1}$$

$$\mathrm{IV(Herb)} = (\mathrm{RA} + \mathrm{RC} + \mathrm{RF})/3 \tag{2}$$

where IV: importance value; RA: relative abundance; RD: relative significance; RF: relative frequency; RC: relative coverage. In order to analyze the changes of plant species richness and diversity in tree layer, shrub layer, and herb layer, the Simpson index (*D*), Shannon–Wiener index (H'), Patrick index (*R*), and Pielou (*J*) index were calculated. The calculation formulas are as follows:

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

$$H\prime = -\sum_{i=1}^{S} P_i \ln P_i \tag{4}$$

$$R = S \tag{5}$$

$$J = \frac{H'}{lnS} \tag{6}$$

In the formula, S is the number of species, and P_i is the importance value of the species i.

2.4. Measurement of Soil Physical and Chemical Properties

Soil physical properties were analyzed as follows: soil bulk density (BD), total porosity (TP), capillary porosity (CP), and non-capillary porosity (NCP) were measured by ring knife immersion method. Soil pH was determined by the potentiometric method [25]. Soil organic carbon (SOC) content was determined by potassium dichromate oxidation dilution calorimetry [26]. Soil total nitrogen (TN) and total phosphorus (TP) were determined by sulfuric acid digestion method [27]. Soil ammonium nitrogen (NH_4^+-N) was determined by potassium chloride extraction-indophenol blue colorimetric method. Soil nitrate nitrogen (NO_3^--N) was determined by original distillation method and copper-chromium column reduction-diazo coupling colorimetry. Available phosphorus (AP) was determined by using the molybdenum antimony anti-colorimetric method with ammonium fluoride hydrochloride extraction.

2.5. Data Processing

One-way analysis of variance (ANOVA) with least significant difference (LSD) test and Student's test were performed using IBM SPSS Statistics 26.0. The relevant charts were completed by GraphPad Prism 9.2.0 software.

3. Results

3.1. Plants Divesity and Type in Different Forests

The total number of plants investigated included 73 families, 106 genera, and 138 species in this study. The top 10 dominant families are *Pinaceae*, *Sapindaceae*, *Poaceae*, *Apocynaceae*, *Rosaceae*, *Primulaceae*, *Fagaceae*, *Santalaceae*, *Asteraceae*, and *Rhamnaceae*. Among them, the vegetation types in the tree layer, shrub layer, and herb layer were 48, 28, and 62 species, respectively, accounting for 34.78%, 20.29%, and 44.93% of the total number of species. With the increase of restoration years, plant diversity was higher in 2021 than 2016 (Table 2). The number of families changed from the highest for MF and the lowest for PM in 2016 to the highest for PY and the lowest for PM in 2021. The number of genera and species is still MF > PY > PM. Among them, PM in 2021 had an increase of seven families, seven genera, and seven species over 2016. PY 2021 increased by eight families, five species, and five genera over 2016. MF 2021 had an increase of one family, two genera, and four species over 2016, and the change in plant diversity was not significant. In terms of plant type, the number of trees is still MF > PY > PM. The number of shrubs changed from the same number of PY and MF in 2016 to PY > MF > PM in 2021. The number of herbs changed from MF > PY > PM to PY > MF > PM. Among them, the abundance of trees and shrubs of PM increased and the abundance of herbs decreased in 2021. The abundance of trees and herbs increased, and the abundance of shrubs decreased in PY and MF.

Table 2. Plants diversity and type in different forests at different years of restoration.

Vegetation Types	Restoration Years	Plants Diversity (NO. of Taxa)			Plants Type (Growth Habit)		
		Family	Genera	Species	Tree	Shrub	Herb
PM	2016	13	19	20	4	1	17
	2021	20	26	27	8	4	14
PY	2016	36	40	40	14	13	16
	2021	44	45	45	15	12	20
MF	2016	38	46	49	23	13	12
	2021	37	48	53	27	9	17

Note: PM: Pinus massoniana forest; PY: Pinus yunnanensis forest; MF: mixed forest of Pinus yunnanensis and Quercus variabilis.

3.2. Sspecies Importance Value and Community Structure in Different Forests

The plant diversity at different levels of the community and their position in the community changed significantly in different restoration stages (Table 3).

For PM in 2016, the dominant species were *Pinus massoniana*, *Dodonaea viscosa*, *Myrsine Africana*, *Arthraxon hispidus*, *Capillipedium assimilale, Arundinella setosa*, and other plants with strong heliophyte, cold resistant, barren resistance, water resistance, and wind resistance. *Silene linearifolia*, *Imperata cylindrical*, *Dalbergia hupeana*, and *Cyperus rotundus* were auxiliary species. By 2021, the vertical structure of *Pinus massoniana* forest was more obvious. The species composition of tree layer, herb layer, and shrub layer changed significantly, and the original dominant species were retained. *Rhamnus leptophylla*, *Broussonetia papyrifera*, and *Morus cathayana* were added to the tree layer. *Myrsine Africana* and *Sophora davidii* appeared in the shrub layer. The barren tolerant species in the herb layer, *Imperata cylindrical*, withdrew from the community, while the plants such as *Caulis fici tikouae, Bidens pilosa, Barreria cristata,* and *Cymbopogon distans* entered the community and occupied a dominant position.

For PY in 2016, the dominant species were *Pinus yunnanensis*, *Myrsine africana*, *Dodonaea viscosa*, *Osteomeles anthillidifolia*, *Carissa spinarum*, *Arundinella setosa*, and other dominant species with heliophyte, cold resistance, barren resistance, and strong sprouting. *Cupressus lusitanica, Viburnum ditatum, Rhamnus leptophylla, Quercus cocciferoides*, and *Smilax china* were auxiliary species. By 2021, the dominant species of PY had changed significantly. *Elaeagnus pungens* and *Phyllanthus emblica* were added to the tree layer. *Osyris wightiana, Smilax china, Toxicodendron succedaneum*, and *Breynia fruticose*, all warm-loving, sun-loving, and barren-tolerant, were added to the shrub layer. *Senecio scandens*, *Dalbergia hupeana*, and *Carissa spinarum*, etc., were added to the herb layer.

Table 3. Importance values of vegetation communities with different restoration years.

Vegetation Types	Restoration Years	Tree Layer	Shrub Layer	Herb Layer
PM	2016	*Pinus massoniana* 0.6712 *Dodonaea viscosa* 0.2622 *Fraxinus malacophylla* 0.1057 *Osteomeles anthyllidifolia* 0.0549	*Dodonaea viscosa* 1.4511	*Arundinella setosa* 0.7760 *Capillipedium assimile* 0.7139 *Silene linearifolia* 0.7511 *Imperata cylindrical* 0.6202 *Cyperus rotundus* 0.4094 *Arthraxon hispidus* 0.3815 *Dalbergia hupeana* 0.1720
	2021	*Pinus massoniana* 0.5250 *Dodonaea viscosa* 0.1943 *Fraxinus malacophylla* 0.1423 *Osteomeles anthyllidifolia* 0.0859 *Myrsine africaba* 0.0739 *Rhamnus leptophylla* 0.0578 *Broussonetia papyrifera* 0.0489 *Morus cathayana* 0.0512	*Dodonaea viscosa* 0.8168 Sophora davidii 0.19 *Myrsine africaba* 0.14	*Cymbopogon distans* 0.8607 *Arundinella setosa* 0.7760 *Silene linearifolia* 0.7511 *Senecio scandens* 0.3944 *Caulis fici tikouae* 0.7555 *Bidens pilosa* 0.5111 *Barleria cristata* 0.4219 *Bidens pilosa* 0.5111
PY	2016	*Pinus yunnanensis* 0.3289 *Dodonaea viscosa* 0.2355 *Cupressus lusitanica* 0.1067 *Carissa spinarum* 0.0755 *Osteomeles anthyllidifolia* 0.0762 *Rhamnus leptophylla* 0.0722 *Viburnum dilatatum* 0.0491 *Myrsine africaba* 0.0166	*Dodonaea viscosa* 0.3983 *Myrsine africaba* 0.3674 *Smilax china* 0.2972 *Quercus cocciferoides* 0.2389 *Osteomeles anthyllidifolia* 0.2084 *Rhamnusleptophylla* 0.1999 *Indigofera ruffruticosa* 0.1999	*Heteropogon contortus* 1.0948 *Dalbergia hupeana* 0.5985 *Arthraxon hispidus* 0.3514 *Silene linearifolia* 0.5728 *Arundinella setosa* 0.4345 *Dodonaea viscosa* 0.2336 *Caulis fici tikouae* 0.2267 *Rubia cordifolia* 0.3332
	2021	*Osteomeles anthyllidifolia* 0.1205 *Albizia julibrissin* 0.0990 *Carissa spinarum* 0.1087 *Cupressus lusitanica* 0.1349 *Dodonaea viscosa* 0.0781 *Elaeagnus pungens* 0.0238 *Phyllanthus emblica* 0.0209	*Myrsine africaba* 0.3570 *Quercus cocciferoides* 0.2117 *Osteomeles anthyllidifolia* 0.1942 *Viburnum dilatatum* 0.1953 *Osyris wightiana* 0.3851 *Smilax china* 0.1798 *Toxicodendron succedaneum* 0.0665 *Breynia fruticose* 0.0961	*Arundinella setosa* 0.6029 *Miscanthus* 0.51 *Myrsine africaba* 0.6145 *Cymbopogon distans* 1.0138 *Senecio scandens* 0.4714 *Eulaliopsis binata* 0.2616 *Dalbergia hupeana* 0.6374 *Carissa spinarum* 0.3531
MF	2016	*Pinus yunnanensis* 0.2417 *Quercus variabilis* 0.3521 *Osyris wightiana* 0.0734 *Myrsine africana* 0.0189 *Carissa spinarum* 0.0336 *Castanopsis delavayi* 0.0667 *Rhamnusleptophylla* 0.0571 *Vaccinium vitis-idaea* 0.1256	*Myrsine africana* 0.5054 *Osyris wightiana* 0.1867 *Quercus variabilis* 0.1127 *Michelia yunnanensis* 0.2162 *Smilax china* 0.1233 *Phyllanthus emblica* 0.0624 *Symplocos sumuntia* 0.0615 *Toxicodendron succedaneum* 0.0685	*Arundinella setosa* 0.6309 *Duhaldea cappa* 0.5743 *Ophiopogon japonicus* 0.8151 *Eulaliopsis binata* 0.6053 *Pinellia ternata* 0.4870 *Osyris wightiana* 0.4239
	2021	*Pinus yunnanensis* 0.2397 *Quercus variabilis* 0.3227 *Viburnum cylindricum* 0.4434 *Schima argentea* 0.0304 *Toxicodendron delavayi* 0.0287 *Osyris lanceolata hochst* 0.0403 *Osyris wightiana* 0.0855 *Olea tsoongii* 0.0220 *Lyonia ovalifolia* 0.0120	*Myrsine africana* 0.4553 *Rhamnus leptophylla* 0.25 *Osyris wightiana* 0.2533 *Quercus variabilis* 0.3015 *Vaccinium vitis-idaea* 0.13 *Carissa macrocarpa* 0.1 *Osyris lanceolata Hochst* 0.3142	*Arundinella setosa* 0.7209 *Osyris wightiana* 0.5401 *Ophiopogon japonicus* 0.7633 *Eulaliopsis binata* 0.3967 *Alfaropsis roxburghiana* 0.4525 *Capillipedium assimile* 0.4842 *Rubia cordifolia* 0.3328 *Isodon enanderianus* 0.3089

For MF in 2016, *Pinus yunnanensis*, *Quercus variabilis*, *Osyris wightiana*, *Myrsine Africana*, *Carissa spinarum*, *Arundinella setosa*, *Duhaldea cappa*, and other plants that prefer light, wind, drought, and acidic soils were dominant. By 2021, the plant diversity of MF experienced a lower amount of change, and a total of four new species entered the community. The species of *Vaccinium vitis-idaea* with smaller importance value in tree layer exited the study area. On the contrary, *Schima argentea*, *Toxicodendron delavayi*, *Osyris lanceolata hochst*, and *Osyris wightiana*, which prefer fertile, moist, and loose soil, entered the community. *Phyllanthus emblica*, *Toxicodendron succedaneum*, *Symplocos sumunta*, and *Smilax china*, with lower importance values, exited, and were replaced by *Carissa spinarum*, *Osyris lanceolata hochst*, and *Elsholtzia ciliata* with water logging resistance in the shrub layer. *Alfaropsis roxburghiana*, *Capillipaedium assimilale*, *Rubia cordifolia*, and *Isodon enanderianus*, which are suitable for growing in a humid and cool environment, entered the community in the herb layer.

3.3. Species Diversity of Different Forests

With the growth of restoration years, the Patrick index and Shannon–Wiener index of PM showed an increased trend in the tree layer, shrub layer, and herb layer. The Simpson index of PM increased in the tree and herb layers and decreased in the shrub layer. The Pielou index of PM increased in the shrub layer and herb layer, while decreasing in the tree layer. The Patrick index, Shannon–Wiener index, and Pielou index of PY increased in the tree layer, shrub layer, and herb layer. Among them, the Pielou index of the tree layer of PY increased significantly ($p < 0.05$). The Simpson index of PY increased in the tree and herb layers and decreased in the shrub layer. The Simpson index, Shannon–Wiener index, and Pielou index of MF showed an increased trend in the tree layer, shrub layer, and herb layer. The Patrick index of MF increased in the tree and herb layers and decreased in the shrub layer. In the tree layer (Figure 1a,b), with the increase of vegetation restoration time, the Patrick index showed MF > PY > PM. The Simpson index and Shannon–Wiener index showed PY > MF > PM. However, the Pielou index changed from the highest for PM in 2016 to the highest for PY in 2021. In the shrub layer (Figure 1e–h), the Patrick index changed from the highest for MF in 2016 to the highest for PY in 2021. The Simpson index, Shannon–Wiener index, and Pielou index still showed PY > MF > PM during the five years of vegetation restoration. In the herb layer (Figure 1i–l), there were no significant difference in species diversity index among the three forests.

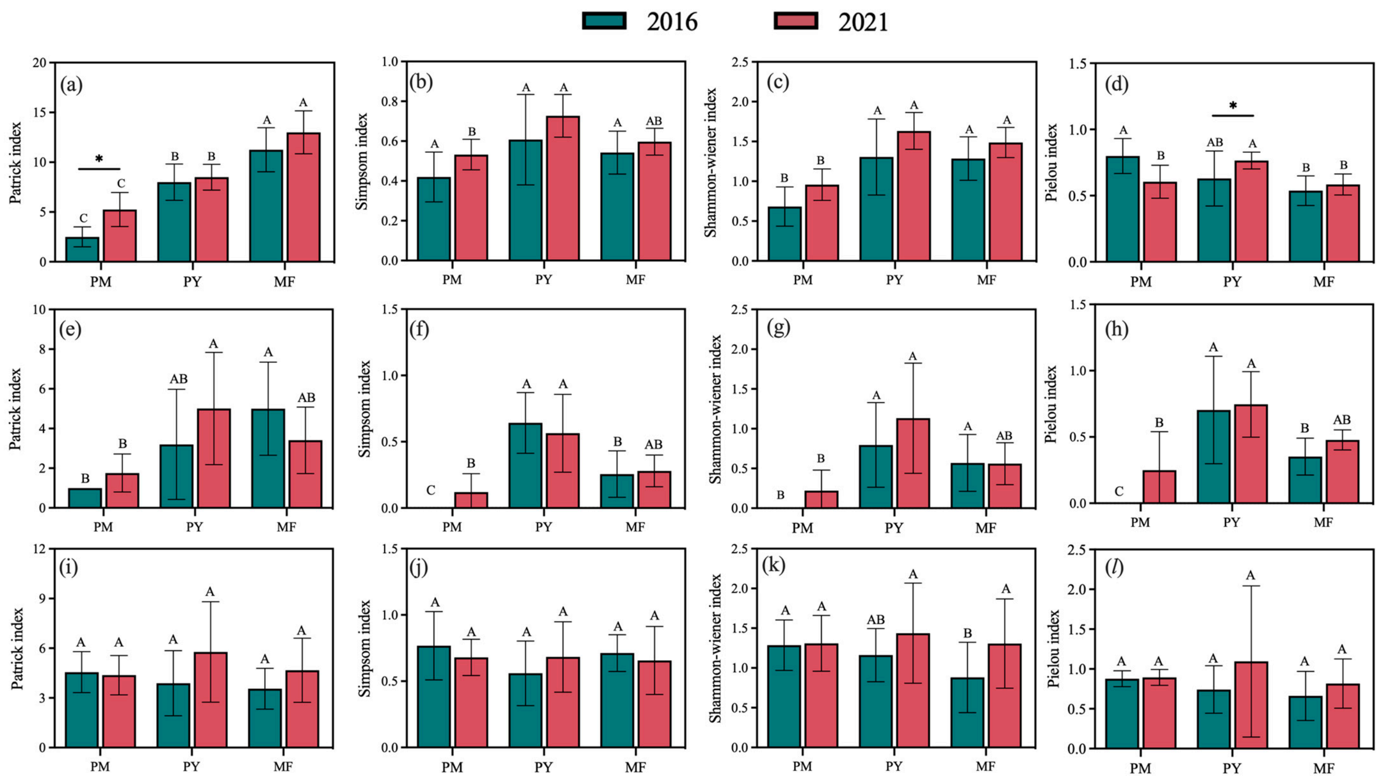

Figure 1. Species diversity of plant communities in different restoration years. (**a**–**d**): species diversity of tree layer; (**e**–**h**): species diversity of shrub layer; (**i**–**l**): species diversity of herb layer. Note: PM: *Pinus massoniana* forest; PY: *Pinus yunnanensis* forest; MF: mixed forest of *Pinus yunnanensis* and *Quercus variabilis*. Capital letters indicate the significance of different forest types in the same year ($p < 0.05$). * indicates the significance of the same forest types and soil layers in different years ($p < 0.05$).

3.4. Soil Physical Characteristics

With the increase of vegetation restoration years, the BD of MF decreased in the 0–10 cm, 10–20 cm, and 20–30 cm soil layers, and decreased significantly in the 0–10 cm soil layer

($p < 0.05$). The BD of PY decreased significantly in the 0–10 cm soil layer ($p < 0.05$). The BD of PM decreased in the 20–30 cm soil layer, but it was not significant. The TP of the three forests was the highest in the 0–10 cm soil layer (Figure 2b). The TP of MF increased by 13.03% and 7.72% in 0–10 cm and 10–20 cm soil layers, respectively. In 2016, the TP of the three forests showed PM > PY > MF in the 0–10 cm soil layer. By 2021, PY and MF gradually increased, reaching the same level of PM. In the 2016–2021 vegetation restoration stage, the CP of PM decreased in the 0–10 cm and 10–20 cm soil layers, while it increased in the 20–30 cm soil layer (Figure 2c). There was no significant difference in MF. By 2021, the NCP of PM increased between 219.48% and 617.05% in the 0–30 cm soil layer (Figure 2d). The NCP of PY increased by 213.31% in 10–20 cm soil layer. MF increased by 256.95% and 172.01% in 0–10 cm and 10–20 cm soil layers, respectively.

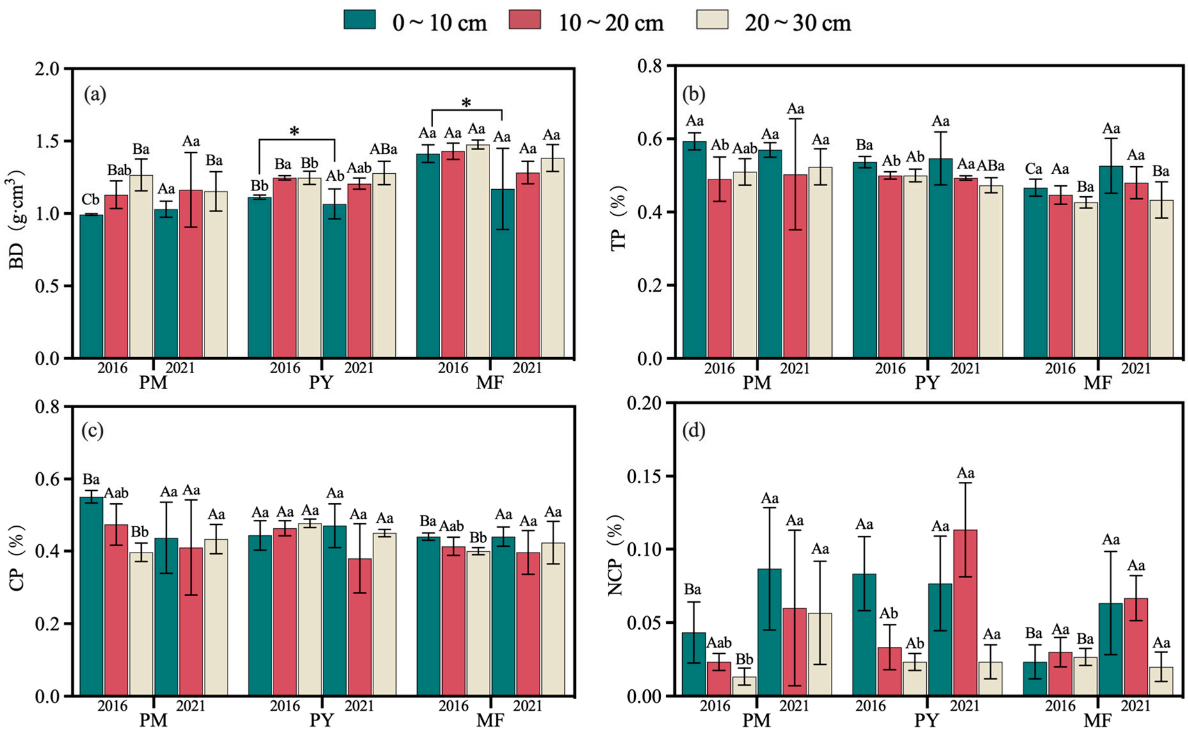

Figure 2. Soil physical properties of different recovery years in different soil layers. Note: PM: *Pinus massoniana* forest; PY: *Pinus yunnanensis* forest; MF: mixed forest of *Pinus yunnanensis* and *Quercus variabilis*. (**a**) BD: bulk density; (**b**) TP: total porosity; (**c**) CP: capillary porosity; (**d**) NCP: non-capillary porosity. Capital letters indicate the significance of different forest types in the same year and soil layers ($p < 0.05$); small letters indicate the significance of different soil layers in the same year and forest types ($p < 0.05$); * indicates the significance of the same forest types and soil layers in different years ($p < 0.05$).

3.5. Soil Chemical Characteristics

In the process of vegetation restoration from 2016 to 2021, soil chemical properties have different changes. The soil pH value of PM increased ($p < 0.05$) from 5.88~6.24 to 7.24~7.34 in 0~30 cm soil layer (Figure 3a). The pH of PY showed a downward trend ($p < 0.05$). The pH of MF increased significantly in the 0~10 cm soil layer and decreased in the 10–30 cm soil layer. The SOC content of PM increased in 10–20 cm soil layer, while the SOC content of PY decreased in the 10–20 cm soil layer (Figure 3b). With the increase of recovery time, the SOC content of MF showed a downward trend, which was more significant ($p < 0.05$) in the 20–30 cm soil layer. The TN content of PM increased in the 10–30 cm soil layer. The TN content of PY was significantly decreased, and it was more significant in the 0–10 cm soil layer ($p < 0.05$) (Figure 3c). The TN content of MF showed a downward trend in the 0–30 cm soil layer, with a range of 91.45%–97.95%. The NH_4^+-N content of PM and PY increased by 22.60%–37.14% and 179.3%–313.33%, respectively (Figure 3d). In contrast, the NH_4^+-N content of MF showed a downward trend in the 0–20 cm soil layer. The NO_3^-–N content of three forests showed an increased trend ($p < 0.05$), increasing by 123.74%–217.45%, 126.27%–287.88%, and 354.1%–428.12%, respectively (Figure 3e). The TP content of PM decreased by 35.14%–69.56%. The TP content of PY decreased significantly in the 0–10 cm soil layer. The TP content of MF was significantly reduced by 42.85% in the 20~30 cm soil layer (Figure 3f). The AP content of PM increased in the 0–20 cm soil layer (Figure 3g). The AP content of PY showed an increasing trend, increasing by 89%–150.67%. The AP content of MF showed a downward trend.

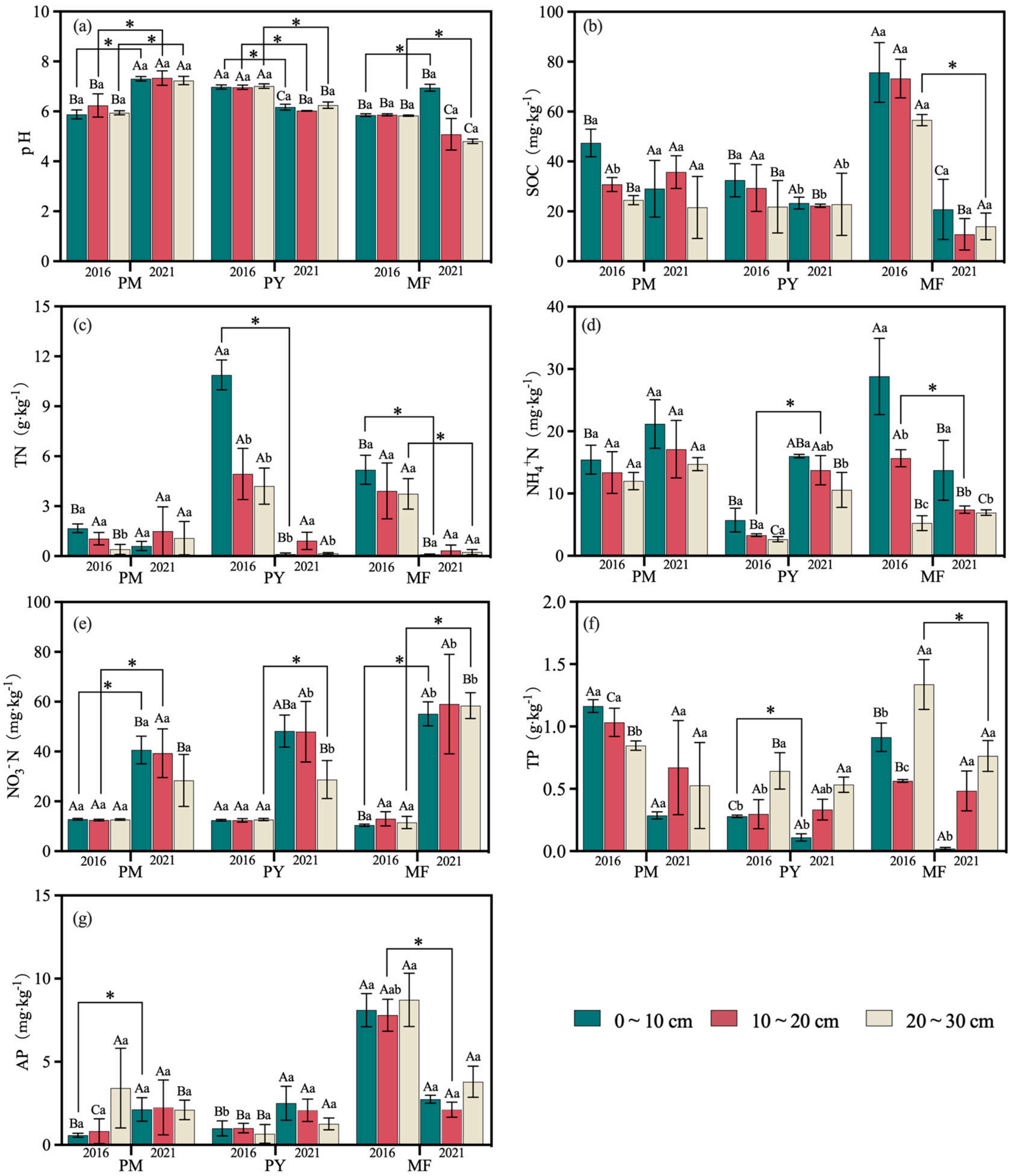

Figure 3. Soil chemical properties of different recovery years in different soil layers. Note: PM: *Pinus massoniana* forest; PY: *Pinus yunnanensis* forest; MF: mixed forest of *Pinus yunnanensis* and *Quercus variabilis*. (**a**) pH: potential of hydrogen; (**b**) SOC: soil organic carbon; (**c**) TN: total nitrogen; (**d**) NH_4^+-N: ammonium nitrogen; (**e**) NO_3^--N: nitrate nitrogen; (**f**) TP: total phosphorus; (**g**) AP: available phosphorus. Capital letters indicate the significance of different forest types in the same year and soil layers ($p < 0.05$); small letters indicate the significance of different soil layers in the same year and forest types ($p < 0.05$); * indicates the significance of the same forest types and soil layers in different years ($p < 0.05$).

4. Discussion

4.1. Effects of Different Restoration Years on Plant Community Succession

The results of this study indicate that vegetation restoration has a positive impact on plant diversity and types. With the increase in restoration years, the plant community gradually evolved from simple to complex. The number of families, genera, and species of PM, PY, and MF in 2021 was higher than that in 2016. This result is consistent with the conclusions of other scholars [28,29]. In PM, the number of tree layers and shrub layers increased, while the number of herb layers decreased. *Pinus massoniana,* as an exotic but native-adapted tree species, is highly competitive and dominates with the passage of recovery time [30]. The shrub layer also gradually recovered, forming a complex community structure together with the tree layer and the herb layer. With the growth and canopy closure of trees and shrubs, the light and growth space of herbaceous plants are limited [31]. By 2021, the vertical structure of the community becomes more obvious. On the basis of the original dominant species being retained, new shade-tolerant species such as *Rhamnus leptophylla* and *Broussonetia papyrifera* were added to the tree layer. *Myrsine africana* and *Sophora davidii* appeared in the shrub layer. The exit of species such as *Imperata cylindrical* in the herb layer and the emergence of barren tolerant species and those more adapted to the micro-environment within the community, such as *Caulis fici tikouae* and *Bidens pilosa*, have led to a more diverse and complex vegetation mix [32]. It is also indicative of a transition from an early successional state, characterized by species adapted to extreme conditions, to a more stable and diverse forest [33]. In PY, significant changes in vegetation types between 2016 and 2021 reflected the resilience and adaptability of the ecosystem. That is, the number of tree layers and herb layers showed the same upward trend, while the shrub layer decreased. Yunnan pine, as a local tree species, is highly adaptable to the environment of karst regions, and can rapidly occupy the ecological niche and form a stable tree layer. The number of herbaceous plants gradually increased as their growing conditions improved under the shade of the tree layer. The decline of the shrub layer may be related to the competition between trees and herbaceous plants. With the gradual depression of the tree layer and the growth of the herbaceous layer, the shrub layer received less light and fewer nutrients, and the space for growth was limited [34]. However, as the restoration process progressed, species such as *Elaeagnus pungens* and *Phyllanthus emblica* were added to the tree layer. New species such as dry sandalwood, *Osyris wightiana*, and *Smilax china,* which are thermophilic, sun-loving, and tolerant of barrenness, also appeared in the shrub layer. The community shifted toward greater diversity and multi-layeredness. The continued increase of species such as *Senecio scandens* and *Dalbergia hupeana* in the herb layer also suggests the important role of certain species in forest regeneration [35]. This process is further illustrated by the substitution patterns observed in MF. Species such *Phyllanthus emblica* and *Smilax china* in the shrub layer were replaced by other species more suited to wet and fertile conditions. This change in the degree of species dominance reflects the evolution of ecological niches in restored forests, where the number of plant species changes in response to environmental conditions [36].

According to the results of the study, the species richness and evenness of PM, PY, and MF showed an overall increasing trend between 2016 and 2021. The community structure became more balanced and diverse after the increase in the number of years of restoration [37]. The increase in species diversity in the tree layer was consistent with the community succession process. That is, over time, new species enter the community and ecological processes become more complex [38]. The species richness of PM increased in 2021 compared to 2016, but the Pielou evenness index decreased. This suggests that although the number of species in the PM increased, the distribution of these species was not uniform, possibly due to the dominance of a few species or the restoration of patches. In addition, no significant change was observed in PM in the herb layer, which may reflect the slower recovery of herbaceous species in poorer or stressed sample sites [39]. For PY and MF, the increase in species richness and evenness of the vegetation communities indicated the increased stability of the community structure. In karst areas, soils are infertile and have poor water-holding capacity due to specific geological conditions [40,41]. However, with the time of restoration, *Pinus massoniana*, which is a dominant tree species in karst areas, has gradually increased its adaptability and resilience, and its special leaf structure is more helpful for reducing water evaporation and resisting drought [42]. At the same time, *Pinus yunnanensis* and *Quercus variabilis* form a mixed forest, more able to play a complementary role in drought and barrenness resistance. The overall results of the study showed that the vegetation restoration showed good signs of increasing species diversity.

4.2. Effects of Different Restoration Years on Soil Properities

According to the results of this study, the BD of PM, PY, and MF showed a decreasing trend, and the TP showed an increasing trend in the soil surface layer. Decreasing BD implies an increase in soil porosity and an improvement in water infiltration, which in turn characterizes a positive contribution to plant growth and soil fertility in the three forests [43]. In the case of PM, pH shifted from weakly acidic in 2016 to neutral in 2021. Improvements in pH acidity favorably promote nutrient availability. In weakly acidic soils, some nutrients that are beneficial to the growth of ponytail pine may form insoluble compounds that reduce their effectiveness. Neutral soils, on the other hand, contribute to the release and increased effectiveness of these nutrients, thereby increasing soil fertility [44]. At the same time, the pH of neutral soils tends to increase the bioavailability of key plant nutrients, such as phosphorus (P) and potassium(K), while P and K are usually limited in acidic soils [45]. In terms of SOC, the SOC content of PM in 2021 increased in the 10–20 cm soil layer. This reflects the accumulation of organic matter over the years. This is consistent with the idea that vegetation restoration leads to an increase in soil organic matter, which in turn supports soil fertility and microbial diversity [46,47]. However, the decline in SOC content in PY and MF suggests that the two forests have not yet captured and retained as much organic matter, which may be due to less effective vegetation cover or slower organic matter turnover [48]. TN levels also showed a similar trend to SOC. That is, total nitrogen (TN) increased in the 10~30 cm soil layer of PM, while it decreased in PY and MF. The increase in TN content in PM indicated enhanced nitrogen (N) cycling. This may have been achieved through nitrogen fixation by certain plant species as well as improved soil structure [49]. On the other hand, the decrease in N content in PY and MF suggests that the N cycle has not been fully restored or may be impeded by soil characteristics or vegetation type. NH_4^+-N content increased significantly in PM and PY compared to 2016 [50]. This suggests an increase in N availability, especially in PM. This increase may be related to the activity of nitrogen-fixing species and microbial processes that enrich the soil. However, the decrease in NH_4^+-N content in MF may reflect changes in the microbial community or a shift to other forms of nitrogen.

5. Conclusions

The natural recovery of vegetation in the forests of the Karst graben area plays a crucial role in restoring ecological balance, enhancing plant diversity, and improving soil properties. This process not only fosters biodiversity by supporting the regeneration of native plant species but also significantly influences soil structure, nutrient cycling, and organic carbon sequestration, thereby contributing to the overall resilience and sustainability of these fragile ecosystems. The conclusions from our study are as follows:

(1) With the increase of vegetation restoration time, the increase of plant diversity in terms of family and genus species was significant. It shows that the increase in restoration time is significant in promoting plant diversity and plant types.

(2) With the increase of vegetation restoration time, newborn tree species gradually arose in the tree, shrub, and herb layers of each stand, and species with less importance values gradually withdrew from the community.

(3) Vegetation species richness and evenness were found to be on the rise compared to 2016, indicating that the time of vegetation restoration positively influences species diversity from a monocommunity to a complex community structure.

(4) Soil pH changed from weakly acidic to neutral, and NH_4^+–N and NO_3^-–N content increased in the three forests. This shows that the physicochemical properties of the soil were enhanced with the increase of vegetation restoration time.

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