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# Effects of Rubber Plantation Restoration in National Parks on Plant Diversity and Soil Chemical Properties

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**Abstract:** Plantations left for natural succession play a significant role in Tropical Rainforest National Parks. Studying the succession and restoration of plantations is crucial for achieving a park's authenticity and integrity, as well as for maximizing its ecological functions. However, the changes in vegetation and soil properties during the natural succession of these decommissioned plantations remain unclear. In this study, we examined rubber [(*Hevea brasiliensis* (Willd. Ex A. Juss.) Muell. Arg] plantations in the Yinggeling area of the National Park of Hainan Tropical Rainforest. We used community surveys, field sampling, and soil property analyses to investigate the species richness, diversity, and species composition of the aboveground plant communities during three succession periods of rubber plantations left for natural succession, including 0 years (ZY), 3 years (TY), and 7 years (SY). The soil pH, total organic carbon, total nitrogen, total phosphorus, available phosphorus, nitrate nitrogen, ammonium nitrogen, and total potassium contents in the three succession periods were analyzed. These results showed that there were 92 species of understory plants in the decommissioned rubber plantations, belonging to 72 genera in 39 families. The highest number of understory plant species was found in the plantations with 3 years of natural succession, totaling 66 species from 49 genera in 29 families. The number of families, genera, and species followed the pattern TY > SY > ZY. The Margalef richness index (F), Simpson index (D), and Shannon–Wiener index (H) of understory plants in the 0-year succession plantations were significantly lower than those in the 3-year and 7-year succession plantations. However, there was no significant difference in the Pielou (EH) index among the succession gradients. The soil pH, nitrate nitrogen (NO3--N), and available phosphorus (AP) in the 0-year succession plantations were significantly higher than those in the 3-year and 7-year succession plantations. There were no significant differences in soil total nitrogen (TN), total phosphorus (TP), total organic carbon (TOC), and ammonium nitrogen (NH4+-N) across the three succession gradients. The soil total potassium (TK) in the 3-year succession plantations was significantly higher than that in the 0-year and 7-year succession plantations. Soil available phosphorus and total phosphorus (TP) were positively correlated with the Margalef index, Simpson index, Shannon–Wiener index, and Pielou index. The recovery rate of understory vegetation in decommissioned rubber plantations was faster than that of the soil. This indicates that the construction of the National Park of Hainan Tropical Rainforest has significantly promoted the recovery of the number of plant species and plant species diversity that have been left from rubber plantation operations. These findings not only deepen our understanding of soil property changes during the vegetation succession of artificial forests, particularly rubber plantations, but they also hold significant implications for guiding tropical forest management and sustainable development.

**Keywords:** rubber plantations left for natural succession; ecological restoration; plant diversity; National Park of Hainan Tropical Rainforest

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## 1. Introduction

Ecological restoration relies on the self-regulating ability of ecosystems, aiming to restore degraded ecosystems to their pre-degradation state [1]. Ecological restoration is of great significance in addressing increasingly severe ecological and environmental problems and has consequently attracted much attention from researchers worldwide [2]. Forest restoration includes two methods: natural restoration and artificial afforestation. Among these, vegetation restoration, a natural method, is one of the most effective forest restoration techniques [3]. Planted forests play a pivotal role in forest resources, yet studies on the natural recovery of plantations, especially rubber [(*Hevea brasiliensis* (Willd. Ex A. Juss.) Muell. Arg] plantations left for natural succession, are scarce. The restoration of understory vegetation in these recovering artificial rubber plantations is primarily reflected in the diversity of understory plants, which enhances biodiversity and contributes to ecosystem stability.

As an integral part of the artificial forest ecosystem, understory vegetation is crucial for maintaining stability, productivity, nutrient recycling, and energy flow within the ecosystem [4]. In recent years, some scholars have made significant progress in researching the biodiversity of understory vegetation in artificial forests and its impacts. For instance, Li et al. [5] studied the effect of understory planting modes on Yunnan pine (*Pinus yunnanensis*) vegetation diversity, finding that a 30% disturbance mode was optimal for planting *Macropanax dispermus* under Yunnan pine forests. Randriamananjara et al. [6] examined differences in understory vegetation diversity and composition between hybrid poplar (*Populus* spp.) and spruce (*Picea* spp.) single plantations and mixed plantations, concluding that mixed plantations had higher understory vegetation diversity.

Artificial rubber plantations are typical artificial forest ecosystems in tropical areas. Research on the understory vegetation of these plantations mainly focuses on the relationship between plant diversity and environmental factors. Studies by Zeng Runjuan et al. [7] have shown that temperature and precipitation are key factors affecting plant diversity in rubber plantations. Wang Qun et al. [8] found that management methods significantly impact plant diversity in these plantations. Comparative analyses have also revealed that understory vegetation diversity in rubber plantations is higher than in Eucalyptusspp. forests but lower than in secondary and natural forests [9–11]. Most ecological processes in ecosystems use soil as a carrier, and the relationship between soil properties and plant diversity evolves with vegetation succession [12]. During plant community succession, soil and plants interact, with different plant communities resulting in varying soil chemical properties, which in turn influence many ecological processes and affect above-ground vegetation succession [13].

Several studies have explored the relationship between plant diversity and soil properties. For example, Zhao Man et al. [14] investigated this relationship in Quercusvariabilis cork–Quercus wutaishansea mixed forests after forest fire disturbance, finding correlations between vegetation species diversity and soil properties. Lu Haifei et al. [15] studied species diversity and soil properties in Eucalyptus grandis plantations at different growth stages, also finding significant correlations. Ma et al. [16] examined the soil characteristics of rocky desertification areas and their impact on plant diversity, identifying nitrogen, phosphorus, and potassium as key factors influencing species composition and distribution. Research by Sanaei et al. [17] demonstrated that tree species diversity enhances plant-soil interactions in temperate forests in Northeast China. Additionally, Spohn et al. [18] revealed that ecosystem management to restore plant diversity may enhance soil carbon sequestration, particularly in warm and arid climates.

Tropical rainforests are among the most complex biological communities on Earth in terms of structure and species diversity. In China, Hainan Island and Xishuangbanna in Yunnan Province are the primary areas of tropical rainforests. The tropical rainforests in Hainan Island, covering about 30% of the area, are key for studying biodiversity [19]. Since the establishment of Hainan Tropical Rainforest National Park, over 330,000 hectares of plantations have been left for natural succession. However, changes in plant community characteristics and soil properties during the natural recovery of these plantations remain unclear. Therefore, this study focused on rubber plantations in the Yinggeling area of Hainan Tropical Rainforest National Park. Using typical sampling methods, we conducted field surveys for three succession periods: 0 years (ZY), 3 years (TY), and 7 years (SY). We measured species richness, diversity, and species composition of the above-ground plant community and assessed soil pH, total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), available phosphorus (AP), nitrate nitrogen, ammonium nitrogen, and total potassium (TK) content during these succession periods.

This study investigates the diversity of understory plant communities and soil properties during the succession process of rubber plantations left for natural succession. The findings reveal the relationship between changes in above-ground plant diversity and soil properties during tropical forest succession, providing insights into soil property changes during vegetation succession in artificial forests. This research offers a scientific basis for the natural restoration of rubber plantations and other artificial forests and is significant for guiding tropical forest management and sustainable development.

## 2. Materials and Methods

### 2.1. Study Area

The study site is located in the Yinggeling area of the National Park of Hainan Tropical Rainforest (109°11′27″~109°34′06″E, 18°49′30″~19°08′41″N), China. The area is situated in the mountainous central and southern part of Hainan Island in China. The central and eastern parts feature red-layer landforms. The area spans Baisha County, Qiongzhong County, Wuzhishan City, Changjiang County, and Ledong County, covering a total area of 861.7 $km^2$. The general control area is 409 $km^2$, and the core protected area is 4520 $km^2$ [20]. The soil in Yinggeling is yellow, and the area falls within a maritime monsoon climate zone, with an average annual temperature of 20–24 °C, average annual precipitation of 1800–2700 mm, and annual evaporation of 1600–2000 mm [21]. According to our previous survey, the artificial forest area in Yinggeling Reserve is 18,399.1933 hectares, with the rubber plantation area accounting for 6567.14 hectares, or 35.69% of the total artificial forest area. With the establishment of the National Park of Hainan Tropical Rainforest, more than 330,000 hectares of planted forests have been left to natural succession. Therefore, this study focuses on rubber plantations in the Yinggeling area of the National Park of the Hainan Tropical Rainforest.

### 2.2. Experimental Design

The typical sample method was used to conduct understory vegetation surveys in rubber plantations of advanced age (more than 21 years old) that had been out of operation for 0, 3, and 7 years in the study area. Three 1 ha plots were selected for each restoration age gradient, and three 20 m × 20 m quadrats were set up diagonally in each plot, resulting in a total of 27 survey quadrats of 20 m × 20 m.

### 2.3. Plant Diversity Survey

In each 20 m × 20 m quadrat, a survey of trees and shrubs was conducted, recording the species name, diameter at breast height, tree height, crown width, longitude, latitude, canopy density, altitude, slope, aspect, and other basic information.

### 2.4. Determination of Soil Chemical Properties

In each 20 m × 20 m quadrat, the plum blossom five-point sampling method was utilized to collect surface soil at a depth of 0−20 cm, following the removal of surface litter and humus [22]. The collected soil was then mixed to create a composite sample. Subsequently, the soil was air-dried, screened, and analyzed for pH, total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), available phosphorus (AP), nitrate nitrogen ($NO_3$-N), ammonium nitrogen (NH4+-N), and total potassium (TK) content [23].

### 2.5. Data Statistical Analysis

Based on the vegetation data obtained from field surveys, the species Marglef richness index (F), Simpson index (D), Shannon–Wiener index (H), and Pielou evenness index ($E_H$) within the quadrat were analyzed and calculated.

(1) Shannon–Wiener index (H): $H' = -\sum_{i=1}^{S} Pi\ln Pi$;
(2) Simpson index (D): $D = 1 - \sum_{S=1}^{S} Pi^2$;
(3) Pielou uniformity index ($E_H$): $E_H = \frac{H'}{\ln S}$;
(4) Marglef richness index (F): $F = \frac{S-1}{\ln N}$.

In the formulas provided, S represents the number of species, N represents the total number of individuals of the species, and Pi represents the proportion of the number of individuals of the i-th species to the total number of individuals.

The preliminary statistical compilation of all vegetation data and soil chemical properties was completed using Excel 2021 office software. Origin 2021 Pro (https://www.originlab.com/2021 (13 July 2024)) was used to conduct single-factor variance analysis (significant level, $p < 0.05$) and draw graphics on the understory vegetation diversity data and soil chemical properties of rubber plantations at different succession times. Canoco 5 (http://canoco5.com (13 July 2024)) was used to conduct redundancy analysis and draw an RDA ranking chart on the relationship between understory plant diversity and soil chemical properties of rubber plantations at different recovery times.

## 3. Results

### 3.1. Analysis of Understory Plant Species Composition of Rubber Plantations Left for Natural Succession

The survey and analysis revealed a total of 92 species of understory plants in rubber plantations that have been left for natural succession, encompassing 72 genera and 39 families. In contrast, only 15 species of understory plants were found in rubber plantations that had undergone 0 years of natural restoration, representing 10 genera and 12 families (Table 1). The rubber plantation in natural succession for 3 years exhibited the highest number of understory plant species, with 66 species from 49 genera and 29 families. Conversely, the rubber plantation in natural succession for 7 years had slightly fewer understory species, with 52 species spanning 45 genera and 28 families. Overall, the order of families, genera, and species follows TY > SY > ZY. The above research results show that during the natural recovery process, compared with the rubber plantations in which the rubber plantations had recovered for 0 years, the understory plants in the rubber plantations in which the rubber plantations had recovered for 3 years and 7 years were significantly richer and more diverse in their composition. The strategy of rubber plantations left for natural succession that actually promoted the natural recovery of the understory plant species.

**Table 1.** Species composition of rubber plantation understory at different successional times.

| ST | NS | NF | NG |
|---|---|---|---|
| ZY | 15 | 12 | 10 |
| TY | 66 | 29 | 49 |
| SY | 52 | 28 | 45 |
| Total | 134 | 81 | 104 |

Note: “ZY” represents a rubber plantation with 0 years of natural succession; “TY” represents a rubber plantation with 3 years of natural succession; “SY” represents a rubber plantation with 7 years of natural succession. ST represents succession time, NS represents the number of species, NF represents the number of families, and NG represents the number of genera.

### 3.2. Analysis of Plant Species Diversity Under Rubber Plantations Left for Natural Succession

The survey results indicate that the average values of the Pielou evenness index (EH), Shannon–Wiener index (H), and Simpson index (D) were highest in the understory plant community of the rubber plantation after 7 years of natural succession, compared to a rubber plantation restored for 3 years. The Margalef richness index (F) was highest in the understory plant community at that time (see Figure 1). Significant differences ($p < 0.05$) were observed in the Margalef richness index, Simpson index (D), and Shannon–Wiener index (H) among these groups (Figure 1). Additionally, there was no significant difference in the Pielou evenness index of the understory plant communities in rubber plantations with natural successions of 0, 3, and 7 years ($p > 0.05$).

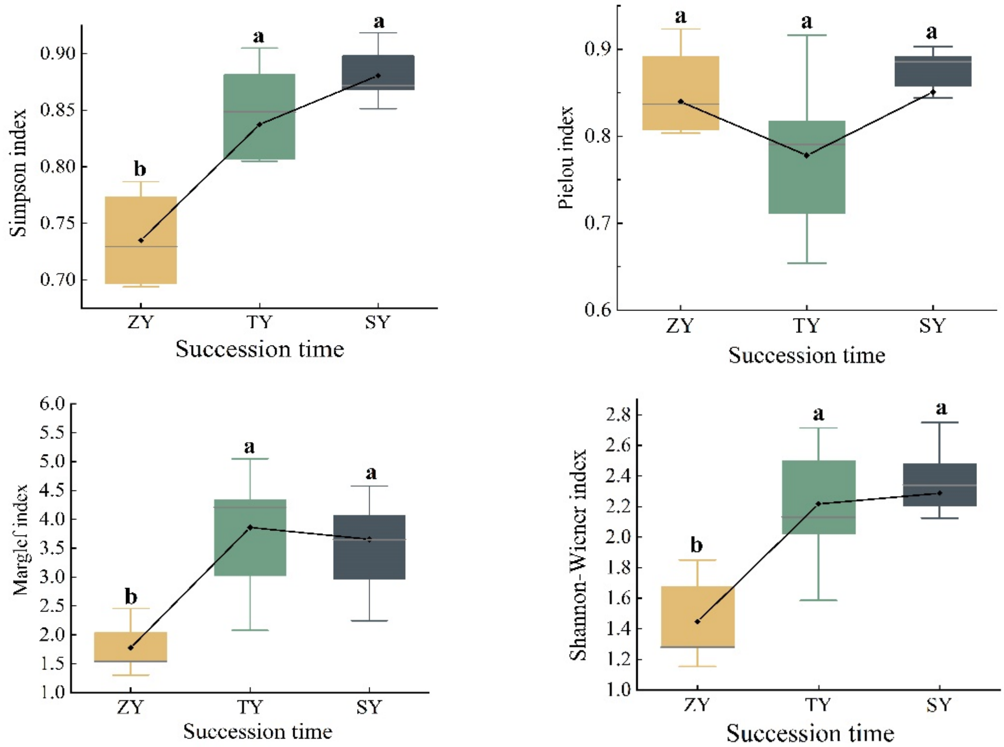


**Figure 1.** Species diversity of understory plants in rubber plantations with different succession times. Note: "ZY" represents a rubber plantation with 0 years of natural succession; "TY" represents a rubber plantation with 3 years of natural succession; "SY" represents a rubber plantation with 7 years of natural succession. Different letters (a, b) indicated significant difference at 0.05 level.

### *3.3. Analysis of Soil Chemical Properties of Rubber Plantations Left for Natural Succession*

#### 3.3.1. Analysis of Soil pH of Natural Succession Rubber Plantations

The soil pH of the rubber plantations with 0, 3, and 7 years of natural succession was all less than 7, indicating acidic soil. The soil pH of the rubber plantation that was left for natural succession in the 0th year of restoration was significantly higher than that of the rubber plantation restored for 3 and 7 years ($p < 0.05$). However, there was no significant difference in the soil pH between the rubber plantations restored for 3 years and 7 years (Table 2).

**Table 2.** Differences in soil pH at different successional times (significant level, $p < 0.05$).

| ST | pH |
|---|---|
| ZY | 5.74 ± 0.58a |
| TY | 5.19 ± 0.19b |
| SY | 5.19 ± 0.26b |

Note: "ZY" represents a rubber plantation with 0 years of natural succession; "TY" represents a rubber plantation with 3 years of natural succession; "SY" represents a rubber plantation with 7 years of natural succession. ST represents succession time. Different letters (a, b) indicated significant difference at 0.05 level.

#### 3.3.2. Analysis of Soil Chemical Properties in Natural Succession Rubber Plantations

During the natural restoration process, the average organic carbon value of the rubber garden soil reached its peak in the 0th year at 4.35 g/kg, which was 10.12% higher than the initial 3 years of restoration and 6.41% higher than the 7th year of restoration. The highest levels of soil total nitrogen and total phosphorus were observed in the first year of natural recovery, with total nitrogen content at 2.96 mg/kg and total phosphorus content at 0.25 g/kg. The soil in the rubber plantations that had been out of operation exhibited the highest total nitrogen and total phosphorus content, while the lowest average content was found after 3 years of natural recovery, with total nitrogen being 61.74% lower than in the initial recovery year and total phosphorus 2.44% lower. The average total potassium content was at its highest in rubber plantations after 3 years of natural restoration, at 13.81 g/kg, and at its lowest after 7 years, measuring 6.41 g/kg, 115.36% lower than after 3 years of natural restoration. Regarding soil available phosphorus content, the rubber plantations left for natural succession had the highest level at 3.45 mg/kg in the first year of natural recovery and the lowest after three years of recovery, at 345.76% lower compared to the initial year of recovery. The ammonium content in the soil of the rubber plantations that ceased operation was 3.45 mg/kg. The highest ammonium nitrogen and nitrate nitrogen contents were found at 0 years of natural recovery, with ammonium nitrogen at 9.05 mg/kg and nitrate nitrogen at 2.81 mg/kg. The levels were at their lowest after 3 years of restoration, with ammonium nitrogen at 6.60 mg/kg, 27.13% lower than in the initial recovery year, and nitrate nitrogen 87.35% lower than at the beginning of natural recovery (Figure 2).

Investigation and analysis results showed that there were no significant differences in soil total nitrogen (TN), total phosphorus (TP), and ammonium nitrogen (NH4+-N) in rubber plantation soils that had been naturally restored for 0, 3, and 7 years ($p > 0.05$). There were significant differences in total organic carbon (TOC) between the rubber plantations with 0 years of succession and the rubber plantations with 3 and 7 years of succession, and the total organic carbon (TOC) of the rubber plantations with 3 years of succession and the rubber plantations with 7 years of succession were also significantly different ($p < 0.05$). There were significant differences in total potassium (TK) in rubber plantation soils with 0, 3, and 7 years of natural succession. There was a significant difference in available phosphorus (AP) between the 0-year and 7-year rubber plantation soils. The nitrate nitrogen (NO3-N) in the rubber plantation soil of 0 years of natural succession was significantly different from that of the rubber plantation soil of 3 years of natural succession and 7 years, but there was no significant difference in soil nitrate nitrogen (NO3-N) in rubber plantation soils of 3 years and 7 years of natural succession (Figure 2).

### *3.4. Relationship Between Plant Diversity and Soil Chemical Properties in Rubber Plantations Left for Natural Succession*

RDA analysis was conducted on the species diversity indices (Margalef index, Simpson index, Shannon–Wiener index, and Pielou index) and eight soil factors of each quadrat (Figure 3). The cumulative total explanation of the four axes was 42.87%, and the top two axes effectively reflect the correlation between species diversity and soil factors in the rubber plantation understory. Soil available phosphorus is positively correlated with the Simpson index, Shannon–Wiener index, and Pielou index (Figure 3). Soil organic carbon is positively correlated with the Shannon–Wiener index, Simpson index, and Marglef index, and nitrate nitrogen is positively correlated with the Simpson index and Marglef index. The order of soil factor explanation rates is pH > TOC (g/kg) > AP(mg/kg) > TP(g/kg) > TK(g/kg) > TN (mg/kg), with pH having a significant positive correlation with plant species diversity under the rubber plantation ($p < 0.05$) (Table 3).

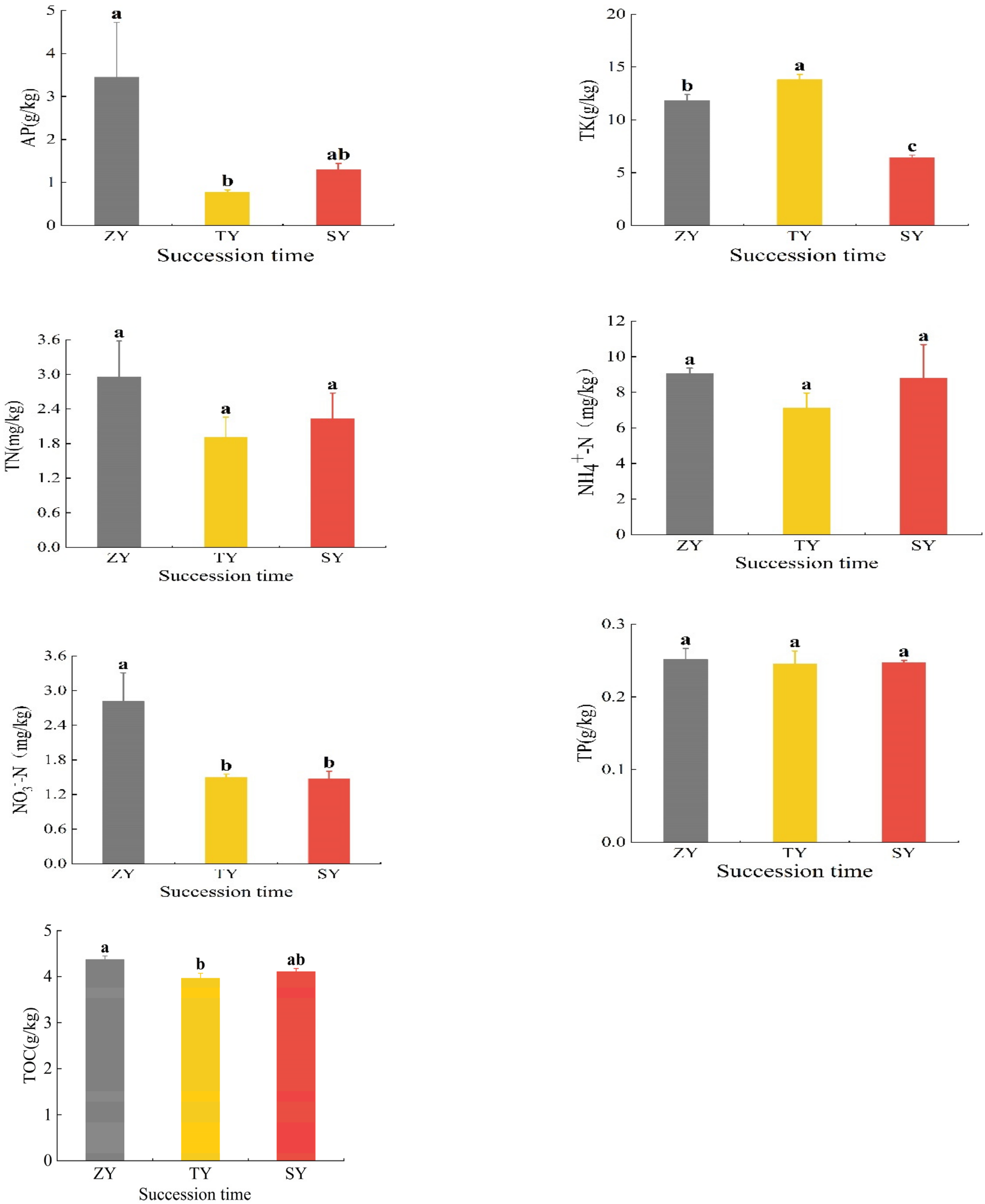


**Figure 2.** Analysis of soil chemical properties of rubber plantations at different successional times. Note: "ZY", "TY", and "SY are the variables, and soil properties as explanatory variables. "ZY" represents a rubber plantation with 0 years of natural succession; "TY" represents a rubber plantation with 3 years of natural succession; "SY" represents a rubber plantation with 7 years of natural succession. Different letters (a, b) indicated significant difference at 0.05 level.

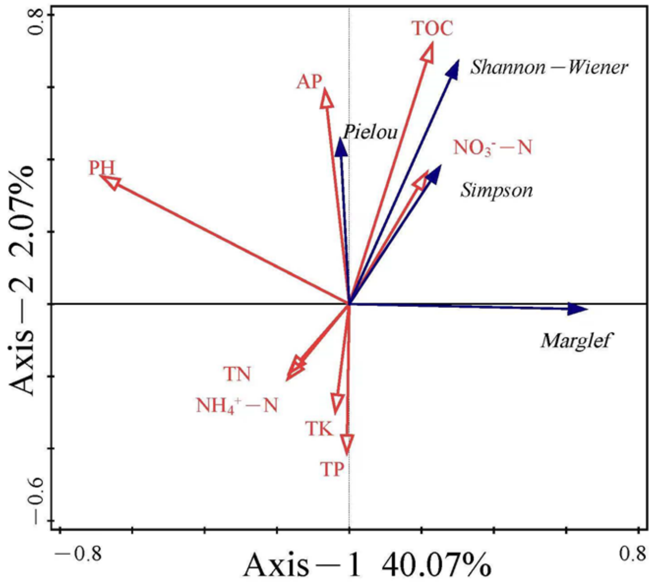


**Figure 3.** RDA ranking of plant diversity and soil physicochemical properties in rubber plantation understory at different succession times. Note: "Pielou", "Shannon–Wiener", "Simpson", and "Marglef" are the variables, and soil properties as explanatory variables.

**Table 3.** Explanatory rate of RDA analysis of soil physicochemical properties.

| Name | Explains % | Contribution % | Pseudo-F | *p* |
|---|---|---|---|---|
| pH | 19.3 | 45.0 | 5.0 | 0.032 |
| $NO_3^-$−(mg/kg) | 6.2 | 14.4 | 1.7 | 0.188 |
| TP(g/kg) | 7.3 | 17.1 | 2.1 | 0.158 |
| $NH_4^+$–N(mg/kg) | 2.1 | 4.8 | 0.6 | 0.496 |
| TK(g/kg) | 0.9 | 2.1 | 0.2 | 0.654 |
| AP(mg/kg) | 3.8 | 8.9 | 1.0 | 0.322 |
| TN(mg/kg) | 3.0 | 7.0 | 0.8 | 0.378 |

### *3.5. Comparative Analysis of the Recovery Speed of Understory Vegetation and Soil Chemical Properties in Rubber Plantations Left for Natural Succession*

As shown in Figure 4, the change rate of the diversity index of the understory vegetation from 0 to 3 years after the natural restoration of the rubber plantation was positive, except for the Pielou index, which was negative. The Margalef index change rate of the understory vegetation reached 54%, the Shannon–Wiener index change rate was 34.71%, and the Simpson index change rate was 12.35%. The recovery rate of soil properties from 0 to 3 years after the natural restoration of rubber plantations was positive. However, except for the change rates of total potassium content and total organic carbon content, the content change rates of other soil properties were negative. The change rate of total potassium content was 14.25%, and the change rate of total organic carbon content was 4.98%, with the change rate of soil available phosphorus content being particularly notable at 345.76%.

The recovery rate of understory vegetation during the natural recovery stage of 3 to 7 years for rubber plantations was lower than that in the 0 to 3-year natural recovery stage. The Margalef index change rate was −5.63%, the Shannon–Wiener index change rate was 3.09%, the Simpson index change rate was 4.20%, and the Pielou index change rate was 6.31%. The change rate of total organic carbon content in the soil from 3 to 7 years after the natural restoration of the rubber plantation was −25.69%, which was 30.67% lower than the period from 0 to 3 years. The change rate of soil available phosphorus content during this period was −25.69%, representing a 40.10% increase from 0 to 3 years, with a significant rise of 385.86%. Overall, the change rate of soil properties in the rubber plantation, except for total phosphorus, total potassium, and total organic carbon, showed a downward trend, while these specific properties exhibited an increasing trend (Figure 4).

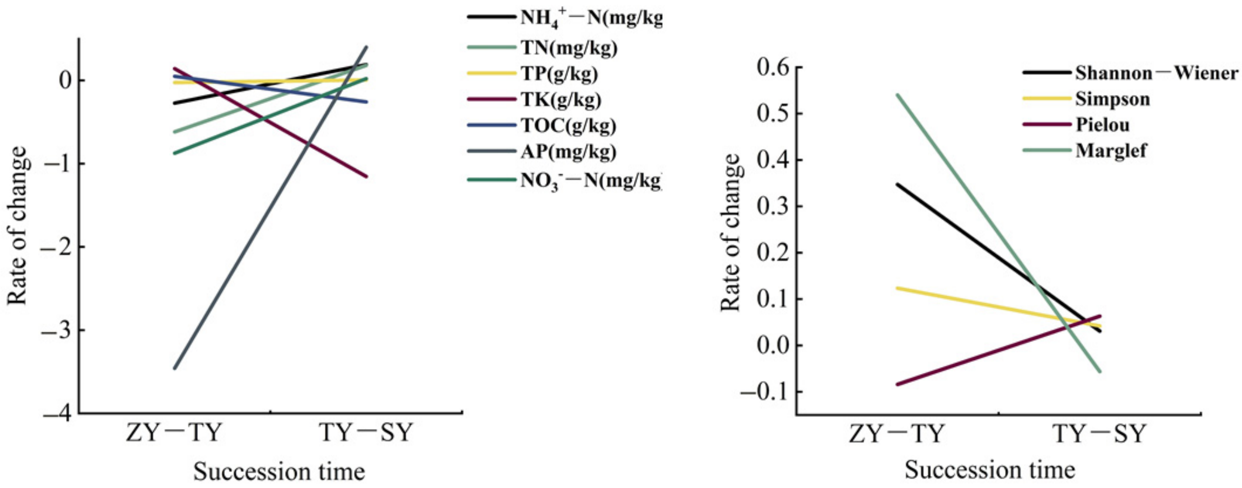


**Figure 4.** Comparison of the recovery rate of understory plants and soil chemical properties of rubber plantation at different succession times. Note: "ZY" represents a rubber plantation with 0 years of natural succession; "TY" represents a rubber plantation with 3 years of natural succession; "SY" represents a rubber plantation with 7 years of natural succession.

## 4. Discussion

### *4.1. The Impact of the Succession Process on Plant Community*

The research results show that the number of species per unit area in the natural succession of the rubber plantation in the 0, 3, and 7 years after the rubber plantation was left from operation was 15 species, 66 species, and 52 species, respectively. The number of species in the latter two succession time types, respectively, reached the first succession time type. 4.4 times and 3.5 times. Human disturbance affects the number of plant species [24]. As the main source of human interference, tending management methods have significant differences in the impact on the diversity of understory plants in rubber forests. The number of understory plant species in rubber forests with normal intensity management is lower than that in rubber forests with poor management, while the number of understory plant species in rubber forests with poor management is lower than that in rubber forests without management [25]. This research results also show that the Marglelef richness index, Simpson index, and Shannon–Wiener index of understory plant communities in the natural succession of the rubber plantation in the 3 and 7 years after the rubber plantation was left were significantly higher than those of 0 years of after the rubber plantation was left. This finding is consistent with previous research showing higher species diversity in the understory of rubber plantations naturally restored after management withdrawal compared to those with 0 years of natural recovery [26,27]. This indicates that the construction of the National Park of Hainan Tropical Rainforest has significantly promoted the recovery of the number of plant species and plant species diversity that are left from rubber plantation operations and provided a material driving force for their positive succession to the tropical rainforest.

The Shannon–Wiener index, Simpson index, and Pielou index of the understory plant community all reached their maximum in the 7th year of succession. The Pielou index did not show significant differences among the 0, 3, and 7-year successions of rubber plantations left for natural succession, consistent with previous studies [28]. The Shannon–Wiener index and Simpson index showed a consistent trend during succession, with the indices in the 0th year of succession significantly lower than those in the 3rd and 7th years. There was no significant difference between the 3rd and 7th years, which is consistent with previous research [29]. After 7 years of succession, rubber plantations exhibit a denser distribution of understory plants, a relatively stable species composition, the longest vegetation succession time, and the highest importance of dominant species. Combined with the Shannon equilibrium degree calculation results, the distribution of plant species is more even, highlighting the importance of dominant species. In contrast, rubber plantations with 0 years of succession are mainly affected by artificial planting and have the most uniform vegetation. The differences in diversity indicators reflect the complexity and dynamics of species composition, quantity, and distribution in the forest restoration process, resulting from the combined action of climatic and biological factors during succession [30]. Understanding that rubber plantation communities are made up of landscape elements and their interaction with human factors is an integral step in developing landscape restoration and conservation strategies [31].

### *4.2. The Impact of the Succession Process on Soil Chemical Properties in Rubber Plantations Left for Natural Succession*

In the past, most studies have focused only on the effects of conversion from natural forests to plantations on productivity and soil quality, while few studies have studied the restoration and succession processes of the transition from plantations to tropical rainforests [32–39]. Research results show differences in the chemical properties of the soil in rubber plantations that have been discontinued during the succession process. The soil pH, nitrate nitrogen, and available phosphorus in rubber plantations with 0 years of natural succession were significantly higher than those in plantations with 3 and 7 years of natural succession. Conversely, soil total nitrogen, total phosphorus, and ammonium nitrogen did not significantly differ during the succession process, though they were highest in the 0th year of succession. The results of this study are not the same as those of some scholars [40,41]. After the rubber plantation stopped artificial interference, the vegetation under the rubber garden began to grow naturally, and then, the number of plant species increased from 15 species in 0 years of natural recovery to 66 species and 52 species in 3 years of natural restoration and 7 years of natural restoration. However, the appearance of these nitrogen-fixing plants is not enough to exert obvious nitrogen-fixing efficiency due to the short time of appearance (Table 4). During vegetation restoration, part of the soil's available phosphorus converts into solid phosphorus, and part is absorbed and utilized by plants. Consequently, phosphorus content gradually decreases during continuous vegetation restoration until it reaches a stable level in the soil.

Vegetation restoration directly affects the size of soil organic carbon pools by altering vegetation structure and composition and changing root exudates and residue inputs [42]. According to this study, there is no significant difference in soil organic carbon during the natural succession process. However, soil organic carbon content reaches its maximum in rubber plantations after 3 years of succession, consistent with previous studies showing that organic carbon content increases during the restoration process [43,44]. The lack of significant differences in the succession process may be due to the insufficient length of the succession period. In this study, rubber plantations naturally succeeded for 3 years, during which understory plant species richness also reached its peak. In the early stages of succession, the rapid growth of pioneer species and the addition of new species increased forest litter thickness, affecting soil organic matter content through litter decomposition. Furthermore, the cessation of artificial fertilization in rubber plantations during natural succession reduced the source of soil organic matter, resulting in no significant increase in soil organic matter.

**Table 4.** List of all the understory plant species of rubber plantations left for natural succession.

| Succession Times | Species | Family |
|---|---|---|
| Rubber plantation with 0 years of natural succession | *Dichroa mollissima* | Hydrangeaceae |
| | *Maesa perlarius* | Primulaceae |
| | *Heptapleurum heptaphyllum* | Araliaceae |
| | *Lithocarpus elaeagnifolius* | Fagaceae |
| | *Sterculia lanceolata* | Malvaceae |
| | *Ficus hirta* | Moraceae |
| | *Ficus hispida* | Moraceae |
| | *Ficus esquiroliana* | Moraceae |
| | *Camellia sinensis var. assamica* | Theaceae |
| | *Trema tomentosa* | Cannabaceae |
| | *Melastoma sanguineum* | Melastomataceae |
| | *Mallotus paniculatus* | Euphorbiaceae |
| | *Aporosa dioica* | Phyllanthaceae |
| | *Heynea trijuga* | Meliaceae |
| | *Castanopsis indica* | Fagaceae |
| Rubber plantation with 3 years of natural succession | *Maesa perlarius* | Primulaceae |
| | *Canarium subulatum* | Burseraceae |
| | *Ormosia pinnata* | Fabaceae |
| | *Cinnamomum parthenoxylon* | Lauraceae |
| | *Litsea monopetala* | Lauraceae |
| | *Ficus fistulosa* | Moraceae |
| | *Ficus variegata* | Moraceae |
| | *Wendlandia uvariifolia* | Rubiaceae |
| | *Eurya nitida* | Pentaphylacaceae |
| | *Toxicodendron succedaneum* | Anacardiaceae |
| | *Aporosa dioica* | Phyllanthaceae |
| | *Thysanolaena latifolia* | Poaceae |
| | *Glochidion lanceolarium* | Phyllanthaceae |
| | *Ficus hirta* | Moraceae |
| | *Ficus hispida* | Moraceae |
| | *Cansjera rheedei* | Opiliaceae |
| | *Mallotus paniculatus* | Euphorbiaceae |
| | *Pterospermum lanceifolium* | Malvaceae |
| | *Engelhardia roxburghiana* | Juglandaceae |
| | *Archidendron lucidum* | Fabaceae |
| | *Lithocarpus caudatilimbus* | Fagaceae |
| | *Macaranga denticulata* | Euphorbiaceae |
| | *Aralia chinensis* | Araliaceae |
| | *Camellia sinensis var. assamica* | Theaceae |
| | *Melastoma sanguineum* | Melastomataceae |
| | *Ardisia quinquegona* | Primulaceae |
| | *Heynea trijuga* | Meliaceae |
| | *Canthium horridum* | Rubiaceae |
| | *Vitex quinata* | Lamiaceae |
| | *Melastoma malabathricum* | Melastomataceae |
| | *Callicarpa longifolia* | Lamiaceae |
| | *Clerodendrum cyrtophyllum* | Lamiaceae |
| | *Dracaena angustifolia* | Asparagaceae |
| | *Oroxylum indicum* | Bignoniaceae |
| | *Bischofia polycarpa* | Phyllanthaceae |
| | *Melastoma candidum* | Melastomataceae |
| | *Ficus nervosa* | Moraceae |
| | *Ficus oligodon* | Moraceae |
| | *Ficus esquiroliana* | Moraceae |
| | *Trema tomentosa* | Cannabaceae |
| | *Elaeocarpus sylvestris* | Elaeocarpaceae |
| | *Pterospermum heterophyllum* | Malvaceae |
| | *Zanthoxylum avicennae* | Rutaceae |

**Table 4.** *Cont.*

| Succession Times | Species | Family |
|---|---|---|
| | *Ficus tinctoria subsp. gibbosa* | Moraceae |
| | *Radermachera hainanensis* | Bignoniaceae |
| | *Toona sureni* | Meliaceae |
| | *Ficus auriculata* | Moraceae |
| | *Artocarpus parvus* | Moraceae |
| | *Tetradium glabrifolium* | Rutaceae |
| | *Melastoma dendrisetosum* | Melastomataceae |
| | *Sterculia lanceolata* | Malvaceae |
| | *Aidia cochinchinensis* | Rubiaceae |
| | *Lithocarpus corneus* | Fagaceae |
| | *Saurauia tristyla* | Actinidiaceae |
| | *Elaeocarpus rugosus* | Elaeocarpaceae |
| | *Aquilaria sinensis* | Thymelaeaceae |
| | *Camellia oleifera* | Theaceae |
| | *Toona ciliata* | Meliaceae |
| | *Chukrasia tabularis* | Meliaceae |
| | *Bombax ceiba* | Malvaceae |
| | *Dalbergia odorifera* | Fabaceae |
| | *Bischofia javanica* | Phyllanthaceae |
| | *Micromelum falcatum* | Rutaceae |
| | *Ceiba speciosa* | Malvaceae |
| | *Blechnopsis orientalis* | Blechnaceae |
| | *Alangium chinense* | Cornaceae |
| Rubber plantation with 7 years of natural succession | *Aporosa dioica* | Phyllanthaceae |
| | *Heynea trijuga* | Meliaceae |
| | *Eurya nitida* | Pentaphylacaceae |
| | *Nauclea officinalis* | Rubiaceae |
| | *Wendlandia uvariifolia* | Rubiaceae |
| | *Saurauia tristyla* | Actinidiaceae |
| | *Ficus variegata* | Moraceae |
| | *Camellia sinensis var. assamica* | Theaceae |
| | *Melastoma sanguineum* | Melastomataceae |
| | *Elaeocarpus rugosus* | Elaeocarpaceae |
| | *Litsea monopetala* | Lauraceae |
| | *Litsea variabilis* | Lauraceae |
| | *Ficus oligodon* | Moraceae |
| | *Liquidambar formosana* | Altingiaceae |
| | *Ficus hispida* | Moraceae |
| | *Alangium chinense* | Cornaceae |
| | *Ficus esquiroliana* | Moraceae |
| | *Machilus chinensis* | Lauraceae |
| | *Macaranga denticulata* | Euphorbiaceae |
| | *Tetradium glabrifolium* | Rutaceae |
| | *Heptapleurum heptaphyllum* | Araliaceae |
| | *Maclurodendron oligophlebia* | Rutaceae |
| | *Cinnamomum parthenoxylon* | Lauraceae |
| | *Peltophorum dasyrrhachis var. tonkinensis* | Fabaceae |
| | *Aralia chinensis* | Araliaceae |
| | *Alsophila spinulosa* | Cyatheaceae |
| | *Acer laurinum* | Sapindaceae |
| | *Carpinus turczaninowii* | Betulaceae |
| | *Mallotus paniculatus* | Euphorbiaceae |
| | *Toxicodendron succedaneum* | Anacardiaceae |
| | *Endospermum chinense* | Euphorbiaceae |
| | *Bischofia javanica* | Phyllanthaceae |
| | *Dalbergia hainanensis* | Fabaceae |
| | *Maesa perlarius* | Primulaceae |

**Table 4.** *Cont.*

| Succession Times | Species | Family |
|---|---|---|
| | *Ficus nervosa* | Moraceae |
| | *Dimocarpus longan* | Sapindaceae |
| | *Maclura cochinchinensis* | Moraceae |
| | *Albizia odoratissima* | Fabaceae |
| | *Melia azedarach* | Meliaceae |
| | *Homalium ceylanicum* | Salicaceae |
| | *Syzygium samarangense* | Myrtaceae |
| | *Syzygium tetragonum* | Myrtaceae |
| | *Boehmeria nivea* | Urticaceae |
| | *Bridelia balansae* | Phyllanthaceae |
| | *Alphitonia incana* | Rhamnaceae |
| | *Lithocarpus caudatilimbus* | Fagaceae |
| | *Trema tomentosa* | Cannabaceae |
| | *Ficus auriculata* | Moraceae |
| | *Allospondias lakonensis* | Anacardiaceae |
| | *Toona sureni* | Meliaceae |
| | *Radermachera hainanensis* | Bignoniaceae |
| | *Glochidion sphaerogynum* | Phyllanthaceae |

### *4.3. The Relationship Between Soil Chemical Properties and Understory Plant Community Diversity in Discontinued Rubber Plantations*

The relationship between soil chemical properties and plant diversity has always been a crucial topic in vegetation restoration research. This relationship is complex and multifaceted. Existing research often focuses on the interplay between plant communities and soil ecological factors during vegetation succession, but conclusions remain controversial and inconsistent. Jun et al. [45] found that establishing a pine-apricot mixed forest improves understory plant diversity and promotes soil improvement, with soil pH, organic matter, capillary porosity, and capillary water holding capacity being the dominant factors affecting understory plant diversity in their study area. Similarly, Lu Haifei et al. [15] studied *E. grandis* forests at different developmental stages and determined that soil organic matter significantly impacts the diversity of understory vegetation. Conversely, Colmanetti et al. [43] indicated that soil characteristics do not limit the growth of natural forests; instead, invasive grass cover negatively impacts the diversity and structure of tree regeneration.

In this study, soil available phosphorus, and total phosphorus were positively correlated with the Marglef index, Simpson index, Shannon–Wiener index, and Pielou index. This indicates that increased understory vegetation diversity during rubber plantation succession enhances soil available phosphorus and total phosphorus. Some studies suggest that soil phosphorus is a key factor affecting plant diversity [46]. Soil phosphorus may be a limiting factor in the early stages of rubber plantation succession. As the community reaches a climax state during succession, soil phosphorus could become a limiting factor. The impact of reduced soil phosphorus on plant community diversity and ecosystem functions in discontinued rubber plantations requires further study. Other soil factors showed a negative correlation with understory species diversity, suggesting that soil nitrogen and potassium are limiting elements for understory plant diversity in the later stages of rubber plantation succession.

### *4.4. Comparison of the Recovery Rate of Understory Vegetation and Soil Properties in Discontinued Rubber Plantations*

The soil health of natural forests with higher biomass was higher than that of rubber plantations, while that of younger rubber plantations was lower, and soil health depended on vegetation structure, and there was a significant positive correlation between soil health and ground vegetation cover [47]. Research results indicate that the recovery rate of understory vegetation in rubber plantations that have been left for natural succession is faster than the recovery rate of soil properties. The restoration of understory vegetation in these plantations can enhance the diversity and stability of the ecosystem. The soil recovery rate is closely related to the decomposition of litter, and the recovery and decomposition rate of understory litter need further research. Soil nutrients are often considered crucial factors for the diversity and growth of understory plants. Many factors influence vegetation recovery, including climatic conditions, soil characteristics, and biological factors. In this study, the rubber plantations that were withdrawn from management exhibited more ecological niches. Following the withdrawal, the number of understory vegetation species increased, leading to a gradual recovery of the understory vegetation. Soil recovery is closely linked to the decomposition of litter and plant roots. Research by Li Mapping et al. [48] demonstrated that nitrogen-fixing tree species, such as winter melon (*Alnus nepalensis* D. Don), significantly enhance soil nutrients and promote the growth of understory vegetation during ecological succession in degraded areas. In this study, the nitrogen-fixing ability of understory species has not yet been explored. During the succession process of the discontinued rubber plantations, the species richness of the understory increased, and soil organic matter content also rose. However, the rate of change in soil organic matter content was slower than that of the understory vegetation diversity index. This may be due to the relatively rapid adaptation of species to ecological niches and the local microenvironment under the forest. The reasons why the recovery rate of understory vegetation in discontinued rubber plantations is faster than the recovery rate of soil properties require further research. This study employs a spatial rather than temporal approach to examine the impact of plant diversity and soil chemical properties on discontinued rubber plantations. Succession is a long-term process and understanding the dynamic changes in forest succession and soil properties, as well as their relationship, is essential. Scientific long-term continuous dynamic monitoring should be conducted.

## 5. Conclusions

The natural recovery process of retired rubber plantations involves long-term succession, leading to changes in understory plant diversity and soil properties. Our research findings indicate that, as retired rubber plantations transition to rainforests, there is an increase in both understory species diversity and soil organic matter content. Notably, the recovery of understory vegetation outpaces that of soil properties, underscoring the need for further investigation into the underlying mechanisms. These results offer valuable insights into the natural recovery of not only rubber plantations but also other decommissioned artificial forests within the Hainan Tropical Rainforest National Park. By considering factors such as understory plant communities, soil conditions, climate, and wildlife, targeted interventions can be implemented to facilitate successful restoration efforts.

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