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Diversity of understory herbaceous plants during succession in rubber plantations in National Park of Hainan Tropical Rainforest, China

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Research Article

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Abstract

Revealing the impact of forest succession processes on changes in plant diversity is crucial for understanding the mechanisms that maintain plant diversity across various succession stages. While previous research has predominantly focused on the influence of environmental factors or management strategies on plant diversity within rubber plantation understories, there is a scarcity of studies examining the effects of forest succession processes on plant diversity. This study focuses on the plant diversity of the understory herbaceous layer within the rubber forest of the Yinggeling area, located in National Park of Hainan Tropical Rainforest. It employs a spatial analysis approach, rather than a temporal one, to examine the characteristics of the understory herbaceous community. The findings revealed that (1) The understory of Yinggeling rubber plantations harbors 175 plant species from 149 genera and 75 families, with Gramineae and Rubiaceae representing 46.45% of total species. And the dominant families are Rubiaceae, Gramineae, and Moraceae, with *Ficus* and *Pteris* being the dominant genera. (2) The dominant species vary with succession duration, with *Tetrastigma pachyphyllum* dominating in 0-year succession, *Paspalum conjugatum* in 3-year succession, and *Microstegium fasciculatum* in 7-year succession. (3) Diversity indices such as the Shannon–Wiener index, Simpson index, and Pielou index peak at 7 years of natural succession, while the species richness is highest at 3 years. (4) The similarity coefficient between understory herbaceous plant communities in rubber plantations undergoing 0 and 3 years of natural succession is highest 0.56, indicating a significant similarity, while similarity is lowest between 0 and 7 years of succession. This research shows that natural restoration helps increase species diversity in the understory herb layer of rubber forests. Succession leads to changes in the dominant families, genera, and species of the herbaceous layer. This change can be attributed to the intraspecific competition and ecological competition that occur during the succession process, leading to changes in biological and resource allocation.

Introduction

Biodiversity encompasses the diversity and variability of organisms along with the ecological complexity of habitats (Webb *et al.* 2002). It serves as the foundation for human survival and development and plays a pivotal role in maintaining ecosystem stability. However, in recent years, the rapid pace of industrialization and burgeoning human economic demands, climate change, deforestation, environmental pollution, and invasive species have precipitated a swift decline in biodiversity (Zhai *et al.* 2012; Zou *et al.* 2023). Plant diversity, a significant component of biological diversity, includes an estimated 300,000 to 350,000 plant species worldwide, driving global material cycling and energy flow processes. The species diversity within a plant community reflects the composition, structure, and function of each component, illustrating the community's appearance, structural characteristics, and dynamic changes (Hu *et al.* 2023). Currently, the study of plant diversity has emerged as a focal point in forest ecology research, with increasing attention from scientific researchers toward understanding how environmental factors influence plant composition and species diversity (Weigel *et al.* 2019; Zhang *et al.* 2023).

The primary goal of forest restoration is to enhance ecosystem services and other ecological functions, making natural forest restoration the best choice. However, the approach to restoring artificial forests must be tailored to local conditions, considering factors such as the extent of

land degradation, hydrothermal conditions, and proximity to the native habitats of animals and plants. Methods may include natural regeneration, planting of a diverse array of native trees, shrubs, and grasses, as well as artificial interventions to facilitate natural regeneration etc. Hua *et al.* (2022). Despite this, considerable expertise has been gained in the establishment and management of artificial forests, which may continue to play a significant role in current forest restoration practices, contributing to the swift achievement of global ecosystem restoration goals. The high-productivity timber supply of artificial forests can reduce or even avoid deforestation of natural forests by humans, thereby protecting forests with richer ecological functions and improving both ecological efficiency and benefits (Wang *et al.* 2022).

Natural rubber (*Hevea brasiliensis*) is an important industrial raw material. Rubber plantations are primarily found in China, yet the unscientific and unreasonable cultivation of rubber poses threats to biodiversity and animal habitats (Ahrends *et al.* 2015; Leepromrath *et al.* 2021). Current research on the plant diversity of rubber plantations is predominantly focused on exploring the development and utilization of understory resources. Long-term cultivation of rubber trees changed the functional diversity of soil microbial communities (Zhou *et al.* 2017). Hainan Province has been identified as a suitable area for planting rubber trees. The first rubber seedlings were imported from Malaysia in the early 20th century and were subsequently planted on a large scale. Since 1952, rubber trees have been widely planted in various soil types across Hainan Island. As of 2020, the rubber planting area in Hainan Province reached approximately 530,000 hectares (Li *et al.* 2024).

Several scholars have undertaken relevant research on plant diversity within rubber plantations. For instance, Wang *et al.* (2023) found that increased plant diversity in rubber plantations significantly enhanced soil biodiversity and ecosystem stability. Conversely, Chen *et al.* (2021) discovered that the rapid and irrational expansion of rubber plantations led to a notable decline in the number of species. Furthermore, Liu *et al.* (Liu *et al.* 2023) demonstrated that integrative cultivation systems within rubber plantations significantly inhibit the growth of understory vegetation and lead to a sharp loss of understory vegetation diversity. In Hainan, studies on rubber plantation plant diversity have primarily focused on the influence of environmental factors or management practices. For example, Zeng *et al.* (2023) identified temperature and precipitation as comprehensive influencers on rubber plantation plant diversity, while Wang *et al.* (2022) emphasized the significant impact of management methods on understory plant diversity in rubber plantations. Herbaceous layer plants constitute a vital component of understory vegetation, and their diversity plays a critical role in the natural succession of forests. Rubber plantations, being artificial ecosystems, exhibit prolonged succession cycles and diminished diversity due to extensive human intervention (Hu *et al.* 2023). Research on the plant diversity characteristics of the understory herb layer in rubber plantations reveals insights into the evolving traits of natural succession processes.

Since the establishment of National Park of Hainan Tropical Rainforest in 2021, a substantial portion of operational rubber plantations has been abandoned rubber plantation, including those within the Yinggeling Branch of National Park of Hainan Tropical Rainforest. The evolving traits of understory vegetation in these abandoned rubber plantations remain largely unexplored, leaving the evolutionary patterns of rubber plantations post-abandonment unknown. Hence, this study aims to investigate the plant diversity and community composition of the understory herbaceous layer during the natural succession of rubber plantations to shed light on this issue.

Materials and methods

Study area

The Yinggeling Branch of Hainan Tropical Rainforest National Park is located in the mountainous region of central and southern Hainan Island, spanning 18°49'30″—19°08'41″N and 109°11'27″—109°34'06″E and covers a total area of 861.7 km^2. The area includes a controlled zone of 40,900 hectares and a core protected area of 45,200 hectares, encompassing Baisha County, Qiongzhong County, Wuzhishan City, Changjiang County, and Ledong County (Zhu *et al.* 2023). The region experiences a tropical maritime monsoon climate within ts mountainous terrain, with Yinggeling Peak reaching an altitude of 1812 m (Zhang *et al.* 2022). The average annual temperature in the Yinggeling Nature Reserve ranges from 20 to 24°C, with an average annual precipitation of 1800 mm and an annual evaporation rate of 1600 mm (Yang *et al.* 2023).

Based on our preliminary survey, the total area of the Yinggeling Branch within Hainan Tropical Rainforest National Park is 88,177 hectares, with artificial forests covering 18,399 hectares, representing 20.9% of the total area. Within the general control area, artificial forests span 17,027 hectares, comprising 41.4% of the total general control area. This includes 5,874 hectares of rubber plantations, accounting for 34.5% of the plantation forests within the general control areas.

Methods

This study's investigation area is situated at the peak management and protection station within the Yinggeling Branch of National Park of Hainan Tropical Rainforest. Sample plots were selected for field surveys along a gradient of different successional times (0, 3, and 7 years). Understory vegetation was surveyed using a sampling method. Three sample plots, each measuring 100 m× 100 m, were chosen from rubber plantations undergoing natural succession for 0, 3, and 7 years, with three 20 m × 20 m quadrats surveyed within each plot. Herbaceous layer plants beneath the rubber plantation canopy were surveyed within the quadrats, recording species name, average height, coverage, and abundance. Additionally, information regarding sample plots' altitude, slope, aspect, soil type, and canopy coverage was recorded (Table 1).

Data analysis

Using a sampling method survey, diversity information regarding herbaceous layer plants beneath rubber plantations with varying succession periods was collected. This included investigating the types and number of individuals within the herbaceous layer (including woody plants, herbs, and ferns with a height ≤ 1 m). Statistical analyses of individual plants, including height and coverage, were conducted, and key values were calculated using relevant methods. Richness indices such as the Margalef index (dM), Shannon–Wiener index (H), Simpson index (P), Pielou index (E), and beta diversity index were computed based on the survey data.

(1) Important value = (relative frequency + relative density + relative significance)/3
(2) Margalef index: $d_M = \frac{S-1}{\ln N}$

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Table 1. Information on rubber plantation plots in National Park of Hainan Tropical Rainforest, China

Plot types	Successional years/a	Altitude /m	Age/a	Canopy coverage	Average height /m	Average diameter at breast height /cm
ZY-1	0	380.14	21	69%	9.49	20.14
ZY-2	0	395	21	86%	9.3	20.91
ZY-3	0	464	26	73%	9.05	18.25
TY-1	3	488	26	51%	10.36	17.26
TY-2	3	460	26	55%	11.97	18.97
TY-3	3	519	26	50%	9.21	18.2
SY-1	7	495	23	55%	11.86	19.03
SY-2	7	496	23	55%	10.98	26.85
SY-3	7	555	23	50%	10.5	15.22

Note: "ZY-1," "ZY-2," and "ZY-3," respectively, represent the 1st, 2nd, and 3rd plots in succession year 0; "TY-1," "TY-2," and "TY-3" represent succession 3, respectively. The 1st, 2nd, and 3rd sample plots in the year; "SY-1," "SY-2," and "SY-3," respectively represent the 1st, 2nd, and 3rd sample plots in the 3rd year of succession.

(3) α diversity:
Shannon–wiener index calculation formula: $H' = -\sum_{i=1}^{S} Pi \ln Pi$
The Simpson index calculation formula: $P = 1 - \sum_{i=1}^{S} Pi^2$
The calculation formula of Pielou index: $E = \frac{-\sum_{i=1}^{S} Pi \ln Pi}{\ln S}$
In the above four formulas, the number of species in the S-quadrat; Pi represents the relative density of the ith species; N is the sum of the numbers of all species in the quadrat.

(4) β diversity
Community β diversity was calculated using Sørensen community similarity
The formula for calculating the Sørensen index: $Cs = 2c/(a+b)$

where a and b are the number of species in each of the two quadrats, and c is the number of species common to the two quadrats.

All raw data recording, summary, statistics, and calculations are processed using Excel 2021. Use Origin 2021 software to conduct variance analysis on herbaceous plants under rubber forests with different succession years.

Results

Community composition of understory herbaceous layer

Plant composition of the herbaceous layer under the rubber plantation

This field survey documented a total of 175 plant species in the herbaceous layer of the rubber plantation, representing 149 genera and 75 families. Notably, species Gramineae and Rubiaceae families collectively comprised 46.45% of the total species diversity.

Among the surveyed species, three varieties from three families and three genera were identified. Notably, the understory herbaceous vegetation consisted of ferns and angiosperms, with no gymnosperms observed. There were 17 fern species, constituting 9.71% of the total, spanning across 10 families and 11 genera. Angiosperms dominated with 158 species, representing 90.29% of the total, distributed across 65 families and 138 genera. Additionally, our survey recorded 9 species of vines, accounting for 5.14% of the total species richness, spread across 6 families and 9 genera.

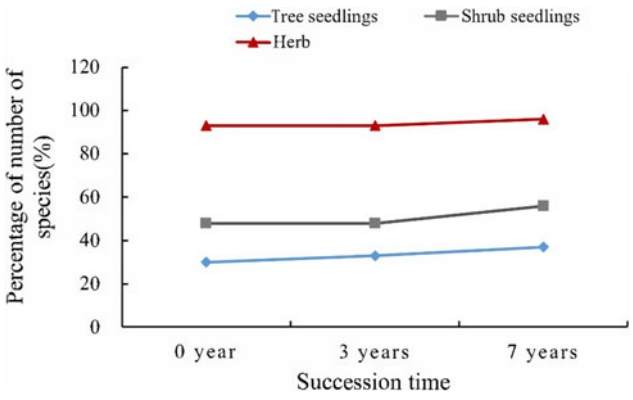

Figure 1. Change trends of various life forms in plant communities in the understory herbaceous layer of rubber plantation at different succession times.

Analysis of the herbaceous layer of the rubber plantation revealed that the highest occurrence of tree seedlings, shrub seedlings, and herbaceous plants in the seventh year of succession. Furthermore, with increasing succession time, there was a notable increase in the proportion of tree seedling species within the community. While shrub seedling species initially decreased and then increased, peaking at 7 years of succession, the trend in herbaceous plants remained less evident (Figure 1).

Species composition of the understory herb layer of rubber plantation

The survey results reveal that the herbaceous layer of the rubber plantation harbors 73 plant species in the initial stages of natural succession (0 years), encompassing 39 families and 67 genera. After 3 years of succession, the number of species increases to 115, maintaining the same family and genus count. At 7 years of succession, although the number of genera rises to 96 within 56 families, the overall species count remains at 101, compared to the 3-year. Despite a decline in species count from 2015 onward, it remains higher than the initial succession period (0 years) (Figure 2). Analysis reveals a trend of initial increase followed by a decrease in the number of plant species, families, and genera over the succession period. The 3-year mark demonstrates this trend

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Table 2. Dominant families in the herbaceous layer of rubber forest understory at 0, 3, and 7 years of succession

	0 years of succession		3 years of succession		7 years of succession	
Number	Family name	Number of species	Family name	Number of species	Family name	Number of species
1	Rubiaceae	8	Poaceae	10	Rubiaceae	8
2	Fabaceae	5	Rubiaceae	7	Moraceae	7
3	Gramineae	5	Lauraceae	5	Poaceae	6
4	Moraceae	3	Moraceae	5	Lauraceae	4
5	Zingiberaceae	3	Asteraceae	5	Phyllanthaceae	4
6	Asparagaceae	2	Phyllanthaceae	4	Sapindaceae	3
	Total	26		36		33
	Proportion (%)	35.62		31.30		32.67

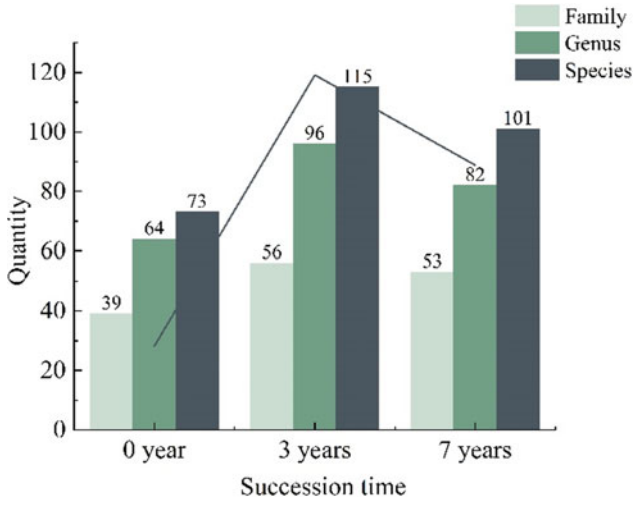

Figure 2. Composition of plant families, genera, and species in the understory herbaceous layer of rubber plantation at different succession times.

prominently. The herbaceous layer exhibits the highest diversity in terms of plant families, genera, and species, while the initial 0-year stage showcases the lowest diversity. These findings highlight the significant influence of succession duration on the herbaceous layer's plant diversity (Figure 2).

Predominant plant families and genera within the understory herbaceous layer of rubber plantations

The survey findings indicate a relatively limited number of species in the understory herb layer of rubber plantations undergoing 0, 3, and 7 years of natural succession, with the top six dominant families and genera outlined for each phase. In rubber plantations with 0 years of natural succession, the top five dominant plant families include *Rubiaceae*, *Fabaceae*, *Gramineae*, *Moraceae*, and *Asparagaceae*, comprising a total of 22 genera, representing 34.38% of the total genera, and 26 species, accounting for 35.62% of the total species. The predominant plant genera in the understory herbaceous layer of rubber plantations at this stage are *Ficus*, *Melastoma*, *Alpinia*, *Pteris*, *Hedyotis*, and *Lasianthus*, totaling 15 species, constituting 20.55% of the total species count (Table 2).

Table 2 illustrates the top six dominant plant families in the understory herbaceous layer of rubber plantations undergoing 3 years of natural succession: Poaceae, Rubiaceae, Lauraceae, Moraceae, Asteraceae, and Phyllanthaceae. These families encompass a total of 28 genera, representing 29.17% of the total genera, and 36 species, accounting for 31.30% of the total species count. Among the dominant genera are *Ficus*, *Pteris*, *Cinnamomum*, *Mallotus*, *Melastoma*, and *Rubus*, totaling 16 species and constituting 13.91% of the total species.

The top six dominant families in the understory herbaceous layer of rubber plantations undergoing 7 years of natural succession are *Rubiaceae*, *Moraceae*, *Poaceae*, *Lauraceae*, *Phyllanthaceae*, and *Sapindaceae*. Together, they encompass 24 genera, representing 29.27% of the total genera, and 33 species, accounting for 32.67% of the total species count. Among the top six dominant genera are *Ficus*, *Lasianthus*, *Syzygium*, *Rubus*, *Hedyotis*, and *Pteris*, totaling 9 species within the genus, constituting 18.81% of the total species (Table 3).

The dominant families in the understory herbaceous layer of rubber plantations undergoing natural succession for 0, 3, and 7 years primarily consist of *Rubiaceae*, *Gramineae*, *Zingiberaceae*, and *Moraceae*. *Lauraceae* and *Phyllophyllaceae* emerge as dominant families in forests with 3 and 7 years of succession and persist across rubber plantations for 20 years. Among the dominant genera in the understory plants of rubber plantations undergoing 0, 3, and 7 years of natural succession, *Ficus* and *Pterospermum* stand out, with *Ficus* being the predominant genus across all stages of succession. Notably, *Melastoma* is the leading genus among the understory herbaceous plants in rubber plantations with 0 and 3 years of natural succession and in forests with 3 and 7 years of succession. Meanwhile, *Rubus* prevails as the dominant genus in the understory herbaceous layer.

Species importance analysis

Table 4 presents statistics on the top ten species with significant importance values within the understory herbaceous layer community of rubber plantations at different stages of succession. *Tetrastigma pachyphyllum* emerges as the dominant species in rubber plantations undergoing natural succession for 0 years, the importance value is 6.95%. In forests with 3 years of succession, *Eargrass* stands out with an importance value of 5.05%. *Microstegium fasciculatum* takes precedence as the top species in the herbaceous layer of rubber plantations with 7 years of natural succession, exhibiting an importance value of 8.96%. Among the top ten species in rubber plantations with natural succession durations of 0, 3, and 7 years, Zingiberaceae and Gramineae plants are prominent. Notably, the Poaceae plant *Microstegium*

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Table 3. Dominant genera in the herbaceous understory of rubber forests in years 0, 3, and 7 of succession

	0 years of succession		3 years of succession		7 years of succession	
Number	Generic name	Number of species	Generic name	Number of species	Generic name	Number of species
1	*Ficus*	5	*Ficus*	5	*Ficus*	6
2	*Melastoma*	2	*Pteris*	3	*Lasianthus*	3
3	*Alpinia*	2	*Cinnamomum*	2	*Syzygium*	3
4	*Pteris*	2	*Mallotus*	2	*Rubus*	3
5	*Hedyotis*	2	*Melastoma*	2	*Hedyotis*	2
6	*Lasianthus*	2	*Rubus*	2	*Pteris*	2
	Total	15		16		19
	Proportion (%)	20.55		13.91		18.81

Table 4. The top 10 species with the highest importance values in each plot

	0 years of succession		3 years of succession		7 years of succession	
Number	Species name	Pi/%	Species name	Pi /%	Species name.	Pi /%
1	*Tetrastigma pachyphyllum*	6.59	*Paspalum conjugatum*	6.05	*Microstegium fasciculatum*	8.96
2	*Microstegium fasciculatum*	6.14	*Pronephrium simplex*	4.47	*Selaginella delicatula*	7.41
3	*Selaginella delicatula*	5.48	*Oplismenus compositus*	4.46	*Sarcandra glabra*	6.72
4	*Cyrtococcum patens* var. *latifolium*	5.23	*Alpinia oxyphylla*	3.77	*Alpinia hainanensis*	5.71
5	*Tabernaemontana bufalina*	5.13	*Cyclosorus parasiticus*	3.71	*Persicaria chinensis*	5.47
6	*Alpinia oxyphylla*	4.37	*Tabernaemontana bufalin*	3.21	*Thysanolaena latifolia*	3.06
7	*Maesa perlarius*	4.29	*Blechnopsis orientalis*	3.09	*Cyclosorus parasiticus*	2.89
8	*Aporosa dioica*	4.17	*Pseudosasa cantorii*	2.55	*Diplazium donianum*	2.45
9	*Codonacanthus pauciflorus*	4.07	*Maesa perlarius*	1.72	*Heptapleurum heptaphyllum*	2.44
10	*Oplismenus compositus*	3.86	*Sarcandra glabra*	1.72	*Piper sarmentosum*	2.19

Note: "Pi" represents the species important value.

fasciculatum ranked second in importance in the 0th year of succession, and by the 7th year of succession, it had become the best species of the herbaceous layer plant in the understory of the rubber forest.

Species diversity analysis of the herbaceous layer community under the rubber plantations

The survey results indicate no significant difference in the Shannon–Wiener index, Simpson index, and Pielou index across the understory herbaceous community of rubber plantations with 0, 3, and 7 years of natural succession. However, there is a significant difference in the Margalef index between the 3-year and 7-year continuous periods. Interestingly, no significant distinction is noted in the Margalef index between the understory herbaceous layer of rubber plantations undergoing 3 and 7 years of succession (Figure 3). The Shannon–Wiener index, Simpson index, and Pielou index peak at 7 years of natural succession, while the Margalef index reaches its highest point at 3 years of natural succession.

Similarity analysis of the herbaceous layer community under the rubber plantations

Table 5 illustrates the similarity of plant communities within the understory herbaceous layer of rubber plantations at varying stages of succession in the Yingge Ling Branch of Hainan Tropical Rainforest National Park. The highest similarity coefficient of 0.56 is observed between the understory herbaceous plants of rubber plantations with 0 and 3 years of natural succession, while the lowest similarity coefficient of 0.46 is noted between the plant communities of rubber plantations with 0 and 7 years of natural succession. Conversely, the similarity coefficient between rubber plantations with 3 and 7 years of natural succession is 0.50.

Discussion

Changes in the number of species in the understory herb layer of rubber plantations at different succession times

A total of 175 plant species were recorded in the herbaceous layer of the rubber plantation during this study, spanning 149 genera and 75 families, with Gramineae and Rubiaceae accounting for 46.45% of the total. The number of plant species in the understory herbaceous layer exhibited an initial increase followed by a decrease. The peak was observed at 115 species during the 3rd year of succession, while the lowest count was 73 species during the initial year of succession. Additionally, as succession years increased, the proportion of tree seedling species within the community showed a rising trend. In contrast, shrub layer species demonstrated an initial decline followed by an increase, reaching

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Table 5. Similarity of plant communities in the herbaceous layer of the rubber plantation understory under different succession times

	0 years of succession	3 years of succession	7 years of succession
0 years of succession	1	0.56	0.46
3 years of succession		1	0.5
7 years of succession			1

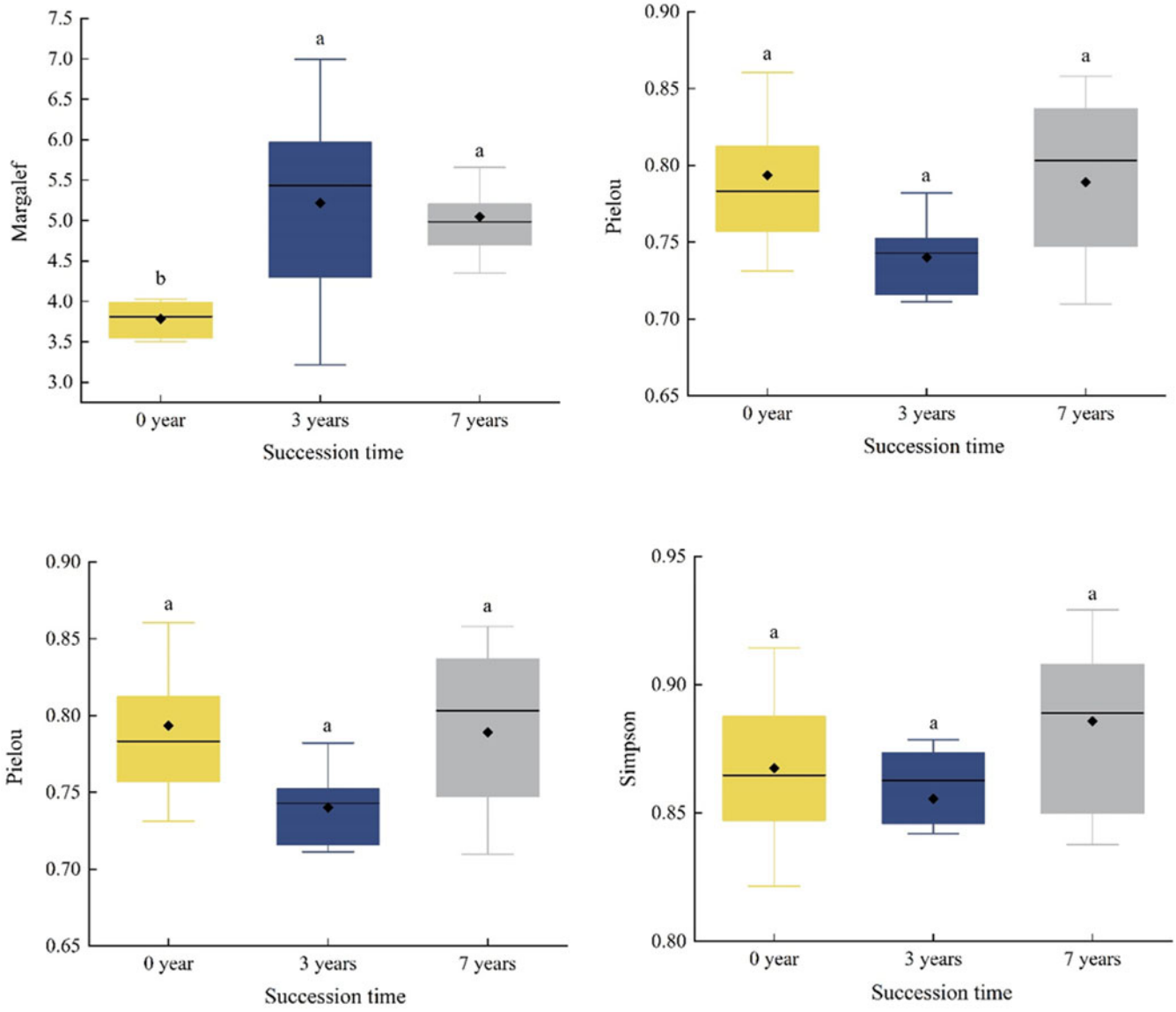

Figure 3. Species diversity in the understory herb layer of rubber forests at different succession stages.

their maximum at 7 years of succession. This trend is likely due to the cessation of artificial management of rubber plantations, which allowed the understory plant communities to recover naturally. Without human interference, the vegetation, especially herbaceous plants, gradually returned to their natural growth state. By the third year of natural recovery, the herbaceous plant community under the rubber canopy reached its dominant period. During this natural recovery, other shrubs, vines, and tree plant communities also recovered. After three years, the growth of these naturally recovered communities, such as tree seedlings and shrub seedlings, began to compete with the herbaceous community for light, water, nutrients, and space, even forming a strong comparative advantage.

Understory herbaceous plants in rubber plantations are notably sensitive to environmental shifts. The proliferation of shrubs and trees, leading to increased canopy density, impedes the growth of understory herbs, aligning with the findings of Xiao Jun *et al.* (2023). Moreover, following natural management in rubber plantation succession, there was an increase in the number of understory plant species and tree and shrub seedlings, consistent

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with the research conducted by Lan Guoyu *et al.* (2014). This surge is attributed to the relatively barren and unsuitable soil surface during the initial 0 years of natural succession. As natural succession progresses, more species find suitable conditions for survival, corroborating the findings of Wei Jianxing *et al.* (2023).

Diversity characteristics of the herbaceous layer community within the rubber plantation

Species richness serves as a vital indicator of community dynamics. The Shannon–Wiener index primarily measures the uncertainty of individual occurrence, with higher values indicating greater diversity. The Simpson dominance index suggests a more uneven distribution of different organism types within the biological community, highlighting the prominence of dominant organisms and their ecological functions. The Pielou evenness index reflects the distribution of individual numbers across all species within the rubber plantation. No significant differences were observed in the Shannon–Wiener index, Simpson index, and Pielou index of the herbaceous layer plant community under the rubber plantation at the three succession times. However, the Margalef index of the understory herbaceous layer of the rubber plantation with 0 years of succession was significantly lower than that of the other two succession times. The Shannon–Wiener index, Simpson index, and Pielou index reached their peaks at 7 years of natural succession in the herbaceous layer community under the rubber plantation, while the Margalef index peaked at 3 years. The reason why the Margalef index model is different from other indices is largely because the Margalef index is more sensitive to changes in species richness than other indices and has a stronger ability to distinguish changes in community diversity (Su *et al.* 2017). Overall, the diversity index of the understory herbaceous layer community in rubber plantations with 0 years of succession was the lowest, whereas it was higher in forests with 7 years of succession. These findings are consistent with those of Chen Li *et al.* (2019), supporting the belief that plant diversity in rubber plantations after near-natural management aligns with this conclusion. The natural restoration of rubber plantations helps to increase the diversity of the understory herbaceous community.

Comparison of the herbaceous layer community within the rubber plantation across different stages of succession

The natural succession of rubber plantations over different years results in varying species counts and community similarities. The plant communities of rubber plantations that have undergone natural succession for 0 and 3 years exhibit the highest similarity, suggesting a considerable total species count. This may be attributed to the relatively short duration of natural succession, maintaining the dominance of herbaceous plants in the understory vegetation community. Conversely, the plant communities of rubber plantations with 7 years and 0 years of natural succession exhibit the lowest similarity, indicating fewer shared species. After 7 years of natural succession, native trees and shrubs have emerged in the understory vegetation community, while unsuitable herbaceous plants have retreated, resulting in changes in community composition. The similarity of plant communities in rubber plantations undergoing natural succession for 3 years and 7 years falls between the two extremes. Although the 7-year succession has initiated the transformation of rubber plantations into tropical rainforests, it is still in its early stages. Nonetheless, with reduced human interference and alterations in the understory microenvironment, the plant community in the herbaceous layer is undergoing changes driven by species competition. In ecology, plant diversity is considered a natural solution for forest restoration, carbon capture, and climate change. Increased plant diversity can also increase carbon sequestration by increasing plant productivity, plant biomass, defoliation, root biomass, and microbial biomass (Duan *et al.* 2023). This study utilizes spatial analysis to examine diversity differences among plants in the herbaceous layer of rubber plantations across different succession years. While this method is straightforward and practical, it lacks the depth of long-term temporal dimension. Future research endeavors should focus on continuous monitoring of plant diversity changes in the herbaceous layer of rubber plantations over extended period to provide a comprehensive understanding of successional dynamics.

Conclusions

There were 175 species of understory plants in 149 genera and 75 families in the Yinggeling area of Hainan Tropical Rainforest National Park, of which 46.45% of the total species were Poaceae and Rubiaceae. In the rubber understory with natural succession of 0, 3, and 7 years, the dominant families were Rubiaceae, Poaceae, and Moraceae, among which *Ficus* and *Pterocarpus* were the dominant genera. The plant species composition and importance values of the understory herbaceous layer in rubber plantations undergoing 0, 3, and 7 years of succession varied with the duration of succession. The highest species count was observed in the 3rd year of succession, whereas the diversity indices—Shannon–Wiener, Simpson, and Pielou—peaked at 7 years of natural succession, with significant differences noted in the Margalef index. In general, natural restoration has increased the species diversity of the understory herbaceous layer of the rubber forest. However, the changes in the community characteristics of the natural restored rubber forest require further analysis of factors such as woody plants, climate environment, and soil.

Data Availability. Data will be made available on request.

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