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Diversity, Interspecific Interaction and Abundance of Undergrowth in Monocultures and Integrated Systems of Natural Rubber Plantation in Danzhou, Southern China

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Abstract

The negative impact of monoculture rubber plantations on biodiversity and associated ecological processes/ecosystem services has led to suggestions on the use of integrated land use systems for rubber cultivation and production in order to ensure environmental sustainability. However, there is paucity of information on the effect of such integrated land use systems on the diversity and abundance of the rubber plantation undergrowth. We evaluated and compared undergrowth plant species composition, richness, abundance, diversity and interaction, in three integrated systems (Rubber-*Strelitzia reginae* Integrated System - RSrIS, Rubber-*Podocarpus nagi* Integrated System – RPnIS & Naturally Managed Rubber Plantation - NMRP) with three Rubber Monoculture Plantations (RMP_1, RMP_2 & RMP_3) adjacent to the integrated systems, respectively, at the Investigation and Experiment Station of Tropical Crops, Danzhou, Hainan, China. Undergrowth species density was higher in the rubber monocultures than in the integrated systems except in RSrIS. Species richness and diversity were also higher in the monocultures except in NMRP. Species similarity/interaction between the monocultures and the integrated systems was highest between RMP_3 and NMRP. The NRMP proved to be the best model of natural rubber integrated system for the conservation of undergrowth species richness, diversity and interspecific interaction. However, the conservation of undergrowth species in other forms of integrated natural systems can be enhanced by considering the ecology of species to be integrated in terms of their growth characteristics, competitive nature, and ability to grow in association with other species.

Key Words: diversity, integrated land use, rubber monoculture, species interaction, undergrowth

Introduction

The economic importance of the rubber (*Hevea brasiliensis*) tree has been recognised globally due to its high quality latex. The species which originated from the Amazon Basin in Brazil naturally grows near the equator between 10° N and 10° S, and has a peak growth altitude of 600 m above sea level (Guardiola-Claramonte et al. 2008). However, it is now widely cultivated around the globe especially in South/East Asia including China. Although China does not fall within the naturally producing areas of natural rubber, it joined the top five producers in 2013 with a pro-

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duction record of 0.86 million tonnes (FAO 2013). The attainment of that height was a reward for China's huge investment in research aimed at growing rubber in areas with climates different from what obtains in its natural area of growth. Presently, China is the fifth largest producer of natural rubber (Jegede 2019); and has also remained its largest consumer globally.

The rapid expansion of the rubber plantation estate in South/East Asia including China could partly be traced to an earlier effort at finding an environmentally friendly alternative to swidden agriculture (shifting cultivation) which was fast degrading the environment due to its intensification and reduced fallow periods caused by the burgeoning human populations in the region (Ziegler et al. 2009). In addition, the successful development of hardy varieties of natural rubber that survived outside its natural areas of growth (Li and Fox 2012; Ahrends et al. 2015) led to its rapid expansion all over continental Southeast Asia; with the production rates tremendously increasing by about 1500% from 1961 to 2011 (FAO 2013). Ziegler et al. (2009) reported that over one million hectares of non-traditional rubber growing land have been converted to rubber plantations to satisfy the ever increasing demand for rubber in tropical Southeast Asia. In China particularly, rubber has expanded rapidly to its tropical areas (Sun et al. 2017), with the rubber tree planting area covering 1.14 million hectares as at the end of 2014 (Zhou et al. 2017). The introduction of rubber trees in China dates back to 1904 with Hainan, Guangdong, Guangxi, Fujian, Yunnan, and Taiwan Provinces being the initial planting areas (He and Huang 1987). Among these, Hainan (He and Huang 1987) and Yunnan, especially Xishuangbanna (Chen et al. 2013), are two of the major planting areas. In Hainan Island, Southern China, rubber plantations account for 25% of the total vegetation in the Island (Lan et al. 2017) with Danzhou as the largest distribution area.

However, the expansion of rubber plantations is not devoid of environmental and ecological consequences. For instance, the conversion of primary and secondary forests to monoculture rubber plantations, and the associated management practices result to loss of different aspects of biological diversity (Li et al. 2007; Bremer and Farley, 2010; Cotter et al. 2012; Xiao 2014; Ahrends et al. 2015; He and Martin 2015; Warren-Thomas et al. 2015; Zheng et al. 2015; Chaudhary et al. 2016; Hidayat et al. 2018; Singh et al. 2019), may negatively affect regional climates (Xu et al. 2014), soil fertility (Zhang and Zhou 2009; Li et al. 2012), and also accelerate soil erosion (Luo and Liu 2012). Given the environmental and ecological consequences of rubber plantation establishment and expansion, and the reduction in the available land for shifting agriculture as a result of increasing human populations, Ziegler et al. (2009) opined that the future of the rubber industry, would to a large extent, depend on developing suitable integrated land use systems that would combine rubber production with the conservation of biological diversity and/or food production. Similarly, He and Martin (2015) recommended the promotion of undergrowth in monoculture rubber plantations as a means of ensuring ecological sustainability and biodiversity conservation. Phommexay et al. (2011) also posited that rubber plantation agroforests which combine rubber trees with forest and edible/other useful plants are the best substitute for monoculture rubber plantations since they promote sustainability by striking a balance between economic gains and biodiversity conservation.

In tandem with the above recommendations, the Rubber Research Institute, Chinese Academy of Tropical Agricultural Sciences (RRI-CATAS) has over the years, introduced some integrated systems of rubber plantation that differ from the conventional intensively managed monoculture system. In 2012 (Lan et al. 2017) RRI-CATAS introduced a system they termed the Naturally Managed Rubber Plantation (NMRP) which excludes the conventional management practices such as regular undergrowth slashing, application of herbicides and inorganic fertilizers, among others. Prior to the introduction of the NMRP system, two other integrated systems had been introduced. In 1996 *Podocarpus nagi* seedlings of about 80 cm height were inter-planted in a part of *Hevea brasiliensis* Plantation established in May 1992 to shield the rubber trees from frequent wind and strong typhoon. In the third integrated system, the bird of paradise flower - *Strelitza reginae*, planted in 2002 mainly for commercial reason and soil conservation especially erosion control, grows in-between rows of *Hevea brasiliensis* plantation established in 2001.

However, He and Martin (2015) observed that restoration concepts in rubber dominated landscapes have not been clearly explained and that their contribution to the conservation of biological diversity equally remains uncertain. Besides an earlier attempt by Lan et al. (2017) to evaluate and compare species composition and abundance between the Naturally Managed Rubber Plantation and an adjacent intensively managed rubber plantation, no study has been conducted to ascertain the impact of these introduced integrated systems on species richness, abundance, diversity and interspecific interaction of the rubber plantation undergrowth flora within the study area. Even outside the study area, there are no available studies on the impact of converting already existing rubber monocultures to integrated systems on biodiversity generally and the diversity/interspecific interaction of the rubber plantation undergrowth in particular, despite the advocacy for the use of integrated natural rubber systems for biodiversity conservation, This study was a step in that direction. The specific research question that was addressed by this study is: How have the introduced integrated systems of rubber plantation affected the undergrowth plant species composition, richness, abundance, diversity and interspecific interaction, in relation to the conventional intensive management approach? It specifically compared plant species composition, richness, density, diversity and interspecific interaction between each of the introduced integrated systems and the intensively managed rubber plantation adjacent to it. In addition, it also determined the extent of improvement or deterioration in all the evaluated indices following the introduction of the integrated systems. It is hoped that the findings of this study will not only encourage the adoption and mainstreaming of effective integrated rubber plantations for ecological sustainability but also point out some limitations associated with some of the already introduced integrated systems that need to be addressed for effective biodiversity conservation in integrated rubber plantation ecosystems.

Materials and Methods

The study area

The study was conducted at the Investigation and Experiment Station of Tropical Crops, Chinese Academy of Tropical Agricultural Sciences, Danzhou (109°28'30"E and 19°32'47"N), North-west of the Hainan Island, China. The climate of the area falls within the tropical island monsoon climate with two seasons - dry and wet season. The wet season occurs from May to October, while the dry season is observed from November to April (Luo 1985). The climate of the area has been described by Wu et al. (2010). The average annual temperature ranges from 21.5 to 28.5°C. The solar radiation is 116 kcal/cm^2 while the annual sunshine is 2100 hours. The average annual rainfall is 1607 mm, which mainly distributes in July, August and September, accounting for more than 70% of the annual rainfall. The average annual relative humidity of the area is 83% while the average annual wind speed is 2 to 2.5 m/s. The climate anomalies are characterized by drought in spring, typhoons (in summer and autumn) and heavy rains.

Selection and description of the study sites

Three sites were purposively chosen for the study in line with the objectives, as follows:

Site 1

The natural rubber plantation in this site (109°28'30'''E and 19°32'47''' N, with an elevation of 114 m) was established with CATAS7-33-97 clone in 2001 using a planting spacing of 3 m×7 m at a density of 476 plants/ha. In 2002, the ornamental herbaceous plant - *Strelitza reginae*, was planted in between rows of the rubber trees in a section of the plantation mainly for commercial reason and soil conservation. *Strelitzia reginae* commonly known as bird-of-paradise flower or crane flower belongs to the family Strelitziaceae. Although, native to South Africa, it has been planted in different parts of the world and is widely used as an ornamental because of its vivid and beautiful orange and purple flowers. At the end of 2014, the average canopy height of this rubber forest was 14.0 m, with a two-stratum structure; the upper layer being the tree layer, with a height of 12 to 16 m, and the lower herbaceous layer, with a height of about 0.4 m. A larger portion of the plantation is still managed intensively as a monoculture. This made it possible to compare the undergrowth species richness, abundance, diversity and interaction between the monoculture and the rubber-strelitzia integrated system.

Site 2

The original natural rubber plantation in this site (109°28'33"E and 19°32'33"N) was harvested in 1991 and replanted with the CATAS7-33-97 clone in May 1992 using a planting spacing of 3 m×7 m at a density of 476 trees/hectare. The soil type was latosol developed from granite, and the site has a slope of about 5° to the southeast. In December 1996, *Podocarpus nagi* seedlings with height of about 80 cm were planted in between the natural rubber trees at a section of the plantation, to shelter the rubber trees from the damaging effects of constant wind and strong typhoons. *Podocarpus nagi*, native to China, Japan and Taiwan, is an upright dense evergreen tree that is used as a screen, hedge, strong accent plant, or farming tree. It belongs to the family Podocarpaceae. It is capable of growing up to 90 ft in height but is usually seen growing to a height of 30 to 40 ft due to its moderately slow growth (Gilman and Watson 1994). It grows both in shade and full sun and tolerates a wide range of soil types (Gilman and Watson 1994). A large portion of the natural rubber plantation in this site is still maintained and managed as a monoculture. This made it possible to evaluate and compare the undergrowth species richness, abundance, diversity and interspecific interaction between the rubber-*Podocarpus nagi* integrated system and the rubber monoculture in this site.

Site 3

The natural rubber trees in this site (109°29'36.5"E and 19°32'36.53"N) were planted in 2005 using a planting spacing of 3 m×7 m at a density of 476 trees/hectare. This site is a fixed sample plot of 1 hectare with an elevation of 70 to 100 m, a slope of 5 to 10° and a stand canopy density of over 85% (Lan et al. 2017). Its status changed to a Naturally Managed Plantation in 2012. Prior to the adoption of the natural management approach, conventional management was carried out. With the natural management approach, anthropogenic interferences are prohibited as much as possible (Lan et al. 2017) and such production activities like undergrowth clearance, application of herbicides and fertilisers, are not allowed. Adjacent to the naturally managed plantation in this site is a conventionally managed natural rubber plantation with which comparisons were made regarding the undergrowth species richness, abundance, diversity and interspecific interaction.

Plant enumeration

Enumeration of the undergrowth plant species was done using the quadrat method. At each site, three plots of 20×20 m (400 m^2) was mapped out at the core of both the monoculture rubber plantation and the integrated system. Then, nine 2×2 m (4 m^2) quadrats were systematically laid at 5 m intervals starting from the North-west to North-east direction down to the southern end of each plot. This quadrat size (4 m^2) falls within the range (0.25 to 16 m^2) specified in literature by Bullock (1996) for the enumeration of grassland, tall herb, short shrub, or aquatic macrophyte communities, among others. Bullock (1996) stated that vegetation with smaller plants, greater plant density or greater species diversity should require smaller quadrats. Undergrowth plant species in all quadrats were identified to species level and the number of individuals counted and recorded, for both the monoculture and the integrated rubber management systems. The identification of the undergrowth plant species was done by an expert taxonomist with the aid of Engel and Phummai (2008). Despite the clumping nature of members of the gramineae family, they were sparsely distributed growing under the shade of the rubber plantations. This fact coupled with the small size of the quadrats used for the study, made it possible for them to be counted.

Data analysis

Species abundance

Density − number of undergrowth plants/area, was used to measure abundance. Species density was computed by first adding the number of the individual plants enumerated for each species in each management system and extrapolating to per hectare using Equation 1.

$$D = \frac{A}{a} \times \frac{n}{1} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{Eqn. 1}$$

Where: D=Density per hectare
A=Area of a hectare
a=Total sampled area in each management system
n=number of individuals enumerated for each plant species

Relative density (%) was computed for each species in a management system using Equation 2.

$$RD = \frac{d}{TD} \times \frac{100}{1} \cdots\cdots\cdots\cdots \text{Eqn. 2}$$

Where: RD = Relative Density (%)
d = density of a species
TD = Total Density for all species in a management system

Species richness

Species richness for each of the monocultures and the integrated systems was determined by counting the number of species recorded in all the sample quadrats in that system.

Species diversity

Alpha (within community) diversity was measured for each of the natural rubber plantation management systems using Shannon-Wiener index (Kent and Coker 1992). Alpha diversity has also been measured using Shannon-Wiener index by other workers (e.g. Chima et al. 2013; Leisbangthem and Singh 2018; Rahman et al. 2019).

Shannon-Wiener Index is expressed as:

$$H = -\sum_{i=1}^{s} pi \ln pi \cdots\cdots\cdots\cdots \text{Eqn. 3}$$

Where: H = Shannon-Wiener index
pi = the proportion of individuals of the ith plant species in a management system
s = the total number of species enumerated in a management system

Beta diversity was measured using Sorenson Similarity Index (Magurran 2004). This helped to determine the extent of similarity in undergrowth species composition between the different natural rubber plantation management systems. Higher similarity in species composition between two rubber plantation management systems indicates higher species interaction between the systems, and *vice versa*. Sorensen index was computed using Equation 4.

$$SI = \frac{2a}{2a+b+c} \cdots\cdots\cdots\cdots \text{Eqn. 4}$$

Where: SI = Sorensen Index
a = the number of species present in both Management systems
b = the number of species present in Management System 1 but absent in Management System 2
c = the number of species present in Management System 2 but absent in Management System 1

However, a slight modification of the Sorensen index formula was made to generate Equation 5 below which enabled the indices to be presented in percentages.

$$SI\ (\%) = \frac{2a}{2a+b+c} \times 100 \cdots\cdots\cdots\cdots \text{Eqn. 5}$$

Where: SI (%) = Sorensen Index per cent
a = the number of species present in both Management systems
b = the number of species present in Management System 1 but absent in Management System 2
c = the number of species present in Management System 2 but absent in Management System 1

Species evenness

Species evenness was calculated for each natural rubber management system after Obasi et al. (2013) by dividing the Shannon-Wiener diversity index for that system by the natural logarithm of its species richness (Equation 6).

$$E = \frac{H}{lnS} \cdots\cdots\cdots\cdots \text{Eqn. 6}$$

Where: E = Species evenness
H = Shannon-Wiener diversity index
S = Species richness

Computation of change index

Change Index (%) was computed to ascertain the extent of change in the populations of undergrowth plant species, number of genera, number of families, species richness, and species diversity, between the Monocultures and the integrated systems in each site. The procedure for the computation of change index was adapted from Salami (1998), Islam and Weil (2000), Aiyeloja and Chima (2011), and

Chima and Uwaegbulem (2012). The calculation of the change index was based on the assumption that the integrated rubber systems are the ideal management systems for the conservation of undergrowth plant species richness, abundance, diversity and interspecific interaction. Hence, the population of each undergrowth plant species, the number of plant species (species richness), genera and families, the density, and the species diversity, in the integrated system were taken as the optimal values in each site. Consequently, the index of change (%) was derived by finding the difference between the value of an evaluated attribute in the integrated system and the rubber monoculture in a particular site and subsequently expressing the computed difference as a percentage of the value in the rubber monoculture. A positive change index was used as an improvement index while a negative change index was used as a degradation index.

Results

Effect of the integrated systems on plant species composition and abundance

The number of species, genera, and families enumerated in both the natural rubber monocultures and adjacent integrated systems, and the indices of change for the integrated system, are presented in Table 1. The number of species, genera, and families decreased in the integrated systems except in the Naturally Managed Rubber Plantation where a state of equilibrium was observed between it and the adjacent monoculture. However, the rate of decrease

Table 1. Summary of plant species composition at different sites/management systems

Index	Site 1			Site 2			Site 3		
	RMP_1	RSrIS	CI (%)	RMP_2	RPnIS	CI (%)	RMP_3	NMRP	CI (%)
Species	11	4	-63.64	17	11	-35.29	19	19	0
Genera	11	4	-63.64	17	10	-41.18	18	18	0
Families	10	4	-60	16	10	-37.5	16	16	0

$RMP_{1,2\&3}$, Rubber Monoculture Plantation in Sites 1, 2 & 3; RSrIS, Rubber-*Strelitzia reginae* Integrated System; RPnIS, Rubber-*Podocarpus nagi* Integrated System; NMRP, Naturally Managed Rubber Plantation; CI (%), Change Index (%).

Table 2. Plant species composition and abundance of undergrowth in Site 1

S/No.	Species	Family	Habit	RMP_1			RSrIS			
				No.	D/ha	RD (%)	No.	D/ha	RD (%)	CI (%)
1	*Asystasia gangetica*	Acanthaceae	Herb	191	53,056	40.21	0	0	0	-100
2	*Cyclosorus parasiticus*	Thelypteridaceae	Herb	10	2,778	2.11	2	556	0.22	-80
3	*Cyrtococcum patens*	Gramineae	Herb	83	23,056	17.47	0	0	0	-100
4	*Dioscorea opposita*	Dioscoreaceae	Non-woody vine	1	278	0.21	2	556	0.22	100
5	*Hevea brasiliensis*	Euphorbiaceae	Tree	2	556	0.42	1	278	0.11	-50
6	*Indocalamus latifolius*	Gramineae	Herb	10	2,778	2.11	0	0	0	-100
7	*Litsea monopetala*	Lauraceae	Tree	59	16,389	12.42	0	0	0	-100
8	*Microlepia speluncae*	Dennstaedtiaceae	Herb	14	3,889	2.95	0	0	0	-100
9	*Podocarpium podocarpum*	Fabaceae	Herb	3	833	0.63	0	0	0	-100
10	*Pteris semipinnata*	Pteridaceae	Herb	6	1,667	1.26	0	0	0	-100
11	*Strelitzia reginae*	Musaceae	Herb	96	26,667	20.21	913	253,613	99.45	851

RMP_1, Rubber Monoculture Plantation in Sites 1; RSrIS, Rubber-*Strelitzia reginae* Integrated System; D/ha, Density per hectare; RD (%), Relative Density (%); CI (%), Change Index (%).

was more in the Rubber-*Strelitzia reginae* Integrated System than in the Rubber-*Podocarpus nagi* Integrated System.

The plant species composition and the abundance of the undergrowth in Site 1 and their indices of change at the Rubber-*Srelitzia reginae* Integrated System, are presented in Table 2. A total of 11 species was recorded at the Rubber Monoculture Plantation while 4 species were recorded at the Rubber-*Srelitzia reginae* Integrated System. Four species were common to both sites while seven species found at the Rubber Monoculture Plantation were absent at the Rubber-*Srelitzia reginae* Integrated System. Populations of species common to both sites were lower at the Rubber-*Srelitzia reginae* Integrated System except *Discorea opposita* and *Strelitzia reginae*.

The plant species composition and abundance of the undergrowth in Site 2 are presented in Table 3. Seventeen species were recorded at the Rubber Monoculture Plantation while eleven species were recorded at Rubber-*Podocarpus nagi* Integrated System. Seven species were common to both sites; ten species found at the Rubber Monoculture Plantation were absent at the Rubber-*Podocarpus nagi* Integrated System, while four species present at the Rubber-*Podocarpus nagi* Integrated System were absent at the Rubber Monoculture Plantation. Populations of some of the undergrowth species reduced at the Rubber-*Podocarpus nagi* Integrated System, while some were completely lost. *Piper betle* and *Cyrtococcum patens* had the highest relative density at the Rubber Monoculture Plantation and Rubber-*Podocarpus nagi* Integrated System, respectively.

Table 4 shows the plant species composition and abundance with their indices of change between the Rubber Monoculture Plantation and Naturally Managed Rubber Plantation at Site 3. Nineteen species were recorded at the

Table 3. Plant species composition and abundance of undergrowth in Site 2

S/No.	Species	Family	Habit	RMP_2			RPnIS			
				No.	D/ha	RD (%)	No.	D/ha	RD (%)	CI (%)
1	*Acacia sinuate*	Mimosaceae	Liana	0	0	0	1	278	0.41	1^+
2	*Alocasia macrorrhiza*	Araceae	Herb	49	13,611	6.12	0	0	0	-100
3	*Centotheca lappacea*	Gramineae	Herb	1	278	0.13	0	0	0	-100
4	*Cyclosorus parasiticus*	Thelypteridaceae	Herb	6	1,667	0.75	11	3,056	4.55	83.33
5	*Cyrtococcum patens*	Gramineae	Herb	65	18,056	8.13	178	49,445	73.55	173.85
6	*Dioscorea opposita*	Dioscoreaceae	Non-woody vine	9	2,500	1.12	4	1,111	1.65	-55.56
7	*Ficus fistulosa*	Moraceae	Tree	6	1,667	0.75	0	0	0	-100
8	*Glycosmis cochinchinensis*	Rutaceae	Tree	3	833	0.37	0	0	0	-100
9	*Hedyotis auricularia*	Rubiaceae	Herb	11	3,056	1.38	0	0	0	-100
10	*Lygodium digitatum*	Lygodiaceae	Herb	0	0	0	1	278	0.41	1^+
11	*Lygodium japonicum*	Lygodiaceae	Herb	11	3,056	1.38	11	3,056	4.55	0
12	*Mallotus paniculatus*	Euphorbiaceae	Tree	3	833	0.37	0	0	0	-100
13	*Microlepia speluncae*	Dennstaedtiaceae	Herb	13	3,611	1.62	12	3,333	4.96	-7.69
14	*Piper betle*	Piperaceae	Liana	478	132,779	59.75	4	1,111	1.65	-99.16
15	*Podocarpium podocarpum*	Fabaceae	Herb	20	5,556	2.5	0	0	0	-100
16	*Podocarpus nagi*	Podocarpaceae	Tree	0	0	0	13	3,611	5.38	13^+
17	*Pteris semipinnata*	Pteridaceae	Herb	4	1,111	0.5	0	0	0	-100
18	*Toxocarpus wightianus*	Asclepiadaceae	Shrub	15	4,167	1.88	4	1,111	1.65	-73.33
19	*Tetrastigma pachyphyllum*	Vitaceae	Liana	22	6,111	2.75	0	0	0	-100
20	*Wedelia chinensis*	Compositae	Herb	84	23,334	10.5	0	0	0	-100
21	*Ziziphus fungi*	Rhamnaceae	Shrub	0	0	0	3	833	1.24	3^+

$^+$Not actually a change index but the population of a species found only in RPnIS.

RMP_2, Rubber Monoculture Plantation in Sites 2; RPnIS, Rubber-*Podocarpus nagi* Integrated System; D/ha, Density per hectare; RD, Relative Density; CI (%), Change Index (%).

Table 4. Plant species composition and abundance of undergrowth in Site 3

S/No.	Species	Family	Habit	RMP$_3$			NMRP			
				No.	D/ha	RD (%)	No.	D/ha	RD (%)	CI (%)
1	*Acacia sinuate*	Mimosaceae	Liana	0	0	0	1	278	0.25	1$^+$
2	*Aporusa dioica*	Euphorbiaceae	Tree	2	556	0.36	0	0	0	-100
3	*Baccaurea ramiflora*	Euphorbiaceae	Tree	11	3,056	1.96	0	0	0	-100
4	*Celastrus hindsii*	Celastraceae	Liana	0	0	0	1	278	0.25	1$^+$
5	*Centotheca lappacea*	Gramineae	Herb	1	278	0.18	0	0	0	-100
6	*Cyclosorus paraiticus*	Thelypteridaceae	Herb	50	13,889	8.92	24	6,667	6.02	-52
7	*Cyrtococcum patens*	Gramineae	Herb	161	44,723	28.74	154	42,778	38.6	-4.35
8	*Dioscorea opposita*	Dioscoreaceae	Non-woody vine	5	1,389	0.89	43	11,945	10.78	760
9	*Ficus hirta*	Moraceae	Tree	2	556	0.36	0	0	0	-100
10	*Ficus hispida*	Moraceae	Tree	1	278	0.18	0	0	0	-100
11	*Hypolytrum hainanense*	Cyperaceae	Herb	3	833	0.54	4	1,111	1	33.33
12	*Litsea monopetala*	Lauraceae	Tree	0	0	0	6	1,667	1.5	6$^+$
13	*Lygodium digitatum*	Lygodiaceae	Herb	0	0	0	2	556	0.5	2$^+$
14	*Lygodium japonicum*	Lygodiaceae	Herb	1	278	0.18	3	833	0.75	66.67
15	*Melia azedarach*	Meliaceae	Tree	2	556	0.36	0	0	0	-100
16	*Microlepia speluncae*	Dennstaedtiaceae	Herb	3	833	0.54	13	3,611	3.26	333.33
17	*Oplismenus compositus*	Gramineae	Herb	0	0	0	42	11,667	10.53	42$^+$
18	*Phaenosperma globosa*	Gramineae	Herb	0	0	0	3	833	0.75	3$^+$
19	*Piper betle*	Piperaceae	Liana	120	33,334	21.42	2	556	0.5	-98.33
20	*Pteris semipinnata*	Pteridaceae	Herb	15	4,167	2.68	20	5,557	5.01	33.33
21	*Polygonum chinense*	Polygonaceae	Herb	1	278	0.18	0	0	0	-100
22	*Schizoloma ensifolium*	Lindsaeaceae	Herb	1	278	0.18	2	556	0.5	100
23	*Synedrella nodiflora*	Compositae	Herb	23	6,389	4.11	57	15,833	14.28	147.83
24	*Tectaria simonsii*	Aspidiaceae	Herb	24	6,667	4.29	11	3,056	2.76	-54.17
25	*Toxocarpus wightianus*	Asclepiadaceae	Shrub	134	37,223	23.93	9	2,500	2.26	-93.28
26	*Ziziphus fungi*	Rhamnaceae	Shrub	0	0	0	2	556	0.5	2$^+$

$^+$Not actually a change index but the population of a species found only in NMRP.
RMP$_3$, Rubber Monoculture Plantation in Sites 3; NMRP, Naturally Managed Rubber Plantation; D/ha, Density per hectare; RD, Relative Density; CI (%), Change Index (%).

Rubber Monoculture Plantation and also at the Naturally Managed Rubber Plantation. Twelve species were common to both sites; seven species found at the Rubber Monoculture Plantation were not found at the Naturally Managed Rubber Plantation and *vice versa*. These values show that the Rubber Monoculture Plantation and the Naturally Managed Rubber Plantation had the highest number of species common between monocultures and the integrated systems. Although total plant undergrowth density was more at the Rubber Monoculture Plantation than the Naturally Managed Rubber Plantation, the change indices indicate that increase in individual species populations between the monocultures and the integrated systems was more the Naturally Managed Rubber Plantation than in any other integrated system. The most dominant species in both the Rubber Monoculture Plantation and the Naturally Managed Rubber Plantation was *Cyrtococuum patens*. On a general note, species dominance was lower in RMP3 when compared with the other monocultures and also lower in NMRP when compared with the other integrated systems.

The total undergrowth plant density (per hectare) for the monocultures and the integrated natural rubber management systems is shown in Fig. 1 while the distribution of the

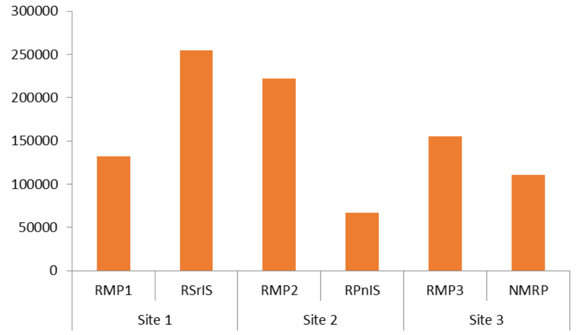

Fig. 1. Undergrowth plant density per hectare for the monocultures and natural rubber integrated systems. $RMP_{1,2\&3}$, Rubber Monoculture Plantation in Sites 1, 2 & 3; RSrIS, Rubber-*Strelitzia reginae* Integrated System; RPnIS, Rubber-*Podocarpus nagi* Integrated System; NMRP, Naturally Managed Rubber Plantation.

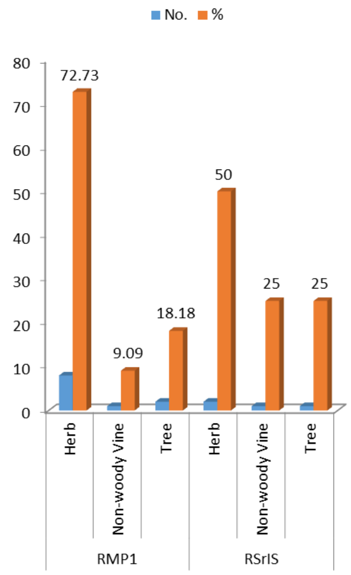

Fig. 2. Percentage distribution of undergrowth plant species among plant forms in Rubber Monoculture Plantation (RMP_1) and the Rubber-*Strelitzia reginae* Integrated System (RSrIS) in Site 1.

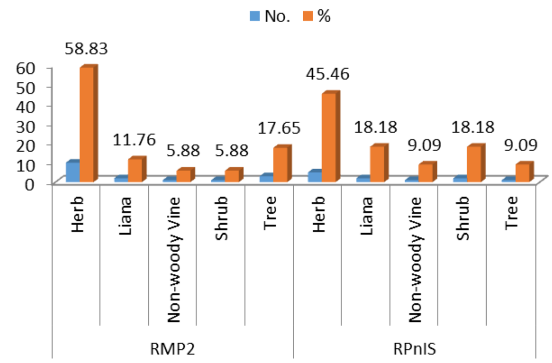

Fig. 3. Percentage distribution of undergrowth plant species among plant forms in Rubber Monoculture Plantation (RMP_2) and the Rubber-*Podocarpus nagi* Integrated System (RPnIS) in Site 2.

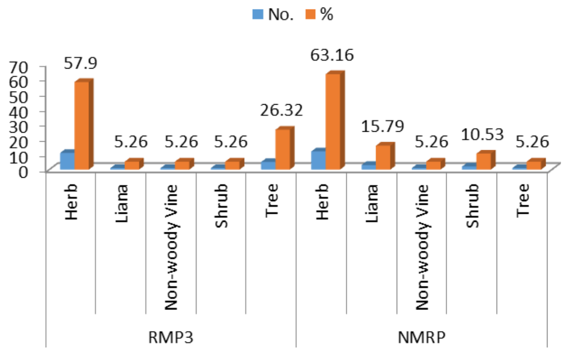

Fig. 4. Percentage distribution of undergrowth plant species among plant forms in Rubber Monoculture Plantation (RMP_3) and the Naturally Managed Rubber Plantation (NMRP) in Site 3.

undergrowth plants among the various plant forms is shown in Fig. 2, 3 and 4 for Site 1 (Rubber Monoculture Plantation and the Rubber-*Strelitzia reginae* Integrated System), Site 2 (Rubber Monoculture Plantation and Rubber-*Podocarpus nagi* Integrated System), and Site 3 (Rubber Monoculture Plantation and Naturally Managed Rubber Plantation), respectively. Total undergrowth plant density was higher in the monocultures than in the integrated systems except between the Rubber Monoculture Plantation and the Rubber-*Strelitzia reginae* Integrated System. On a general note, the lowest and the highest undergrowth plant density was recorded at Rubber-*Podocarpus nagi* Integrated System and the Rubber-*Strelitzia reginae* Integrated System, and also when the integrated systems are considered separately. However, in monocultures, total undergrowth plant density was highest in the Rubber Monoculture Plantation at Site 2, followed by the Rubber Monoculture Plantation at Site 3 and the Rubber Monoculture Plantation at Site 1, respectively. Herbaceous plant species dominated the plant communities in both the monocultures and the integrated systems. However, the percentages of woody species relatively increased in the integrated systems except tree species in Naturally Managed Rubber Plantation.

Effect of the integrated systems on plant species richness, diversity and interspecific interaction

The species richness and alpha diversity indices for both the monocultures and the integrated rubber management systems are presented in Table 5. Between the Rubber Monoculture Plantation & the Rubber-*Strelitzia reginae* Integrated System in Site 1 and the Rubber Monoculture Plantation & the Rubber-*Podocarpus nagi* Integrated System in Site 2, undergrowth plant species richness, number of individuals, species diversity, and species evenness decreased in the integrated systems except in the Rubber-*Strelitzia reginae* Integrated System where the number of individuals was higher and Rubber-*Podocarpus nagi* Integrated System where a state of equilibrium in species evenness was maintained between it and Rubber Monoculture Plantation in Site 2. However, between Rubber Monoculture Plantation and the Naturally Managed Rubber Plantation in Site 3, both undergrowth plant species evenness and diversity improved in the Naturally Managed Rubber Plantation while the number of individuals reduced, and the species richness remained constant.

The similarity (beta diversity) indices are presented in Table 6. Between the monocultures and the integrated systems in each site, the highest similarity/species interaction was observed between the Rubber Monoculture Plantation & the Naturally Managed Rubber Plantation in Site 3, followed by the Rubber Monoculture Plantation & the Rubber-*Strelitzia reginae* Integrated System in Site 1, while the lowest similarity and species interaction was observed between Rubber Monoculture Plantation & Rubber-*Podocarpus nagi* Integrated System in Site 2. Looking at the monocultures and the integrated systems in all the sites collectively, the highest similarity/species interaction was observed between the Rubber Monoculture Plantation & the Naturally Managed Rubber Plantation in Site 3, while species similarity/interaction was lowest between Rubber Monoculture Plantation in Site 3 & the Rubber-*Strelitzia reginae* Integrated System in Site 1. Considering the monocultures alone, the highest species similarity/interaction was observed between the Rubber Monoculture Plantation in Site 2 & the Rubber Monoculture Plantation in Site 3, fol-

Table 5. Undergrowth species richness and diversity indices for the different management systems

Index	Site 1			Site 2			Site 3		
	RMP_1	RSrIS	CI (%)	RMP_2	RPnIS	CI (%)	RMP_3	NMRP	CI (%)
Taxa (species)	11	4	-63.64	17	11	-35.29	19	19	0.00
Individuals	475	918	93.26	800	242	-69.75	560	399	-28.75
Shannon H	1.64	0.04	-97.56	1.57	1.12	-28.66	1.90	2.06	0.84
Species evenness	0.41	0.26	-36.59	0.28	0.28	0.00	0.35	0.41	17.14

$RMP_{1,2\&3}$, Rubber Monoculture Plantation in Sites 1, 2 & 3; RSrIS, Rubber-*Strelitzia reginae* Integrated System; RPnIS, Rubber-*Podocarpus nagi* Integrated System; NMRP, Naturally Managed Rubber Plantation; CI (%), Percentage Change Index.

Table 6. Similarity indices for the different management systems

	RMP_1	RSrIS	RMP_2	RPnIS	RMP_3	NMRP
RMP_1	1	53.33	42.86	36.36	33.33	40.00
RSrIS		1	19.05	26.67	17.39	17.39
RMP_2			1	50.00	50.00	44.44
RPnIS				1	46.67	66.67
RMP_3					1	63.16
NMRP						1

$RMP_{1,2\&3}$, Rubber Monoculture Plantation in Sites 1, 2 & 3; RSrIS, Rubber-*Strelitzia reginae* Integrated System; RPnIS, Rubber-*Podocarpus nagi* Integrated System; NMRP, Naturally Managed Rubber Plantation.

lowed by the Rubber Monoculture Plantation 1 & Rubber Monoculture Plantation in Site 2, while the Rubber Monoculture Plantation in Site 1 & the Rubber Monoculture Plantation in Site 3 had the lowest similarity/species interaction. When the integrated systems were considered alone, the highest similarity/species interaction was observed between the Rubber-*Podocarpus nagi* & the Naturally Managed Rubber Plantation, followed by the Rubber-*Strelitzia reginae* Integrated System & Rubber-*Podocarpus nagi* Iintegrated System, while the lowest similarity/species interaction was observed between the Rubber-*Strelitzia reginae* Integrated System & the Naturally Managed Rubber Plantation.

Discussion

On a general note the species richness, diversity, and abundance of the undergrowth decreased in the rubber integrated systems except in the naturally managed system where the species diversity slightly increased and in the Rubber-*Strelitzia reginae* Integrated system where abundance was higher than in the monocultures. The reason for the lower species richness in the Rubber-*Strelitzia reginae* Integrated system is probably due to the nature and ecology of *Strelitzia reginae*. The invasive and colonizing nature of *Strelitzia reginae* has almost led to the extermination of the other undergrowth plant species in the integrated system as a result of fierce competition and its stifling nature. The very high dominance of *Strelitzia reginae* (99.45%) in the integrated system also explains why the diversity of the undergrowth in the system was the lowest for all the systems (monocultures inclusive). As observed by Amubode (1996) species diversity not only considers species richness but also the manner in which the individuals are distributed amongst the species. Thus, high species dominance, reduces diversity and *vice versa*. Invasive plant species alter ecosystem structure and function and reduce the productivity of forest in the affected area (Gaertner et al. 2009; Holzmueller and Jose 2011), and are also capable of reducing native species diversity which could lead to the extinction of endangered native species (Schmitz and Simberloff 1997; Webster et al. 2006). The choice of Stelitzia reginae for the integrated system was mainly commercial as it was cultivated for the production of cut-flowers. Although native to South Africa, Stelitzia reginae has been planted in different parts of the world because of its vivid and beautiful orange and purple flowers. Its aggressive root system and clumping nature also make it capable of checking erosion by being able to bind the soil particles together and protect the soil against direct impact of rainfall, respectively. However, its negative impact on species richness and interaction as revealed by this study makes it unsuitable for natural rubber integration systems especially when undergrowth plant diversity and interspecific interaction are desired.

Between the Rubber Monoculture and the Rubber-*Podocarpus nagi* Integrated System, species richness, diversity and abundance, were also lower in the latter. Lower species richness in the Rubber-*Podocarpus nagi* Integrated System is most likely due to inadequate spacing which led to more canopy closure in the integrated system, thereby reducing the amount of sunlight reaching the forest floor for the growth and sustenance of the undergrowth flora which usually comprises pioneer species. The original rubber plantation in this site was harvested in 1991 and replanted in May 1992. In December 1996, *Podocarpus nagi* seedlings with height of about 80 cm were planted in-between the rubber trees at a section of the plantation, to shelter the rubber trees from the damaging effects of frequent winds and strong typhoons *Podocarpus nagi* has a variety of uses and is recommended for buffer strips around parking lots, median strip planting in highways, screen, shade tree, residential street tree (Gilman and Watson 1994), among other uses. However, it appears that its integration was not anticipated at the time the rubber trees were planted to allow for adequate spacing giving the enormous space required to accommodate the architecture of the two tree species and also allow some appreciable amount of sunlight to get to the undergrowth. Hence, the observed negative effects on undergrowth species diversity and abundance. It has been demonstrated through research that the composition and vitality of competing species under a tree canopy varies greatly from those growing in open field conditions (Hannerz and Hanell 1997).

However, the trend between the Naturally Managed Rubber Plantation and the adjacent Rubber Monoculture differed from that of the other integrated systems as the number of species, genera and families remained the same while the diversity and species evenness improved marginally in the Naturally Managed Rubber Plantation. Only abundance was lower in the Naturally Managed Rubber. The improvement recorded in Naturally Managed Rubber Plantation relative to the monocultures/other integrated systems is indicative of its ability to contribute to plant diversity restoration/conservation in rubber undergrowth, and may not be unconnected to the management practices adopted. The near natural management approach was modelled after the Jungle rubber which allows the growth of the natural rubber trees with other associated species. In addition, some management practices adopted in the conventionally/intensively managed rubber monocultures like fertilizer application and regular slashing of the undergrowth are not allowed in the naturally managed system. Better performance of other aspects of biodiversity in Jungle rubber than in intensively managed rubber monocultures have been reported for birds by Probowo et al. (2016) and termites by Jones et al. (2003). However, the lower undergrowth abundance recorded in the Naturally Managed Rubber Plantation could be as a result of more intense competition for space as the undergrowth in the naturally managed plantation are growing bigger in size as a result of minimal disturbance, and the impact of the bigger undergrowth especially on the intensity of light that reaches the forest floor.

The domination of both the rubber monocultures and the integrated systems by herbaceous plant species indicates that the undergrowth in all the systems is still in their early stages of succession including the Naturally Managed Rubber Plantation which is several years younger than the other two integrated systems. However, the improved percentages of the woody plant forms in the integrated systems especially the Rubber-*Podocarpus nagi* Integrated System and the Naturally Managed Rubber Plantation when compared with the rubber monocultures, is indicative of possible future woody species recovery in the integrated systems.

The highest species similarity/interaction observed between the Naturally Managed Rubber Plantation and the adjacent monoculture when the monocultures were compared with the integrated systems at the respective sites, could be attributed to the minimal disturbance in the Naturally Managed Rubber Plantation and more exchange of seeds between the two sites by seed dispersers whose populations and diversity may have been enhanced by the higher undergrowth diversity in the Naturally Managed Rubber Plantation. However, the lowest species similarity/species interaction, observed between the Rubber Monoculture Plantation in Site 3 and the Rubber-*Strelitzia reginae* Integrated System in Site 1, is attributable to two possible reasons: one, the longer distance between them than any other two systems which may have limited the exchange of seeds between the sites, and two, the invasive, colonizing and clumping nature of *Strelitzia reginae*, which has almost led to the extermination of other species in the system through fierce competition and its stifling nature. It should be noted that species richness, diversity and evenness, were lowest at the Rubber-*Strelitzia reginae* Integrated System.

The trend in undergrowth plant species similarity/interaction between the rubber monocultures reflected two patterns: one, the degree of disturbance and two, the proximity of the plantations to each other. For instance, highest species similarity occurred between the Rubber monocultures in Sites 2 and 3 which were not as disturbed as the Rubber monoculture in Site 1, followed by the Rubber Monocultures in Sites 1 and 2 which have the shortest distance between them, while the lowest species similarity/interaction was observed between Rubber Monocultures in Sites 1 and 3 which were the farthest and also the highest and the least disturbed, respectively. High degree of site disturbance can impact negatively on species similarity/interaction by directly reducing species richness while longer distance between sites may limit the exchange of seeds between sites by dispersers.

The implications of these findings for effective conservation of undergrowth plant species diversity and interspecific interaction in natural rubber integrated systems cannot be overemphasized. For instance, the ecology of species and their impact on other species must be considered when making choice of species for integrated systems for whatever reason and use. In addition, choice and decision regarding spacing must consider the growth characteristics of species to be integrated and make adequate provisions to accommodate the architecture/structure of the species when fully grown while also providing space for light penetration to sustain the diversity of the undergrowth. To further improve species diversity and interspecific interaction of the undergrowth in the integrated systems, management operations should be targeted towards controlling the populations of species that have invasive, stifling, and colonizing tendencies. For instance, *Discorea opposita*, a non-woody vine capable of rapidly colonizing favourable landscapes was found in all the natural rubber plantation systems with the highest population in the Naturally Managed Rubber Plantation. When its population in the Naturally Managed Rubber Plantation was compared with that of the adjacent Monoculture Rubber Plantation, an increase of 760% was observed. If this high rate of population increase is not checked, there is the tendency that it will dominate the Naturally Managed Rubber Plantation with a likely negative impact on its undergrowth diversity and interspecific interaction.

Conclusion

Undergrowth species density was higher in the natural rubber monocultures than in the integrated systems except in the Rubber-*Strelitzia reginae* Integrated System. Similarly, species richness and diversity were also higher in the monocultures except in the Naturally Managed Rubber Plantation. Species similarity/interaction between the monocultures and the integrated systems was highest between Rubber Monoculture Plantation in Site 3 and the Naturally Managed Rubber Plantation. The Naturally Managed Rubber Plantation proved to be the best model of natural rubber integrated systems for the conservation of undergrowth species richness, diversity and interspecific interaction, despite the fact that it was the youngest of the integrated systems. However, the conservation of undergrowth species in other forms of rubber integrated systems can be enhanced by considering the ecology of species to be integrated in terms of their growth characteristics, competitive nature, and ability to promote undergrowth and/or grow in association with other species. The need for further research to ascertain the impact of the integrated systems on other aspects of biodiversity is emphasized.

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