Journal of Environmental Management 292 (2021) 112747

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Challenges of the establishment of rubber-based agroforestry systems: Decreases in the diversity and abundance of ground arthropods

Chang-An Liu [a,b,*], Ming-Yue Liang [a,c], Jian-Wei Tang [a], Yan-Qiang Jin [a], Zhi-Bin Guo [d,**], Kadambot H.M. Siddique [e]

[a] CAS Key Laboratory of Tropical Plant Resources and Sustainable Use, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Menglun, Mengla, Yunnan, 666303, China
[b] Center of Economic Botany, Core Botanical Gardens, Chinese Academy of Sciences, Menglun, Mengla, Yunnan, 666303, China
[c] University of Chinese Academy of Sciences, Beijing, 100049, China
[d] Soil and Fertilizer Research Institute of Anhui Academic of Agricultural Science, No. 40 Southern Nongke Road, Luyang District, Hefei, Anhui, 230031, China
[e] The UWA Institute of Agriculture, The University of Western Australia, Perth, WA, 6009, Australia

ARTICLE INFO

Keywords:
Ground arthropod diversity
Ants
Spiders
Rubber plantations
Xishuangbanna

ABSTRACT

The global land area devoted to rubber plantations has now reached 13 million hectares, and the further expansion of these rubber plantations at the expense of tropical forests will have significant adverse effects on the ecological environment. Rubber-based agroforestry systems are considered a preferable approach for ameliorating the ecological environment. Many researchers have focused on the positive effects of rubber-based agroforestry systems on the ecological environment, while ignoring the risks involved in the establishment of rubber-based agroforestry systems. The present study investigated the effects of different-aged rubber-based agroforestry systems on the abundance and diversity of ground arthropods. It has been observed that the abundance and taxon richness of ground arthropods generally showed no difference when comparing young and mature rubber plantations. The rubber-based agroforestry systems significantly decreased the understory vegetation species, along with the abundance and taxon richness of ground arthropods compared to the same aged-rubber monoculture plantations. In addition, the change in the abundance and taxon richness of ground arthropods was greatly affected by the understory vegetation species and soil temperature. The abundance and taxon richness of ground arthropods decreased with the decrease in number of species of understory vegetation. The study results indicate that the establishment of rubber-based agroforestry systems have adversely affected the abundance and richness of ground arthropods to an extant greater than expected. Therefore, single, large rubber-based agroforestry systems are not recommended, and the intercropping of rubber and rubber-based agroforestry systems must be designed to promote the migration of ground arthropods between different systems.

1. Introduction

At present, the global area of rubber (*Hevea brasiliensis*) plantations is 13 million hectares, while that in Southeast Asia accounts for 84% of the world's rubber plantation area (Ahrends et al., 2015; Warren-Thomas et al., 2015). Land-use conversion from tropical forests into monoculture rubber plantations exerts widespread negative effects on the environment, including the loss of biodiversity and soil acidification (Zhai et al., 2012). In addition, the conversion of tropical rainforests to rubber plantations reduces soil organic carbon by approximately 50%, and increases greenhouse gas emissions (van Straaten et al., 2015). Additionally, land-use conversion from tropical forests to monoculture rubber plantations increases runoff and soil erosion (Neyret et al., 2020). Rubber plantations involving intensive management practices reduce the diversity of canopy spider assemblages by decreasing the complexity of the vegetation (Zheng et al., 2015). Termite species richness declines in rubber, relative to primary forest sites, and to a greater degree as the trees aged in the rubber plantations (Hidayat et al., 2018). Finally, tropical rainforest conversion into rubber plantations alters the composition of soil fungal communities, thus resulting in a net loss of

* Corresponding author. CAS Key Laboratory of Tropical Plant Resources and Sustainable Use, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Menglun, Mengla, Yunnan, 666303, China.
** Corresponding author.
E-mail addresses: liuchangan@xtbg.ac.cn (C.-A. Liu), guozhibin1450@126.com (Z.-B. Guo).

https://doi.org/10.1016/j.jenvman.2021.112747
Received 28 November 2020; Received in revised form 20 April 2021; Accepted 30 April 2021
Available online 7 May 2021
0301-4797/

diversity (Lan et al., 2020).

Rubber-based agroforestry systems are considered a preferable approach for enhancing ecosystem services (Jiang et al., 2017; Rao et al., 2021). Rubber–*Theobroma cacao* and rubber-*Flemingia macrophylla* plantations increase contents of soil carbon, nitrogen and phosphorus, relative to the same aged rubber plantations (Chen et al., 2019). The conversion of rubber plantations into rubber–*F. macrophylla* plantations alters soil carbon and nitrogen fractions, and improves soil dissolved organic carbon, nitrate nitrogen, and microbial activities (Liu et al., 2018). Rubber-based nitrogen-fixing systems reduce the release of soil exchangeable Ca and Mg by mitigating soil acidification processes compared to rubber plantations (Liu et al., 2019). Rubber–*Clerodendranthus spicatus* and rubber–*Amomum villosum* systems are useful for maximizing the utilization of water resources by promoting the soil physical conditions (Jiang et al., 2017). Splash erosion can reach 50 t ha^{-1} within rubber plantations, while the establishment of rubber agroforestry systems can significantly reduce splash erosion (Liu et al., 2016).

Ground arthropods form an important component of soil ecosystems, playing a significant role in biotic and abiotic interactions as food sources and consumers (Liu et al., 2014; Sanchez-Montoya et al., 2020). Ground arthropods are able to improve soil physical and chemical properties, thus they are often used as indicators of environmental changes, and are easily disturbed by land use/land cover change (Li et al., 2013; VanTassel et al., 2015). Xishuangbanna is one of the most biodiverse areas of China, with 25% and 20% of the animal and higher plant species in China, respectively (Mann, 2009). Rubber plantations provide major income for rural villages in Xishuangbanna, occupying more than 24% of the total land area in this region (Mei, 2015). The local government is promoting the establishment of rubber-based agroforestry systems to mitigate the negative effects of rubber plantation expansion on the ecological environment. Rubber plantations are commonly intercropped with beverage crops, fruits, and Chinese medicinal plants for further economic benefit. These intercropped cash crops generally exhibit dense growth, which inhibits other plant growth under the rubber trees. *F. macrophylla* is a perennial multipurpose shrub legume, known for its high N-fixing capacity and therapeutic uses (Wang, 2015). Rubber–*F. macrophylla* systems have been widely popularized in Xishuangbanna (Liu et al., 2019).

The conversion of rubber plantations into rubber-based systems alters both the soil's physical and chemical properties. Changing the ecological environment in rubber-based systems will have a significant impact on the diversity and abundance of ground arthropods. Therefore, this study aimed to accomplish the following: (1) examine the effects that rubber-based systems (rubber–*F. macrophylla* systems) exert on the diversity and abundance of ground arthropods; (2) elucidate the main factors affecting the diversity and abundance of ground arthropods in rubber and rubber-based systems; and (3) assess the potential impacts of changes in the diversity and abundance of ground arthropods in rubber-based systems on sustainability.

2. Materials and methods

2.1. Study site

The experimental site was situated in Xishuangbanna on the southwest border of China (21°33′ N, 101°28′ E). This region is characterized by a tropical monsoon climate with an alternation of wet (May–October) and dry (November–April) seasons. The average annual temperature is 21.5 °C, and average annual precipitation is about 1500 mm, of which about 80% occurs during the rainy season, with little precipitation in the dry season (Liu et al., 2015a). The soil is rhodic ferralsol (FAO taxonomy).

2.2. Experimental design

Rubber plantations were established in May 1994 and 2006 on the same slope and with the same aspect, with a tree gap within and between rows of 2.5 and 8.0 m, respectively. In July 2010, *F. macrophylla* was planted (10,830 plants ha^{-1}) in the 8 m gap between two rows of rubber trees in the two different-aged rubber plantations. Management practices for the rubber and rubber- *F. macrophylla* plantations are described in more detail in the study by Liu et al. (2019). In August 2015, four stand types were selected: young rubber plantation (R1, rubber trees planted in 2006), young rubber–*F. macrophylla* plantations (RF1, *F. macrophylla* introduced to R1 in 2010), mature rubber plantation (R2, rubber trees planted in 1994), and mature rubber–*F. macrophylla* plantations (RF2, *F. macrophylla* introduced to R2 in 2010). Three replicate sites were selected within the two different-aged rubber and rubber–*F. macrophylla* plantations. Each replication site consisted of 20 × 25 m^2 survey plots (including four rows of rubber trees and three 8 m gaps). The understory vegetation species in R1 was dominated by *Lobelia angulate*, *Cyclosorus acuminatus*, *Rungia pectinate, Pogonatherum paniceum*, *Crassocephalum rubens*, *Cyathocline purpurea*, *Blumea fistulosa, Melastoma malabathricum*, *Blumea axillaris*, *Selaginella uncinate*, *Ageratina adenophora*, *Bidens pilosa*, *Thunbergia grandiflora*, *Kyllinga brevifolia*, *Sinodolichos lagopus*, *Hedyotis auricularia*, *Dioscorea bulbifera*, and *Selaginella helferi*; RF1 was dominated by *F. macrophylla*; R2 was dominated by *Hedyotis auricularia*, *Ottochloa nodosa*, *Imperata cylindrica*, *Curculigo capitulata*, *Fargesia caduca*, *Thysanolaena latifolia*, and *Apluda mutica*; RF2 was dominated by *F. macrophylla*, *Hedyotis auricularia*, *Curculigo capitulata* and *Ottochloa nodosa*.

In order to determine the influence of different-aged rubber and rubber-based systems on the diversity and abundance of ground arthropods, pitfall traps (8 cm in diameter, 10 cm in depth) filled with 50 ml of 70% ethanol solution were buried flush with the ground surface between the rows of rubber trees in each stand type (Liu et al., 2012). Each replication site included three 8 × 20 m gaps, with three traps placed in each gap. Therefore, there were nine traps per replicate and 27 traps per stand type. Sampling was conducted in August and November 2015, as well as January, April, August, and November 2016, and January and April 2017. Each of the sampling periods consisted of three consecutive days (performed both during the day and night). The collected individuals (juveniles and adults) of ground arthropods were preserved in 75% ethanol. In the laboratory, these specimens were counted and identified to the lowest possible taxonomic level (genus), based on established keys of insects and spiders in China (Zheng and Gui, 1999; Yin, 2000).

Soil water content was determined gravimetrically in the 0–10 cm soil layer, using a 5 cm diameter soil auger during collection of the ground arthropods. For each replicate site, nine core soil samples were taken and combined into a composite sample. The composite sample was dried at 105 °C to a constant weight. The soil temperature at the 10 cm depth in each stand type was recorded at 08:00, 14:00, and 20:00 h daily for three consecutive days, when the ground arthropods were collected. Next, the mean daily soil temperature was calculated as the average of the three daily readings. For each replicate site, nine soil samples were taken in the 0–10 cm soil layer, and combined into a composite sample in August 2015, January and August 2016, and January 2017. The air-dried soil samples were then sieved through a 2 mm grid for the determination of soil available phosphorus (AP), NH_4^+, NO_3^-, pH, exchangeable Al, and particle size distribution. Next, the sieved samples were sieved continuously (at <0.25 mm) for analysis of total phosphorus (TP), soil organic carbon (SOC), and total nitrogen (TN). Soil AP was extracted using 0.03 mol L^{-1} NH_4F and 0.025 mol L^{-1} HCl, and then determined colorimetrically (Anderson and Ingram, 1989). Soil NH_4^+ and NO_3^- contents were extracted with 2 mol L^{-1} KCl and analyzed with an Auto Analyzer 3 (SEAL Analytical GmbH, Germany). Soil pH was measured in a 1: 2.5 soil: liquid mixture. Soil exchangeable Al was extracted with 1 mol L^{-1} KCl and determined by

Table 1
The main groups of ground arthropod communities and their relative abundance (%) in each stand type.

Month-Year	Stand type	Groups and relative abundance				
Aug 2015	R1	*Myrmicaria* (34.0)	*Odontoponera* (23.3)	*Pardosa* (12.0)	*Leptogenys* (9.3)	*Carabidae* (4.0)
	RF1	*Pheidole* (33.3)	*Odontoponera* (20.8)	*Leptogenys* (14.6)	*Pachycondyla Smith* (8.3)	*Porcellio* (8.3)
	R2	*Leptogenys* (41.1)	*Trochosa* (17.1)	*Odontoponera* (14.4)	*Odontomachus* (6.8)	*Pardosa* (5.5)
	RF2	*Leptogenys* (43.8)	*Odontoponera* (36.5)	*Pardosa* (5.2)	*Myrmicaria* (5.2)	*Pheidole* (1.0)
Nov 2015	R1	*Odontoponera* (43.3)	*Velarifictorus* (18.7)	*Trigonidium* (8.8)	*Staphylinidae* (4.7)	*Evarcha* (4.1)
	RF1	*Odontoponera* (41.9)	*Leptogenys* (14.3)	*Opiliones* (7.6)	*Velarifictorus* 7.6)	*Camponotus* (6.7)
	R2	*Leptogenys* (16.1)	*Odontoponera* (14.0)	*Velarifictorus* (13.0)	*Trochosa* (10.4)	*Myrmicaria* (8.3)
	RF2	*Leptogenys* (28.8)	*Velarifictorus* (19.6)	*Odontoponera* (15.0)	*Trochosa* (11.8)	*Staphylinidae* (4.6)
Jan 2016	R1	*Odontoponera* (51.0)	*Leptogenys* (8.8)	*Velarifictorus* (7.8)	*Camponotus* (3.9)	*Pardosa* (2.9)
	RF1	*Odontoponera* (52.7)	*Opiliones* (12.7)	*Rhaphidophoridae* (7.3)	*Pardosa* (3.6)	*Trochosa* (1.8)
	R2	*Odontoponera* (32.6)	*Pardosa* (14.6)	*Velarifictorus* (11.2)	*Crematogaster* (10.1)	*Opiliones* (5.6)
	RF2	*Pardosa* (34.3)	*Leptogenys* (13.4)	*Odontoponera* (10.4)	*Trochosa* (10.4)	*Velarifictorus* (9.0)
Apr 2016	R1	*Velarifictorus* (20.3)	*Odontoponera* (17.9)	*Pardosa* (12.0)	*Camponotus* (9.3)	*Opiliones* (5.9)
	RF1	*Odontoponera* (26.6)	*Pardosa* (14.7)	*Opiliones* (11.9)	*Reduviidae* (11.2)	*Staphylinidae* (9.8)
	R2	*Pardosa* (28.4)	*Leptogenys* (18.9)	*Velarifictorus* (14.5)	*Opiliones* (9.5)	*Odontoponera* (7.5)
	RF2	*Pardosa* (25.5)	*Leptogenys* (24.5)	*Velarifictorus* (19.1)	*Staphylinidae* (10.9)	*Odontoponera* (4.5)
Aug 2016	R1	*Odontoponera* (32.8)	*Leptogenys* (16.4)	*Myrmicaria* (11.5)	*Pardosa* (6.6)	*Trochosa* (4.9)
	RF1	*Odontoponera* (59.4)	*Carabidae* (12.5)	*Velarifictorus* (9.4)	*Forficulidae* (6.3)	*Trochosa* (3.1)
	R2	*Odontoponera* (31.8)	*Leptogenys* (27.1)	*Crematogaster* (15.9)	*Pardosa* (9.3)	*Trochosa* (3.7)
	RF2	*Leptogenys* (35.0)	*Odontoponera* (17.0)	*Opiliones* (16.0)	*Pardosa* (12.0)	*Myrmicaria* (6.0)
Nov 2016	R1	*Odontoponera* (48.4)	*Myrmicaria* (10.4)	*Opiliones* (8.2)	*Leptogenys* (7.7)	*Pardosa* (6.0)
	RF1	*Odontoponera* (39.7)	*Leptogenys* (15.9)	*Carabidae* (11.1)	*Pardosa* (7.9)	*Opiliones* (4.8)
	R2	*Odontoponera* (19.0)	*Leptogenys* (15.9)	*Crematogaster* (15.1)	*Opiliones* (11.1)	*Pardosa* (9.5)
	RF2	*Odontoponera* (31.8)	*Leptogenys* (27.1)	*Pardosa* (13.1)	*Velarifictorus* (9.3)	*Crematogaster* (5.6)
Jan 2017	R1	*Odontoponera* (40.0)	*Leptogenys* (29.5)	*Pardosa* (7.6)	*Trochosa* (5.7)	*Velarifictorus* (1.9)
	RF1	*Odontoponera* (26.9)	*Camponotus* (25.0)	*Leptogenys* (19.2)	*Opiliones* (17.3)	*Pardosa* (5.8)
	R2	*Camponotus* (19.2)	*Trochosa* (17.3)	*Leptogenys* (11.5)	*Pardosa* (9.6)	*Odontoponera* (9.6)
	RF2	*Camponotus* (36.2)	*Odontoponera* (23.4)	*Pardosa* (17.0)	*Leptogenys* (8.5)	*Staphylinidae* (4.3)
Apr 2017	R1	*Odontoponera* (18.8)	*Pardosa* (15.8)	*Trochosa* (12.1)	*Opiliones* (11.3)	*Camponotus* (7.4)
	RF1	*Pardosa* (23.3)	*Odontoponera* (22.6)	*Camponotus* (10.1)	*Opiliones* (8.8)	*Crematogaster* (6.3)
	R2	*Trochosa* (22.7)	*Camponotus* (16.7)	*Velarifictorus* (9.2)	*Opiliones* (8.3)	*Pardosa* (7.8)
	RF2	*Camponotus* (28.8)	*Odontoponera* (15.2)	*Pardosa* (12.9)	*Velarifictorus* (11.4)	*Leptogenys* (8.3)

R1: rubber plantations established in 2006; R2: rubber plantations established in 1994; RF1: *Flemingia macrophylla* introduced to R1 in 2010; RF2: *Flemingia macrophylla* introduced to R2 in 2010.

Table 2
The loss of the main groups of ground arthropod communities in in differently aged rubber–*Flemingia macrophylla* plantations compared to the same aged rubber plantations.

Month-Year	Stand type	Groups				
Jan in 2016 and 2017	RF1	*Myrmicaria*	*Evarcha*	*Oecophylla*	*Blattella*	*Collembola*
	RF2	*Blattella*	*Oxyopes*	*Odontomachus*	*Loxoblemmus*	*Reduviidae*
Apr in 2016 and 2017	RF1	*Kalotermes Hagen*	*Pachycondyla*	*Lucanidae*		
	RF2	*Reduviidae*	*Evarcha*	*Odontomachus*	*Loxoblemmus*	*Oecophylla*
Aug in 2015 and 2016	RF1	*Myrmicaria*	*Opiliones*	*Teleogryllus*	*Staphylinidae*	*Reduviidae*
	RF2	*Crematogaster*	*Oxyopes*	*Teleogryllus*	*Trigonidium*	*Tetrigidae*
Nov in 2015 and 2016	RF1	*Geotrupes*	*Pachycondyla*	*Odontomachus*	*Loxoblemmus*	*Teleogryllus*
	RF2	*Geotrupes*	*Pachycondyla*	*Odontomachus*	*Evarcha*	*Myrmicaria*

R1: rubber plantations established in 2006; R2: rubber plantations established in 1994; RF1: *Flemingia macrophylla* introduced to R1 in 2010; RF2: *Flemingia macrophylla* introduced to R2 in 2010.

titration with NaOH (Hou et al., 2012). Soil particle size distribution was measured according to the method described by van Reeuwijk (2002) using sodium hexametaphosphate. Soil TP was analyzed by acid digestion and hydrofluoric acid decomposition with an ICP-AES (iCAP6300, Thermo Fisher Scientific USA). SOC and TN were analyzed by dry combustion with an elemental analyzer (Elementar Analysensysteme GmbH, Germany). Soil bulk density in the 0–10 cm soil layer was measured in January 2016 (Robertson et al., 1999), and nine soil core samples in each replicate plot were taken and weighed, dried at 105 °C to a constant weight, and then reweighed.

2.3. Statistical analysis

The assumptions of normality and homogeneity of variance in the response variables were tested via Kolmogorov–Smirnov tests. When necessary, data were transformed with $\log_{10}$ (x), or $\log_{10}$ (x+1) if zeros were present. One-way ANOVA from the SAS package was used to conduct analysis of variance. The differences among rubber plantations and rubber-based systems were evaluated with the least significant difference (LSD) at $P \leq 0.05$. The path analytic method is an extension of multiple regression analysis and estimates the magnitude and strength of effects with a hypothesized causal system. In this study, a path analysis model was used to determine the effects of species of plant, soil temperature, SOC, TP, NH_4^+, NO_3^-, and bulk density on the diversity and abundance of ground arthropods. Redundancy analysis (RDA) was conducted to evaluate the correlations the mainly ground arthropods composition (i.e. the species only recorded once would be eliminated during the experimental period) and environmental variables. The "forward selection" procedure was performed to select the driving factors for each data set in the analysis. The entire process was performed using CANOCO 5.0 (Trial version contributed by Dr. Furnas. Ter Braak and Šmilauer, 2012).

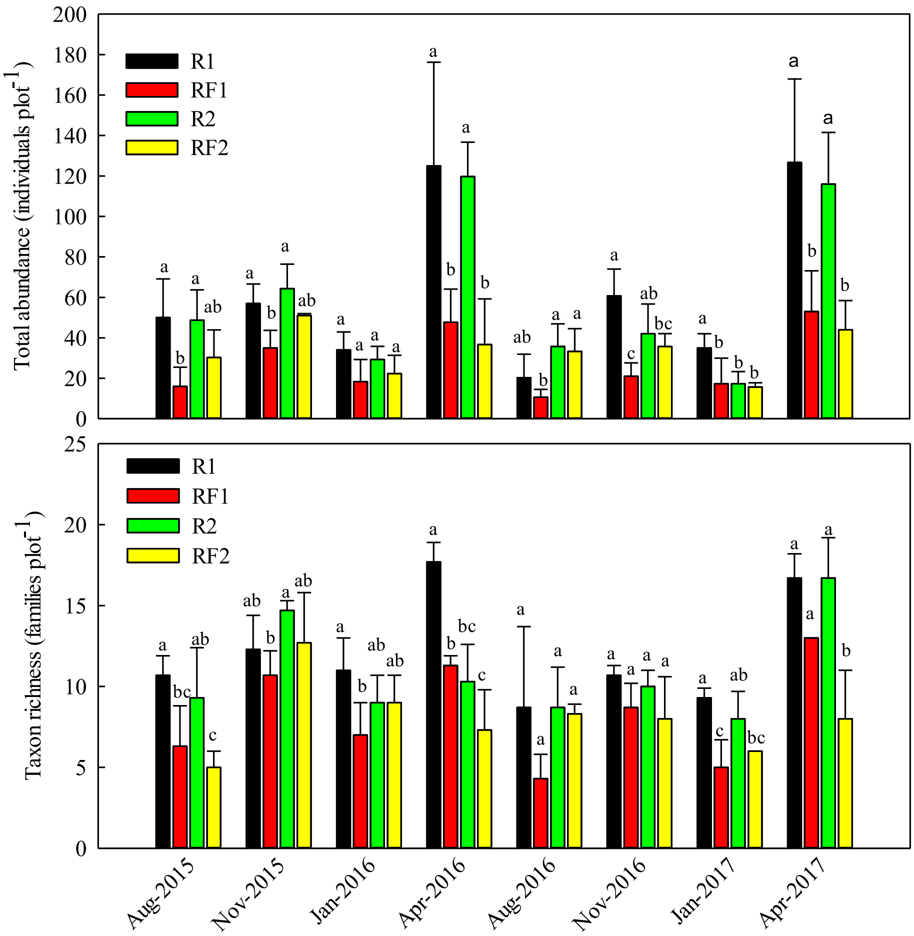

Fig. 1. Total abundance and taxon richness of ground arthropods in each replicate plot (including 9 traps) for each stand type from August 2015 to April 2017. R1: rubber plantations established in 2006; R2: rubber plantations established in 1994; RF1: *Flemingia macrophylla* introduced to R1 in 2010; RF2: *Flemingia macrophylla* introduced to R2 in 2010. Data are analyzed for each sampling period, and different letters in each sampling period indicate significant differences at $P \leq 0.05$. Bars are standard deviations of the mean ($n = 3$).

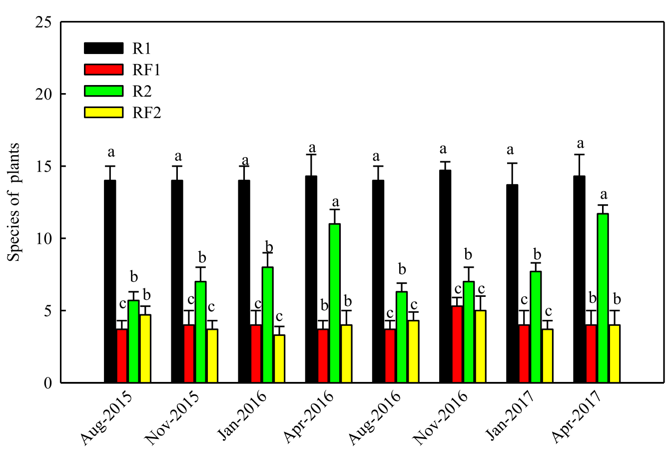

Fig. 2. Species of understory vegetation in each replicate plot for each stand type from August 2015 to April 2017. R1: rubber plantations established in 2006; R2: rubber plantations established in 1994; RF1: *Flemingia macrophylla* introduced to R1 in 2010; RF2: *Flemingia macrophylla* introduced to R2 in 2010. Data are analyzed for each sampling period, and different letters in each sampling period indicate significant differences at $P \leq 0.05$. Bars are standard deviations of the mean ($n = 3$).

3. Results

3.1. Abundance and richness of ground arthropods

The introduction of *F. macrophylla* to young and mature rubber plantations altered the main groups of ground arthropods (Table 1). In January 2016 and 2017, *Rhaphidophoridae* and *Opiliones* as the main groups in young rubber–*F. macrophylla* plantations replaced *Leptogenys* and *Velarifictorus* in young rubber plantations; *Leptogenys* and *Staphylinidae* as the main groups in mature rubber–*F. macrophylla* plantations replaced *Crematogaster* and *Opiliones* in mature rubber plantations. In April 2016 and 2017, *Reduviidae*, *Staphylinidae*, and *Crematogaster* as the main groups in young rubber–*F. macrophylla* plantations replaced *Velarifictorus*, *Camponotus*, and *Trochosa* in young rubber plantations; *Staphylinidae*, *Odontoponera*, and *Leptogenys* as the main groups in mature rubber–*F. macrophylla* plantations replaced *Opiliones* and *Trochosa* in mature rubber plantations. In August 2015 and 2016, *Pheidole*, *Pachycondyla*, *Porcellio*, *Velarifictorus*, and *Forficulidae* as the main groups in young rubber–*F. macrophylla* plantations replaced *Myrmicaria*, *Pardosa*, and *Leptogenys* in young rubber plantations; *Myrmicaria*, *Pheidole*, and *Opiliones* as the main groups in mature rubber–*F. macrophylla* plantations replaced *Trochosa, Odontomachus*, and *Crematogaster* in mature rubber plantations. In November 2015 and 2016, *Leptogenys*, *Opiliones*, *Camponotus*, and *Carabidae* as the main groups in young rubber–*F. macrophylla* plantations replaced *Trigonidium*, *Staphylinidae*, *Evarcha*, and *Myrmicaria* in young rubber plantations; *Staphylinidae* and *Carabidae* as the main groups in mature rubber–*F. macrophylla* plantations replaced *Myrmicaria* and *Myrmicaria* in mature rubber plantations. The introduction of *F. macrophylla* to young and mature rubber plantations would result in the loss of *Blattella*, *Collembola*, *Crematogaster*, *Evarcha*, *Geotrupes*, *Kalotermes Hagen*, *Loxoblemmus*, *Lucanidae*, *Myrmicaria, Odontomachus*, *Oecophylla*, *Opiliones*, *Oxyopes*, *Pachycondyla Smith*, *Reduviidae*, *Staphylinidae*, *Tetrigidae*, *Teleogryllus* and *Trigonidium* (Table 2).

In all plantation treatments, April had the highest abundance of

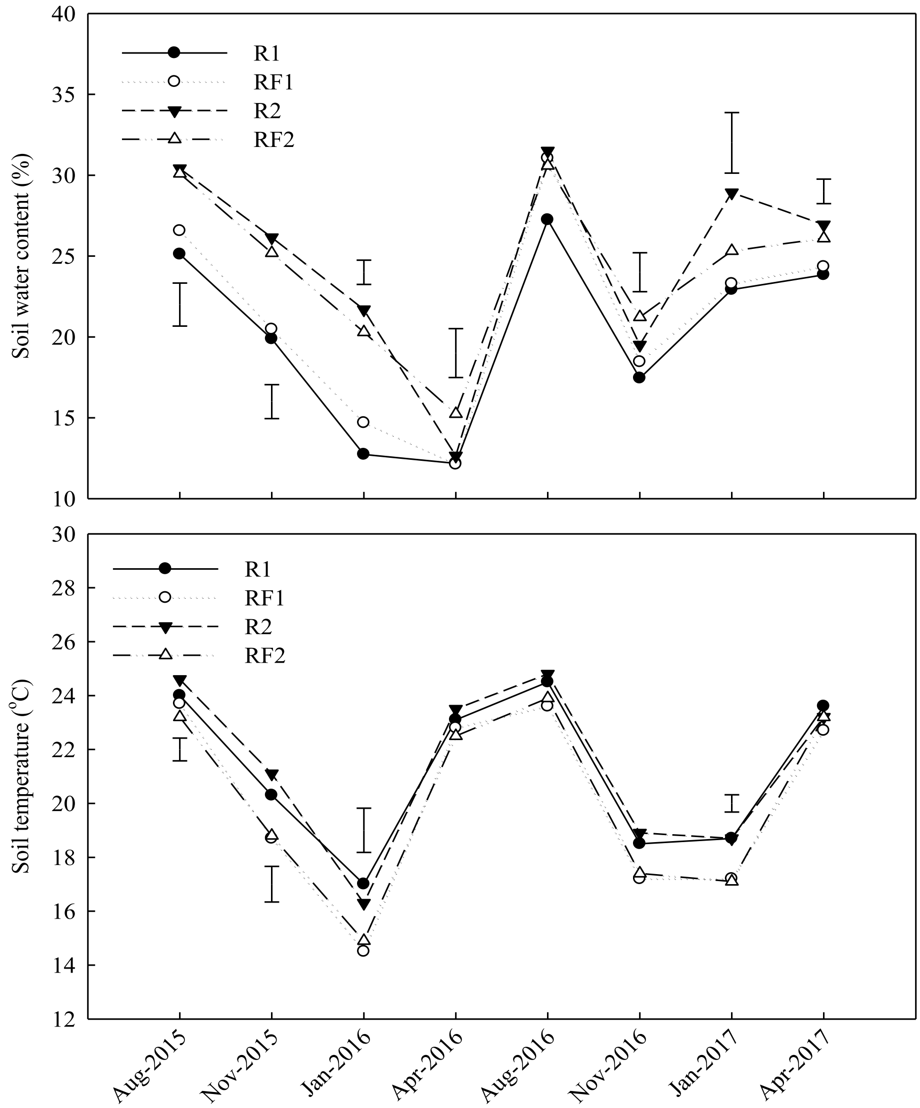

Fig. 3. Soil water content and temperature in the 0–10 cm soil layer in differently aged rubber and rubber–*Flemingia macrophylla* plantations from August 2015 to April 2017. R1: rubber plantations established in 2006; R2: rubber plantations established in 1994; RF1: *Flemingia macrophylla* introduced to R1 in 2010; RF2: *Flemingia macrophylla* introduced to R2 in 2010. Error bars are LSD at $P \leq 0.05$.

ground arthropods among all month (Fig. 1). The abundance of ground arthropods did not differ significantly between young and mature rubber plantations. The introduction of *F. macrophylla* to the young plantations significantly decreased the abundance of ground arthropods during the experimental period, with the exceptions of January and August 2016. The introduction of *F. macrophylla* to the mature plantations decreased the abundance of ground arthropods, with significant declines in April 2016 and 2017. The taxon richness of ground arthropods did not differ significantly between young and mature rubber plantations during the experimental period, with the exception of April 2016. The introduction of *F. macrophylla* to young and mature plantations decreased the taxon richness of ground arthropods, with significant declines in August 2015, January and April 2016, and January 2017 in young rubber plantations, and August 2015 and April 2017 in mature rubber plantations.

3.2. Species of plants and soil properties

The number of understory vegetation species significantly decreased as the trees in the rubber plantations aged (Fig. 2). The introduction of *F. macrophylla* to young and mature plantations significantly decreased the number of understory vegetation species. Soil water content in the 0–10 cm soil layers increased as the trees in the rubber plantations aged (Fig. 3). The introduction of *F. macrophylla* to young rubber plantations increased soil water content in the 0–10 cm soil layers. The introduction of *F. macrophylla* to young and mature rubber plantations decreased soil temperature at 10 cm depth (Fig. 3). Tree age in the rubber and rubber–*F. macrophylla* plantations had no significant impact on soil temperature. The introduction of *F. macrophylla* to young rubber plantations increased SOC and AP (Fig. 4). Soil TN did not differ between plantation treatments for the duration of the study. The introduction of *F. macrophylla* to mature rubber plantations mitigated soil acidification and decreased exchangeable Al. The introduction of *F. macrophylla* to young and mature rubber plantations increased soil NO_3^- and decreased soil bulk density (Fig. 5). Soil sand, silt, and clay contents were in the ranges of 14.3–18.3%, 47.9–54.0%, and 31.4–35.9%, respectively, for the two different-aged rubber and rubber–*F. macrophylla* plantations (Fig. 5).

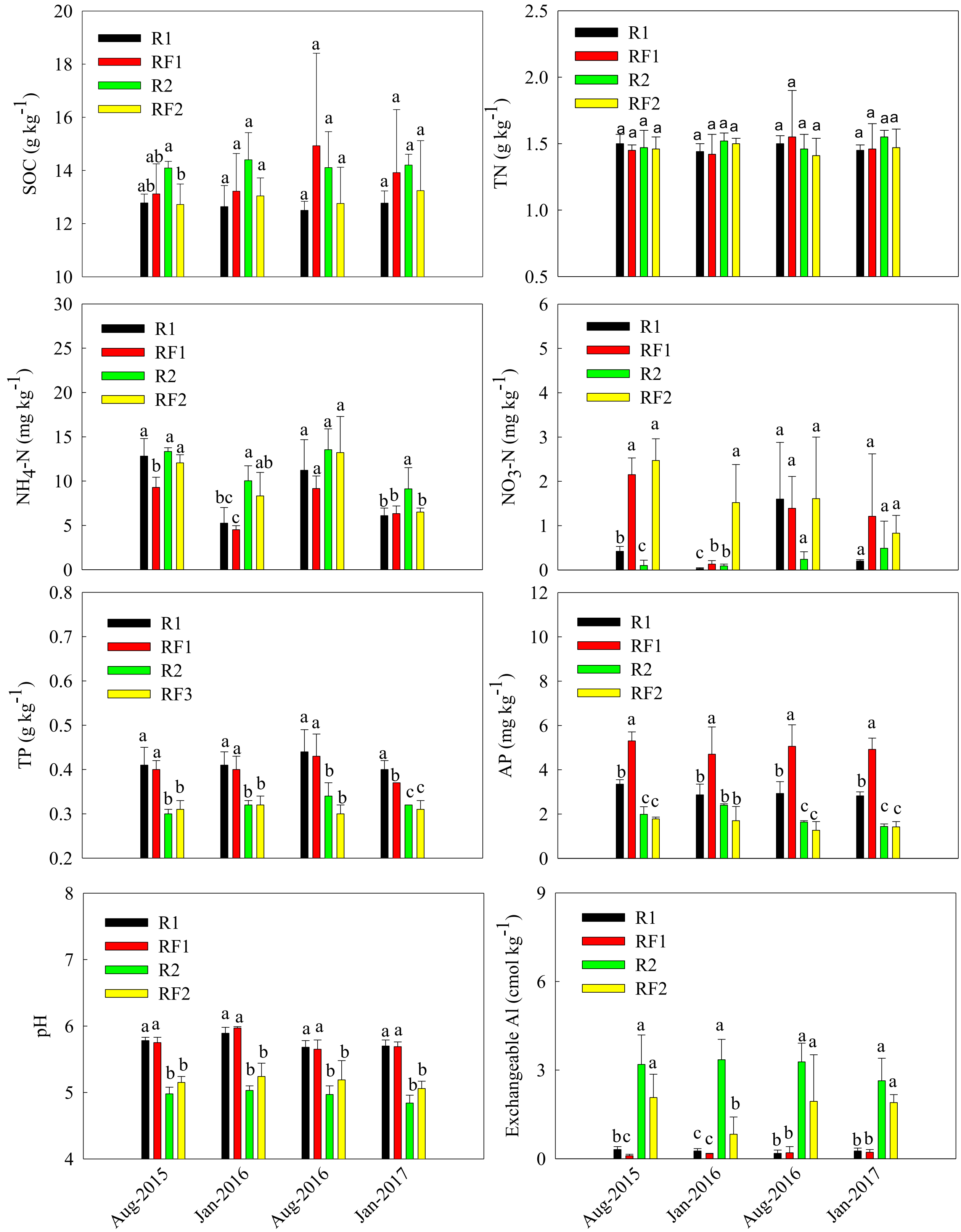

Fig. 4. Soil organic carbon (SOC), total nitrogen (TP), ammonium nitrogen (NH_4–N), nitrate nitrogen (NO_3–N), total phosphorus (TP), available phosphorus (AP), pH, and exchangeable Al in the 0–10 cm soil layer in differently aged rubber and rubber–*Flemingia macrophylla* plantations from August 2015 to April 2017. R1: rubber plantations established in 2006; R2: rubber plantations established in 1994; RF1: *Flemingia macrophylla* introduced to R1 in 2010; RF2: *Flemingia macrophylla* introduced to R2 in 2010. Data are analyzed for each sampling period, and different letters in each sampling period indicate significant differences at $P \leq 0.05$. Bars are standard deviations of the mean ($n = 3$).

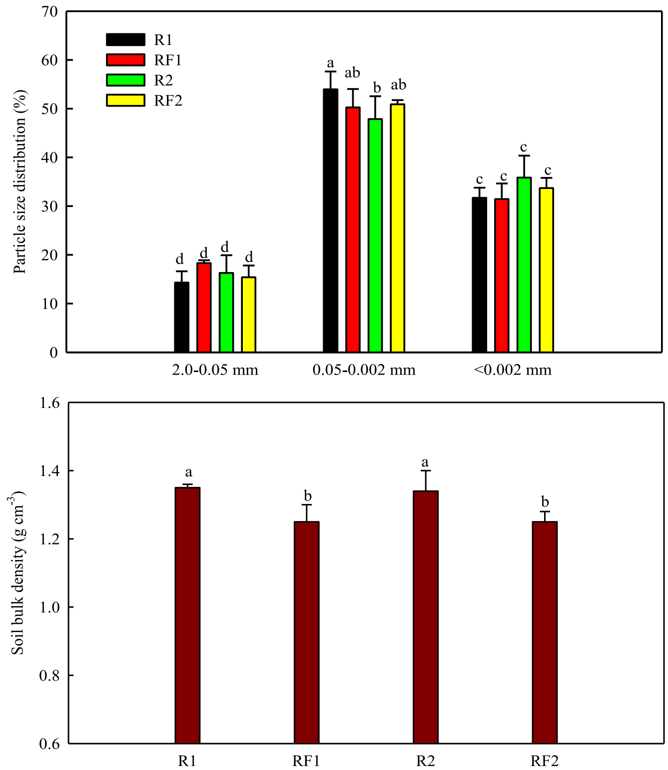

Fig. 5. Soil particle-size and bulk density in the 0–10 cm soil layers in differently aged rubber and rubber–*Flemingia macrophylla* plantations in January 2016. Different letters indicate significant differences at $P \le 0.05$. Bars are standard deviations of the mean ($n = 3$). R1: rubber plantations established in 2006; R2: rubber plantations established in 1994; RF1: *Flemingia macrophylla* introduced to R1 in 2010; RF2: *Flemingia macrophylla* introduced to R2 in 2010.

3.3. Relationships between environmental factors and the abundance and richness of ground arthropods

The path analyses identified that plant species, soil temperature, water content, SOC, NH_4^+, NO_3^-, and TP explained as much as 55% of the variability in the abundance of ground arthropods, which was greatly affected by plant species, soil temperature, water content, and NO_3^- (Table 3). The path analyses identified that plant species, soil temperature, SOC, NH_4^+, NO_3^-, and BD explained as much as 43% of the variability in the taxon richness of ground arthropods, which was greatly affected by plant species, soil temperature, and NO_3^- (Table 4). Species of plant had a significant positive correlation with the abundance and taxon richness of ground arthropods ($P < 0.0001$) (Fig. 6). Soil temperature at the 10 cm depth had a significant positive correlation with the abundance of ground arthropods ($P < 0.0001$). The abundance and taxon richness of ground arthropods decreased with the decrease of species of understory vegetation in rubber and rubber-*F. macrophylla* plantations. The forward selection procedure in the RDA showed that three environmental variables (i.e. soil temperature, water content and pH) were the main variables regulating the variation in the composition of the abundant subcommunity (Fig. 7).

4. Discussion

In the present study, the rubber-based agroforestry systems decreased the abundance and taxon richness of ground arthropods compared to the rubber monoculture plantations. Meanwhile, the abundance, richness, and community composition of ground arthropods were shown to be sensitive to changes in the environment. Sahara mustard (*Brassica tournefortii*, hereafter mustard) invades the arid southwestern United States, and has a strong negative impact on native annual plant diversity and biomass—the abundance and species richness of ground arthropods decreased when mustard cover increased (Heather et al., 2014). The establishment of a non-native plant species (*Asclepias syriaca*) in poplar forest plantations altered the community composition

Table 3
Path analyses examining the direct and indirect effects of plant species, soil temperature, soil water content, soil organic carbon (SOC), ammonium nitrogen (NH_4^+), nitrate nitrogen (NO_3^-), and total phosphorus (TP) on the abundance of ground arthropods in the 0–10 cm soil layer. The total effect was estimated as the sum of direct and indirect effects. R^2 indicates the proportion of variation explained by the multiple regression models in each case.

	Variable	Direct effect	Indirect effect							Total effect
			$\rightarrow x_1$	$\rightarrow x_2$	$\rightarrow x_3$	$\rightarrow x_4$	$\rightarrow x_5$	$\rightarrow x_6$	$\rightarrow x_7$	
The total abundance of ground arthropods $R^2 = 0.55$, $P < 0.0001$	Species of plants (x_1)	0.4736		0.0791	0.0522	−0.0377	0.0145	0.0595	−0.1407	0.5005
	Soil temperature (x_2)	0.5142	0.0728		−0.0764	−0.0158	−0.1131	−0.0125	−0.0178	0.3514
	Soil water (x_3)	−0.2214	−0.1116	0.1773		0.0131	−0.1472	−0.0465	0.0804	−0.2559
	SOC (x_4)	0.2026	−0.0882	−0.0401	−0.0143		−0.0578	−0.0249	0.0614	0.0387
	NH_4^+ (x_5)	−0.2595	−0.0265	0.2241	−0.1256	0.0451		−0.0383	0.1139	−0.0668
	NO_3^- (x_6)	−0.1470	−0.1916	0.0436	−0.0701	0.0344	−0.0676		0.0488	−0.3495
	TP (x_7)	−0.3438	0.1937	0.0266	0.0518	−0.0362	0.0859	0.0209		−0.0011

Table 4
Path analyses examining the direct and indirect effects of plant species, soil temperature, soil organic carbon (SOC), ammonium nitrogen (NH_4^+), nitrate nitrogen (NO_3^-), and bulk density (BD) on the taxon richness of ground arthropods in the 0–10 cm soil layer. The total effect was estimated as the sum of direct and indirect effects. R^2 indicates the proportion of variation explained by the multiple regression models in each case.

	Variable	Direct effect	Indirect effect						Total effect
			$\rightarrow x_1$	$\rightarrow x_2$	$\rightarrow x_3$	$\rightarrow x_4$	$\rightarrow x_5$	$\rightarrow x_6$	
The taxon richness of ground arthropods $R^2 = 0.43$, $P < 0.0001$	Species of plants (x_1)	0.3542		0.0470	−0.0300	0.0192	0.0999	−0.0058	0.4845
	Soil temperature (x_2)	0.3057	0.0545		−0.0126	−0.1496	−0.0210	0.0133	0.1903
	SOC (x_3)	0.1610	−0.0659	−0.0239		−0.0765	−0.0419	0.0513	0.0041
	NH_4^+ (x_4)	−0.3433	−0.0198	0.1333	0.0359		−0.0644	0.0398	−0.2185
	NO_3^- (x_5)	−0.2470	−0.1433	0.0259	0.0273	−0.0895		0.0713	−0.4093
	BD (x_6)	0.1640	−0.0125	0.0247	0.0504	−0.0834	−0.0260		0.1172

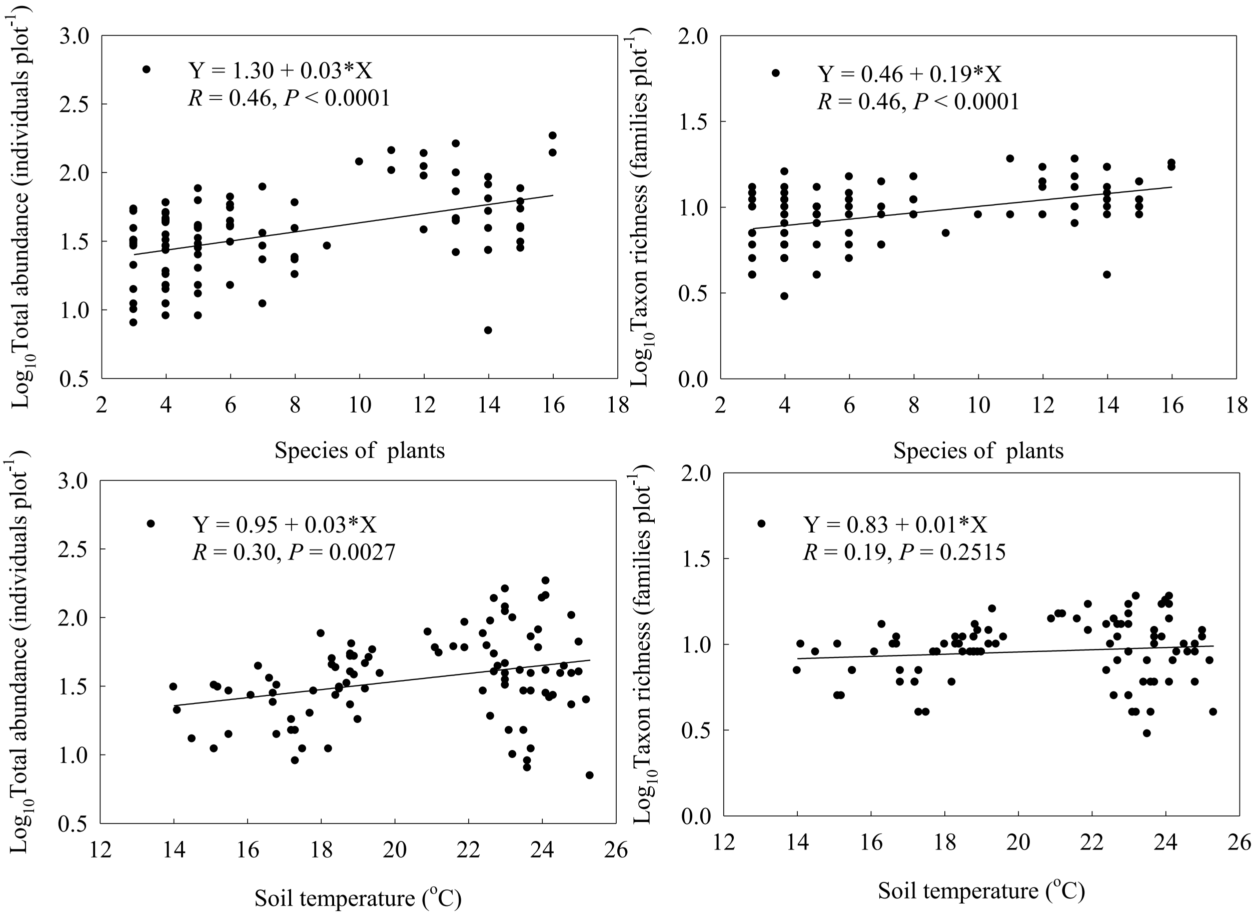

Fig. 6. Relationships between species of plant, soil temperature at 10 cm depth, and the abundance and taxon richness of ground arthropods.

of ground-dwelling arthropods, thereby reducing the diversity of arthropods and conservation value of the novel ecosystem (Gallé et al., 2015). The predators and decomposers of ground-dwelling arthropods in salt-affected grasslands of northwestern China are mainly influenced by plant density and vegetation cover (Pan et al., 2018). Plant species richness has exhibited a significant positive correlation with macro-arthropod order diversity in the most agroforestry systems in the humid tropics of Mexico, and agroforestry systems with more plant species are sustainable for food production by increasing the diversity of soil macro-arthropods (Villanueva-López et al., 2019). The strong sprouting ability of *F. macrophylla* inhibited other plant growth under rubber trees (Fig. 8), and almost no vegetation survived in young rubber–*F. macrophylla* plantations. The path analyses identified that the loss of abundance and richness of ground arthropods in rubber and rubber–*F. macrophylla* plantations were caused by the decline in plant species richness. Ants and spiders are the two main groups of ground arthropods in rubber and rubber–*F. macrophylla* plantations (Table 1). Spiders can use the low herbaceous plants under rubber plantations to spin webs for food (Fig. 9); however, the introduction of *F. macrophylla* to rubber plantations inhibited other plant growth under rubber trees, hence destroying the environment for spinning webs. *F. macrophylla* was introduced in the rubber plantations with rows 1.0 m apart and plants 0.8 m apart. The wide spacing within and between rows of *F. macrophylla* are not conducive for spinning webs. Plants can provide food sources for ants either directly or indirectly, and the decline in plant species richness in rubber–*F. macrophylla* plantations would lead to a shortage in food resources, thus affecting the abundance and richness of ants. The decrease of plant species richness in rubber–*F. macrophylla* plantations resulted in the loss of phytophagous ground arthropods, such as *Teleogryllus*, *Loxoblemmus*, *Trigonidium* and *Tetrigidae*. In addition, the decrease of phytophagous ground arthropods led to the loss of predatory ground arthropods (Fig. 7).

Soil temperature has been shown to be the most important factor affecting the composition of ground-active arthropods in desertified regions (Liu et al., 2015b). Zhu et al. (2019) reported that *Robinia pseudoacacia* afforestation reduced soil temperature and evapotranspiration rate by intercepting the amount of incident solar radiation in the Loess Plateau of China, leading to higher diversity of ground arthropods. Low relative humidity and high temperature reduced the diversity of macro-arthropods in the humid tropics (Bos et al., 2007). The path analyses identified that the change in the abundance and richness of ground arthropods in rubber and rubber–*F. macrophylla* plantations were mainly influenced by soil temperature. When *F. macrophylla* was introduced into the two different-aged rubber plantations, soil temperatures at the 10 cm depth decreased. *F. macrophylla* can grow more than 2 m tall in rubber–*F. macrophylla* plantations, and the dense *F. macrophylla* intercepts considerable incident solar radiation (Fig. 6 C). Low temperature and high relative humidity in rubber–*F. macrophylla* plantations are not conducive for cave building by ants and other ground-dwelling arthropods. Therefore, low temperature and high relative humidity in rubber–*F. macrophylla* plantations have a negative impact on the abundance and richness of ground arthropods. Additionally, the abundance and richness of ground arthropods are affected by soil texture, bulk density, organic matter, pH, and soil electrical conductivity (Liu et al., 2014; Pan et al., 2018). In this study, the abundance and richness of ground arthropods were significantly affected by soil NO_3^-, not soil texture, bulk density, total P, or available P. The change in soil NO_3^- in rubber and rubber–*F. macrophylla* plantations was caused by the different understory vegetation species under rubber trees (Liu et al., 2018), which affected the abundance and

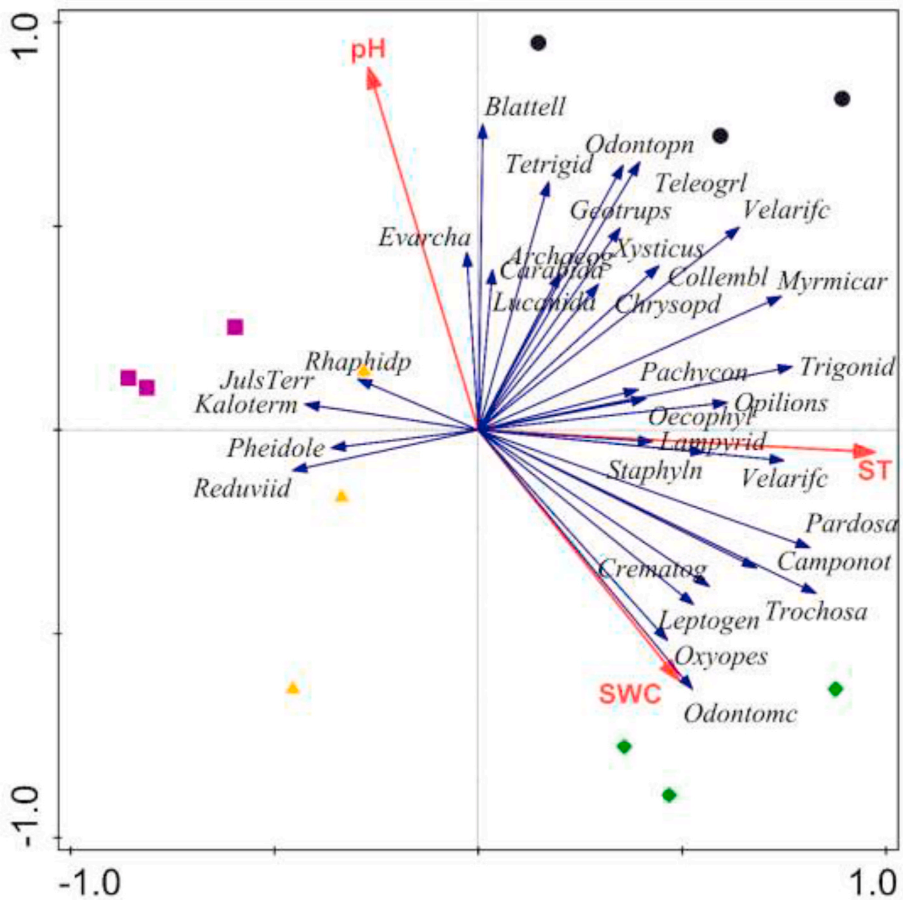

Fig. 7. Redundancy analysis (RDA) showing the relationship between the ground arthropods composition and environmental variables. ST: soil temperature; SWC: soil water content; Black point: rubber plantations established in 2006 (R1); Purple square: *Flemingia macrophylla* introduced to R1 in 2010; Green diamond: rubber plantations established in 1994 (R2); Yellow triangle: *Flemingia macrophylla* introduced to R2 in 2010.

Fig. 8. *Flemingia macrophylla* inhibits plant growth under rubber trees. A: Sloping fields in the rubber plantations; B: Sloping fields in the rubber–*Flemingia macrophylla* plantations; C: Rubber–*F. macrophylla* plantations.

richness of ground arthropods.

Previous research has demonstrated that the abundance and richness of soil arthropods are higher in the dry season than the rainy season in tropical seasonal rainforests and *Amomum* plantations (Yang et al., 2003). In fragmented tropical seasonal rainforests, and species and individuals of soil arthropods in the litterfall layer were higher in the dry season than the rainy season (Yang and Sha, 2001). In this study, April showed the greater numbers of individuals of ground arthropods than other months in young and mature rubber plantations. The dry and warm environment in April in rubber plantations may be explain the increase in individuals of ground arthropods. However, in rubber–*F. macrophylla* plantations, the individuals of ground arthropods did not significantly increase in April, relative to other months. The results of this study indicate that the establishment of rubber-based agroforestry systems has adversely affected the abundance and richness of ground arthropods more than expected. Therefore, the establishment of environmentally friendly rubber-based agroforestry systems must solve the problem of the decrease of the abundance and richness of ground arthropods.

5. Conclusion

Rubber-based agroforestry systems are a preferable approach for ameliorating the ecological environment in rubber planting areas. In this study, we observed that the establishment of rubber-based agroforestry systems decreased understory vegetation species, along with the abundance and taxon richness of ground arthropods. The change in the abundance and taxon richness of ground arthropods was greatly affected

Fig. 9. Spiders' webs in the rubber plantations.

by understory vegetation species and soil temperature. In other words, the establishment of rubber-based agroforestry systems reduced the diversity and abundance of ground arthropods. Single, large rubber-based agroforestry systems are not recommended, and intercropping of rubber and rubber-based agroforestry systems must be designed to promote the migration of ground arthropods between different systems.

Declaration of competing interest

The authors declare no competing interests.

Acknowledgments

We would like to acknowledge Dr. Ren-Bin Zhu for the identification of plant species, and the Public Technology Service Center of XTBG, CAS, for their support with soil analyses. This study was funded by the National Natural Science Foundation of China (31470639 and 31901303), the Natural Science Foundation of Yunnan Province (2017FB059 and 2016FA047) and the Key Program of CAS (KFZD-SW-312).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.112747.

Author statement

Chang-An Liu and Zhi-Bin Guo: Conceptualization; Chang-An Liu: Investigation; Chang-An Liu, Ming-Yue Liang, and Jian-Wei Tang: Writing-Original draft preparation. Kadambot H.M. Siddique, Zhi-Bin Guo and Yan-Qiang Jin: Writing-Reviewing and Editing.

References

Ahrends, A., Hollingsworth, P.M., Ziegler, A.D., Fox, J.M., Chen, H., Su, Y., Xu, J., 2015. Current trends of rubber plantation expansion may threaten biodiversity and livelihoods. Global Environ. Change 34, 48–58.

Bos, M.M., Höhn, P., Saleh, S., Büche, B., Buchori, D., Steffan-Dewenter, I., Tscharntke, T., 2007. Insect Diversity Responses to Forest Conversion and Agroforestry Management. Stability of Tropical Rainforest Margins. Springer, Berlin, Heidelberg, pp. 277–294.

Chen, C., Liu, W., Wu, J., Jiang, X., Zhu, X., 2019. Can intercropping with the cash crop help improve the soil physico-chemical properties of rubber plantations? Geoderma 335, 149–160.

Gallé, R., Erdélyi, N., Szpisjak, N., Tölgyesi, C., Maák, I., 2015. The effect of the invasive Asclepias syriaca on the ground-dwelling arthropod fauna. Biologia 70 (1), 104–112.

Heather, L., VanTassel, H., Hansen, A.M., Barrows, C.W., Latif, Q., Simon, M.W., Anderson, K.E., 2014. Declines in a ground-dwelling arthropod community during an invasion by Sahara mustard (Brassica tournefortii) in aeolian sand habitats. Biol. Invasions 16, 1675–1687.

Hidayat, M.R., Endris, W.M., Dwiyanti, Y., 2018. Effect of a rubber plantation on termite diversity in Melawi, West Kalimantan, Indonesia. Agric. Nat. Res. 52, 439–444.

Hou, E.Q., Wen, D.Z., Li, J.L., Zuo, W.D., Zhang, L.L., Kuang, Y.W., Li, J., 2012. Soil acidity and exchangeable cations in remnant natural and plantation forests in the urbanised Pearl River Delta, China. Soil Res. 50, 207–215.

Jiang, X.J., Liu, W., Wu, J., Wang, P., Liu, C., Yuan, Z.Q., 2017. Land degradation controlled and mitigated by rubber-based agroforestry systems through optimizing soil physical conditions and water supply mechanisms: a case study in Xishuangbanna, China. Land Degrad. Dev. 28 (7), 2277–2289.

Lan, G., Wu, Z., Yang, C., Sun, R., Chen, B., Zhang, X., 2020. Tropical rainforest conversion into rubber plantations results in changes in soil fungal composition, but underling mechanisms of community assembly remain unchanged. Geoderma 375, 114505.

Li, F.R., Liu, J.L., Liu, C.A., Liu, Q.J., Niu, R.X., 2013. Shrubs and species identity effects on the distribution and diversity of ground-dwelling arthropods in a Gobi desert. J. Insect Conserv. 17, 319–331.

Liu, J.L., Li, F.R., Liu, C.A., Liu, Q.J., 2012. Influences of shrub vegetation on distribution and diversity of a ground beetle community in a Gobi desert ecosystem. Biodivers. Conserv. 21, 2601–2619.

Liu, R., Zhu, F., An, H., Steinberger, Y., 2014. Effect of naturally vs manually managed restoration on ground welling arthropod communities in a desertified region. Ecol. Eng. 73, 545–552.

Liu, W.J., Luo, Q.P., Li, J.T., Wang, P.Y., Lu, H.J., Liu, W.Y., Li, H.M., 2015a. The effects of conversion of tropical rainforest to rubber plantation on splash erosion in Xishuangbanna, SW China. Nord. Hydrol 46, 168–174.

Liu, R., Zhu, F., An, H., Steinberger, Y., 2015b. Effectiveness of afforested shrub plantation on ground-active arthropod communities and trophic structure in desertified regions. Catena 125, 1–9.

Liu, W., Zhu, C., Wu, J., Chen, C., 2016. Are rubber-based agroforestry systems effective in controlling rain splash erosion? Catena 147, 16–24.

Liu, C.A., Nie, Y., Zhang, Y.M., Tang, J.W., Siddique, K.H.M., 2018. Introduction of a leguminous shrub to a rubber plantation changed the soil carbon and nitrogen fractions and ameliorated soil environments. Sci. Rep. 8, 17324.

Liu, C.A., Nie, Y., Rao, X., Tang, J.W., Siddique, K.H.M., 2019. The effects of introducing Flemingia macrophylla to rubber plantations on soil water content and exchangeable cations. Catena 172, 480–487.

Mann, C.C., 2009. Addicted to rubber. Science 325, 564–566.

Mei, C.C., 2015. The Spatial-Temporal Evolution of Rubber Plantation and the Distribution Patterns of Aboveground Biomass Carbon Storage in Xishuangbanna. M. Sc degree thesis. University of Chinese Academic of Sciences (in Chinese with English abstract).

Neyret, M., Robain, H., de Rouw, A., Janeau, J.L., Durand, T., Kaewthip, J., Trisophon, K., Valentin, C., 2020. Higher runoff and soil detachment in rubber tree plantations compared to annual cultivation is mitigated by ground cover in steep mountainous Thailand. Catena 189, 104472.

Pan, C., Feng, Q., Liu, J., Li, Y., Li, Y., Yu, X., 2018. Community structure of grassland ground-dwelling arthropods along increasing soil salinities. Environ. Sci. Pollut. Res. 25, 7479–7486.

Rao, X., Liu, C.A., Tang, J.W., Nie, Y., Liang, M.Y., Shen, W.J., Siddique, K.H.M., 2021. Rubber-leguminous shrub systems stimulate soil N2O but reduce CO2 and CH4 emissions. For. Ecol. Manage. 480, 118665.

Robertson, G.P., Coleman, D.C., Bledsoe, C.S., Sollins, P., 1999. Standard Soil Method for Long-Term Ecological Research. Oxford Univ. Press, New York, pp. 75–77.

Sanchez-Montoya, M.M., Tockner, K., von Schiller, D., Minano, J., Catarineu, C., Lencina, J.L., Barbera, G.G., Ruhi, A., 2020. Dynamics of ground-dwelling arthropod metacommunities in intermittent streams: the key role of dry riverbeds. Biol. Conserv. 241, 108328.

Ter Braak, C.J.F., Smilauer, P., 2012. Canoco Reference Manual and User's Guide: Software for Ordination, Version 5.0. Microcomputer Power, Ithaca, NY.

van Reeuwijk, L.P., 2002. Procedures for Soil Analysis, sixth ed. International Soil Reference and Information Centre (ISRIC), Wageningen, The Netherlands.

van Straaten, O., Corre, M.D., Wolf, K., Tchienkoua, M., Cuellar, E., Matthews, R.B., Veldkamp, E., 2015. Conversion of lowland tropical forests to tree cash crop plantations loses up to one-half of stored soil organic carbon. Proc. Natl. Acad. Sci. Unit. States Am. 112, 9956–9960.

VanTassel, H.L.H., Barrows, C.W., Anderson, K.E., 2015. Post-fire spatial heterogeneity alters ground-dwelling arthropod and small mammal community patterns in a desert landscape experiencing a novel disturbance regime. Biol. Conserv. 182, 117–125.

Villanueva-López, G., Lara-Pérez, L.A., Oros-Ortega, I., Ramírez-Barajas, P.J., Casanova-Lugo, F., Ramos-Reyes, R., Aryal, D.R., 2019. Diversity of soil macro-arthropods correlates to the richness of plant species in traditional agroforestry systems in the humid tropics of Mexico. Agric. Ecosyst. Environ. 286, 106658.

Wang, F.J., 2015. The Content of Nitrogen Fixed by Flemingia Macrophylla and its Effects on the Growth of Rubber and Concentration of Soil Total Nitrogen in Rubber-F. Macrophylla Intercropped Systems in Different Stand Ages. M.Sc degree thesis. University of Chinese Academic of Sciences (in Chinese with English abstract).

Warren-Thomas, E., Dolman, P.M., Edwards, D.P., 2015. Increasing demand for natural rubber necessitates a robust sustainability initiative to mitigate impacts on tropical biodiversity. Conserv. Lett. 8, 230–241.

Yang, X., Sha, L., 2001. Species composition and diversity of soil mesofauna in the 'Holy Hills' fragmentary tropical rain forest of Xishuangbanna, China. Chin. J. Appl. Ecol. 12 (2), 261–265 (in Chinese with English abstract).

Yang, X., Liu, H., Zheng, Z., Sha, L., 2003. Effect of planting Amomum on soil arthropod communities in tropical seasonal rain forest in Xishuangbanna. Chin. J. Ecol. 22 (4), 10–15 (in Chinese with English abstract).

Yin, W.Y., 2000. Pictorial Keys to Soil Animals of China. Science Press, Beijing (In Chinese).

Zhai, D.L., Cannon, C.H., Slik, J.W.F., Zhang, C.P., Dai, Z.C., 2012. Rubber and pulp plantations represent a double threat to Hainan's natural tropical forests. J. Environ. Manag. 96, 64–73.

Zheng, L.Y., Gui, H., 1999. Classification of Insects in China (In Chinese). Nanjing Normal University Publishing House.

Zheng, G., Li, S., Yang, X., 2015. Spider diversity in canopies of Xishuangbanna rainforest (China) indicates an alarming juggernaut effect of rubber plantations. For. Ecol. Manage. 338, 200–207.

Zhu, Y., Wang, Y., Chen, L., 2019. Responses of ground-active arthropods to black locust (Robinia pseudoacacia L.) afforestation in the Loess Plateau of China. Catena 183, 104233.