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The effects of introducing *Flemingia macrophylla* to rubber plantations on soil water content and exchangeable cations

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ABSTRACT

Rubber-based (*Hevea brasiliensis*) agroforestry systems are the best way to resolve the environmental problems caused by rubber monoculture. Rubber–*Flemingia macrophylla* (nitrogen-fixing plants) systems have become popular in Xishuangbanna, Southwest China. Soil water content and exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}) are important for sustainably managing forest ecosystems. In this study, we investigated the responses of soil water content and exchangeable cations in rubber and rubber–*Flemingia macrophylla* systems. Soil water content increased in the 0–90 cm soil layer as the rubber plantations aged, and the mature rubber plantations had similar soil water storage to rainforests. The rubber plantations use soil water in the 30–90 cm soil layer to avoid drought stress during the long, dry season. The introduction of *Flemingia macrophylla* to the young rubber plantations significantly increased soil water depletion in the 30–90 cm soil layer. The introduction of *Flemingia macrophylla* to the mature rubber plantations had no significant effects on soil water in the 0–90 cm soil layer. The introduction of *Flemingia macrophylla* to the differently aged rubber plantations mitigated soil acidification by decreasing nitrogen inputs. The total exchangeable cations in the 0–90 cm soil layer sharply decreased as the rubber plantations aged due to the acceleration of soil acidification. When soil pH was below 5.5, 7.85 cmol kg^{-1} of soil exchangeable cations were released when the pH decreased by one unit. However, the introduction of *Flemingia macrophylla* to the differently aged rubber plantations effectively reduced the release of soil exchangeable cations by mitigating soil acidification. In conclusion, rubber–*Flemingia macrophylla* systems can mitigate soil acidification and reduce the release of soil exchangeable cations relative to rubber monoculture.

1. Introduction

Rubber (*Hevea brasiliensis*) plantations in Southeast Asia have expanded due to unprecedented economic growth in the area (Ahrends et al., 2015; Warren-Thomas et al., 2015; Lang et al., 2017). Ninety-seven percent of the world's natural rubber is produced in this region (FAO, 2013). Historically, rubber was planted in the equatorial zone between 10° north and 10° south at a maximum altitude of 600 m a.s.l (Guardiola-Claramonte et al., 2010). To pursue economic benefits, the cultivation of *H. brasiliensis* was extended to higher latitudes and altitudes in South America, Southeast Asia and Africa (Liu et al., 2014). Over the last several decades, more than 1 million ha of non-traditional rubber-growing land has been converted into rubber plantations to satisfy the market demands of China, Laos, Thailand, Vietnam, Cambodia, and Myanmar (Mann, 2009; Ziegler et al., 2009). In southwestern China, the tropical rainforests of Xishuangbanna have been deforested and replaced with > 0.47 million ha of rubber plantations (Mei, 2015). The expansion of rubber plantations has led to soil organic carbon losses and ecosystem degradation, which threatens environmental biodiversity as well as the livelihoods of residents (i.e., more and more people rely on tapping for a living). The establishment of rubber-based agroforesty systems is a primary management practice to ensure ecological security in rubber-growing areas (Liu et al., 2016; Chen et al., 2017; Liu et al., 2018). In recent years, environmentally friendly rubber plantation constructions have become highly valued by the Chinese government (Bai, 2015). *Flemingia macrophylla* is a perennial leguminous leafy shrub that can biologically fix nitrogen. It is widely planted throughout the Xishuangbanna area in an attempt to resolve the environmental problems caused by monoculture rubber plantations.

Soil hydrological and biogeochemical cycles are highly dependent on soil water in forested ecosystems (Kiikkilä et al., 2002; Lozano et al., 2013; Goodrick et al., 2016). For example, Tan et al. (2011) reported

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that rubber plantations act as "water pumps" in China's tropical regions, which can result in water shortages in the dry seasons. However, Wang and Li (1981) reported that rubber plantations exhibit similar hydrology to rainforests, have good functions in regard to soil and water conservation and would not cause water shortages. Therefore, whether rubber plantations have good water holding capacities remain controversial. The incremental increases in biomass in rubber plantations decreases as the plantation ages (Wang, 2015), and young rubber plantations may use more water than mature plantations to produce higher biomass. However, in the studies above, the impact of plantation age on soil water content was not considered, and the long-term dynamic changes in soil water content in different soil layers were not measured. Rubber-based agroforestry systems are considered the best way to resolve environmental problems caused by rubber monoculture. *Flemingia macrophylla*, with its strong sprouting ability and high biomass, can cause water shortages in dry seasons in rubber plantations. The age of the rubber trees in rubber–*Flemingia macrophylla* systems affected the biomass of *Flemingia macrophylla* (Wang, 2015), and soil water content maybe affected by *Flemingia macrophylla* in differently aged systems. While rubber–*Flemingia macrophylla* systems have become popular in China's Xishuangbanna area, the soil water dynamics in the differently aged rubber and rubber–*Flemingia macrophylla* systems have received little attention.

Soil exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}) are important indicators of soil buffering and storage capacities, which represent the major plant-available reservoir. Their contents are usually related to plant productivity (Chen et al., 2013; Kopittke et al., 2017). The addition of nitrogen can increase Ca^{2+} and Mg^{2+} leaching by reducing pH in acidic soils (Sun et al., 2007; Shi et al., 2016). In China's Xishuangbanna area, large amounts of nitrogen fertilizers have been applied to the soil each year to improve rubber production. In addition, sulfur powder has been sprayed on rubber plantations to control powdery mildew (Zhou et al., 2016). These applications of nitrogen fertilizer and sulfur powder may increase Ca^{2+} and Mg^{2+} leaching in rubber plantations by accelerating soil acidification. The high N-fixing capacity of *Flemingia macrophylla* (Wang, 2015) reduced N inputs in intercropped rubber–*Flemingia macrophylla* plantations. According to local management practices, no nitrogen is applied to rubber–*Flemingia macrophylla* plantations two years after *Flemingia macrophylla* is introduced to the plantation. The introduction of *Flemingia macrophylla* to rubber plantations may decrease Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} leaching by mitigating soil acidification. The degree of soil acidification in differently aged rubber plantations may differ, and the response of soil exchangeable cations to the introduction of *Flemingia macrophylla* to differently aged rubber plantations is unknown.

The objectives of this study were to: (1) examine the soil water dynamics in the 0–90 cm soil layer in differently aged rubber and rubber–*Flemingia macrophylla* systems; (2) study the effects of nitrogen fertilizer and sulfur powder application in differently aged rubber plantations in regard to the soil exchangeable Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}; and (3) examine the effects of introducing *Flemingia macrophylla* to differently aged rubber plantations, and its potential for decreasing nitrogen inputs on the soil exchangeable Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}.

2. Materials and methods

2.1. Study site

This study was conducted in Xishuangbanna (21°33′N, 101°28′E; 880 to 900 m asl), Yunnan Province, southwestern China. The region has a typical tropical monsoon climate, with an annual mean temperature of 21.8 °C. The area receives mean annual precipitation of approximately 1500 mm, 80% of which occurs in the May to October rainy season (Li et al., 2012). Xishuangbanna contains the largest area of tropical rainforest tin China. Its biodiversity is rich, being part of the Indo-Burma world biodiversity hotspot (Myers et al., 2000). The soil in this area is classified as laterite (Oxisol), which developed from arenaceous shale sediment (Wang et al., 1996; Li et al., 2012).

In 1991, 2000, and 2003, tropical forests with slopes ranging from 47 to 58% in Xishuangbanna were deforested before sugarcane (*Saccharum officinarum* L.) was planted. In May 1994, 2003, and 2006, three adjacent rubber tree plantations replaced the sugarcane at these sites. The spacing between the adjacent rows was 8 m. The trees were planted at a density of 450 individuals ha^{-1} (Fig. 1A). In accordance with local practices for rubber trees up to three years of age, fertilizer was applied at rates of 27.0 kg N ha^{-1}, 5.9 kg P ha^{-1}, and11.2 kg K ha^{-1} across two applications each year (May and October). The fertilizer was applied between trees at a depth of 20 cm using spades. For rubber trees more than three years of age, the application rates were 54.0 kg N ha^{-1}, 11.8 kg P ha^{-1}, and 22.4 kg K ha^{-1}, which were administered in the same manner. Rubber plantation farmers generally spray sulfur powder at 30–60 kg ha^{-1} yr^{-1} on the rubber trees to control powdery mildew. Plantation weeds were cut twice each year (April/May and November/December) and left on the ground. In July 2010, *Flemingia macrophylla* was introduced to the differently aged rubber plantations at a density of 10,830 plants ha^{-1} (Fig. 1B). From 2011 onwards, the *Flemingia macrophylla* was cut each year in December and left as ground cover. From 2012 onwards, no nitrogen was applied to the rubber–*Flemingia macrophylla* plantations due to the strong nitrogen fixing ability of *Flemingia macrophylla*. The inputs of P, K, and S remained the same as that of the adjacent rubber plantations.

Fig. 1. Photographs showing the (A) rubber and (B) rubber–*Flemingia macrophylla* plantations.

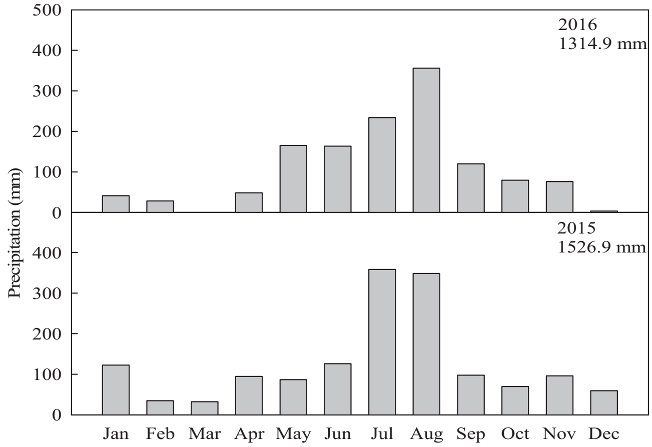

Fig. 2. Distribution of precipitation at the study site in 2015 and 2016.

2.2. Experimental design, sampling, and measurements

Three replicate sites were selected within each rubber and rubber–*Flemingia macrophylla* plantation. Each replication site consisted of 20 × 25 m^2 survey plots (four rows of rubber trees, and three 8-m wide hedgerows) containing nine sampling subplots (8 × 6 m^2), three at each slope position (upper, middle, and lower slope).

The soil water content was determined gravimetrically to a depth of 90 cm, with five sampling depths: 0–10 cm, 10–30 cm, 30–50 cm, 50–70 cm, and 70–90 cm, using a 5 cm diameter soil auger. At each replicate site, nine core soil samples (i.e., one from each subplot) were taken at each depth, which were combined in a composite sample. The composite sample was dried at 105 °C to constant weight for at least 24 h. In April 2015, soil bulk density was determined according to the method by Robertson et al. (1999).

In each subplot, one composite soil sample was collected with a soil auger, avoiding the fertilization holes, to a depth of 90 cm at five sampling depths as follows: 0–10 cm, 10–30 cm, 30–50 cm, 50–70 cm, and 70–90 cm. The collections were made after carefully removing the litter-fall and/or grass layer. At each replicate site, nine soil core samples (i.e., one from each subplot) were taken at each depth, and these were combined in a composite sample in March 2011, and June 2015. The composite samples were air-dried, ground, and sieved (< 2 mm) to determine soil pH and exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+).

Soil pH was determined in CO_2-free de-ionized water using a pH electrode, with a soil: liquid ratio of 1:2.5 (w/v). The exchangeable elements (Ca, Mg, K and Na) were extracted with 1 mol L^{-1} NH_4OAc, and the concentrations of each base cation in the extracts measured using inductively coupled plasma-atomic emission spectrometry (ICP-AES) (Yuan et al., 2007).

2.3. Statistical analysis

Statistical analysis was carried out using the SAS software package (SAS Institute, 1990). Differences among treatments were evaluated with the least significant difference (LSD) at $P \leq 0.05$. The relationships between soil pH and exchangeable cations were extensively tested using Pearson's correlation analysis.

3. Results

3.1. Precipitation and soil water content

Most of the precipitation in this study occurred between May and October. 2016 was a dry year with 1314.9 mm precipitation, while 2015 was an average year with 1526.9 mm precipitation (Fig. 2). The water content in each soil layer (0–10, 10–30, 30–50, 50–70, and 70–90 cm) was similar for the duration of the experiment. Soil water content improved as the trees aged in the rubber and rubber–*Flemingia macrophylla* plantations (Fig. 3). From April 2015 to April 2017, soil water content did not significantly differ between R1 and RF1 in the 0–30 cm soil layer. However, soil water depletion increased significantly in the 30–90 cm soil layer in RF1 compared with R1. In RF2, soil water depletion increased significantly in the 30–90 cm soil layer in August 2015, and January and August 2016 relative to R2. No significant differences were observed between R3 and RF3 for soil water content in the 30–90 cm soil layer. Soil water content generally

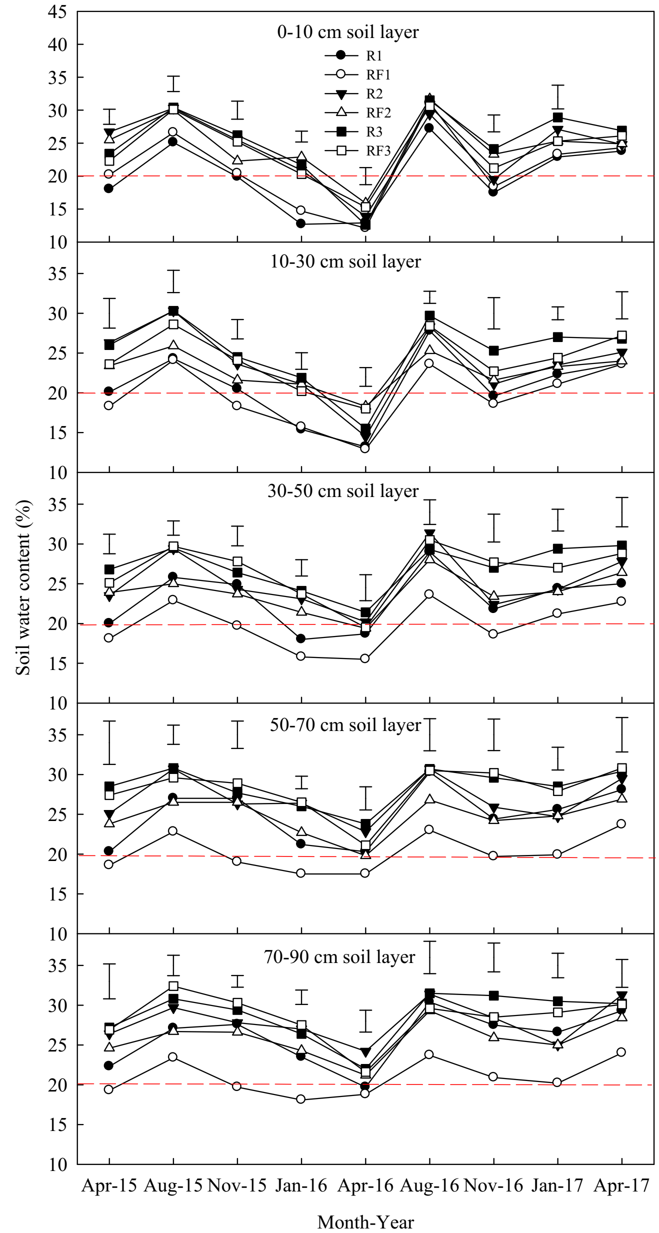

Fig. 3. Profile of soil water content in the 0–10, 10–30, 30–50, 50–70, and 70–90 cm soil layers during the various treatments from April 2015 to April 2017. R1: rubber plantations established in 2006; R2: rubber plantations established in 2003; R3: rubber plantations established in 1994; RF1: *Flemingia macrophylla* introduced to R1 in 2010; RF2: *Flemingia macrophylla* introduced to R2 in 2010; RF3: *Flemingia macrophylla* introduced to R3 in 2010. Error bars are LSD at $P \leq 0.05$.

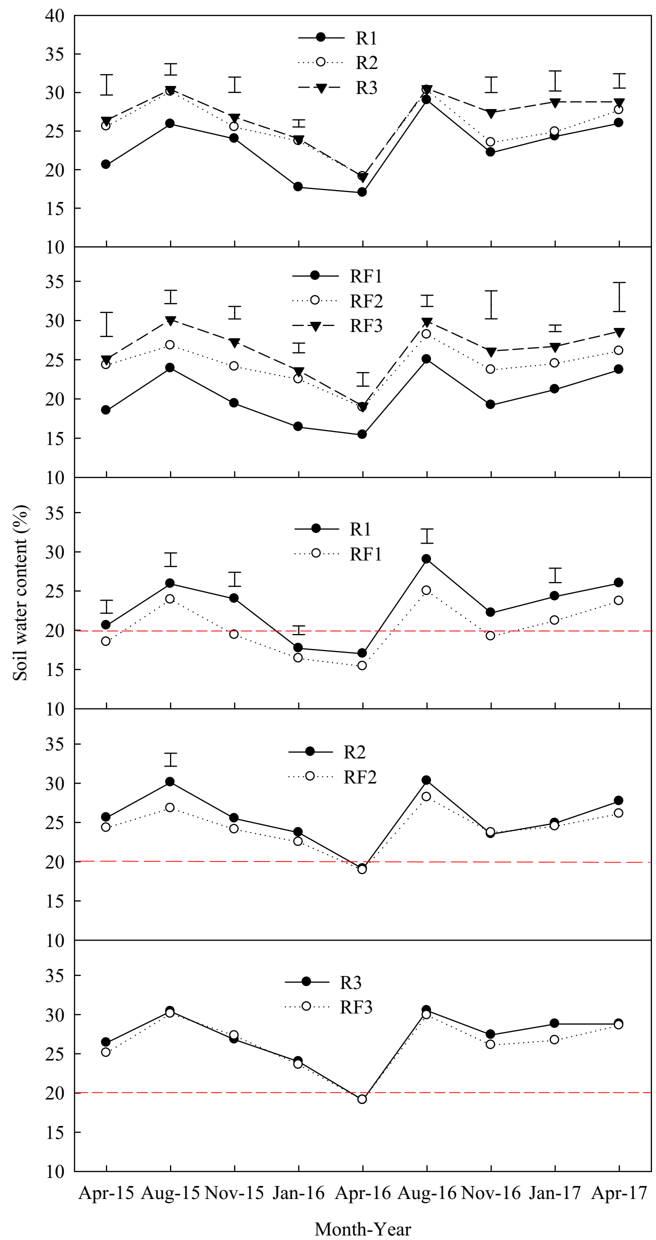

Fig. 4. Profile of average water content in the 0–90 cm soil layer during the various treatments from April 2015 to April 2017. R1: rubber plantations established in 2006; R2: rubber plantations established in 2003; R3: rubber plantations established in 1994; RF1: *Flemingia macrophylla* introduced to R1 in 2010; RF2: *Flemingia macrophylla* introduced to R2 in 2010; RF3: *Flemingia macrophylla* introduced to R3 in 2010. Error bars are LSD at $P \leq 0.05$.

increased with increasing soil depth from 30 to 90 cm in the differently aged rubber plantations in dry seasons.

The average water content in the 0–90 cm soil layers improved as the trees aged in the rubber and rubber–*Flemingia macrophylla* plantations (Fig. 4). From April 2015 to April 2017, R1 had significantly higher average water content in the 0–90 cm soil layers than RF1, except for April 2016, where there was no significant difference. R2 had consistently higher soil water content in the 0–90 cm soil layers than RF2, but significant differences were only observed in August 2015. Soil water content in the 0–90 cm soil layers did not differ between R3 and RF3. Total soil water content in the 0–90 cm soil layers in January, April, August, and November improved as the trees aged (Table 1). The introduction of *Flemingia macrophylla* to R1 significantly increased soil water depletion and decreased total soil water content in the 0–90 cm soil layers. While the introduction of *Flemingia macrophylla* to R2 and R3 also decreased total soil water contents in the 0–90 cm soil layers, significant soil water depletion was only observed in August in RF2 and January in RF3. In dry seasons, the average values for total soil water content in the 0–90 cm soil layer in January, April, and November for R1 and RF1 was generally below 280 mm, and the corresponding values for R2, R3, RF2, and RF3 were generally above 290 mm. In rainy seasons, the average values for total soil water content in the 0–90 cm soil layer in August was above 300 mm for all plantation types. Total soil water content in the 0–90 cm soil layer was significantly affected by plantation age, the introduction of *Flemingia macrophylla*, and their interactions (Table 1).

3.2. Exchangeable soil cations and pH

Total soil exchangeable cations (Ca^{2+}, Mg^{2+},K^+, and Na^+) decreased significantly as the trees aged in the rubber and rubber–*Flemingia macrophylla* plantations (Table 2). In this study, the average soil exchangeable cations in the 0–90 cm soil layer in R2 and R3 decreased significantly over the four-year experimental period, but no significant differences were observed in R1, RF1, RF2, or RF3 (Fig. 5). After four years, the average soil exchangeable cations had declined by 0.48, 3.80, and 2.72 cmol kg^{-1} for R1, R2, and R3, respectively, and only 0.22, 0.86, and 0.80 cmol kg^{-1} for RF1, RF2, and RF3, respectively (Fig. 5). At the start of the experiment, the average soil exchangeable cations in the 0–90 cm soil layer only differed with plantation age; after four years, differences between plantation age, the introduction of *Flemingia macrophylla*, and their interactions became apparent (Table 3). The soil exchangeable soil cations mainly comprised Ca^{2+} and Mg^{2+}, which accounted for 82–97% of total soil exchangeable cations (Fig. 6). After four years, any changes in the soil exchangeable cations in the plantations were mainly due to changes in Ca^{2+} and Mg^{2+}.

The average values for soil pH in the 0–90 cm soil layer in R1, R2, and R3 decreased significantly after four years, but those in RF1, RF2, and RF3 did not differ (Fig. 7). The average values of the exchangeable cations and pH in the 0–90 cm soil layer had a significant positive correlation in all treatments at soil pH < 5.5 ($R^2 = 0.87$, $P = 0.0007$; Fig. 8).

4. Discussion

4.1. Soil water content in rubber and rubber–Flemingia macrophylla plantation systems

High annual evapotranspiration rates reportedly cause water shortages in rubber plantations during dry seasons (Tan et al., 2011). However, Wang and Li (1981) suggest that rubber plantations have good water retention functionality. Water use strategies in rubber plantations have been affected by local precipitation. Reduced stomatal regulation is sufficient with 2100 mm of annual precipitation, and stricter stomatal regulation is needed when annual precipitation is 1400 mm (Kumagai et al., 2015). In previous studies, the effect of plantation age on soil water content was not considered. In the current study, soil water content improved with the increased ages of the rubber plantations from April 2015 to April 2017. In the study sites, the biomass increment amounts of 8-, 11-, and 20-year-old rubber plantations were 14.38, 9.88, and 5.91 t ha^{-1} y^{-1}, respectively (Wang, 2015). The young rubber plantations used more water than mature rubber plantations to produce higher biomass.

Rubber trees originate from the Amazon Basin, where annual precipitation is ~2000 mm, so they have adapted to a moist environment (Priyadarshan et al., 2005). However, to pursue economic interests, rubber trees are now grown at higher latitudes and altitudes in Southeast Asia, where the dry seasons extend from November to April. During this period, the rubber trees shed their leaves over a short period (Kumagai et al., 2015). The water use strategies of rubber trees during

Table 1
Two-way ANOVA for average values of total water content in the 0–90 cm soil layer in different months of the experimental period within the rubber and rubber–*Flemingia macrophylla* plantations with age and N-fixing species as factors (mean ± SD, n = 3).

	January	April	August	November
R1	273.9 ± 8.3d	275.7 ± 17.0b	347.9 ± 2.7bc	298.3 ± 14.3b
R2	297.6 ± 1.9c	298.6 ± 11.1ab	368.8 ± 11.2a	302.3 ± 4.1b
R3	321.6 ± 7.1a	305.2 ± 6.3a	368.0 ± 13.5a	331.6 ± 8.0a
RF1	237.2 ± 5.5e	242.7 ± 9.2c	302.9 ± 3.7d	244.5 ± 14.1c
RF2	291.2 ± 3.5c	288.8 ± 19.4ab	337.6 ± 3.9c	299.0 ± 16.0b
RF3	309.8 ± 3.4b	299.3 ± 14.9ab	364.5 ± 13.9ab	329.4 ± 8.9a
	F-value	F-value	F-value	F-value
Age	188.4*	16.4*	29.1*	38.5*
N-fixing species	51.1*	6.3*	35.5*	12.9*
Age * N-fixing species	13.2*	1.7	7.5*	9.6*

R1: rubber plantations established in 2006; R2: rubber plantations established in 2003; R3: rubber plantations established in 1994; RF1: *Flemingia macrophylla* introduced to R1 in 2010; RF2: *Flemingia macrophylla* introduced to R2 in 2010; RF3: *Flemingia macrophylla* introduced to R3 in 2010. Values within a column followed by the same letter do not significantly differ at $P \leq 0.05$.
* Mean $P \leq 0.05$.

long, dry seasons are of concern for many researchers. Liu et al. (2014) reported that rubber trees taken up large proportions of shallow soil water after rainfall in dry seasons using superficial lateral roots in the top 30 cm of soil. Rubber trees primarily uptake water from 30 to 80 cm soil layer during dry seasons (Wu et al., 2017). In this study, soil water content generally increased with increasing soil depth from 30 to 90 cm in the differently aged rubber plantations during the dry seasons. However, it was observed that, even in the dry seasons, the soil water content in the 30–90 cm soil layer remained > 20% (~60% of field water capacity), which indicates that rubber trees could thrive during long, dry seasons in the study region. In this study, the soil water content in the 0–90 cm soil layer was > 290 mm in the mature rubber plantations (R2 and R3) during the rainy/dry season, which is close that in the tropical rainforests of this region (Wang, 1979).

Rubber–*Clerodendranthus spicatus* and rubber–*Amomum villosum* agroforestry systems promote the formation of 3D hydraulic redistributions in the soil profile, and improve soil infiltration (Jiang et al., 2017). Wu et al. (2016) reported consistently higher soil water contents in a rubber–*Flemingia* agroforestry system than rubber monoculture but this finding is not consistent with our results. In the current study, the introduction of *Flemingia macrophylla* to the mature rubber plantations had no significant effect on soil water content in the 0–90 cm soil layer. However, introducing *Flemingia macrophylla* to the young rubber plantations significantly increased soil water depletion in the 30–90 cm soil layer. The annual biomass of *Flemingia macrophylla* reached 23.02 t ha^{-1} after four years, when introduced to 4-year-old rubber plantations (Wang, 2015). The young rubber–*Flemingia macrophylla* systems needed to deplete more water to produce high biomasses of *Flemingia macrophylla* when compared to rubber plantations of the same age. However, when *Flemingia macrophylla* was introduced to mature rubber plantations, *Flemingia* growth was limited by the high crown density of the mature trees. These findings indicate that *Flemingia macrophylla* growth in mature rubber plantations does not require high water depletion and, correspondingly, did not have significant impacts on soil water content. The inconsistent findings of Wu et al. (2016) only came from a mature rubber–*Flemingia macrophylla* system, and suggest that the water use patterns of young rubber–*Flemingia macrophylla* systems require more attention. The introduction of *Flemingia macrophylla* to young rubber plantations significantly increased soil water depletion in the 30–90 cm soil layers, and also increased the rubber trees' primarily uptake of water in the 30 to 80 cm soil layer during the dry season (Wu et al., 2017). During the dry seasons, the soil water content in RF1 was generally < 20% (~60% of field capacity), suggesting that water stress could occur in the young rubber–*Flemingia macrophylla* plantations.

4.2. Exchangeable soil cations in the rubber and rubber–Flemingia macrophylla plantation systems

In the present study, soil exchangeable cations sharply decreased with increasing age of the rubber plantations. There are three possible reasons for this phenomenon. Firstly, rubber trees use large amounts of

Table 2
Total exchangeable soil bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+) (cmol kg^{-1}) in rubber and rubber–*Flemingia macrophylla* plantations in 2011 and 2015 (mean ± SD, n = 3).

Year	Soil depth (cm)	R1	R2	R3	RF1	RF2	RF3
March 2011	0–10	9.51 ± 0.54a	9.04 ± 0.41ab	6.00 ± 0.26c	8.31 ± 1.22ab	7.83 ± 0.79b	6.39 ± 0.87c
	10–30	9.86 ± 0.16a	8.53 ± 0.57b	4.97 ± 0.76c	10.15 ± 0.19a	8.53 ± 1.09b	5.36 ± 0.91c
	30–50	9.88 ± 0.79a	7.57 ± 0.33b	4.68 ± 0.46c	9.94 ± 0.65a	7.59 ± 0.71b	5.00 ± 1.32c
	50–70	10.08 ± 0.73a	6.94 ± 0.50b	4.53 ± 0.25c	10.01 ± 0.67a	7.07 ± 0.89b	4.45 ± 0.92c
	70–90	9.90 ± 0.11a	6.67 ± 1.00b	4.57 ± 0.22c	9.95 ± 0.76a	6.99 ± 1.10b	4.81 ± 0.77c
June 2015	0–10	9.47 ± 0.47a	5.18 ± 0.49c	3.05 ± 0.36d	8.65 ± 0.34a	7.00 ± 0.65b	4.82 ± 1.06c
	10–30	9.40 ± 0.26a	4.70 ± 0.58c	2.35 ± 0.84d	9.69 ± 0.52a	7.01 ± 0.71b	4.43 ± 0.71c
	30–50	9.01 ± 0.41a	3.83 ± 0.32c	1.94 ± 0.43d	9.65 ± 0.32a	6.80 ± 0.33b	4.16 ± 1.44c
	50–70	9.33 ± 0.30a	3.18 ± 0.52 cd	1.86 ± 0.16d	9.50 ± 0.42a	6.43 ± 0.13b	4.40 ± 1.84c
	70–90	9.66 ± 0.52a	2.87 ± 0.85 cd	1.93 ± 0.14d	9.74 ± 0.36a	6.45 ± 0.41b	4.21 ± 1.47c

R1: rubber plantations established in 2006; R2: rubber plantations established in 2003; R3: rubber plantations established in 1994; RF1: *Flemingia macrophylla* introduced to R1 in 2010; RF2: *Flemingia macrophylla* introduced to R2 in 2010; RF3: *Flemingia macrophylla* introduced to R3 in 2010. Values within a row followed by the same letter do not significantly differ at $P \leq 0.05$.

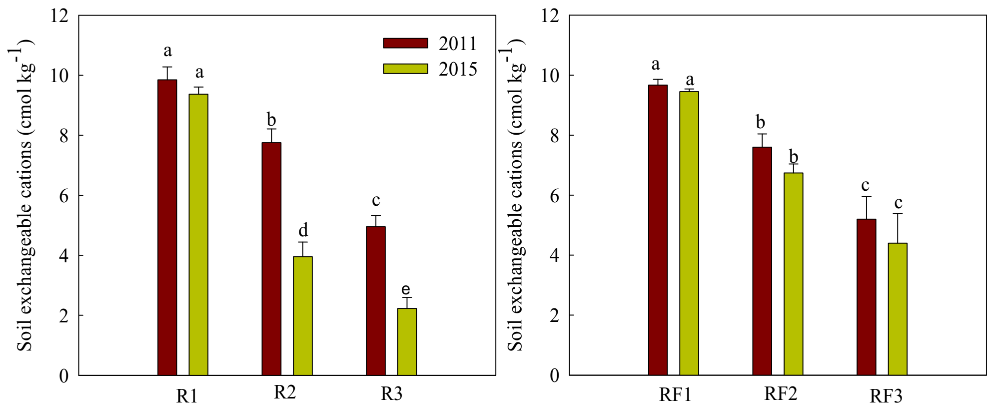

Fig. 5. Change in average values of total exchangeable soil bases (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}) in the 0–90 cm soil layer of the different aged rubber and rubber–*Flemingia macrophylla* plantations in 2011 and 2015. R1: rubber plantations established in 2006; R2: rubber plantations established in 2003; R3: rubber plantations established in 1994; RF1: *Flemingia macrophylla* introduced to R1 in 2010; RF2: *Flemingia macrophylla* introduced to R2 in 2010; RF3: *Flemingia macrophylla* introduced to R3 in 2010. Different letters above the bars indicate significant differences at $P \leq 0.05$. The bars are standard deviations of the mean (n = 3).

Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} from the soil (Zhang et al., 2007). For example, Berthrong et al. (2009) reported that the conversion of non-forested lands to forest plantations significantly decreased soil nutrient cations (Ca, Mg, K) in the 0–30 cm soil layers. Secondly, the Ca, Mg, and K in soil were taken away from the latex of the rubber trees. Nutrient losses of K, Ca, and Mg from the latex were 10.1 and 28.4 g tree^{-1} y^{-1}, 0.25 and 0.72 g tree^{-1} y^{-1}, and 1.68 and 5.49 g tree^{-1} y^{-1} from 8- and 22-year-old rubber trees, respectively (Cao et al., 2010). Thirdly, soil acidification enhances the losses of exchangeable cations, and losses of exchangeable cations can enhance soil acidification (Foster et al., 1989; Lu et al., 2009). Application of nitrogen fertilizer and sulfur powder in the rubber plantations lead to soil acidification (Fig. 7), and exchangeable soil cations and soil pH had a significant positive correlation at soil pH < 5.5 (Fig. 8). In another study, the Ca percentage dropped precipitously when soil pH dropped below 5 (Brady and Weil, 2002). In the current study, 7.85 cmol kg^{-1} of exchangeable soil cations were released when soil pH decreased by one unit. However, the introduction of *Flemingia macrophylla* to the rubber plantations mitigated soil acidification, and effectively reduced the release of soil exchangeable cations, when compared with the same aged rubber plantations, due to the reduction in fertilizer inputs. The reductions in soil cations in the rubber plantations were also caused by Ca and Mg losses in the soil.

Table 3
Two-way ANOVA for average values of total exchangeable soil bases (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}) in the 0–90 cm soil layer in different months of the experimental period within the rubber and rubber–*Flemingia macrophylla* plantations with age and N-fixing species as factors (mean ± SD, n = 3).

	2011	2015
R1	9.85 ± 0.43a	9.37 ± 0.24a
R2	7.75 ± 0.46b	3.95 ± 0.49c
R3	4.95 ± 0.38c	2.23 ± 0.37d
RF1	9.67 ± 0.19a	9.45 ± 0.09a
RF2	7.60 ± 0.44b	6.74 ± 0.30b
RF3	5.20 ± 0.75c	4.40 ± 0.99c
	F-value	F-value
Age	148.3*	230.5*
N-fixing species	0.0	50.7*
Age * N-fixing species	0.4	12.0*

R1: rubber plantations established in 2006; R2: rubber plantations established in 2003; R3: rubber plantations established in 1994; RF1: *Flemingia macrophylla* introduced to R1 in 2010; RF2: *Flemingia macrophylla* introduced to R2 in 2010; RF3: *Flemingia macrophylla* introduced to R3 in 2010.Values within a column followed by the same letter do not significantly differ at $P \leq 0.05$.

* Mean $P \leq 0.05$.

5. Conclusions

Soil water content increased in the 0–90 cm soil layer with increasing plantation age. The mature rubber plantations had similar soil water storage capacities as rainforests in the region. The rubber plantations used water in the 30–90 cm soil layer to avoid drought stress during long, dry seasons. The introduction of *Flemingia macrophylla* to the young rubber plantations significantly increased soil water depletion in the 30–90 cm soil layer. Therefore, this study suggests that plantation age should be considered when selecting crops for intercropping with rubber trees to avoid competition for soil water

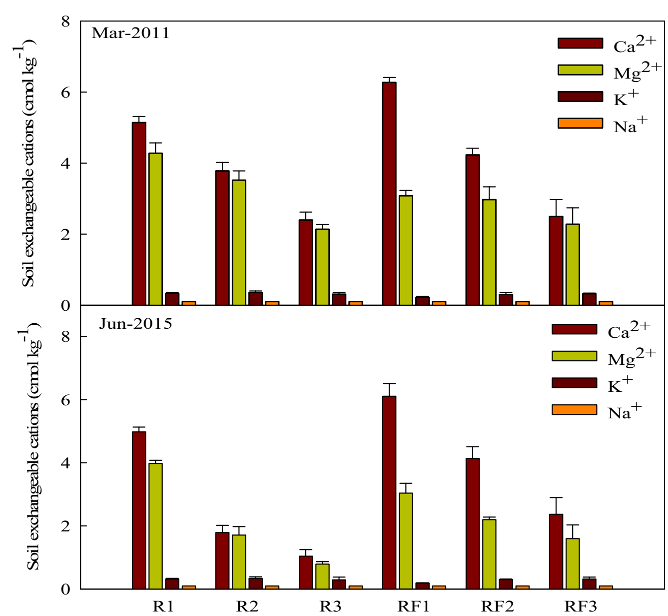

Fig. 6. Average values of the exchangeable soil Ca^{2+}, Mg^{2+}, K^{+} and Na^{+} in the 0–90 cm soil layer of the different aged rubber and rubber–*Flemingia macrophylla* plantations in 2011 and 2015. R1: rubber plantations established in 2006; R2: rubber plantations established in 2003; R3: rubber plantations established in 1994; RF1: *Flemingia macrophylla* introduced to R1 in 2010; RF2: *Flemingia macrophylla* introduced to R2 in 2010; RF3: *Flemingia macrophylla* introduced to R3 in 2010. Different letters indicate significant differences at $P \leq 0.05$. The bars are standard deviations of the mean (n = 3).

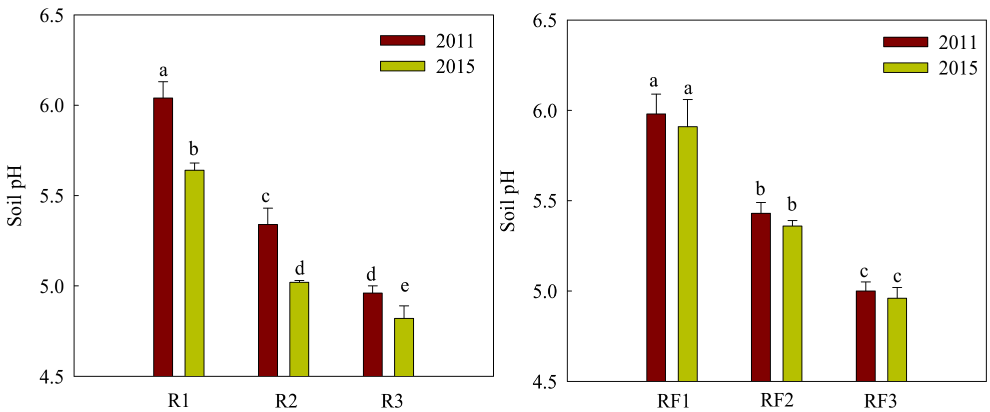

Fig. 7. Change in average values of soil pH in the 0–90 cm soil layer of the different aged rubber and rubber-*Flemingia macrophylla* plantations from 2011 to 2015. R1: rubber plantations established in 2006; R2: rubber plantations established in 2003; R3: rubber plantations established in 1994; RF1: *Flemingia macrophylla* introduced to R1 in 2010; RF2: *Flemingia macrophylla* introduced to R2 in 2010; RF3: *Flemingia macrophylla* introduced to R3 in 2010. Different letters indicate significant differences at $P \leq 0.05$. The bars are standard deviations of the mean (n = 3).

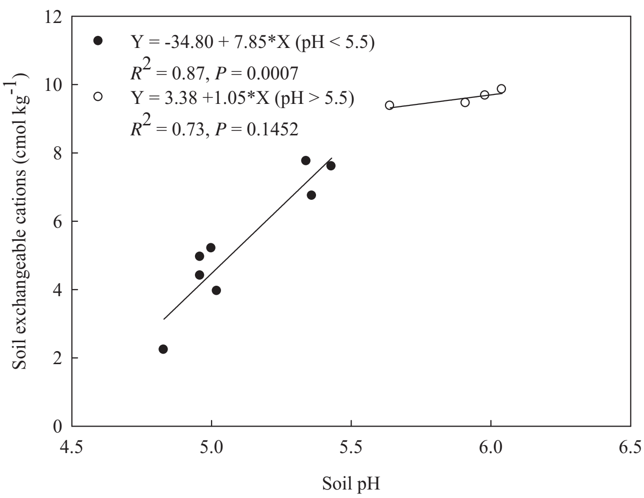

Fig. 8. Relationship between soil pH and the average values of the soil exchangeable cations in the 0–90 cm soil layer in all the treatments.

resources. Soil acidification in the rubber plantations resulted in large losses of total exchangeable soil cations. The introduction of *Flemingia macrophylla* to differently aged rubber plantations effectively reduced the release of soil exchangeable cations by mitigating soil acidification.

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