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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.