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Effects of rubber-based agroforestry systems on soil aggregation and associated soil organic carbon: Implications for land use

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ABSTRACT

Rubber-based agroforestry (*Hevea brasiliensis*) systems are considered the best way to improve soil properties and the overall environmental quality of rubber monoculture, but few reports have examined soil aggregate stability in such systems. The objective of this study was to examine the management and landscape effects on water stable soil aggregates, soil aggregate-associated carbon, nitrogen content and soil carbon, and nitrogen accumulation in Xishuangbanna, southwestern China. Treatments were rubber monoculture (Rm) and four rubber-based agroforestry systems: *H. brasiliensis*–*C. arabica* (CAAs), *H. brasiliensis*–*T. cacao* (TCAs), *H. brasiliensis*–*F. macrophylla* (FMAs) and *H. brasiliensis*–*D. cochinchinensis* (DCAs). The results showed that, with the exception of CAAs, the rubber-based agroforestry treatments significantly increased total soil organic carbon (SOC) and N contents and enhanced the formation of macroaggregates compared to the rubber monoculture treatment. SOC and N contents in all water-stable aggregate fractions were significantly higher in rubber-based agroforestry systems (except CAAs) compared to rubber monoculture. The macroaggregate fractions contained more organic carbon and nitrogen than the microaggregate fractions. The proportions of C and N loss from slaking and sieving were shown to have significantly negative correlations with the mean weight diameter and the SOC and N concentrations in bulk soil. The results suggest that soil surface cover with constant leaf litter fall and extensive root systems in the rubber-based agroforestry systems increased soil organic carbon and nitrogen, helped improve soil aggregation, reduced soil erosion, decreased carbon and nitrogen loss, and ultimately improved the carbon and nitrogen accumulation rates. Given that the soil physical-chemical properties improvement and the patterns of the intercropping system played key roles in managing artificial forests, we recommend that local governments and farmers should prefer *T. cacao*, *F. macrophylla* and *D. cochinchinensis* and not *C. arabica* as the alternative interplanted tree species within rubber plantations.

1. Introduction

The spread of monoculture rubber plantations has occurred throughout the Xishuangbanna Region, resulting in 22.14% of the landscape covered by rubber (Xu et al., 2014) and barely 3.6% of that occupied by important tropical seasonal rainforest (Li et al., 2007). The transformation from both primary and secondary forests to rubber (plantations) and its continued intensification has resulted in numerous negative environmental consequences, particularly increased soil erosion (Mann, 2009), reduced water infiltration (Ziegler et al., 2009), soil nutrient loss and environmental degradation (Chaudhary et al., 2009; Qiu, 2009). The concentrations of organic carbon and nitrogen have also been reported to decline especially when native ecosystems are converted to rubber (Li et al., 2012). Thus, a combined planting pattern of rubber and interplanting or a rubber-based agroforestry system could improve biodiversity, ecosystem services and the use of natural resources, which are important ways to promote the sustainable development of agriculture and the environment (Nath et al., 2005; Viswanathan and Shivakoti, 2008; van Noordwijk et al., 2012). However, over the past decade, the types of agroforestry systems and their soil properties have varied extensively. Although several studies concerning the temporal and spatial variability of soil properties have been conducted in this region (Zhang et al., 2007; Li et al., 2012), soil organic carbon (SOC) and the impacts on soil aggregates under different rubber-based agroforestry systems has received little attention.

Soil aggregates are the basic units of the soil structure that control the dynamics of soil organic matter (SOM) and nutrient cycling (Jastrow et al., 1996; Chevallier et al., 2004). SOM is known to have a strong relationship with aggregate formation and stabilization. Soil aggregation is described using a hierarchical model (HM) and is generally divided into macroaggregates (>0.25 mm) and microaggregates

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(0.25–0.053 mm) with differing binding agents. Soil microaggregates are typically formed by binding microbial polysaccharides with smaller soil particles such as silt and clay, whereas macroaggregates are typically formed by more transient factors such as enmeshment by fugal hyphae and fine roots (Rochester, 2011). This concept is supported by the observation that slaking-resistant macroaggregates (>0.25 mm) contain more organic matter than microaggregates (<0.25 mm) and more labile organic matter is abundant in macroaggregates than in microaggregates (Jastrow et al., 1996; Six et al., 2000). Therefore, macroaggregates are thought to be sensitive to changes in soil management such as cultivation practice and organic inputs, whereas microaggregates are less sensitive.

Management practices, such as agroforestry systems and interplanting, which promote the maintenance and accumulation of soil C, have been increasingly accepted by farmers because of the growing interest in the conservation of SOM (Jose, 2009; Ramachandran Nair et al., 2009). For example, agroforestry systems that leave more plant residues on the soil surface generally allow for improvements in soil aggregation and aggregate stability. SOM can increase the amount of aggregates, especially macroaggregates, and promote the stability of aggregates (Elliott, 1986; Six et al., 2000). Meanwhile, soil aggregation can increase SOC storage by reducing loss from microbial mineralization and by water erosion. For the former, soil organic matter can be physically protected from microbial decomposition through sorption to clay minerals (Oades, 1984; Hassink et al., 1993) or other organic molecules and through isolation in micropores (Adu and Oades, 1978; Foster, 1981) and enclosure within soil aggregates (Tisdall and Oades, 1982), thus reducing the risk of being decomposed to CO_2 into the atmosphere. Mineralization studies using intact versus crushed aggregates revealed the existence of a physically protected SOC pool in soil macroaggregates. For the latter, erosion reduced the amount of soil C by causing the degradation of the soil structure and removing C from one site and depositing it elsewhere (Gregorich et al., 1998). Water erosion tends to redistribute the smallest and least dense particles (small aggregate or clay), and organic C losses can be sensitive and extensive compared to bigger aggregates where organic C accumulate (Woods and Schuman, 1988). Organic C loss from soil occurs mainly through the mineralization of soil organic matter to CO_2, whereas plenty of losses can also occur by the leaching of soluble organic C and by the flowing away of C bonded in clay. Although numerous studies have examined the mechanism and influence of aggregates in protecting SOC from mineralization (Woods and Schuman, 1988; Gregorich et al., 1998), few studies focus on the efficiency and mechanism of aggregates in protecting SOC against the destructibility and loss from erosion and leaching in that study area.

We aimed to evaluate the influence of rubber-based agroforestry system management on soil aggregate stability, soil fertility and SOC and N loss in tropical hillside rubber plantations. Specifically, the objectives of this study were (1) to compare the differences in water stable aggregates, soil carbon, soil nitrogen and aggregate-associated carbon and nitrogen concentrations among rubber monoculture and four rubber-based agroforestry systems and (2) to prove the hypothesis of whether increased organic matter inputs, which varied in rubber-based agroforestry systems, could help improve soil aggregation, C storage and N availability relative to rubber monoculture management.

2. Materials and methods

2.1. Study sites

The studied areas are located in the Xishuangbanna Tropical Botanical Garden (XTBG; 21°55′39″N, 101°15′55″E) in Yunnan Province, SW China. The climate is characterized by annual average temperatures ranging from 24 to 29 °C, high annual average atmospheric humidity (86%), and an average annual rainfall of 1557 mm with three seasons (fog-cool season: from November to February; hot-dry season: from March to April; and rainy season: from May to October) (Vogel et al., 1995). The tropical southern monsoon dominates the climate and contributes 80–90% of the annual rainfall during the rainy season, whereas the subtropical jet streams prevail and deliver dry and cold air during the dry season. The research plots have slopes between 27 and 31° and are sandy loam in texture. The mean elevation of the plot is 760 m, ranging from 710 to 860 m (Fig. 1). The soils are classified as laterites (Oxisols) developed from arenaceous shale sediments approximately 2 m deep (Vogel et al., 1995). The parent material consisted of a 30–40 cm thick layer of gravel deposited by a distributary of the Mekong River.

Studies were conducted in a typical catchment (19.3 ha) covered with rubber monoculture (clone PB86) arranged in double rows and planted at a density of 2 m × 4.5 m; there were 16-m-wide gaps between the rows. Rubber trees were tapped every other day from the end of March to mid-November (approximately 120 times per year), and the annual mean latex yield was approximately 250 kg ha^{-1}. The experiment included four rubber-based agroforestry ecosystems that represented different land uses and management (CAAs, *H. brasiliensis*–*C. arabica*; TCAs, *H. brasiliensis*–*T. cacao*; FMAs, *H. brasiliensis*–*F. macrophylla*; and DCAs, *H. brasiliensis*–*D. cochinchinensis*). The four associated intercrops (approximately 10 years old) were planted in the 16 m interrows between the double rows of rubber monoculture. In CAAs, *C. arabica* trees were planted in five rows, each 1 m apart and containing plants spaced 1.6 m apart. *C. arabica* trees reached approximately 2.2 m high and were 4 m apart from the rubber trees. In TCAs, *T. cacao* trees were planted in five rows, with rows and plants within row spaced 2 m apart. *T. cacao* trees reached approximately 3.6 m and were approximately 3.5 m apart from the rubber trees. In FMAs, *F. macrophylla* trees were planted in eight rows, each spaced 1 m apart and 0.8 m between each plant in each row. *F. macrophylla* trees reached 4.2 m and were 3 m apart from the rubber trees. In DCAs, *D. cochinchinensis* trees were planted in five rows, with 1.5 m apart and 2.5 m between each plant in each row. *D. cochinchinensis* trees reached approximately 2.3 m and were 3.5 m apart from the rubber trees (Table 1).

Morphological characteristics of the understory plant species and the rubber tree in the different types of the rubber-based agroforestry systems were shown in Table 1. The crops' leaf area index (LAI) and canopy closure rate were determined by using a plant canopy analyzer (LAI-2200; Li-Cor Inc., USA). Litterfall was collected from 1 m^2 areas on the soil surface. The samples were oven-dried at 65 °C and then weighed.

The sites were selected in this study were based on similarities in soil parent material, rubber age (the sites had approximately 25-year-old rubber, and rubber tree diameters were approximately 20–25 cm), and similar geographical position with a common north-facing slope (ranging from 85° to 94°). A commercial fertilizer containing N, P and K was point-applied in March and August at a dose of approximately 0.1 kg N per tree hole per year in each study site (Li et al., 2012).

2.2. Sampling and measuring methods

Using the S-shaped sampling strategy, 32 undisturbed soil samples for soil structure determination in each soil depth (0–5, 5–15 and 15–30 cm) were collected in different ecosystems or agro-ecosystems in November 2014, and eight soil samples were mixed into 2 kg soil samples (Bissonnais, 1996) resulting in four mixed soil samples. Prior to the determination of water-stable aggregation, the soils were oven-dried at 45 °C. The analysis of water-stable soil aggregates was carried out using a modified Yoder type apparatus (Yoder, 1936). Briefly, a bank of sieves 200 mm in diameter with mesh aperture of 0.053, 0.25, 0.5, 1, 2 and 5 mm, containing 100 g air-dried soil on the top of the sieve, were submerged in deionized water for 10 min at room temperature. Soils were then sieved under water by moving the sieves up and down for a period of 5 min. It should to be noted that floating organic materials or floatable plant materials, which may increase a slight