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Research Paper

How do plants share water sources in a rubber-tea agroforestry system during the pronounced dry season?

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ABSTRACT

Extensive cultivation of rubber plantations in Xishuangbanna in southwest (SW) China has resulted in negative hydrological consequences, particularly drought, during the pronounced dry season. Although rubber-tea agroforestry is regarded as the most successful agroforestry system for improving the sustainability of rubber agriculture and environmental conservation, plant water use patterns and their related interactions have rarely been examined in such systems. How do coexisting plants compete and share water under water deficit remains to be explored. Therefore, we used stable isotope (δD and $\delta^{18}O$) methods to determine the spatial water use patterns of both rubber trees and tea trees in a rubber-tea agroforestry system during the pronounced dry season and explored the movement of soil water in this system. The results of the MixSIAR model (a Bayesian mixing model) indicated that tea trees primarily uptake water from the 5–30 cm soil layer (40.3%, on average), and rubber trees primarily uptake water from the 30–80 cm soil layer (35.3%, on average) and absorb soil water evenly along slopes during the dry season. These results suggest that rubber trees and tea trees have different but complementary water use patterns. We also observed that the soil of the uphill and downhill tea rows contained much more water; however, the collaborative hydraulic redistribution in the studied agroforestry system could redistribute the soil water along the slope and below the ground well. Therefore, soil drought on terraces can be alleviated during the dry season. Our results confirmed that the tea tree is an appropriate crop for intercropping with rubber trees when considering water sharing and water management and provided a practical analysis of water use benefits from a rubber agroforestry system during drought stress.

1. Introduction

During the Anthropocene, the pervasiveness, magnitude, and variety of human effects were as important as natural forces in shaping geological, ecological, and environmental patterns (Corlett, 2015). One of the best examples of human effects can be observed in rubber plantations, which gradually replaced nearly half of the native tropical primary forests in Xishuangbanna over the last 50 years. This change was encouraged by local policy, and these crops and related forestry restoration areas are now prevalent throughout Southeast Asia (Fox et al., 2014). However, these areas are not as 'green' as they appear (Xu, 2011).

Rubber trees (*Hevea brasiliensis*) are native to the tropical rainforest of the Amazon Basin and are a source of great economic and social value throughout Southeast Asia. Compared with primary tropical forests, areas of rubber monoculture have significantly lower biodiversity, lower total biomass carbon stocks, rapidly fluctuating microclimate temperatures and negative hydrological effects (Fox et al., 2014; Liu et al., 2014; Ziegler et al., 2009). In addition, current planting patterns are inferior in terms of rubber quality and quantity, particularly for rubber trees planted in mountainous areas with high latitudes and elevation. Because of the low genetic diversity in rubber plantations, these areas are more vulnerable to powdery mildew and leaf blight (Mann, 2009). In addition, the environmental pollution problems caused by pesticides, chemical fertilizers, herbicides, and other chemicals cannot be underestimated. Currently, these negative effects are being exacerbated by the dramatic expansion of rubber plantations. By 2050, rubber plantations could occupy more than double or triple the current land area, largely at the expense of evergreen broadleaf forests and secondary vegetation in Southeast Asia (Fox et al., 2014; Ziegler et al., 2009). Accordingly, rubber plantations appear to present a conflict between economic growth and conservation goals.

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Although rubber-based agroforestry systems, which combine agricultural, ecological and forestry techniques to create more diverse, productive, healthy, and sustainable land use, provide a promising solution to these problems and various types of rubber-based agroforestry systems have been applied in practice (Feng, 2007; Fox et al., 2014; Parham, 2005), not all agroforestry systems were designed with a comprehensive consideration of ecological principles. Below-ground interactions and associations between rubber trees and other intercropped species remain poorly documented, particularly regarding water use (Ziegler et al., 2009). Rubber trees have been referred to as 'water pumps' because rubber trees can deplete water sources at the basin scale (Tan et al., 2011). More water is evapotranspirated from rubber plantations (approximately 1125 mm annually) than from local rain forests (approximately 969 mm annually). Soil water storage during the rainy season is not sufficient to maintain the high evapotranspiration rates of rubber trees, resulting in zero water flow and water shortages during the dry season in monoculture rubber plantations. Therefore, the soil moisture contents in monoculture rubber plantations approach the permanent wilting point during the dry season (Vogel et al., 1995). Nevertheless, rubber trees have strong adaptability regarding water uptake because rubber trees can opportunistically absorb a large amount of shallow soil water after rainfall to meet their high water demands (Liu et al., 2014). Decades of rubber tree cultivation in Xishuangbanna have reduced streamflow and dried up wells in many villages (Qiu, 2009). However, it is worth mentioning that below-ground interspecific competition for water in the rubber agroforestry systems could enhance the water utilization of rubber trees and thus reduce water loss (Wu et al., 2016a,b). As the most important input for rubber agroforestry systems, water availability and interspecific competition for water would greatly affect the growth and survival of the plant community, particularly in light of increasingly serious seasonal drought in this region (Qiu, 2010). Accordingly, observations of the particular water use patterns of rubber trees on the community scale during the dry season are urgently required (Guardiola-Claramonte et al., 2010; Qiu, 2009; Ziegler et al., 2009).

The most famous ancient product of 'Big-leaf' tea (*Camellia sinensis* var. *assamica*) is sold as 'ancient trees organic pu-erh' in Yunnan Province, and its price rose from approximately 20 yuan per kg in the early 1990s–1200 yuan (approximately 175 USD) per kg in 2007 (Mann, 2009). This cash crop was deemed the best species for intercropping with rubber trees because rubber-tea intercropping can not only generate higher expected land value than rubber or tea monoculture under current socio-economic circumstances (Guo et al., 2006) but also help increase rubber yields and biomass (Feng, 2007), result in better water and soil conservation (Liu et al., 2016), and improve ecosystem stability (Parham, 2005; Xu, 1993). In addition, our previous study determined that tea is the appropriate intercrop in terms of water use because the interspecific competition for water in a rubber-tea agroforestry system is moderate. This agroforestry system also retained much more soil water than a rubber monoculture and improved the water use efficiency of rubber trees (Wu et al., 2016b). However, previous studies merely explain that drought stress and interspecific competition for water cause rubber trees to increase the absorption of deep soil water (Liu et al., 2014; Wu et al., 2016a,b). In fact, rubber trees show well-developed root systems, and their lateral roots extend over 9 m (Priyadarshan, 2011). How competing species coexist with water deficits or how below-ground sharing patterns of water sources work in rubber-tea agroforestry systems remain to be studied. Thus, further observation of the below-ground spatial water use patterns (i.e., the water use patterns along the slope) in such agroforestry systems could help us identify the mechanism that allows ideal intercrop sharing of water sources with the rubber tree. Such knowledge could also significantly aid practical reforms of existing rubber agroforestry systems, which were designed without comprehensive consideration of the water use of the plant community.

Measurements of water isotopic compositions (i.e., δD and $\delta^{18}O$) provide insights into hydrologic cycles and ecological processes across multiple temporal and spatial scales. Plant uptake does not fractionate source water (White et al., 1985), δD or $\delta^{18}O$, and therefore, stable isotopes can be used to track the sources of plant water without destructive below-ground sampling, enabling study of the potential competitive interactions among species in a community and identification of hydraulic redistribution (Dawson, 1993; Ehleringer and Dawson, 1992). After decades of development and improvement, this mature technology was widely applied in studies of plant–water relations (Asbjornsen et al., 2011; Silvertown et al., 2015). Therefore, we used stable isotope methods to investigate the water use patterns of rubber trees and tea trees coexisting in the same dry environment. We selected a rubber-tea agroforestry system for observation and divided the experimental field into seven sites (i.e., seven locations along the slope) to measure the soil water content (SWC) at each site for three soil layers (i.e., 0–5, 5–30, and 30–80 cm depths); concurrently, we measured the δD and $\delta^{18}O$ of water in the soil and in the plant xylem to quantitatively distinguish the plant water sources and study below-ground water transport. We hypothesized that (1) the uphill and downhill tea rows would contain much more soil water than the terrace (i.e., rubber rows) because the undergrowth cover could decrease evaporation and capture more water from rainwater, slope runoff and fog drip, allowing (2) rubber trees to take more water from uphill and downhill tea rows than from rubber rows because of their sensitivity to soil moisture and strong adaptability to water uptake. Although (3) tea trees should have different water use patterns from rubber trees because of below-ground niche separation, (4) tea trees should also have collaborative water use patterns (e.g., complementary water use patterns for promoting coexistence and water transport) to take advantage of limited water sources during the pronounced dry season.

2. Materials and methods

2.1. Study site

The study site is located in the Xishuangbanna Tropical Botanical Garden (XTBG; 21°55′39″N, 101°15′55″E) in Yunnan, southwestern China. The annual mean temperature in this area is 22 °C, with a total mean annual rainfall of 1500 mm. The climate is dominated by tropical southern monsoons from the Indian Ocean between May and October and by subtropical jet streams between November and April (Zhang, 1988). Therefore, three seasons are apparent in this area: a rainy season, a foggy-cool season and a hot-dry season. Rainfall during the rainy season (mean temperature 25 °C) accounts for approximately 84% of the total annual rainfall. The foggy-cool season is the coldest period, with dense fog in the morning and at night. The hot-dry season is a transitional period, with less rainfall and higher air temperatures. The foggy-cool and hot-dry seasons are collectively referred to as the dry season because little rainfall occurs during these periods.

Observations were conducted in a rubber-tea agroforestry system containing 25-year-old rubber trees (clone PB86) in double rows separated by 2 m; trees within the rows were separated by a distance of 4.5 m, and each double-row was separated by 18 m. The investigated agroforestry system is located in a catchment spanning an altitudinal range of approximately 560–680 m and has a slope of approximately 27°–31°, and the rubber trees were tapped every other day from the end of March to mid-November