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Coffee performs better than amomum as a candidate in the rubber agroforestry system: Insights from water relations

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ABSTRACT

Rubber (*Hevea brasiliensis*) plantations have been facing a double challenge of land degradation and seasonal drought in Southeast Asia. Various cash crops are recently interplanted with rubber trees to face these issues. However, the water relations between rubber trees and the intercrops remain poorly understood. This study aims to evaluate the influences of three cash intercrops, namely two herbaceous plants (*Amomum villosum* and *Alpinia oxyphylla*) and a woody beverage (*Coffea arabica*), on rubber water utilization through both spatial and temporal scales. We investigated the plant water-absorption dynamics, root biomass, and intrinsic water use efficiency (WUE_i) throughout a whole year (2017–2018). The results showed that rubber trees (43.5 ± 2.6%) and intercrops (69.1 ± 3.2%) highly depended on soil water from the 0–20 cm depths. An interspecific water competition occurred in all the rubber-based agroforestry practices, because of their similar water source and root distribution in the vertical soil profiles. Overall, the WUE_i of rubber trees was relatively higher during the dry season (δ^{13}C: − 30.79 ± 1.12‰) compared to the rainy season (δ^{13}C: − 31.65 ± 0.99‰). Coffee (*C. arabica*) better facilitated the soil water availability than the other intercrops, suggesting its suitability as an intercrop for rubber trees. Alpinia-oxyphylla (*A. oxyphylla*) played a moderate role on soil water retention. Amomum (*A. villosum*), however, aggravated the soil water deficit in the agroforestry practice. Given the differences in water relations to rubber trees, the introduction of woody crops rather than herbaceous crops can improve the resistance of rubber plantation to the frequent drought stress in this region.

1. Introduction

Nowadays, the South-East Asia region has become the largest latex production base in the world (Fox et al., 2014). A widespread rubber (*Hevea brasiliensis* (Willd. ex A. Juss.) Muell. Arg.) monoculture has replaced 4,700,000 ha of natural ecosystems in this region (Li and Fox, 2012; Zhang et al., 2019). What is more, it is predicted that the area of higher altitudes (> 600 m) dedicated to rubber will double or triple by 2050 (Fox et al., 2014; Zhang et al., 2015). This expansion of rubber monoculture is a main driving factor behind the severe land degradation in the uplands of China, Laos, Myanmar, Thailand, and Vietnam (Ziegler et al., 2009). Thus, the rubber-based agroforestry systems has been recently established to provide a promising solution for the sustainable development of rubber cultivation (Lin, 2010; Hammond et al., 2017; Chen et al., 2019). These tree-based systems are artificial farming practices of deliberately integrating trees with cash crops to benefit from the resulting ecological and economic interactions (van Noordwijk et al., 2015; Pavlidis and Tsihrintzis, 2017).

Xishuangbanna region is one of the major rubber planting areas in South-East Asia, which has been currently experiencing a dramatic downward trend in fog frequency and stream flow due to the land-cover transition (Liu et al., 2007; Tan et al., 2011). Different types of rubber

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agroforestry practices are implemented to balance the negative ecological consequences and the economic benefits (Iqbal et al., 2006; Snoeck et al., 2013; Smajgl et al., 2015). These rubber-crop agroforestry practices will make the maximum use of limited water resources during the drought periods (Schwendenmann et al., 2010), with the potential to minimize water competition among the co-occurring species. Nevertheless, not all of the agroforestry practices have the same impact on the water utilization of rubber trees. A strong interspecific competition for water resources can exist in the agroforestry practices (Carr and Lockwood, 2011; Gao et al., 2018; Yang et al., 2020), and this competition may affect both the growth and latex yields of rubber trees. In spite of the efforts over the last decades, the evaluation of the trade-offs between additional values and competition effects of intercrops on the main species remains very challenging to agro-ecologists (Smajgl et al., 2015; Burgess et al., 2019). To date, most of the previous studies in Xishuangbanna mainly focus on the effects of intercrops on controlling surface runoff, soil erosion, and soil nutrient loss in the rubber-based agroforestry practices (Liu et al., 2016; Zhu et al., 2018; Chen et al., 2019; Jiang et al., 2020).

Stable isotopes of hydrogen (δ^2H) and oxygen (δ^{18}O) are commonly used to investigate the water–soil–plant relations in different ecosystems (Schwendenmann et al., 2010; Wu et al., 2016; Hardanto et al., 2017; Yang et al., 2020). The underlying assumption is that xylem water of plants has no isotopic fractionation from soil water during the root water uptake process (Ehleringer and Dawson, 1992). Based on the δ^2H and δ^{18}O in water pools, Wu et al. (2016) found that rubber trees exhibit a relatively higher range of plasticity in depth of water uptake than the intercropped shrubs. Hardanto et al. (2017) showed that rubber trees in the jungle stands take up water from deeper soil strata than in the monoculture. The intercrops might also have both positive and negative impacts on the rubber trees' intrinsic water use efficiency (WUE_i), depending on the intensity of water competition (Wu et al., 2016, 2019). It should be noticed that species mixtures with contrasting root patterns will explore larger soil volumes to improve the efficiency of water utilization (van Noordwijk et al., 2015). Therefore, studies on the characteristics of root depth will give a better understanding of the water utilization in rubber agroforestry practices.

On the perspective of sustainable agriculture, this study aims to characterize the water use strategies of rubber trees and three prevailing intercrops in Xishuangbanna, namely, amomum (*Amomum villosum* Lour.), alpinia-oxyphylla (*Alpinia oxyphylla* Miq.), and coffee (*Coffea arabica* L.). Amomum (*A. villosum*) is a perennial herbaceous plant species of Zingiberaceae family, and its seeds (Chinese medicine name: Sharen) have medicinal values of anti-inflammation and gastrointestinal protection (Wang et al., 2018). Alpinia-oxyphylla (*A. oxyphylla*) is also a perennial herb known for its medicinal properties for hundreds of years in southern China. Its fruits (Chinese medicine name: Yizhi) have anti-inflammatory effects on osteoarthritis (Lee et al., 2019). The fruits of coffee (*C. arabica*) can be used to produce a very popular beverage, which have the potential to reduce the risk of neurodegenerative diseases (Bitter et al., 2020). The commonality of these intercrops is that they all exhibit good economic benefits and broad market prospects. Even so, the successful application of these intercropping practices still relies on the knowledge of water relations between plants, which remain poorly understood. The main objective of this study is to characterize the water relations between rubber trees and the intercrops through both spatial (vertical pattern) and temporal (seasonal pattern) scales. We hypothesized that (1) rubber trees would have more flexible water sources than the cash crops, and (2) the WUE_i of rubber trees would be distinctly affected by the herbaceous and woody intercrops. The findings of this study will provide a scientific database for the reasonable selection of intercrops in the rubber-based agroforestry practices.

2. Materials and methods

2.1. General methodology

In Xishuangbanna, a 6.9 ha zone was established for long-term demonstration and observation around 2010 (Section 2.2). In total, four rubber-based agroforestry practices were selected for this study, counting in a rubber monoculture (Section 2.3). We investigated the root distribution in the early dry season of 2017 (Section 2.4). Isotope samplings for the partitioning of plant water sources and the prediction of intrinsic water use efficiency (WUE_i) were performed during a period of 12 months (Sections 2.5 and 2.6).

2.2. Study site

The study site is located in Xishuangbanna Tropical Botanical Garden (XTBG; 21° 55′ 39″N, 101° 15′ 55″E, and elevation 750 m), Yunnan Province, southwestern China. The soil thickness is approximately 2.0 m, with a clay soil texture (22.5 ± 0.4% sand, 29.8 ± 0.6% silt, and 47.8 ± 0.6% clay). The soil bulk density of 0–160 cm depths is 1.2–1.3 g cm^{-3}. The soil organic matter, total nitrogen, and hydraulic conductivity (0–20 cm) are 24.9–38.1 g kg^{-1}, 1.6–2.3 g kg^{-1}, and 3.2 × 10^{-4} cm s^{-1}, respectively. The drought period in this region is prolonged from November to March/April, which is co-effected by the tropical monsoon from Indian Ocean and the subtropical jet streams from northern continent (Liu et al., 2007, 2016). The mean annual air temperature and precipitation are 21.7 °C and 1487.0 mm, respectively.

Supporting meteorological measurements were conducted by the Tropical Rainforest Ecosystem Station of Chinese Ecosystem Research Network (CERN). Net radiation (CNR-1, Kipp and Zonen Inc., Delft, Netherlands), air temperature (HMP45, Vaisala Inc., Helsinki, Finland), and rainfall amount (52203, RM Young Inc., Michigan, USA) were monitored by sensors on a 55 m tall tower. The surface soil water content (CS615-L, Campbell Scientific Inc., Utah, USA) and surface soil heat flux (HFT-3, Campbell Scientific Inc., Utah, USA) were measured at a depth of 5 cm. All the meteorological data were collected using a data logger (CR1000, Campbell Scientific Inc., Utah, USA).

2.3. Settlement description

The rubber trees (clone PB86) are planted on a 6.9 ha level catchment. There were both small (~ 3.0 m) and big (~ 18.0 m) gaps between the rubber trees (~ 370 plants ha^{-1}). The rubber trees received uniform managements including fertilization, latex extraction, and control of understory growth. The mean diameter at breast height (DBH), leaf area index (LAI), and canopy spread area of the rubber trees were 37.8 ± 5.3 cm, 2.4 m^2 m^{-2}, and 11 m^2, respectively. By 2010, amomum (*A. villosum*), alpinia-oxyphylla (*A. oxyphylla*), and coffee (*C. arabica*), are planted in the small gaps of the rubber monoculture (Rm) (Fig. S1). Amomum (1.5 ± 0.1 m height) and alpinia-oxyphylla (1.9 ± 0.1 m height) are planted with multiple rows in the rubber-amomum (RAv) and the rubber-alpinia oxyphylla (RAo) practices. Coffee (6.6 ± 0.9 m height) is grown in single row in the rubber-coffee (RCa) practice. The aerial distances between these rubber-based agroforestry practices are about 150–300 m. The four rubber practices (i.e. Rm, RAv, RAo, and RCa) were treated as randomized treatments in this study, which had gentle slopes after 10 years of similar field managements.

2.4. Fine root measurements

The fine roots of rubber trees and intercrops were excavated when there was less rainfall at the end of October 2017. Six soil profiles (n = 6) were dug in each of the four treatments: three near the rubber rows, and the other three close to the mid-rows of rubber trees. The roots were collected using the traditional diameter class approach (McCormack et al., 2014; Kou et al., 2018). In brief, the soil cuboids of 0–160 cm depths (15 cm length × 15 cm width) were dug first at 10 cm increments (0–10, 10–20, and 20–30 cm), then at 20 cm increments (30–50, 50–70, 70–90, 90–110, and 110–130 cm), and at 30 cm increments (130–160 cm). All the elastic and flexible roots were manually picked out from soil cuboids, flushed with water in 20-mesh sieves, and separated according to the following root classes: rubber (dark-brown exterior, coarsely structured with latex), amomum/alpinia-oxyphylla (while exterior, with fibrous roots), and coffee (faint-yellow exterior, finer structured with small root diameters). For this step, the roots of rubber trees were found in all the soil cuboids (9 depths × 6 replicates × 4 treatments). However, the roots of intercrops were not accessible in some of the soil cuboids. The total root samples were 54 in Rm, 72 in RAv (54 rubber + 18 amomum), 81 in RAo (54 rubber + 27 alpinia oxyphylla), and 98 in RCa (54 rubber + 44 coffee). Finally, the fine roots were scanned using the WinRHIZO software (Regent Instruments Inc., Quebec, Canada) to obtain root length (RL, cm), root diameter (RD, cm), root length density (RLD, cm cm^{-3}), and root surface area density (RSD, cm^2 cm^{-3}).

2.5. Isotopic sampling and measurements

Three suberized twigs of rubber and coffee (n = 3) were sampled every 30–45 days between August 2017 and July 2018. At the same time, three (n = 3) root crowns (i.e. the connection between the above- and belowground tissues) were collected for the herbaceous species of amomum and alpinia-oxyphylla (Barnard et al., 2006). The phloem tissues were removed to avoid the isotopic contamination (Ehleringer and Dawson, 1992). Soil samples were collected using a bucket auger (4 cm in diameter) at three random locations (n = 3) from seven soil depths (0–5, 5–10, 10–20, 20–40, 40–60, 60–110, and 110–160 cm). With the same bucket auger, soil water content (SWC) of 0–160 cm depths was determined from the weight loss of samples at 105 °C for 48 h. Groundwater was sampled monthly from a deep well (− 40 m) about 1.5 km away from the experimental fields. During the study periods, 102 rain samples were collected using a polyethylene bottle attached to a steel funnel (Yang et al., 2018). All the water samples were cryogenically extracted using a vacuum distillation system (LI-2100, Lica United Technology Limited Inc., Beijing, China).

The fully sun-exposed leaves of rubber trees and the intercrops (50–80) were collected on the dates of xylem and soil sample collection. The bulk leaves were divided into three equal parts (n = 3), oven dried at 65 °C for 48 h, and finely smashed using a pulverizer (Wu et al., 2019). Powders of the bulk leaves were filtered by 100-mesh sieves, sealed in Zip-lock bags, and stored in a glass dryer until the $\delta^{13}C$ measurements. Several studies have revealed that the $\delta^{13}C$ of plant bulk leaves depends on the ratio between the partial pressures of CO_2 in chloroplasts and in ambient air, which can be construed as a relative index of leaf-level intrinsic water use efficiency (WUE_i) (Farquhar et al., 1989; Cernusak et al., 2008; Kanpanon et al., 2015). There is also a strong positive relationship between the bulk leaf $\delta^{13}C$ and WUE_i among C_3 photosynthesis plants (Ehleringer and Dawson, 1992; Moreno-Gutiérrez et al., 2012). Therefore, maintaining high bulk leaf $\delta^{13}C$ for plants conducts to high levels of WUE_i.

The δ^2H and $\delta^{18}O$ in water samples were analyzed using the DELTA-V-Advantage isotope ratio mass spectrometer combined with a high-temperature conversion elemental analyzer (Thermo Fisher Scientific, Bremen, Germany). To avoid any "memory effect", the 1st injection (n = 4) of the auto-sampler (AS1310, Thermo Fisher Scientific, Bremen, Germany) was discarded for each measurement. The $\delta^{13}C$ of bulk leaves were measured using a flash combustion elemental analyzer (Flash EA) coupled with the DELTA-V-Advantage isotope ratio mass spectrometer (Thermo Fisher Scientific, Bremen, Germany). The precision of δ^2H, $\delta^{18}O$, and $\delta^{13}C$ measurements were ± 0.4‰, ± 0.14‰, and ± 0.03‰, respectively.

2.6. Models and statistical analyses

The Budyko's aridity index (AI) was used to detect drought stress in the study area. AI < 1 indicates the meteorological water-limited conditions. It was calculated by the ratio of rainfall to potential evapotranspiration (P_{ET}). P_{ET} was calculated by 1.26 times of equilibrium evapotranspiration (ET_{eq}) as described by Tang et al. (2014):

$$ET_{eq} = ((R_n - G) \times s)/(s + \gamma) \tag{1}$$

where R_n is the net radiation (W m^{-2}), G is the soil heat flux (W m^{-2}), s is the slope of the function relating saturation vapor pressure and temperature, γ is the psychrometric constant (kPa K^{-1}).

The contributions of different water sources to plants were analyzed using the MixSIAR model (Stock and Semmens, 2013). This model was based on the isotopic mass balance principles:

$$\delta^2H_x = \delta^2H_{s1} \times f_1 + \delta^2H_{s2} \times f_2 + \ldots + \delta^2H_{si} \times f_i \tag{2}$$

$$\delta^{18}O_x = \delta^{18}O_{s1} \times f_1 + \delta^{18}O_{s2} \times f_2 + \ldots + \delta^{18}O_{si} \times f_i \tag{3}$$

$$f_1 + f_2 + \ldots + f_i = 1 \tag{4}$$

where δ^2H_x ($\delta^{18}O_x$) are the isotopic values of xylem water (‰), δ^2H_{s1} ($\delta^{18}O_{s1}$), δ^2H_{s2} ($\delta^{18}O_{s2}$), and δ^2H_{si} ($\delta^{18}O_{si}$) are the isotopic values of soil water (‰), f_1, f_2, and f_i are contribution proportions of the potential source water (%).

In this study, the potential water sources of different species were first defined as the water from the seven soil layers (0–5, 5–10, 10–20, 20–40, 40–60, 60–110, and 110–160 cm). Afterwards, the water uptake depths of rubber trees were assumed to be down to 0–160 cm based on the root investigation (see Section 3.3). Accordingly, the water uptake depths were restricted to 0–50 cm for amomum, 0–70 cm for alpinia-oxyphylla, and 0–160 cm for coffee. Because we did not sample the soil water of 40–50 cm and 60–70 cm, the isotopic values of these missing layers were obtained by linear fitness of the adjacent layers. Ground water was excluded from the potential water sources because of the deep-water depth (> 10 m). The parameters of MixSIAR model were specified with fixed effect (treatment), SIAR (process + residual), MCMC (normal), and no discrimination (0). A simple sensitivity analysis was performed to investigate the influences of soil depth assumption (i. e. the soil sampling depth vs. the root depth of different plants) on water source prediction. For comparison, outputs of the model ($f_{0\text{–}5\ cm}$, $f_{5\text{–}10\ cm}$, ... and $f_{110\text{–}160\ cm}$) were subjectively combined into shallow (0–20 cm), middle (20–60 cm), and deep (60–160 cm) layers.

The relative difference in soil water content (RDSW) was calculated for the three rubber-based agroforestry practices. It was achieved by assuming that the intercrops caused greater SWC fluctuations in the agroforestry practices (i.e. RAv, RAo, and RCa) compared to the monoculture (Rm). This hypothesis was reasonable because these treatments had similar geological properties and management practices. The positive (or negative) values of RDSW refer to facilitate (or competitive) roles of different intercrops on rubber trees. In this study, RDSW of the 0–20 cm, 20–60 cm, and 60–160 cm were acquired using a modified formula of Gao et al. (2018):

$$\mathrm{RDSW}_{agroforestry} = \left(\sum_{i=1}^{n} \frac{\theta_{a,i} - \theta_{ck,i}}{\theta_{ck,i}} \times LT_i\right) \Big/ \left(\sum_{i=1}^{n} LT_i\right) \tag{5}$$

where θ_a and θ_{ck} are SWC in the agroforestry system and the monoculture (%), LT is the thickness of the soil layer (cm), i is the number of sampling layer (0–5, 5–10, 10–20, 20–40, 40–60, 60–110, and 110–160 cm).

All statistical analyses were performed utilizing the SPSS 17.0 (probability level: $P \leq 0.05$). One-way analysis of variance (ANOVA), including Duncan (D), was used to analyze the differences in AI, RLD, isotopes, RDSW, and source water contributions. Repeated measures two-way ANOVA was used to evaluate the effects of soil depth and season on SWC. Geometric mean regression (GMR) was used for the fitting of regression equation, because both of the two variables were random and subjected to measurement errors.

3. Results

3.1. Drought stress and soil wetness at the experimental site

The multi-year (2008–2017) means of Budyko's aridity index (AI) demonstrated that the plants in this region were subjected to a prolonged period of atmospheric drought stress (0.48 ± 0.12) from November to April (Fig. 1). The severe drought always occurred in February ($AI = 0.22 \pm 0.23$), whereas the wettest month was July ($AI = 2.88 \pm 0.99$) during 2008–2017. The rainfall amount and mean air temperature during the study period of 2017–2018 were 1620 mm and 22.2 ± 3.1 °C, respectively. In drought months, the AI values of 2017–2018 (0.52 ± 0.29) were similar to the long-term means ($P > 0.05$), indicating a typical drought year.

The soil water content (SWC) was higher in the 0–20 cm depths compared to the 20–60 cm and 60–160 cm depths during the rainy months (Table 1). Meanwhile, SWC of the 0–20 cm depths was similar to the deep soil layers between November 2017 and March 2018. The transition periods occurred in October 2017 and April 2018, and the highest SWC fluctuated between the 0–20 cm depths and the deep soil layers during this period. Concerning the seasons, SWC of 0–20 cm and 20–60 cm depths decreased noticeably for all treatments during the dry season($P < 0.05$). This trend of shallow SWC was in line with the annual AI. No significant differences of SWC in the 60–160 cm depths happened between the rainy season and dry season. The mean SWC was higher in RAo ($21.81 \pm 1.70\%$) and RCa ($22.19 \pm 2.48\%$) than Rm ($20.50 \pm 2.49\%$), while it was lower in RAv ($20.38 \pm 1.97\%$) than Rm ($P < 0.05$).

3.2. Isotopic characteristics of different water pools

The isotopic composition of soil water changed with both season and depth, especially in the 0–20 cm and 20–60 cm soil layers (Figs. 2 and S2). The δ^2H and $\delta^{18}O$ of these two soil layers progressively became positive from the rainy season to dry season. With similar patterns, the isotopic values of precipitation were more positive ($\delta^2H = -33.4 \pm 17.6‰$, $\delta^{18}O = -5.18 \pm 2.13‰$) during the dry season, and gradually turned negative ($\delta^2H = -55.1 \pm 23.8‰$, $\delta^{18}O = -7.60 \pm 3.36‰$) toward the rainy season ($P < 0.001$). The isotopic values of the 60–160 cm soil water were close to those of groundwater ($\delta^2H = -60.8 \pm 1.3‰$, $\delta^{18}O = -9.27 \pm 0.43‰$), which experienced little changes during the whole study period of 2017–2018. Compared to Rm, the three agroforestry practices of RAv, RAo, and RCa, significantly depleted the isotopic compositions of soil water in the 0–20 cm and 20–60 cm depths ($P < 0.05$). Furthermore, the isotopic values of soil water were more depleted in RCa than the other treatments. In the 60–160 cm soil layers, however, no significant differences in soil water δ^2H and $\delta^{18}O$ occurred among treatments.

For all the plants, the isotopic values of xylem water varied within the ranges of soil water δ^2H and $\delta^{18}O$ (Figs. 3 and S3). Rubber trees generally had more positive xylem water δ^2H and $\delta^{18}O$ during the dry season (Table 2). In addition, xylem δ^2H and $\delta^{18}O$ of the rubber trees differed significantly among treatments ($P < 0.05$). Among these treatments, the isotopic differences of rubber xylem δ^2H and $\delta^{18}O$ were lower during the rainy season. This isotopic pattern (i.e. more positive xylem δ^2H and $\delta^{18}O$ in the dry season) was also applicable to the intercrops of amomum, alpinia-oxyphylla, and coffee. Positive linear relationships existed between the xylem isotopic compositions of rubber trees and those of amomum in RAv ($y = 0.6x - 1.3$, $R^2 = 0.07$, $P = 0.503$), alpinia-oxyphylla in RAo ($y = 1.3x + 2.5$, $R^2 = 0.59$, $P < 0.05$), and coffee in RCa ($y = 1.1x + 1.6$, $R^2 = 0.51$, $P < 0.05$), indicating similar water sources between rubber trees and the intercrops.

3.3. Water uptake depth for plants in the agroforestry practices

The depths of plant water uptake could be determined using the isotopic intersections between xylem water and soil water profiles (Figs. 3 and S3). In this way, the rubber trees mainly derived water from the 0–40 cm soil layers during the dry season, and from the 0–20 cm soil layers during the rainy season. The switch of water source to deep soil layers was most pronounced for the rubber trees in Rm. Amomum mainly took up soil water from the 0–20 cm depths during the whole study period of 2017–2018. Another herbaceous species of alpinia-oxyphylla could derive soil water to a depth about 40 cm. As a deep-rooted plant, coffee trees had the ability to absorb water from soil layers of more than 40 cm. In fact, rubber trees and the intercrops might acquire water from shallow and/or deep soil strata (e.g. May 2018 in all the treatments) when the isotopic intersections were more than one between the xylem water and soil water profiles.

The MixSIAR model predicted that the mean contribution of the 0–20 cm soil water to rubber trees was 40.5% (14.6–68.6%) in Rm, 45.3% (15.8–81.8%) in RAv, 41.3% (16.5–58.7%) in RAo, and 46.7% (13.7–71.3%) in RCa. Meanwhile, the percentage of water uptake from the 0–20 cm depths was 73.7% (34.3–93.1%) for amomum, 69.3% (51.1–95.3%) for alpinia-oxyphylla, and 64.3% (36.9–97.6%) for coffee

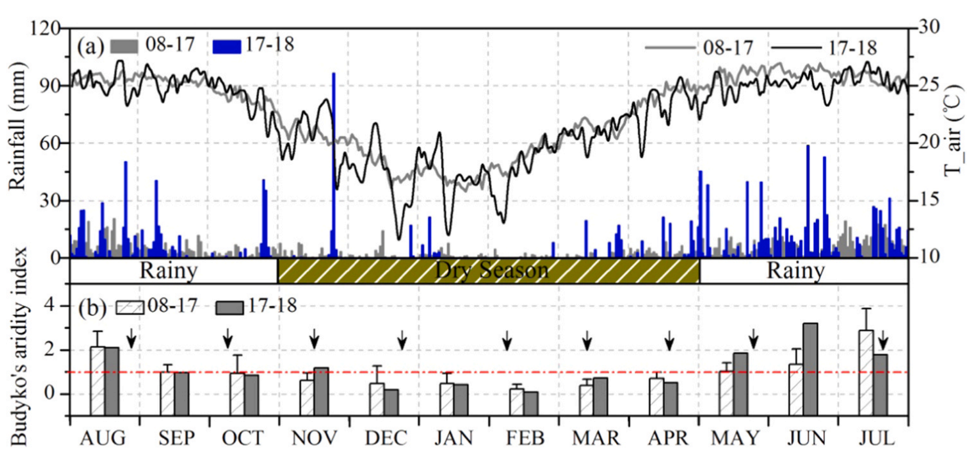

Fig. 1. Seasonal variations of rainfall amount, air temperature (a), and Budyko's aridity index (b) between August 2017 and July 2018. Each vertical error bar represents one standard deviation (± 1 SD) for average of that month (n = 10) during 2008–2017. Arrows indicate the dates of sampling. Colored area indicates the drought periods (November–April) in this region.

Table 1
Mean soil water content (SWC, %) values (± 1 SD) in rubber-based agroforestry (Rm, RAv, RAo, and RCa) practices.

	Depth (cm)	Rainy season (May–October)				Dry season (November–April)					
		Aug 2017 (%)	Oct 2017 (%)	May 2018 (%)	Jul 2018 (%)	Nov 2017 (%)	Dec 2017 (%)	Feb 2018 (%)	Mar 2018	Apr 2018 (%)	Month
Rm	0–20	23.83 (1.76)^{Aa}	21.40 (2.63)^{b}	24.71 (4.06)^{Aa}	21.24 (1.14)^{Ab}	18.03 (0.82)^{Bc}	19.54 (0.59)^{Bbc}	18.53(0.80)^{c}	19.78 (0.52)^{bc}	24.93 (1.00)^{Aa}	< 0.001
	20–60	21.53 (2.34)^{ABbc}	19.96 (0.76)^{cd}	25.65 (2.51)^{Aa}	19.63 (0.25)^{Bcd}	19.37 (0.20)^{Ad}	20.18 (0.12)^{Acd}	19.35(1.38)^{d}	19.43 (0.17)^{d}	22.11 (1.07)^{Bb}	< 0.001
	60–160	20.60 (2.20)^{Bab}	20.50 (0.21)^{abc}	19.22 (1.78)^{Bbc}	19.49 (0.07)^{Bbc}	18.91 (0.21)^{ABc}	19.89 (0.02)^{ABbc}	18.61(0.50)^{d}	20.53 (0.03)^{abc}	21.59 (1.13)^{Ba}	< 0.05
	Depth × Season	< 0.05 0.014	0.44	< 0.05	< 0.05	< 0.05	< 0.05	0.33	0.23	0.001	
RAv	0–20	22.12 (0.84)^{Aa}	24.70 (1.76)^{Aa}	27.02 (3.86)^{Ab}	24.14 (2.79)^{Ab}	17.49 (0.09)^{a}	17.31 (0.28)^{Bb}	18.19 (1.13)^{Bb}	18.29 (1.75)^{Bb}	22.28 (0.37)^{Ab}	< 0.001
	20–60	20.42 (0.13)^{Bab}	21.72 (1.47)^{Ba}	22.16 (1.12)^{Ba}	22.04 (1.31)^{ABa}	17.33 (0.09)^{cd}	16.85 (0.11)^{Bd}	18.86 (0.18)^{ABbc}	21.75 (0.88)^{Aa}	18.88 (1.54)^{Bbc}	< 0.001
	60–160	21.02 (0.78)^{ABbc}	23.98 (0.84)^{Aa}	20.65 (0.09)^{Bbc}	21.23 (0.23)^{Bb}	18.14 (0.08)^{d}	18.00 (0.08)^{Ad}	19.76 (0.58)^{Ac}	17.29 (0.27)^{Bd}	18.75 (0.12)^{B}	< 0.001
	Depth × Season	< 0.05 0.001	< 0.05	< 0.001	< 0.05	0.57	< 0.05	< 0.05	< 0.05	< 0.001	
RAo	0–20	28.08 (3.94)^{Aa}	25.25 (1.55)^{Aa}	27.28 (4.36)^{Ac}	25.72 (2.68)^{Ac}	19.32 (0.40)^{Bb}	19.18 (0.47)^{Bc}	18.79 (1.38)^{Bc}	21.07 (0.23)^{Ac}	25.22 (1.09)^{Ac}	< 0.001
	20–60	23.82 (0.33)^{Ba}	22.10 (0.57)^{Bbc}	21.01 (0.76)^{Bc}	23.31 (0.51)^{ABa}	19.61 (0.45)^{ABd}	19.24 (0.59)^{Bd}	22.38 (0.39)^{Abc}	19.38 (0.47)^{Bd}	21.33 (0.61)^{Bc}	< 0.001
	60–160	22.35 (0.24)^{Ba}	20.99 (0.22)^{Babc}	20.88 (0.87)^{Babc}	20.83 (0.40)^{Babc}	20.30 (0.21)^{Ac}	20.63 (0.38)^{Abc}	18.18 (0.17)^{Bd}	20.73 (0.34)^{Abc}	21.89 (0.34)^{Bab}	< 0.001
	Depth × Season	< 0.05 < 0.001	< 0.001	< 0.05	< 0.05	< 0.05	0.001	< 0.05	< 0.001	0.01	
RCa	0–20	24.98 (1.15)^{Aa}	22.80 (0.96)^{Ab}	32.61 (0.66)^{Acd}	25.11 (0.98)^{Ac}	19.20 (0.52)^{b}	19.30(1.05)^{d}	18.55 (0.31)^{Bcd}	20.78 (0.33)^{Bd}	27.27 (1.51)^{Ad}	< 0.001
	20–60	24.20 (0.39)^{Ab}	21.24 (0.38)^{Bbc}	33.83 (0.84)^{Aab}	22.13 (0.77)^{B}	18.67 (0.43)^{d}	19.83 (0.43)^{cd}	20.63 (0.84)^{Ac}	20.53 (0.44)^{Bc}	24.00 (1.24)^{Bb}	< 0.001
	60–160	21.73 (0.40)^{Bb}	19.56 (0.26)^{Cc}	20.91 (0.10)^{Bb}	19.67 (0.11)^{Cc}	19.20 (0.69)^{cd}	19.07 (0.16)^{cd}	18.47 (0.27)^{Bd}	21.42 (0.31)^{Ab}	23.31 (0.99)^{Ba}	< 0.001
	Depth × Season	< 0.001 < 0.001	< 0.001	< 0.001	< 0.001	0.40	0.33	< 0.05	< 0.05	< 0.001	

Rm: rubber monoculture, RAv: rubber-amomum practice, RAo: rubber-alpinia oxyphilla practice, RCa: rubber-coffee practice; within a month, SWC of different depths not sharing the same capital letter are significantly different ($P \leq 0.05$); within a soil depth, SWC of different months not sharing the same lowercase letter are significantly different ($P \leq 0.05$); the interactive effects between soil depth and season are tested by a repeated-measures ANOVA ($P \leq 0.05$).

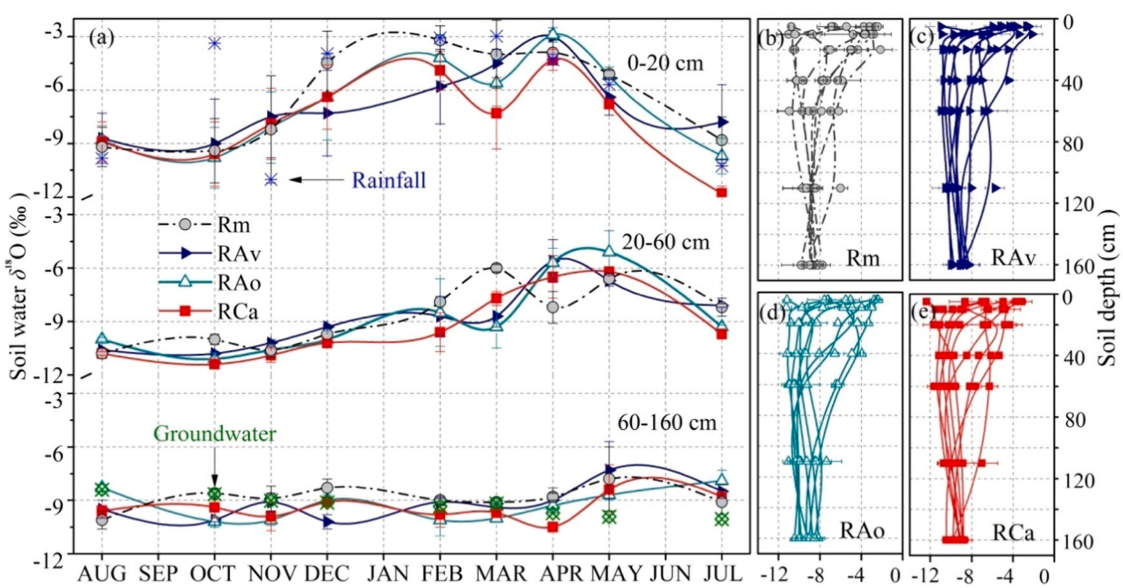

Fig. 2. Seasonal patterns (a) and vertical profiles (b–e) of soil water $\delta^{18}O$ in rubber monoculture (Rm), and rubber-amomum (RAv), rubber-alpinia oxyphylla (RAo) practice, rubber-coffee (RCa) practices. The seasonal trends of $\delta^{18}O$ in rainfall and groundwater are also shown. Each vertical error bar represents the standard deviation (± 1 SD) for average of rainwater (n = 1–14), soil water in 0–20 cm (n = 9), 20–60 cm (n = 6), 60–160 cm (n = 6), and groundwater (n = 3). Each horizontal error bar represents the standard deviation (± 1 SD) for average of an individual soil stratum (n = 3).

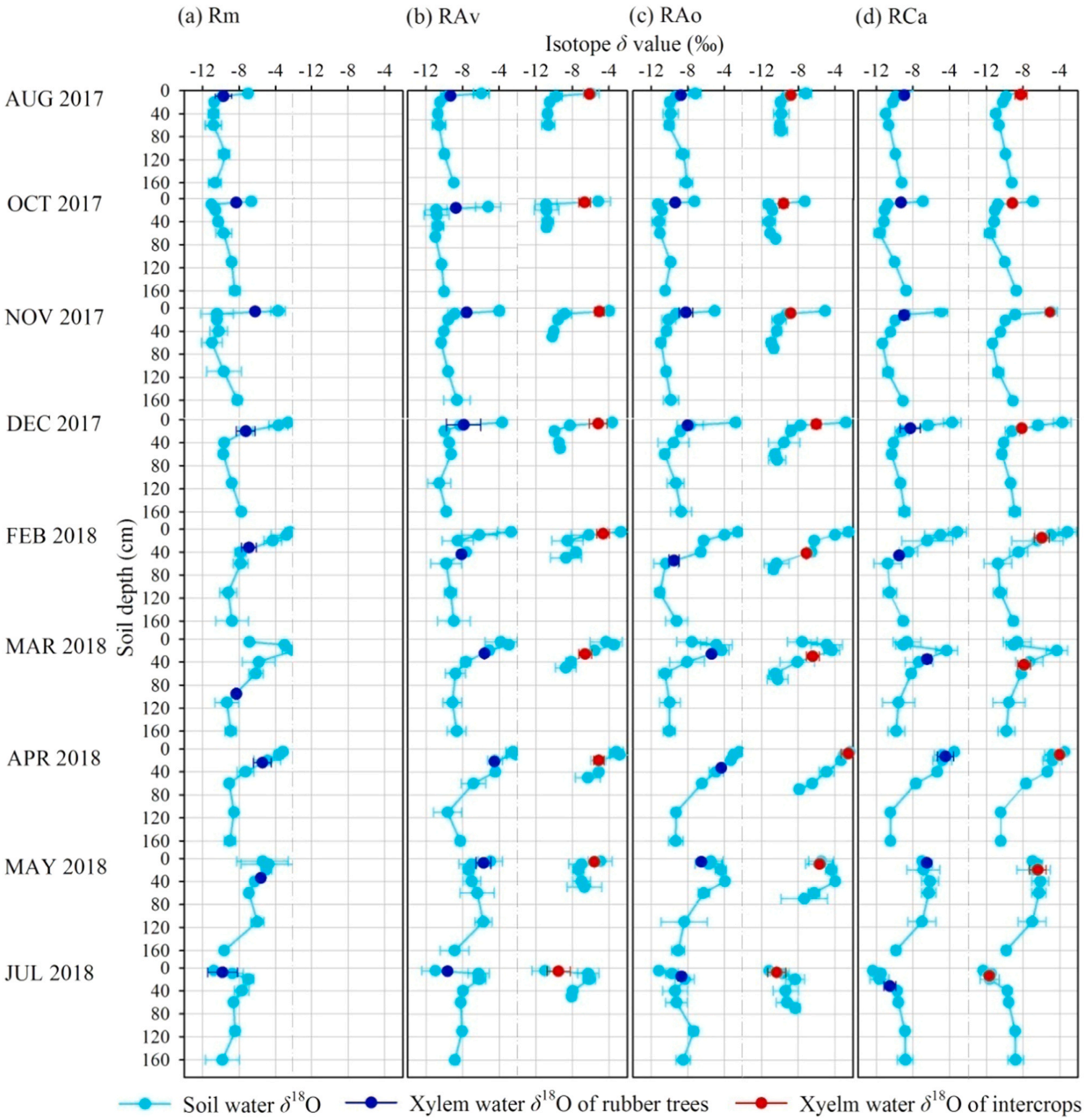

Fig. 3. Vertical patterns of xylem water $\delta^{18}O$ and soil water $\delta^{18}O$ in rubber monoculture (Rm) (a), and rubber-amomum (RAv) (b), rubber-alpinia oxyphylla (RAo) (c), rubber-coffee (RCa) (d) practices. Each horizontal error bar represents the standard deviation (± 1 SD) for average of xylem water (n = 3) and soil water (n = 3).

trees. These partitioning results were acquired according to the actual root length of crops in the rubber practices. The contribution of the 0–20 cm soil water would be undervalued by 7.9% (4.0–23.2%) for amomum, and 12.4% (1.5–31.0%) for alpinia-oxyphylla if the root depths of these intercrops were roughly assumed as 160 cm ($P < 0.05$). Note that rubber trees still heavily depended on the 0–20 cm soil water under seasonal drought stress. The mean contribution of the 0–20 cm soil water to rubber trees also slightly increased (1.2–2.1%) during the rainy season, except for RAo (− 5.9%). Meanwhile, all the intercrops heavily depended on the 0–20 cm soil water during both the dry and rainy seasons.

3.4. Fine root distribution and its relationship with plant water uptake

The vertical root length density (RLD) showed that rubber trees and all the intercrops were mainly shallow-rooted (Fig. 4). The mean RLD of rubber trees (0.22 ± 0.20 cm cm^{-3}) did not significantly differ between treatments ($P \geq 0.51$), with 60.5–74.5% of their fine roots distributed in the 0–20 cm soil layers. However, the fine roots of amomum (0.11 ± 0.08 cm cm^{-3}) and alpinia-oxyphylla (0.35 ± 0.30 cm cm^{-3}) were restricted to 0–50 cm and 0–70 cm depths, respectively. The fine roots of coffee (0.46 ± 0.62 cm cm^{-3}) penetrated the soil till a depth of 160 cm. Moreover, the fine roots of coffee were more plentiful (3. 68 cm cm^{-3}) than rubber trees (1. 31 cm cm^{-3}) in the 0–20 cm soil layers.

A positive linear relationship (y = 7.7x − 128.9, R^2 = 0.26,

Table 2
Mean δ^2H, δ^{18}O, and δ^{13}C (‰) values (± 1 SD) of soil water, xylem water, and bulk leaves in rubber-based agroforestry (Rm, RAv, RAo, and RCa) practices.

	Isotopic pools		Dry season (November–April)				Rainy season (May–October)				
			Rm (‰)	RAv (‰)	RAo (‰)	RCa (‰)	Rm (‰)	RAv (‰)	RAo (‰)	RCa (‰)	P
δ^2H	Soil (cm)	0–20	−34.1 (18.7)^{Aa}	−40.4 (19.2)^{Aab}	−42.0 (18.1)^{Aab}	−46.5 (17.9)^{Ab}	−62.3 (16.6)^{c}	−64.2(12.7)^{c}	−67.6(14.7)^{c}	−74.2 (15.3)^{c}	< 0.001
		20–60	−61.8 (11.8)^{B}	−61.8 (12.7)^{BC}	−72.8(8.2)^{BC}	−65.2 (14.2)^{BC}	−60.51 (18.2)	−66.3(14.5)	−70.8(11.7)	−69.7(13.8)	0.29
		60–160	−61.5 (6.9)^{Bab}	−69.3 (5.6)^{Ccd}	−73.7(5.7)^{Cd}	−73.0(5.3)^{Cd}	−56.9 (10.2)^{a}	−62.4(9.6)^{ab}	−63.0(8.4)^{b}	−65.1(7.8)^{bc}	< 0.001
	Xylem	Rubber	−52.5 (8.0)^{Ba}	−55.9 (10.5)^{Ba}	−57.8(8.1)^{Ba}	−57.8 (11.5)^{Ba}	−65.7(5.6)^{b}	−71.7(3.2)^{b}	−69.0(4.5)^{b}	−71.8(6.7)^{b}	< 0.001
		Intercrop	—	−39.6 (9.7)^{Aa}	−47.0 (12.8)^{Aab}	−45.1 (14.5)^{Aab}	—	−55.7 (11.1)^{b}	−69.3(10.8)^{c}	−71.3 (12.3)^{c}	< 0.001
		P	< 0.001	< 0.001	< 0.001	< 0.001	0.53	0.07	0.42	0.57	
δ^{18}O	Soil (cm)	0–20	−4.55 (2.51)^{Aa}	−5.77 (2.66)^{Aab}	−5.58 (2.39)^{Aab}	−6.45 (2.46)^{Ab}	−8.00 (2.74)^{c}	−8.02(2.07)^{c}	−8.86(2.00)^{cd}	−9.64 (2.02)^{d}	< 0.001
		20–60	−8.16 (1.83)^{B}	−8.93 (1.67)^{B}	−8.80(2.05)^{C}	−8.96 (1.76)^{B}	−8.27 (3.03)	−8.96(1.85)	−9.47(1.82)	−9.83(1.43)	0.24
		60–160	−8.23 (0.80)^{Ba}	−9.74 (1.10)^{Bc}	−10.02 (0.92)^{Cc}	−9.79 (0.98)^{Bc}	−7.86 (1.95)^{a}	−8.51 (1.35)^{ab}	−8.48(1.49)^{ab}	−9.28 (0.98)^{bc}	< 0.001
	Xylem	Rubber	−6.85 (0.79)^{Bab}	−6.34 (1.81)^{Aa}	−7.10 (1.76)^{Bab}	−7.52 (1.79)^{Aabc}	−8.35 (1.31)^{bc}	−8.35 (1.31)^{bc}	−8.33(0.94)^{bc}	−8.80 (1.16)^{c}	< 0.05
		Intercrop	—	−5.49 (0.70)^{Aa}	−6.17 (1.68)^{ABab}	−6.51 (1.39)^{Aab}	—	−6.98 (1.27)^{b}	−9.10(0.88)^{c}	−8.87 (1.56)^{c}	< 0.001
		P	< 0.001	< 0.001	< 0.001	< 0.001	0.96	0.09	0.47	0.42	
δ^{13}C	Leaf	Rubber	−30.67 (0.68)^{ab}	−30.91 (1.43)^{abc}	−31.43 (0.84)^{b}	−30.18 (1.21)^{Aa}	−30.83 (0.50)^{ab}	−32.27 (0.61)^{Bc}	−32.14(0.84)^{Bc}	−31.36 (0.99)^{Abc}	< 0.001
		Intercrop	—	−30.81 (0.33)^{a}	−31.06 (0.58)^{ab}	−34.44 (0.52)^{Bc}	—	−31.21 (0.32)^{Aab}	−31.35(0.58)^{Ab}	−34.72 (0.39)^{Bc}	< 0.001
		P		0.83	0.226	< 0.001		< 0.05	0.05	< 0.001	

Rm: rubber monoculture, RAv: rubber-amomum practice, RAo: rubber-alpinia oxyphylla practice, RCa: rubber-coffee practice; within a rubber practice, δ values of different isotopic pools not sharing the same capital letter are significantly different ($P \leq 0.05$); within an isotopic pool, δ values of different rubber practices not sharing the same lowercase letter are significantly different ($P \leq 0.05$).

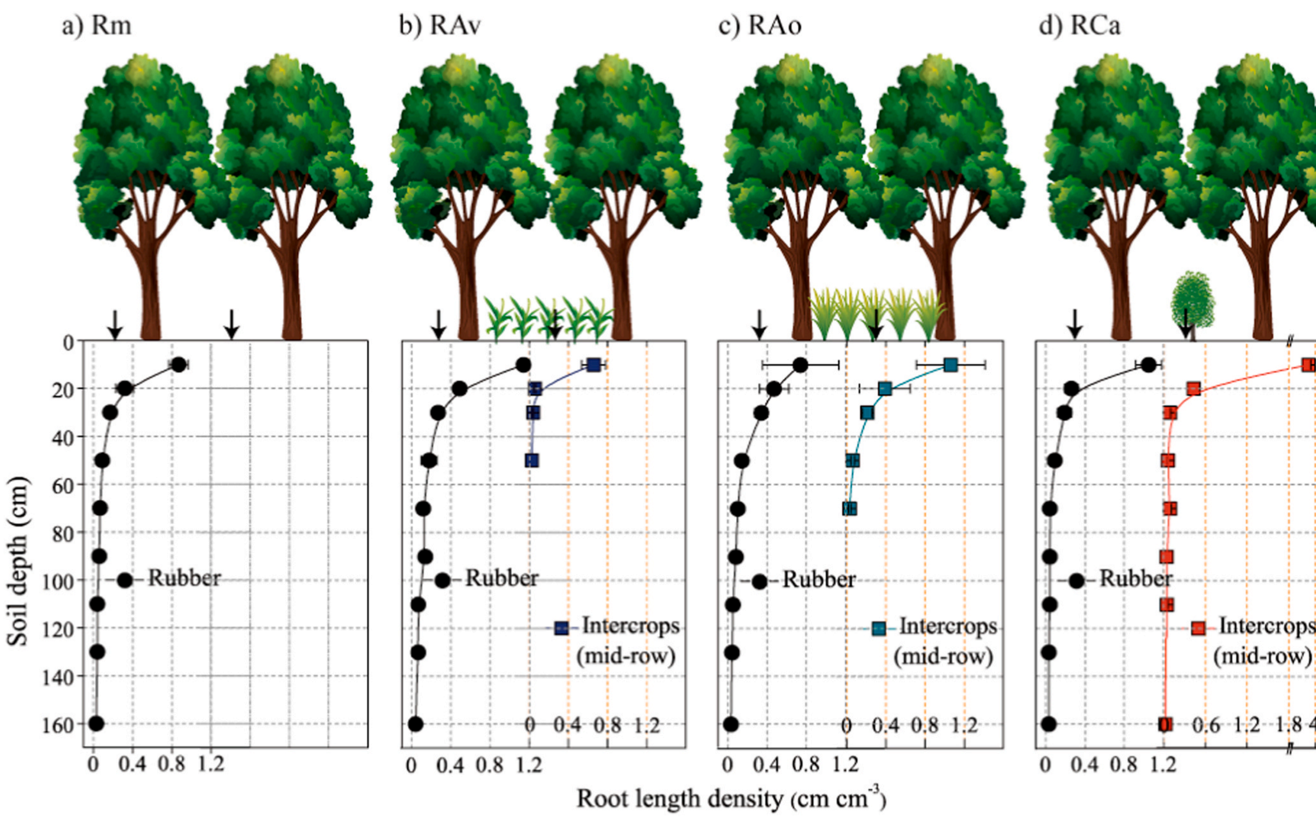

Fig. 4. Vertical profiles of fine root length density (RLD) in rubber monoculture (Rm) (a), and rubber-amomum (RAv) (b), rubber-alpinia oxyphylla (RAo) (c), rubber-coffee (RCa) (d) practices. Each horizontal error bar represents the standard deviation (± 1 SD) for average of an individual soil stratum (n = 6). Arrows indicate the positions of root sampling. Note that: number of the replicates might be less than six (n = 3–5) for intercrops because not all soil cuboids contained fine roots during the root excavation.

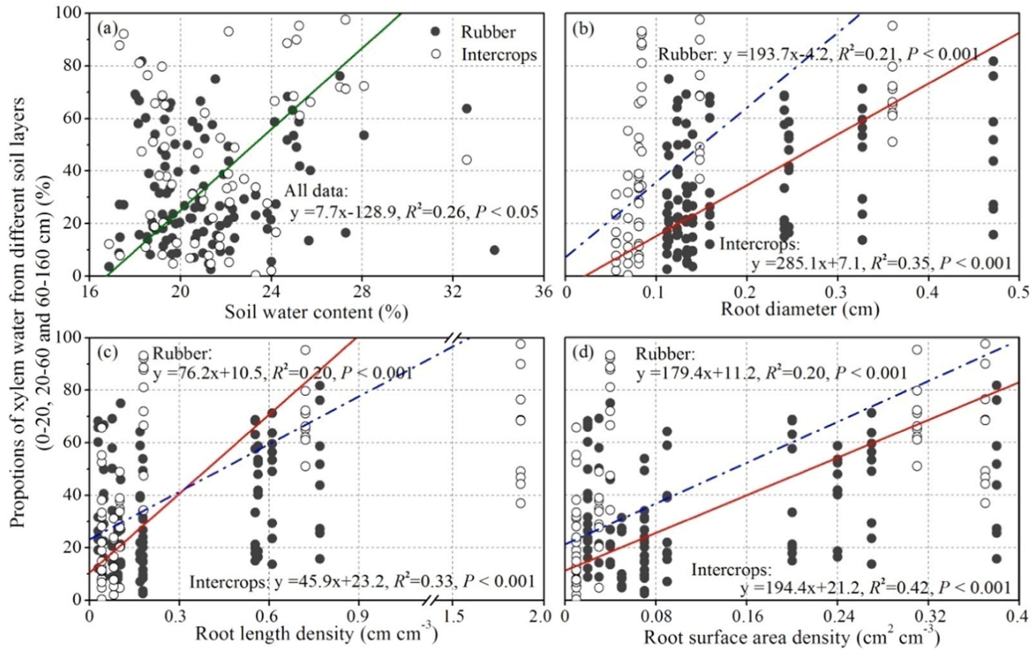

Fig. 5. Solid lines are linear regressions fitted to the data (green solid line: all data; red solid line: rubber data; blue dotted line: intercrop data). Source water contribution as functions of soil water content (a), root diameter (b), root length density (c), and root surface area density (d) at the experimental site. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$P < 0.05$) existed between the source water contribution and SWC in the 0–160 cm soil layers (Fig. 5). However, the correlations were not significant when rubber trees ($P = 0.19$) and the intercrops ($P = 0.17$) were considered separately. For rubber trees and the intercrops, the values of the source water contribution exhibited positive correlations with the root diameter ($P < 0.001$), root length density ($P < 0.001$), and root surface area density ($P < 0.001$).

3.5. *Leaf $\delta^{13}C$ and RDSW in the rubber agroforestry practices*

The bulk leaf δ^{13}C of rubber trees exhibited similar seasonal trends in both the monoculture and agroforestry practices (Fig. 6a). Nevertheless, the mean δ^{13}C values of rubber trees were ranked in descending order as $-30.71 \pm 1.17‰$ in RCa, $-30.74 \pm 0.59‰$ in Rm, $-31.51 \pm 1.28‰$ in RAv, and $-31.75 \pm 0.94‰$ in RAo (i.e. RCa > Rm > RAv > RAo). Meanwhile, the values of rubber δ^{13}C significantly differed between Rm and RAv ($P < 0.05$), as well as between Rm and RAo ($P < 0.001$). The bulk leaf δ^{13}C of rubber trees was not significant different between Rm and RCa ($P = 0.85$), and between RAv and RAo ($P = 0.41$). Overall, rubber trees maintained higher δ^{13}C values during the dry season (δ^{13}C: $-30.79 \pm 1.12‰$) than the rainy season (δ^{13}C: $-31.65 \pm 0.99‰$) ($P < 0.05$). This phenomenon was

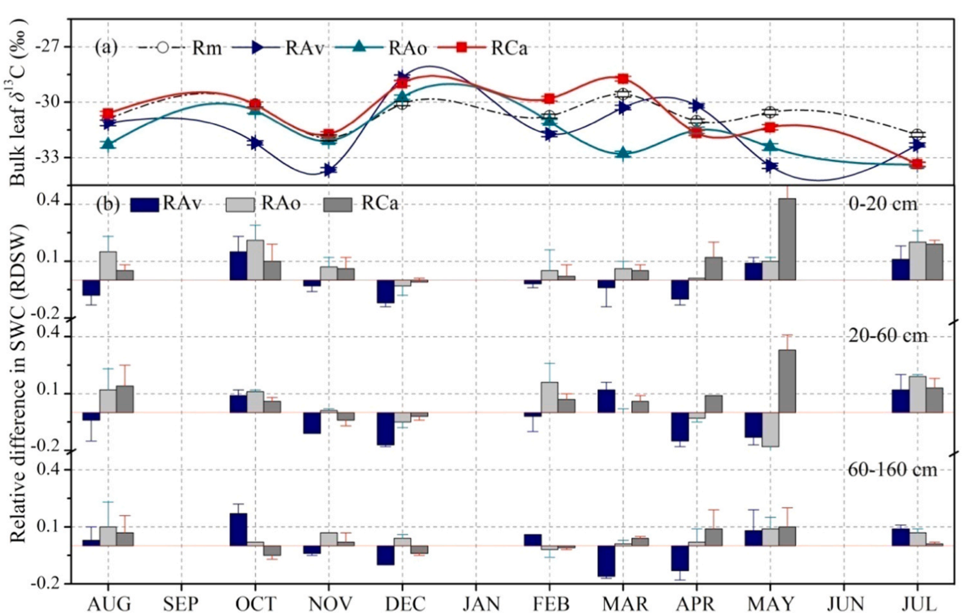

Fig. 6. Seasonal variations of rubber bulk leaf δ^{13}C (a) and relative difference in soil water content (b) in rubber agroforestry practices. Rm: rubber monoculture, RAv: rubber-amomum practice, RAo: rubber-alpinia oxyphylla practice, RCa: rubber-coffee practice. Each vertical error bar represents the standard deviation ($\pm$ 1 SD) for average of that month (n = 3).

more apparent in RAv and RCa. The bulk leaf δ^{13}C of the intercrops was presented as a reference in this study (Fig. S4). No significant difference occurred between the bulk leaf δ^{13}C of amomum (− 30.99 ± 1.28‰) and alpinia-oxyphylla (− 31.19 ± 0.57‰). The bulk leaf δ^{13}C (− 34.56 ± 0.41‰) was significantly lower for coffee than the two herbaceous species ($P < 0.001$).

The relative difference in soil water content (RDSW) of the 0–160 cm soil layers was negative (− 0.01 ± 0.09) in RAv during the study periods (Fig. 6b). Compared to RAv, overall positive values of RDSW were observed in RAo (0.06 ± 0.07) and RCa (0.08 ± 0.07) ($P < 0.05$). To better explain the water utilization characteristics of plants, a schematic representation of source water contribution, bulk leaf δ^{13}C, and RWSD is summarized for the rubber trees and intercrops (Fig. 7). During the dry season, a noticeable decline in RDSW of 0–20 cm was observed in RAv (− 0.06 ± 0.04) and RAo (− 0.03 ± 0.03) ($P < 0.05$), indicating more shallow soil water loss in these two agroforestry practices. In RAv, the values of RDSW were also negative in the 20–60 cm (− 0.06 ± 0.09, $P = 0.37$) and 60–160 cm (− 0.07 ± 0.07, $P < 0.05$) soil layers during the drought periods. Meanwhile, the RDSW values of 0–20 cm depths were significantly higher in RAo and RCa than RAv under drought stress ($P < 0.05$). During the rainy season, the values of RDSW were positive in RCa (0.13 ± 0.07), RAo (0.10 ± 0.04), and RAv (0.06 ± 0.04). However, there were no significant differences in RDSW of 0–20, 20–60, and 60–160 cm depths between treatments during the rainy season.

4. Discussion

4.1. Vertical patterns of water relations in different agroforestry practices

The results of this study showed that the intercrops favorably affected soil water retention in the rubber-based agroforestry practices (Table 1). This finding was also confirmed by the vertical signatures of soil water δ^{2}H and δ^{18}O (Figs. 2 and S2). The ranges of soil water δ^{2}H and δ^{18}O in this study were similar to those reported by Liu et al. (2014), Wu

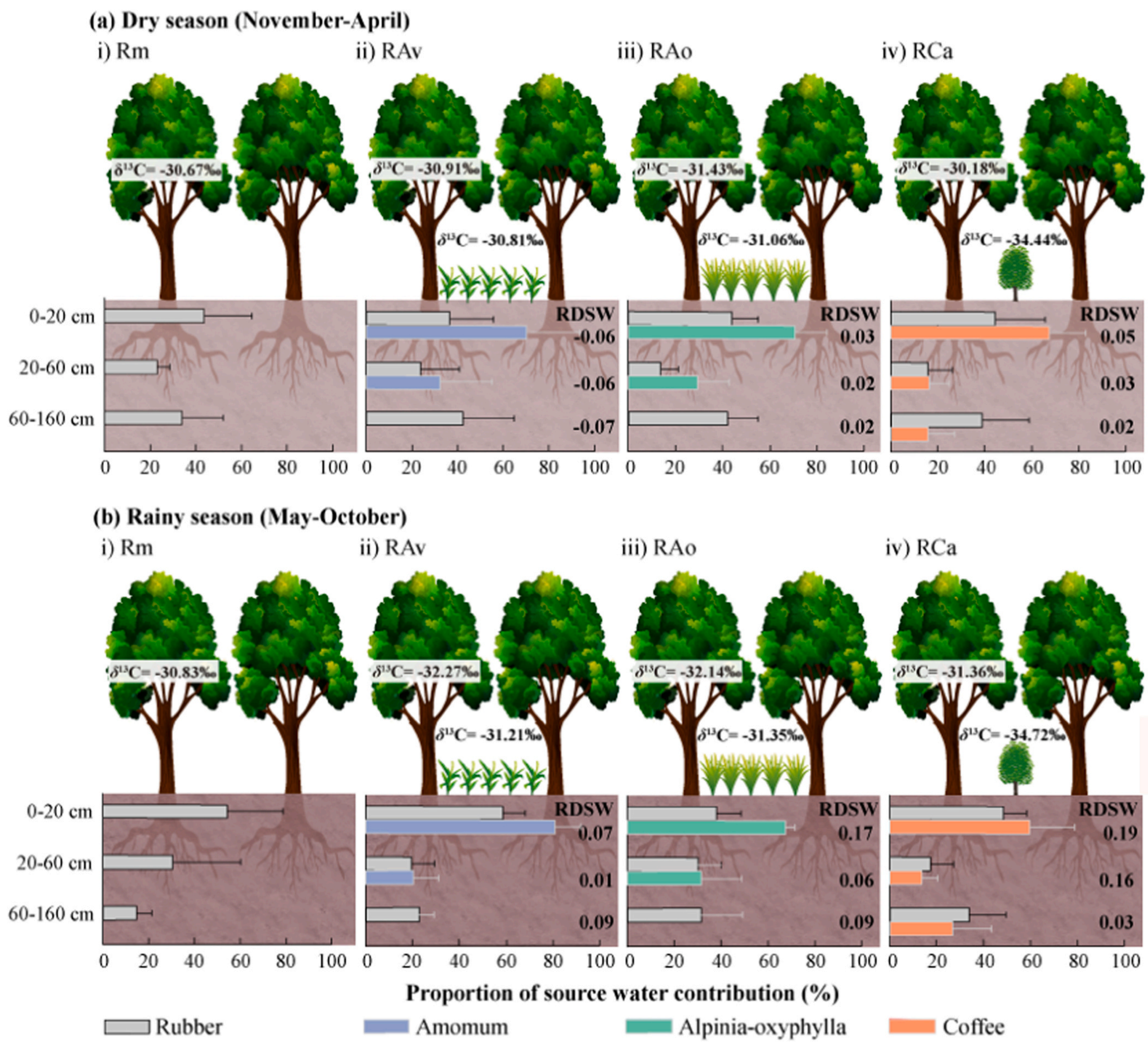

Fig. 7. Rm: rubber monoculture, RAv: rubber-amomum practice, RAo: rubber-alpinia oxyphylla practice, RCa: rubber-coffee practice. Each horizontal error bar represents the standard deviation (± 1 SD) for average of the dry months (n = 5, five sampling campaigns between November and April), and the rainy months (n = 4, four sampling campaigns between May and October). Schematic showing the mean values of bulk leaf δ13C, relative difference in soil water content, and source water contribution during the dry season (a) and the rainy season (b).

et al. (2019), and Yang et al. (2020) in the same region. Theoretically, soil water evaporation should result in more positive δ-values because of the Rayleigh distillation (Gat, 1996; Brooks et al., 2010; Dawson and Simonin, 2011). The δ^2H and δ^{18}O of shallow (0–20 cm) and middle (20–60 cm) soil layers were more positive in Rm compared to the other three agroforestry practices. It reflected that surface soil water in the agroforestry practices has less evaporation due to the cover shading of intercrops (Lin, 2010; Hardanto et al., 2017). Soil water evaporation is always regarded as an ineffective source of water loss, because it does not directly contribute to crop yields in agricultural lands (Carr and Lockwood, 2011; Yang et al., 2018). Therefore, the effect of water retention is not only beneficial for soil water supplies, but is also an advantage for the increasing of plant water use efficiency. Furthermore, the other hydrologic processes such as canopy interception can also influence the status of soil water. For example, Liu et al. (2018) found that the throughfall amounts are reported to be closely related to the canopy structures in the rubber-tea (*Camellia sinensis*) and the rubber-cocoa (*Coffea arabica*) agroforestry practices. As a result, the canopy interception of multiple canopies may result in a high spatial heterogeneity of soil water content and rainfall erosivity in the rubber plantations (Liu et al., 2018).

The plants highly depended on water from the 0–20 cm soil layers, despite the various functional traits in our agroforestry practices (Figs. 3 and S3). The rubber trees took up 43.5 ± 2.6% (40.5–46.7%) of their water from the 0–20 cm soil layers. Accordingly, the three intercrops derived 69.1 ± 3.2% (64.3–73.7%) of their water from 0 to 20 cm soil layers during the whole study periods. Plant species having contrasting water sources always coexist in various ecosystems (Jackson et al., 1995; Meinzer et al., 1999; Drake and Franks, 2003; Moreno-Gutiérrez et al., 2012). This complementary water use is beneficial for the temporal and spatial partitioning of vertical water resources (van Noordwijk et al., 2015; Schwendenmann et al., 2015). However, a serious competition of shallow water sources had been detected in this study, as also reported in other plant communities (Meinzer et al., 1999; Rossatto et al., 2012; Yang et al., 2020). The plant water use characteristics in this region were related to the abundance of surface soil water supply (Table 1). Therefore, most plants with shallow rooted systems may have interspecific water competition, and rely on surface soil water (Drake and Franks, 2003; Goldsmith et al., 2012; Goldberg et al., 2017).

The rubber trees seemed to be able to tap the deeper (20–60 cm) soil water during the drought periods; yet, this plasticity for deep water uptake was not as strong as those of previous studies (Liu et al., 2014; Wu et al., 2016). For instance, Liu et al. (2014) found that the water uptake depth of rubber trees increases markedly (> 70 cm) when soil moisture is gradually depleted in the late dry season. Wu et al. (2016) also demonstrated that rubber trees can switch their main water source (> 75%) to the 50–110 cm soil water during the dry season. Our results showed that 67.4 ± 4.8% of the rubbers' fine roots were concentrated in the 0–20 cm soil profiles (Fig. 4). In this study, the positive relationships between the source water contribution and root characteristics could offer some evidences for this view (Fig. 5). A previous research also found the positive upward-opening relationships between source water contribution and root length density in a semiarid revegetated ecosystem (Gao et al., 2018). However, the contribution of water sources decreases exponentially with the increase of root length density in their analysis (Gao et al., 2018). One possible explanation is that the fine-root system of different species is morphologically, chemically, and functionally heterogeneous (Pregitzer et al., 2002; Kou et al., 2018). To our limited knowledge, it was the first report that directly investigated the fine root distribution of rubber trees in this area, which provided valuable evidence on the water competition relations between rubber trees and their intercrops.

4.2. Seasonal dynamics of water relations in different agroforestry practices

The ideal habitat for rubber trees should have plenty of monthly rainfall (> 100 mm) and small temperature fluctuation (24–28 °C) (Iqbal et al., 2006; Liu et al., 2016). However, our study site is located in the tropical area of South-East Asia, where the non-native rubber trees experience a 6 month-long drought period (Fig. 1). The total amount of monthly rainfall during the dry months of 2017–2018 (November to April) was less than 100 mm (8–85 mm). As a result, the SWC in all the treatments sharply declined during the dry season ($P < 0.05$, Table 1). The soil moisture during the dry season was more plentiful in RAo ($P = 0.12$) and RCa ($P < 0.05$) compared to Rm. Thus, the intercrops of alpinia-oxyphylla and coffee likely had beneficial effects on the promotion of soil water availability, which provided further cases for the positive role of intercrops in soil water retention in the rubber-based agroforestry practices (Burgess et al., 2019; Jiang et al., 2020; Yang et al., 2020). On the contrary, the soil moisture was even worse in RAv than in the rubber monoculture ($P < 0.05$), implying a negative impact of amomum on rubber trees (i.e. the role of interspecific water competition > soil water retention). Additional irrigation should be applied if amomum is used as a intercrop with rubber trees.

The water-absorbing proportion from 0 to 20 cm soil layers to rubber trees slightly increased from 41.1 ± 19.1% (November–April) to 46.5 ± 14.3% (May–October), when the monthly rainfall is more abundant (102–334 mm) during the rainy season (Figs. 3 and S3). Meanwhile, amomum also improved the utilization of 0–20 cm soil water (68.5 ± 22.1% to 80.1 ± 10.8%) during the season transform ($P < 0.05$). Similarly, alpinia-oxyphylla increased the 0–20 cm water-absorbing proportion between the dry season (67.7 ± 4.0%) and the rainy season (70.7 ± 13.5%). These findings are consistent with the results of several other studies (Dodd et al.,1998; Zegada-Lizarazu et al., 2007; Asbjornsen et al., 2008), which suggested that the herbaceous species are more dependent on rainfall recharged soil water than do tall trees. Coffee trees were less dependent on the 0–20 cm soil water during the rainy season (59.9 ± 19.3%) than the dry season (67.7 ± 15.8%). Several studies showed that plants can adjust their water resource after heavy rainfall events or irrigation campaigns (West et al., 2007; Zegada-Lizarazu et al., 2007; Liu et al., 2014). Indeed, this ability to quickly switch and absorb rainwater will put plants at an advantage if an interspecific water competition occurs during the drought periods (Sekiya and Yano, 2002). However, the surface water (e.g., rainwater or stream) may not be a reliable long-term water source for some species that are always subjected to seasonal drought (Ehleringer and Dawson, 1992; Brooks et al., 2010). The contrasting water uptake patterns of herbaceous and woody species suggested that these intercrops might have specific influences on rubber trees.

It will be possible to assess the impacts of drought stress on plant water use strategies, if the source water partitioning and the measurement of intrinsic water use efficiency (WUE_i) are combined (Ehleringer and Dawson, 1992). Meanwhile, the stable carbon isotopes (i.e. an indicator of plant WUE_i) of coexisting C_3 plants can be analyzed to characterize the water relations between plants living in the same environmental condition (Cernusak et al., 2008; Moreno-Gutiérrez et al., 2012). Here, the values of bulk leaf δ^{13}C (− 30.79 ± 1.12‰) showed that rubber trees improved their WUE_i during the dry season than the rainy season (− 31.65 ± 0.99‰) (Figs. 6 and 7). A high WUE_i is likely a feedback of the rubber trees to the drought stress (Wu et al., 2016); and it may enhance the normal growth of rubber trees during the drought periods, which in turn will lead to a high latex yield during the subsequent rainy season (δ^{13}C = − 31.81‰ ~ − 29.59‰). This phenomenon principally occurs because the raising water use efficiency will lower the transpiration-induced water loss of plants under drought stress (Emmerich, 2007; Yu et al., 2008; Monson et al., 2010). Therefore, a high WUE_i likely ensures the normal physiological activity of rubber trees during the dry season (Snoeck et al., 2013; Kanpanon et al., 2015;

Hondrade et al., 2017). Nonetheless, rubber trees had lower bulk leaf δ^{13}C during the rainy season, because of the relatively plentiful supply of shallow soil water (Table 2). This could be described as a wasteful water use behavior, which is be beneficial for high latex yields of rubber trees during the non-drought periods (Wu et al., 2016).

4.3. Implications

In Xishuangbanna (Yunnan Province, southwestern China), maintaining consistent water supply remains one of the biggest challenges in the rubber plantations. The drought stress will always enhance the intense interspecific water competition among coexisting species, when the rainfall recharged soil water is not available for shallow rooted plants (Dawson, 1996; Meinzer et al., 1999; Yang et al., 2018). Even so, rubber trees are commonly referred as "water pumps" because of their high water-uptake (Tan et al., 2011). In this context, there is an ideal expectation that rubber trees and the intercrops will always share the limited water through temporal and/or spatial partitioning of resource utilization (Liu et al., 2014; Wu et al., 2016, 2019). However, our previous results revealed that the complementary water use did not occur between rubber trees and the intercrops of galangal (*Alpinia officinarum*), tea (*Camellia sinensis*), and cocoa (*Theobroma cacao*). The results of this study also showed that all the intercrops (i.e. amomum, alpinia-oxyphylla, and coffee) competed for shallow soil water resources with rubber trees during the whole study period of 2017–2018 (Fig. 7). Nevertheless, the unfavorable interspecific water competition between rubber trees and intercrops can be partly compensated by the increasing effects of plant shades (i.e. multiple-layered canopies) and rainfall infiltration (Zhu et al., 2018; Jiang et al., 2020).

Coffee seem an appropriate intercrop to rubber plantation because of its positive impacts on soil water availability. On the contrary, amomum would exacerbate the soil water shortages in the rubber plantation. Thus, it is important to identify the main crop species and its optimal growing environment before establishing an agroforestry practice (Lin, 2010; Gao et al., 2018). In the rubber-based agroforestry practices, the overstory trees remain the primary species in terms of economic returns, while the intercrops represent just subsidiary species that are mainly used to provide additional benefits (Iqbal et al., 2006; Smajgl et al., 2015; Chen et al., 2019). As a result, the growth of rubber trees should not be hindered by the intercropping practices. In Xishuangbanna, only few studies have explored the seasonal dynamics of water sources for rubber trees (Liu et al., 2014; Wu et al., 2016, 2019; Yang et al., 2020). The water relation between rubber trees and other intercrops should be more explored in this region.

5. Conclusions

The interspecific water relations between rubber trees and three intercrops described in this study allow us to concluded that: (1) rubber trees exhibited a weak plasticity in the depth of water uptake, relying on 0–20 cm soil water during both the dry and rainy seasons. Meanwhile, all of the intercrops exhibited interspecific competition for shallow soil water with the rubber trees; (2) both of rubber trees and intercrops were shallow rooted in the 0–160 cm soil profiles. Specifically, 60.5–74.5% of the rubbers' fine roots concentrated in the 0–20 cm soil strata; (3) all rubber trees maintained higher intrinsic WUE_i during the dry season than the rainy season; (4) application of coffee trees had the best facilitation effect on the water acquisition of rubber trees, while growing amomum significantly decreased soil water content in the rubber agroforestry practices.

Authors' contributions

B.Y., L.S., and W.J.L. conceived the experimental frame for this study; B.Y. and X.J.M. conducted the experiments and wrote the manuscript with input from the other co-authors.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2020.106593.

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