Agriculture, Ecosystems and Environment 298 (2020) 106937

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Intercrops improve surface water availability in rubber-based agroforestry systems

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ARTICLE INFO

Keywords:
Complementarity
Intercrops
Root distribution
Seasonal drought
Water competition

ABSTRACT

Despite the development of rubber agroforestry systems for ecological and economic benefits in Southeast Asia, knowledge of their water uptake dynamics and interspecific water interactions remains limited. The objective of this study is to reveal the water relations (i.e., competition/complementarity) between rubber (*Hevea brasiliensis*) trees and different kinds of intercrops. We investigated the stable isotopes (δD and δ^{18}O), fine root length density, and soil water content (SWC) under three agroforestry practices and one rubber monoculture across a year (2017/2018). Our results indicated that rubber trees acquired more than 40.5 ± 21.3 % of their water from shallow (0 − 20 cm) soil stratum, as do perennial galangal (*Alpinia officinarum*), tea (*Camellia sinensis*), and cocoa (*Theobroma cacao*). The complementarity hypothesis was not supported for rubber trees and the intercrops. In the dry season (November to April), there was strong interspecific competition for shallow water resources where the intercropping was practiced. However, intercropping increased the available soil water, enabling rubber trees to acquire more (9.4–24.3 %) shallow soil water. In the wet season (May to October), interspecific water competition was less pronounced based on the relative difference in soil water content (RDSW). Higher relative water content, in the order rubber-galangal > rubber-tea > rubber-cocoa, further showed that facilitative effects dominated interspecific water competition in all the agroforestry practices. This information regarding water relations between rubber trees and their intercrops will be essential to optimize land and water resource utilization in this region.

1. Introduction

Agroforestry systems are managed plant communities based on the ecological principles of species coexistence in natural forest communities (Anderson and Sinclair, 1993). They always consist of multiple species and vertical structures, providing many advantages, such as high productivity, valuable profits, and sustainable land use (Pavlidis and Tsihrintzis, 2017). Complementary resource use has been suggested as an explanation for the higher productivity of such systems (Fernández et al., 2007; Schwendenmann et al., 2015). As droughts become more intense and frequent (IPCC, 2013), it will be an important reason for the development of agroforestry practices in the future. However, the water uptake dynamics and interspecific water interactions between species intercropped in various agroforestry systems are still key issues for agro-ecologists.

Stable isotope techniques (δD and δ^{18}O) are commonly used to trace water source for plants, given a consensus that isotope fractionation does not occur during the root water uptake process (Ehleringer and Dawson, 1992). Such techniques significantly improve our understanding of the water relations in agroforestry systems (Asbjornsen et al., 2008; Lin, 2010; Tobella et al., 2017; Tang et al., 2018). For example, Asbjornsen et al. (2008) found that coexisting trees and shrubs in the agricultural landscape extract water from different depths in the soil profile. In another agroforestry parkland, Tobella et al. (2017) has reported a negative relationship between tree size and the groundwater acquisition. In addition, they provide scientific support for the water managements in agroforestry practices (Smith et al., 1997; Wu et al., 2016; Tobella et al., 2017). For instance, Smith et al. (1997)

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https://doi.org/10.1016/j.agee.2020.106937
Received 9 April 2019; Received in revised form 17 March 2020; Accepted 29 March 2020
Available online 25 April 2020

suggested that competition for water can be reduced between trees and crops where groundwater is accessible. Wu et al. (2016) showed that rubber (*Hevea brasiliensis*) trees exhibit wasteful water behavior unless they are intercropped with crops. Nevertheless, these techniques are expected to provide more implications for the optimization of agroforestry practices.

Complementary water use is presumed to be a fundamental hypothesis in various agroforestry practices (Vandermeer, 1989; Schwendenmann et al., 2015). It is based on the diversity of functional traits among co-occurring species, which plays a positive role in minimizing the temporal and spatial competition of limited water resources (Meinzer et al., 1999; Gao et al., 2018; Tang et al., 2018). That is, the deep rooted trees can acquire water from larger soil volumes, where are inaccessible to the annual crops (Lott et al., 2003; Wu et al., 2016). Therefore, the complementarity is ultimately dependent on the water potential in soil stratum, and the differences of root distributions between trees and crops (van Noordwijk et al., 2015). It should also be noted that plant species in agroforestry systems do not simply exist as separate individuals, which can have a wide range of both positive and negative impacts on the plant productivities. Generally, species mixtures with contrasting root patterns are more effective and efficient than the monocultures in efficiency of use of water and nutrients (Monteith et al., 1991; Pavlidis and Tsihrintzis, 2017). Moreover, agroforestry farmers prefer to choose the mixed species with complementarity because of their better yields. Evaluating the trade-offs between the competition effects and the added values of intercrops on the main crop is therefore essential for the promotion of agroforestry practices.

Southeast Asia is the biggest rubber planting area worldwide, producing over 90 % of global natural latex (Fox et al., 2014). It can bring enormous profits to farmers, especially the smallholders. However, the rapid expansion of rubber plantations has caused serious negative hydrological consequences in Xishuangbanna, in tropical southwest China (Li et al., 2012; Liu et al., 2014). Various rubber-based agroforestry practices for slowing soil organic matter loss (Chen et al., 2017) and reducing water runoff volumes (Zhu et al., 2018) have shown promise there. Nevertheless, these agroforestry practices are not all equally suitable for the growth of rubber trees. The water consumption characteristics of different agroforestry practices are still unclear in this region.

The objective of this study is to investigate the water uptake dynamics and interspecific water interactions for three types of rubber-based agroforestry practices, using the intercrops galangal (*Alpinia officinarum*), tea (*Camellia sinensis*), and cocoa (*Theobroma cacao*). Our hypotheses were that (i) the water source used by rubber trees would be modified by the intercropping practices, (ii) trees would exhibit a relatively higher range of water uptake plasticity than the intercrops, and (iii) some agroforestry practices might be inappropriate because of strong interspecific water competition.

2. Materials and methods

2.1. Study site

The study was conducted at the Xishuangbanna Tropical Botanical Garden (XTBG) in southwestern China (21° 55′ 39″N, 101° 15′ 55″E, and elevation 750 m). The site is located between two east-west hills on flat land sloping less than 15° from south to north. The local climate (1965–2004) is dominated by tropical monsoons, with mean annual air temperature and precipitation of 21.7 °C and 1487 mm (Liu et al., 2014). Soil thickness is approximately 2 m with a clay loam texture, containing 42 % sand, 34 % silt and 24 % clay. Supporting meteorological measurements were conducted to provide half-hourly air temperature (HMP45, VaisalaInc., Helsinki, Finland), soil water content (CS615-L, Campbell Scientific Inc., Utah, USA), soil heat flux (HFT-3, Campbell Scientific Inc., Utah, USA) and precipitation (52203, RM Young Inc., Michigan, USA). To determine local drought stress, we used the Budyko aridity index (AI), calculated as the ratio of rainfall amount to potential evapotranspiration (P_{ET}). P_{ET} was estimated as 1.26 times the equilibrium evapotranspiration (ET_{eq}), as described in Tang et al. (2014):

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

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

2.2. Experimental layout

The rubber trees in our catchment were planted on level bench terraces (370 trees ha^{-1}), after clear-cutting of the primary forests around 1970. The 50-year-old trees were arranged in double rows 3 m apart, separated by 18 m gaps, and received uniform management by local farmers (e.g., control of understory growth, fertilization, and latex extraction). Mean leaf area index (LAI) and canopy spread were 2.4 m^2 m^{-2} and 11 m^2 (Liu et al., 2014). By 2010, more than ten species of intercrops had been planted between the rubber rows. In this study, the rubber monoculture and three rubber based agroforestry practices were selected to be regarded as the "control (CK)" and the "randomized set of treatments". Mean trunk diameter of the rubber trees was 37.8 ± 5.3 cm according to a survey conducted in 2019 (n = 5, in each of the four treatments). The three kinds of intercrops have been demonstrated as optimal cash crops for intercropping with rubber trees because of their medical or economic benefits. Galangal (*Alpinia officinarum*) is a perennial herb, which was planted in small clumps of 10 − 20 propagules (0.5 m × 0.5 m, and 1.7 ± 0.2 m tall). Tea (*Camellia sinensis*) shrubs, native to Southeast Asia, were arranged in double rows (1.0 m × 1.0 m, and 1.5 ± 0.1 m height). Cocoa (*Theobroma cacao*), a fruit tree originating from South America, was planted in single rows (4.7 ± 0.7 m height) between the rubber trees (Supplementary Fig. S1). After long-term cultivation and management, the treatments had common characteristics, such as well-drained soil and gently sloping geomorphology. Aerial distances between the agroforestry practices were less than 500 m. In each of the treatments, four sampling plots were randomly selected with dimensions of 6 m (perpendicular to rows) × 9 m (along rows).

2.3. Root excavation

Root sampling was performed in October and November 2017. The roots were sampled for both rubber trees and the intercrops. Soil volumes of 15 cm × 15 cm × 160 cm deep were excavated using spades and hand cutters. Three such volumes were collected close to the rubber trees, and three near the intercrops (in mid-rows). Each soil volume was divided into strata by 10 cm increment from the surface down to 30 cm deep, by 20 cm increment in the 30 − 130 cm layer, and by 30 cm increment in the 130 − 160 cm layer. In total, 313 soil samples were obtained. The fine roots of trees and intercrops were manually picked out, flushed with water and separated in 2 mm sieves. Root length density (RLD) was calculated for each stratum of the 0 − 160 cm soil profiles by the WinRHIZO software (Regent Instruments Inc., Quebec, Canada).

2.4. Isotopic sampling and measurements

On each sampling date between August 2017 and July 2018, three suberized twigs were cut from the sunny side of the randomly selected trees and shrubs. Phloem tissues were removed to avoid isotopic contamination. Specially, the root crown of galangal was sampled for xylem water analysis (Barnard et al., 2006). A 4 cm diameter bucket auger was used to collect soil samples from seven depth zones (0 − 5 cm, 5 − 10 cm, 10 − 20 cm, 20 − 40 cm, 40 − 60 cm, 60 − 110 cm and

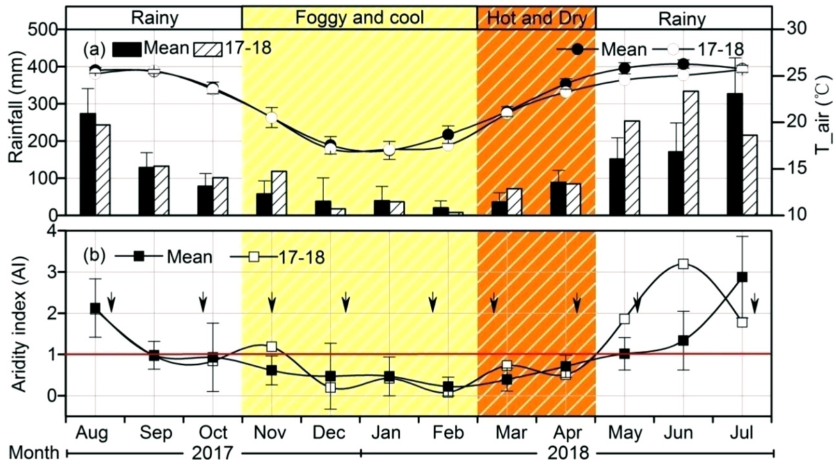

Fig. 1. Seasonal pattern of (a) rainfall, air temperature, and (b) Budyko's aridity index. Multi-year means of AI (2008-2017) are also shown. Error bars represent one standard deviation. Arrows indicate the sampling dates.

110 − 160 cm) at three random locations per plot, providing 12 locations in total for each treatment and the control. Soil water content (SWC, %) was determined by drying soil samples at 105 °C for 24 h. Groundwater was sampled monthly from a deep well (∼ 40 m). Rainwater was collected using a lab-made rain collector with a ping-pong ball to prevent evaporation. Immediately following collection, all samples were sealed with parafilm and frozen (−20 °C).

Liquid water in plant and soil samples was extracted cryogenically by a vacuum line (LI-2100, Lica United Technology Limited Inc., Beijing). The isotopic composition of water samples was determined using a high-temperature conversion elemental analyzer (TC/EA) coupled with a DELTA V Advantage isotope ratio mass spectrometer (all from Thermo Fisher Scientific, Bremen, Germany). An AS1310 autosampler (Thermo Fisher Scientific, Bremen, Germany) was used for automated water samplings and injections (n = 4, with the first injection being eliminated in case of "memory effect"). Average precision of the TC/EA-IRMS was 0.6 ± 1.6 % for δD and 0.02 ± 0.13 % for δ^{18}O based on lab calibration measurements. The monthly weighted mean for isotopic composition in rainwater was calculated as:

$$\delta_{p,mean} = \left(\sum_{i=1}^{n} \delta_{p,i} \times PPT_i\right) / \left(\sum_{i=1}^{n} PPT_i\right) \quad (2)$$

where $\delta_{p,i}$ is the δ value (%) of the ith rainfall, PPT_i is the ith rainfall amount (mm).

2.5. Water source and water interactions

The Bayesian-mixing model MixSIAR was used to predict the relative water absorbing proportions from each soil layer, following the method of Muñoz-Villers et al. (2018). This model has greater statistical power to accommodate uncertainties in isotope signatures, multiple sources and prior information. The dual isotopes (δD and δ^{18}O) in individual xylem samples, and the mean ± SD for soil water at the sampled depths, were the model inputs. No ground water was included in the model, because the water table in the experimental area was at approximately 10 m below the surface. The fixed effect, SIAR, and no discrimination (0) were specified as described by Yang et al. (2018). The Markov Chain Monte Carlo (MCMC) length was set as "normal". The estimated contributions of each soil stratum were combined into three layers for comparison: shallow, 0 − 20 cm; middle, 20 − 60 cm; and deep, 60 − 160 cm.

Relative difference in soil water content (RDSW) was used to evaluate the degree of competition or facilitation in the water interactions between plants. We assumed that where soil moisture differed in an agroforestry system relative to the monoculture that this was caused by the intercrops. Therefore, significant SWC decline (or increase) reflects interspecific water competition (or complementarity) between rubber trees and the intercrops. The RDSW of the shallow, middle, and deep layers was calculated using a modified form of the formula of Gao et al. (2018):

$$RDSW_{agroforestry} = \left(\sum\nolimits_{i=1}^{n} \frac{\theta_{\acute{a},i} - \theta_{CK,i}}{\theta_{CK,i}} \times LT_i\right) / \left(\sum\nolimits_{i=1}^{n} LT_i\right) \quad (3)$$

where $\theta_{a,i}$ and $\theta_{CK,i}$ are the SWC percentages for a rubber agroforestry practice and the monoculture, respectively, in the ith soil layer; LT_i is the layer thickness of the ith soil layer (cm). Here, negative values of RDSW in an agroforestry system refer to the existence of water competition between rubber trees and the intercrops.

2.6. Statistical analyses

All statistical analyses were performed using SPSS (version 17.0, Chicago: SPSS Inc.). One-way analysis of variance (ANOVA) was used to compare the SWC between months and treatments, and the RDSW among treatments, with significance specified as $P < 0.05$. Comparisons of AI between the dry and wet seasons, and of the RLD among treatments, were made using a paired t-test. To test the interactive effects of treatments, soil depth and season on water uptake of rubber trees, the three-way ANOVA was performed including Tukey's HSD test.

3. Results

3.1. Seasonal drought during the study period

Mean annual air temperature and precipitation between 2008 and 2017 were 22.6 ± 3.1 °C and 1412 ± 180 mm (Fig. 1). Mean AI values for each month across this period (2008–2017) suggested that a prolonged annual drought, of more than six months, was typical for the region. Noting that an AI value of less than 1 indicates meteorologically water-limited conditions, the mean AI in the dry season months (November to April) was 0.48 ± 0.12, compared to 1.54 ± 0.67 in the wet season months (May-October). October, with an AI of 0.93 ± 0.83 was defined as a transition period between the dry and wet seasons. Overall, the seasons could be classified into rainy (May-October), foggy and cool (November-February), and hot and dry (March-April).

Mean air temperature and precipitation in the study period of 2017–2018 were 22.2 ± 2.9 °C and 1619.9 mm, respectively. The wettest month was June 2017 (AI = 3.19), with mean air temperature and precipitation of 25.1 °C and 333.7 mm, respectively. Rainfall was

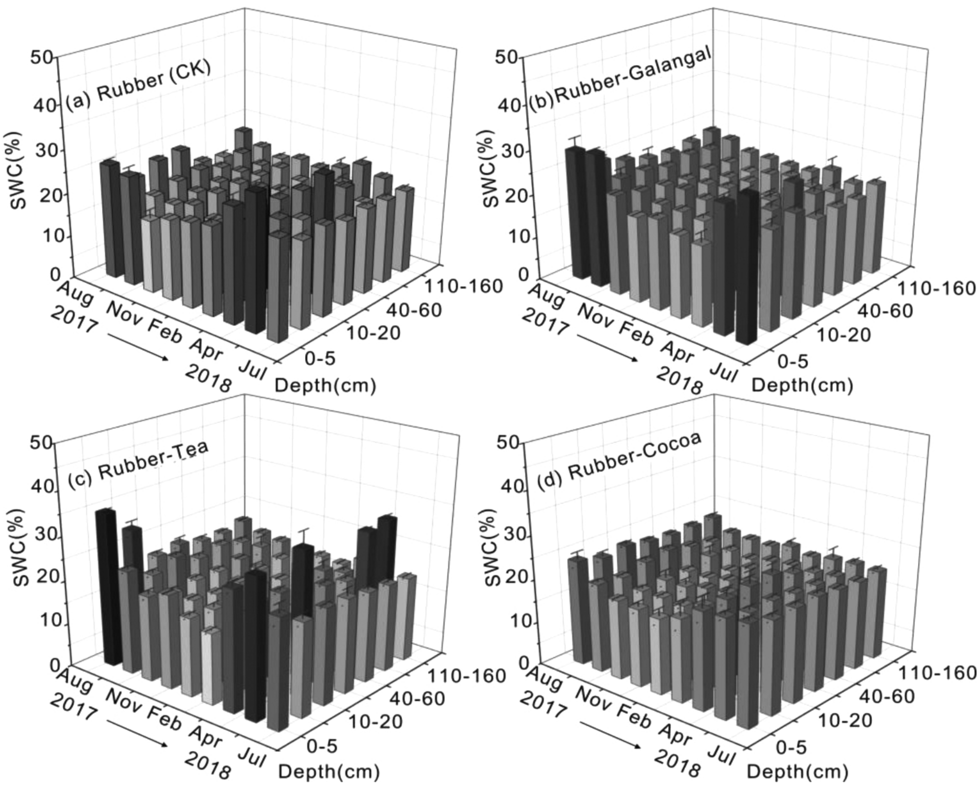

Fig. 2. Mean gravimetric soil water content (SWC) in (a) the monoculture, (b) the rubber-galangal system, (c) the rubber-tea system, and (d) the rubber-cocoa system. Error bars represent one standard deviation.

also relatively abundant (118.9 mm) in November 2017 (AI = 1.19). The most serious water deficit occurred in February 2018 (AI = 0.08). In this month, mean air temperature and precipitation were 17.5 °C and 8.1 mm, respectively. Compared to the long-term mean AI values, there were corresponding normal ($P \geq 0.577$), dry (0.52 ± 0.29), and wet (1.79 ± 0.53) seasons in this study.

3.2. Vertical distribution of soil moisture and fine roots

Soil water content (SWC) underwent pronounced ($P < 0.001$) seasonal variation in all the treatments (Fig. 2). The SWC in the shallow layer declined sharply in the dry season and increased in the wet season. This trend was consistent with the seasonal changes in local AI. In the dry season, the SWC in the rubber-galangal and rubber-tea agroforestry systems were slightly lower than that in the monoculture. In the wet season, the SWC showed a smaller increase in the rubber-cocoa system. Overall, the SWC was higher in the rubber-galangal (21.7 ± 2.0 %, $P < 0.001$) and rubber-tea (21.0 ± 2.7 %, $P < 0.05$) systems. The SWC in the rubber-cocoa (20.6 ± 1.5 %) system was similar to that of the monoculture (20.5 ± 2.5 %, $P = 0.799$).

Rubber tree fine roots were predominantly distributed in shallow (0 − 20 cm) soil layers (Fig. 3). Mean RLD of the agroforestry rubber trees, compared to 0.19 ± 0.18 cm cm^{-3} in the monoculture, were 0.18 ± 0.15 cm cm^{-3} ($P = 0.649$) in the rubber-galangal system, 0.18 ± 0.18 cm cm^{-3} ($P = 0.115$) in the rubber-tea system, and 0.13 ± 0.13 cm cm^{-3} ($P < 0.05$) in the rubber-cocoa system, respectively. Among the treatments, 60.7–72.5 % of the rubber trees' fine roots were concentrated in the 0 − 20 cm soil layers. The rubber trees also had plenty of lateral roots (ranging from 0.14 ± 0.14 cm cm^{-3} to 0.21 ± 0.23 cm cm^{-3}). Fine roots of the tea and cocoa intercrops penetrated to a depth of 160 cm; those of the perennial galangal reached 130 cm. Mean RLD were 0.05 ± 0.02 cm cm^{-3} for galangal, 0.05 ± 0.03 cm cm^{-3} for tea, and 0.07 ± 0.05 cm cm^{-3} for cocoa. The roots of galangal were also found adjacent to the rubber trees, mainly because the intercrops were planted in multiple rows.

3.3. Water uptake patterns for rubber trees and intercrops

Soil water δD and δ^{18}O significantly varied with months and depths (Fig. 4). In August 2017, the soil water δD and δ^{18}O exhibited little vertical variation in any treatments. In this case, xylem water and soil water often overlapped with two or more intersections. Then, the vertical signatures of δD and δ^{18}O were gradually enriched from shallow (0 − 20 cm) to middle (20 − 60 cm) soil stratum. In May and July 2018, the shallow soil water δD and δ^{18}O became depleted again due to the influences of rainwater. Xylem water δD and δ^{18}O levels were within the ranges found in the 0 − 160 cm soil layer (Fig. S2), indicating that plants were primarily using this source during this period. Man values of rainwater δD and δ^{18}O decreased from -33.4 ± 17.6‰ and -5.17 ± 2.13‰, respectively, in the dry season, to -55.1 ± 23.8‰ and -7.60 ± 3.36‰ in the wet season, respectively. Isotopic compositions of groundwater changed little during the study period, with mean δD and δ^{18}O values of -60.8 ± 1.3‰ and -9.27 ± 0.43‰, respectively.

Throughout the study year, the rubber trees and all intercrops predominantly absorbed water from the shallow soil layers (Table 1). The contributions of water at this depth to rubber trees were 40.5 ± 21.3 % in the monoculture, 44.9 ± 19.7 % in the rubber-galangal system, 46.9 ± 22.9 % in the rubber-tea system, and 53.0 ± 20.0 % in the rubber-cocoa system. In all treatments, the rubber trees could take up water from below 60 cm in the dry season. However, rubber tree maximum utilization of deep (60 − 160 cm) soil water varied among the treatments. This probably reflected an influence of intercrops on their water uptake. The contributions of shallow soil water were 42.8 ± 17.6 % with galangal intercropping, 63.6 ± 21.2 % with tea, and 67.2 ± 15.0 % with cocoa, respectively. All treatment groups had significant correlations between root water uptake and fine root distribution (Fig. 5). In the dry season, these correlations were more prominent for both the rubber trees ($y = -157.7x^2 + 173.5x + 8.9$, R^2

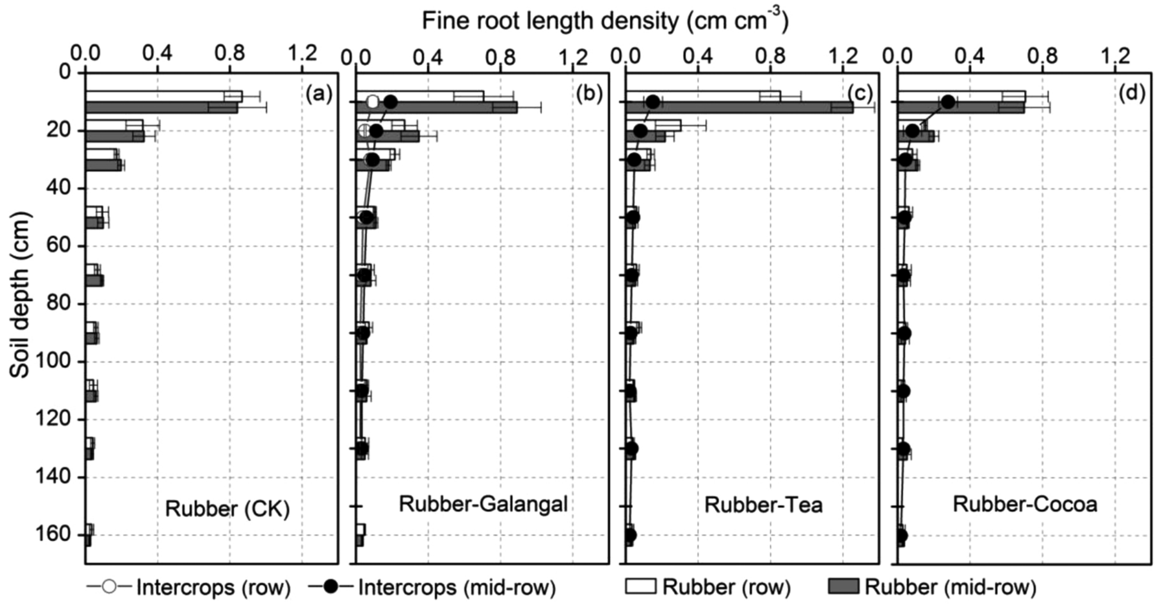

Fig. 3. Vertical profiles of root length density (RLD) in (a) the monoculture, (b) the rubber-galangal system, (c) the rubber-tea system, and (d) the rubber-cocoa system. Error bars represent one standard deviation.

= 0.40, $P < 0.001$) and the intercrops ($y = -194.6x^2 + 706.6x + 4.0$, $R^2 = 0.45$, $P < 0.001$). The three-way ANOVA results for rubber tree water uptake (Table S1) showed significant effects of soil depth and interaction between soil depth and treatments.

3.4. Interspecific water interactions among depths and seasons

In the three intercropping practices, relative differences in soil water content (RDSW) between treatments in all soil layers were significantly higher than zero ($P < 0.05$) (Fig. 6). The RDSW showed a decreasing pattern from the rubber-galangal system (mean 0.04 ± 0.06, $P = 0.007$) to the rubber-tea (0.03 ± 0.09, $P = 0.023$) and rubber-cocoa (0.01 ± 0.05, $P = 0.045$) systems. Only RDSW of the rubber-galangal system was significantly different from zero in all three soil layers ($P < 0.05$). The RDSW in the rubber-tea system had a higher value in the shallow soil layer ($P < 0.05$). In the rubber-cocoa system, however, RDSW did not differ from zero for any soil layer.

The water sources and RDSW are summarized in Fig. 7. In the dry season, the shallow (0 − 20 cm) soil water contribution to the rubber trees was 39.9 ± 20.8 % in the monoculture. This proportion increased to 51.8 ± 23.5 % in the rubber-galangal system, 52.2 ± 24.8 % in the rubber-tea system, and 51.0 ± 19.1 % in the rubber-cocoa system. Meanwhile, the shallow water contributions were 40.0 ± 18.5 % for galangal, 73.0 ± 16.3 % for tea, and 65.1 ± 14.9 %. Negative values of RDSW were apparent in the rubber-tea system in all layers, and in the rubber-cocoa system in the shallow and middle layers. In the wet season, rubber trees' absorption from the shallow layers was 41.3 ± 21.8 % (monoculture), 36.3 ± 13.2 % (rubber-galangal), 40.3 ± 16.2 % (rubber-tea) and 55.4 ± 21.5 % (rubber-cocoa). Except in the monoculture (−6.0 %), the water contributions of the deep soil stratum were higher in the intercropping systems (2.5–29.6 %). In the same period, water uptake proportions from shallow soil stratum were 46.2 ± 14.1 % for galangal, 51.8 ± 22.8 % for tea, and 69.8 ± 15.7 % for cocoa. The RDSW values across the different agroforestry practices mostly remained positive during this period.

4. Discussion

4.1. Water uptake patterns of the rubber trees subjected to drought

Soil water content (SWC) is a key factor affecting the rubber tree water uptake patterns (Fig. 2). Among the three rubber-based agroforestry systems, intercropping with galangal and tea significantly improved SWC compared to the monoculture. It has been suggested by many previous reports that agroforestry practices can promote good soil water conditions by capturing more rain, and reducing soil water evaporation and surface runoff (Monteith et al., 1991; Anderson and Sinclair, 1993; Asbjornsen et al., 2008). As a result, the rubber trees in such systems could acquire more water from shallow soil stratum in the dry season. This confirmation that facilitative effects of intercropping benefit main crops will be useful in the development of the agriculture and forestry sectors under projected future drought scenarios (Smith et al., 1997; Gao et al., 2018).

There is a consensus that deep-rooted trees possess dimorphic root systems, which will allow them to use water primarily from the shallow and deep soil layers in the wet and dry seasons, respectively (Ehleringer and Dawson, 1992; Moreno et al., 1996). Nevertheless, we found that the rubber trees in the four groups predominantly absorbed water from shallow soil layers throughout the dry (November-April) and wet (May-October) seasons (Fig. 4 and Table 1). This finding contrasts with those of Smith et al. (1997); West et al. (2012), and Yang et al. (2015), who reported that tall trees heavily relied on deep soil water under water stress. Two explanations are possible for this discrepancy. First, in our study, higher fine root length density (RLD) in the surface soil stratum might predispose the rubber trees to utilize water at this depth (Fig. 5). Priyadarshan (2011) also reported that the lateral root systems of rubber trees can help them to use water from the surface soil stratum. Second, the rubber trees in the study region have evolved to defoliate in the dry season (Fig. S3), reducing water loss through leaf transpiration. Surface soil water might therefore be sufficient in the dry season.

As in the dry season, the rubber trees typically utilized shallow soil water in the wet season. However, the proportion of water they absorbed from deep soil layers was slightly higher in the agroforestry systems (Table 1). Rubber trees have been considered to be “water pumps” because they are associated with water depletion (Tan et al., 2011; Liu et al., 2014; Wu et al., 2016). The annual latex production of

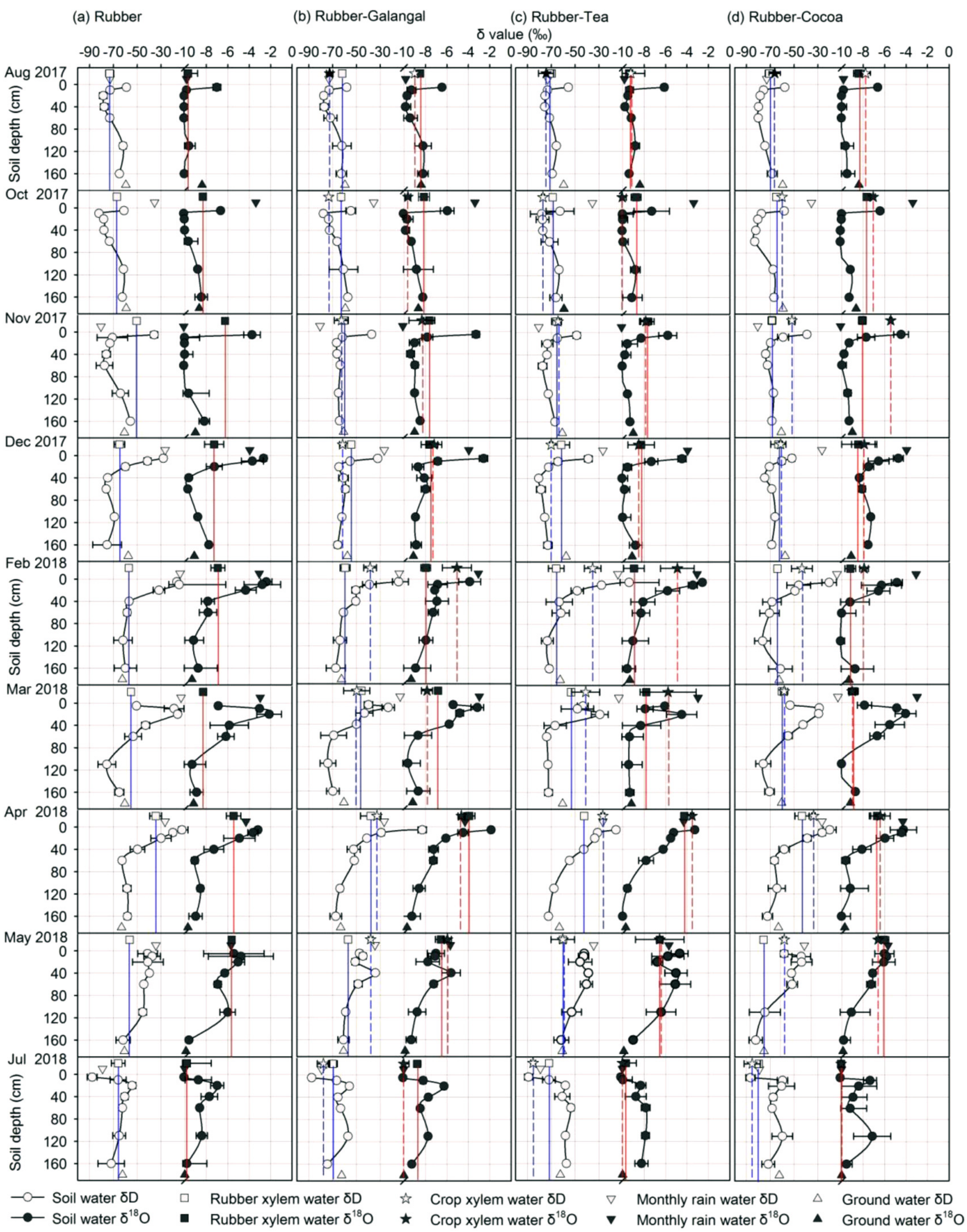

Fig. 4. Seasonal variation of δD and $\delta^{18}O$ in soil water, ground water and xylem water. Monthly weighted means of δD and $\delta^{18}O$ in rainfall are also presented. Error bars represent one standard deviation.

Table 1
Mean water uptake proportion from shallow (0-20 cm), middle (20-60 cm), and deep (60-160 cm) soil layers in rubber agroforestry systems.

	Soil depth (cm)	Rubber monoculture (%)	Rubber-Galangal system (%)		Rubber-Tea system (%)		Rubber-Cocoa system (%)	
Dry season	Shallow (0 – 20)	43.7 ± 21.2	53.1 ± 28.3	40.0 ± 21.4	68.0 ± 24.7	73.0 ± 20.1	61.8 ± 20.2	65.1 ± 20.3
	Middle (20 – 60)	22.9 ± 5.70	34.1 ± 27.4	35.9 ± 25.0	22.2 ± 25.4	14.1 ± 9.20	16.9 ± 6.70	12.2 ± 2.90
	Deep (60 – 160)	34.2 ± 17.9	12.9 ± 6.30	24.1 ± 18.9	9.8 ± 9.400	12.9 ± 11.1	21.3 ± 21.5	22.8 ± 20.8
Wet season	Shallow (0 – 20)	54.3 ± 25.0	53.0 ± 25.3	46.2 ± 20.7	40.3 ± 22.9	51.8 ± 33.8	55.4 ± 26.4	69.8 ± 19.0
	Middle (20 – 60)	30.8 ± 29.6	13.1 ± 8.60	32.8 ± 31.7	16.5 ± 5.40	34.3 ± 38.6	14.8 ± 6.90	9.1 ± 8.100
	Deep (60 – 160)	14.9 ± 6.50	33.9 ± 22.9	21.1 ± 21.3	43.2 ± 55.4	13.9 ± 17.2	29.8 ± 25.9	21.0 ± 18.1

Note: Values of the second columns in the rubber agroforestry systems indicate the water absorbing percentages of the intercrops.

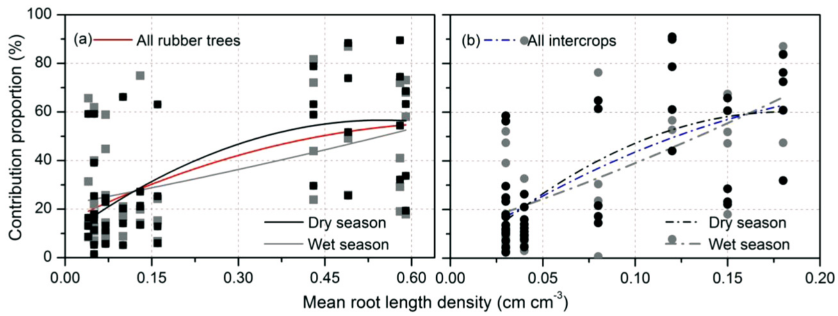

Fig. 5. Relationship between the soil water contribution and fine root distribution for (a) rubber trees (all: y = -81.9x^2 + 116.2x + 14.7, R^2 = 0.31) and (b) intercrops (all: y = -932.1x^2 + 501.1x + 2.8, R^2 = 0.40). Correlation of different periods are also presented for rubber trees (dry season: y = -157.7x^2 + 173.5x + 8.9, R^2 = 0.40; wet season: y = 12.7x^2 + 44.5x + 21.9, R^2 = 0.18) and intercrops (dry season: y = -194.6x^2 + 706.6x + 4.0, R^2 = 0.45; wet season: y = 336.4x^2 + 244.2x + 11.3, R^2 = 0.32). $P < 0.001$ was observed in each equation.

the study region was approximately 1500 kg ha^{-1}, requiring approximately 5000 kg ha^{-1} water (Mann, 2009). The rubber tree peak growth period occurs in the wet season. It is possible that surface soil water was insufficient to meet the associated demand, forcing the trees to tap deep soil water. Water competition between the rubber trees and the intercrops may also be responsible for the greater reliance on deep soil water in the agroforestry systems.

4.2. Water complementarity

Despite their varying growth habits as herbs, shrubs and small trees, all the intercrops, like the rubber trees, predominantly absorbed water from the shallow soil layers (Fig. 4). Local annual rainfall is plentiful (~ 1500 mm), so dependency on surface soil water can be ascribed to the shallow root networks of these intercrops (Schenk and Jackson, 2005). Water competition between the rubber trees and intercrops showed that their niche separation in terms of water use patterns was less evident than previously reported (Eggemeyer et al., 2009; West et al., 2012; Liu et al., 2014; Gao et al., 2018). The most intense competition for shallow soil water appeared in the rubber-cocoa system (Table 1). This result is consistent with the previous findings that cocoa trees mainly take up shallow-layer water in tropical areas (Carr and Lockwood, 2011; Wu et al., 2016).

In several previous studies, complementary water use patterns have been reported in a cocoa-Gliricidia (*Gliricidia* spp.) agroforestry system (Schwendenmann et al., 2010), a rubber-tea system (Wu et al., 2016), and a jujube (*Ziziphus jujuba*)-daylily (*Hemerocallis fulva*) system (Gao et al., 2018). In this study, soil moisture deficit (i.e., negative RDSW) resulting from intense interspecific water competition occurred mainly in the dry season (Fig. 6). The RDSW was positive in the rubber-galangal system ($P > 0.05$), while negative values of RDSW were observed in the rubber-tea and rubber-cocoa systems. However, the decline of SWC did not reduce the utilization of surface soil water by the rubber trees. On the contrary, the rubber trees probably absorbed more shallow soil water in all the agroforestry practices (Fig. 7). These results suggested that complementarity was operating through increased surface water availability rather than by divergence in water acquisition depth. Thus, more surface water is likely to be consumed in intercropping agroforestry systems.

The water use pattern of rubber trees was less clear in wet months, as reflected by the weaker gradients of soil water δD and δ^{18}O (Fig. 4). The δD and δ^{18}O of xylem water and soil water often overlapped across all layers. In fact, this is a common feature in tropical and subtropical areas (Drake and Franks, 2003; Querejeta et al., 2007). About 80 % of the total rainfall occurs between May and October in this area (Zhu et al., 2018). Under such conditions, plant water uptake patterns tend to be determined by other parameters, such as soil moisture conditions and leaf water potential (Stahl et al., 2013; Yang et al., 2015). However, the increased degrees of RDSW were less pronounced than that reported in a semiarid agroforestry system (Gao et al., 2018). Compared to those in the dry season, RDSWs in the wet season were higher in all of the agroforestry systems (Fig. 7). This showed that facilitative effects dominated interspecific water competition in the agroforestry systems. It was not necessary for the rubber trees to acquire water from deeper sources. We can therefore infer that both the rubber trees and intercrops still relied mainly on shallow soil water in the wet season. The role of shallow soil water as a potential resource might be underestimated during this period. Furthermore, there is mounting concern that models of agroforestry systems have the potential to advance ecological understanding of the interactions in agroforestry practices in both space and time (Luedeling et al., 2016; Burgess et al., 2019; Dupraz et al., 2019). Therefore, further studies of agroforestry models can be expected to provide more insights to the above-mentioned issues.

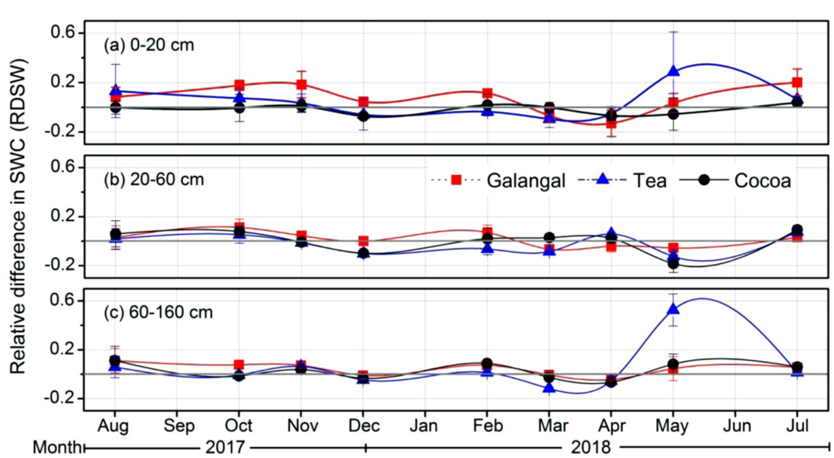

Fig. 6. Relative difference in soil water content (RWSD) in shallow (0-20 cm), middle (20-60 cm), and deep (60-160 cm) soil layers for (a) the rubber-galangal system, (b) the rubber-tea system, and (c) the rubber-cocoa system. Error bars represent one standard deviation.

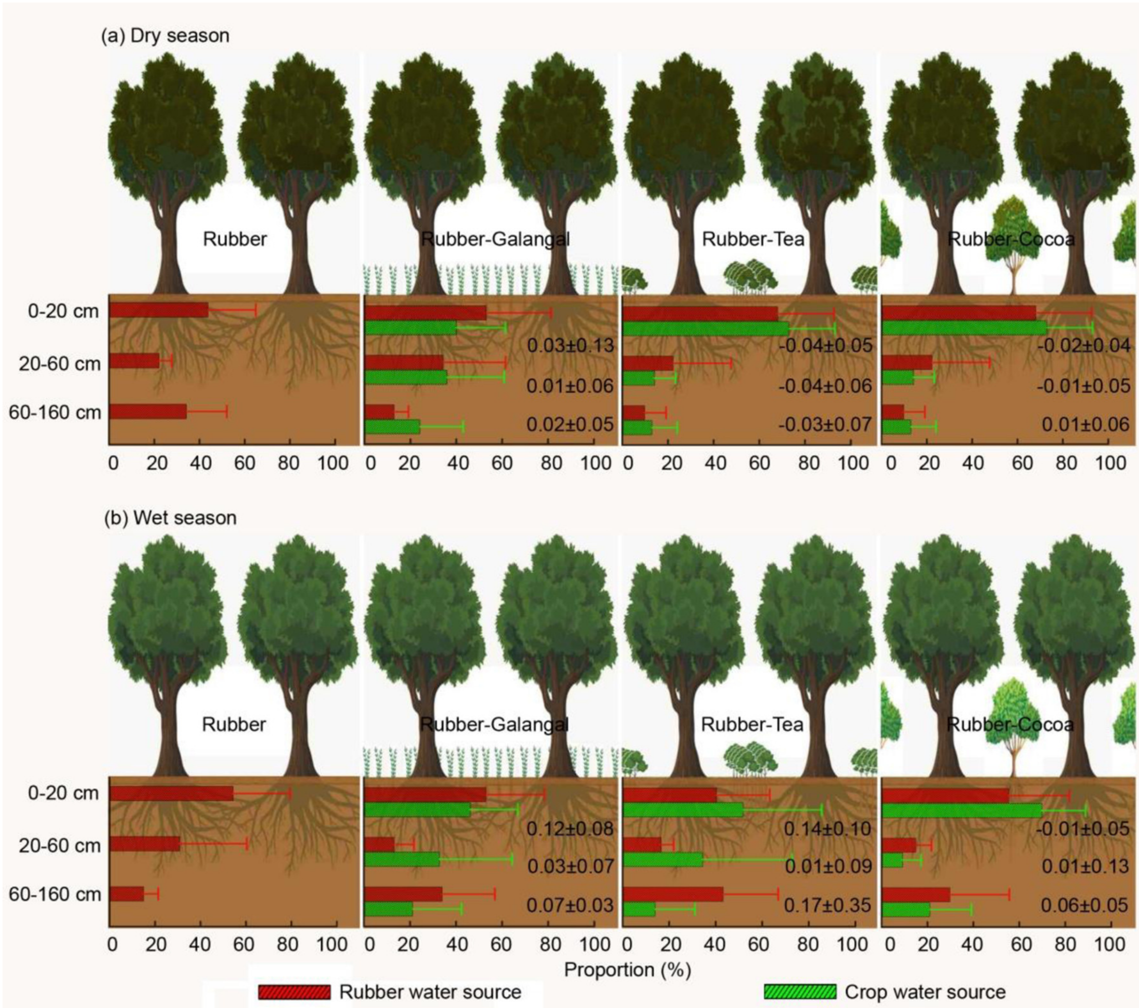

Fig. 7. Schematic illustrating the water source of rubber trees and intercrops in the dry and wet seasons. Numbers indicate the comprehensive impact of intercrops on soil water content (i.e., RDSW). Error bars represent one standard deviation.

5. Conclusion

In this study, the water uptake patterns of rubber trees were observed for three types of intercropping agroforestry practices. Our results showed that interspecific water competition occurred between the rubber trees and the intercrops during both dry (November-April) and wet (May-October) seasons. This was probably because the fine roots of the rubber trees (≥ 60.7 %) and the intercrops (50.2–62.4 %) were mainly concentrated in the shallow (0 − 20 cm) soil stratum. In the dry season, the rubber trees could absorb more shallow soil water where intercrops were present. This indicated that the intercrops enhanced soil moisture availability at this time. Water competition between the rubber trees and the intercrops was also observed in the peak wet season, during which the rubber trees still competed for shallow water resources with the intercrops. Increased RDWS values suggested that the intercrops were consistently facilitative in this respect in all the agroforestry systems. The facilitative effects were greatest in the rubber-galangal system followed by the rubber-tea system and the rubber-cocoa system. These findings should encourage the development of rubber-based agroforestry practices in Southeast Asia, which aim to improve soil water management and maximize latex productivity.

Declaration of Competing Interest

The authors declare that there are no known competing financial interests or personal relationships that will influence the current work reported in this paper.

Acknowledgements

The authors thank the two anonymous reviewers for providing the valuable comments. We wish to thank M.N. Liu, H.L. Qin, and Y. Deng for their contribution to this work. The study was funded by the Natural Science Foundation of China (31700560, 31670452), the Natural Science Foundation of Yunnan Province (2018FB043), the "Western Light Program" of the Chinese Academy of Sciences, and the CAS135-Program (2017XTBG-F01). It was supported by Xishuangbanna Station for Tropical Rainforest Ecosystem Studies (XSTRE) and the Central Laboratory of XTBG.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agee.2020.106937.

References

Anderson, L.S., Sinclair, F.L., 1993. Ecological interactions in agroforestry systems. Agrofor. Abstr. 6, 57–91.
Asbjornsen, H., Shepherd, G., Herlmers, M., Mora, G., 2008. Seasonal pattern in depth of water uptake under contrasting annual and perennial systems in the corn belt region

of the Midwestern US. Plant Soil 308, 62–92.
Barnard, R.L., de Bello, F., Gilgen, A.K., Buchmann, N., 2006. The δ^{18}O of root crown water best reflects source water δ^{18}O in different types of herbaceous species. Rapid Commun. Mass Spectrom. 20, 3799–3802.
Burgess, U., Graves, A., Palma, J., Jalón, S.G., Palma, J.H.N., Dupraz, C., Noordwijk, M.V., 2019. Modelling agroforestry systems. In: Mosquera-Losada, M.R., Prabhu, R. (Eds.), Agroforestry for Sustainable Agriculture. Burleigh Dodds Science Publishing Limited, pp. 209–238.
Carr, M.K.V., Lockwood, G., 2011. The water relations and irrigation requirements of cocoa (*Theobroma cacao* L.): a review. Exp. Agr. 47, 653–676.
Chen, C.F., Liu, W.J., Jiang, X.J., Wu, J.E., 2017. Effects of rubber-based agroforestry systems on soil aggregation and associated soil organic carbon: implications for land use. Geoderma 299, 13–24.
Drake, P.L., Franks, P.J., 2003. Water resource partitioning, stem xylem hydraulic properties, and plant water use strategies in a seasonally dry riparian tropical rainforest. Oecologia 137, 321–329.
Dupraz, C., Wolz, K.J., Lecomte, I., Talbot, G., Vincent, G., Mulia, R., Bussière, F., Ozier-Lafontaine, H., Andrianarisoa, S., Jackson, N., Lawson, G., Dones, N., Sinoquet, H., Lusiana, B., Harja, D., Domenicano, S., Reyes, F., Gosme, M., Noordwijk, M.V., 2019. Hi-sAFe: a 3D agroforestry model for integrating dynamic tree-crop Interactions. Sustainability 11, 2293.
Eggemeyer, K.D., Awada, T., Harvey, F.E., Wedin, D.A., Zhou, X.H., Zanner, C.W., 2009. Seasonal changes in depth of water uptake for encroaching trees *Juniperus virginiana* and *Pinus ponderosa* and two dominant C_4 grasses in a semiarid grassland. Tree Physiol. 29, 157–169.
Ehleringer, J.R., Dawson, T.E., 1992. Water uptake by plants: perspectives from stable isotope composition. Plant Cell Environ. 15, 1073–1082.
Fernández, M.E., Gyenge, J.E., Schlichter, T.M., 2007. Balance of competitive and facilitative eff ;ects of exotic trees on a native patagonian grass. Plant Ecol. 188, 67–76.
Fox, J.M., Castella, J.C., Ziegler, A.D., Westley, S.B., 2014. Rubber plantations expand in mountainous Southeast Asia: what are the consequences for the environment? Asia Pacific Issues 114, 1–8.
Gao, X.D., Liu, Z.P., Zhao, X.N., Ling, Q., Huo, G.P., Wu, P., 2018. Extreme natural drought enhances interspecific facilitation in semiarid agroforestry systems. Agric. Ecosyst. Environ. 265, 444–453.
IPCC, 2013. Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Li, H.M., Ma, Y.X., Liu, W.J., Liu, W.J., 2012. Soil changes induced by rubber and tea plantation establishment: comparison with tropical rain forest soil in Xishuangbanna, SW China. Environ. Manage. 50, 837–848.
Lin, B.B., 2010. The role of agroforestry in reducing water loss through soil evaporation and crop transpiration in coffee agroecosystems. Agric. For. Meteorol. 150, 510–518.
Liu, W.J., Li, J.T., Lu, H.J., Wang, P.Y., Luo, Q.P., Liu, W.Y., Li, H.M., 2014. Vertical patterns of soil water acquisition by non-native rubber trees (*Hevea brasiliensis*) in Xishuangbanna, southwest China. Ecohydrology 7, 1234–1244.
Lott, J.E., Khan, A.A.H., Black, C.R., Ong, C.F., 2003. Water use in *Grevillea roobusta*-maize overstory agroforestry system in semi-arid Kenya. Forest Ecol. Manage. 180 (1–3), 45–59.
Luedeling, E., Smethurst, P.J., Baudron, F., Bayala, J., Huth, N.I., Noordwijk, M., Ong, C.K., Mulia, R., Lusiana, B., Muthuri, C., Sinclair, F.L., 2016. Field-scale modeling of tree–crop interactions: challenges and development needs. J. Agric. Food Syst. Community Dev. 142, 51–69.
Mann, C.C., 2009. Addicted to rubber. Science 325, 564–566.
Meinzer, F.C., Andrade, J.L., Goldstein, G., Holbrook, N.M., Cavelier, J., Wright, S.J., 1999. Partitioning of soil water among canopy trees in a seasonally dry tropical forest. Oecologia 121, 293–301.
Monteith, J.L., Ong, C.K., Corleet, J.E., 1991. Microclimatic interactions in agroforestry systems. In: Jarvis, P.G. (Ed.), Agroforestry: Principles and Practice. Elsevier, Amsterdam.
Moreno, F., Fernandez, J.E., Clothier, B.E., Green, S.R., 1996. Transpiration and root water uptake by olive trees. Plant Soil 184, 85–96.
Muñoz-Villers, L.E., Holwerda, F., Alvarado-Barrientos, M.S., Geissert, D.R., Dawson, T.E., 2018. Reduced dry season transpiration is coupled with shallow soil water use in tropical montane forest trees. Oecologia 188, 303–317.
Pavlidis, G., Tsihrintzis, V.A., 2017. Environmental benefits and control of pollution to surface water and groundwater by agroforestry systems: a review. Water Resour. Manag. 32, 1–29.
Priyadarshan, P., 2011. Biology of Hevea Rubber. CABI, Wallingford, UK.
Querejeta, J.I., Estrada-Medina, H., Allen, M.F., Jiménez-Osornio, J.J., 2007. Water source partitioning among trees growing on shallow karst soils in a seasonally dry tropical climate. Oecologia 152, 26–36.
Schenk, H.J., Jackson, R.B., 2005. Mapping the global distribution of deep roots in relation to climate and soil characteristics. Geoderma 126, 129–140.
Schwendenmann, L., Veldkamp, E., Moser, G., Hölscher, D., Köhler, M., Clough, Y., Anas, I., Djajakirana, G., Erasmi, S., Hertel, D., Leitner, D., Leuschner, C., Michalzik, B., Propastin, P., Tjoa, A., Tscharntke, T., Straaten, O.V., 2010. Eff ;ects of an experimental drought on the functioning of a cacao agroforestry system, Sulawesi, Indonesia. Glob. Change Biol. Bioenergy 16, 1515–1530.
Schwendenmann, L., Pendall, E., Sanchez-Bragado, R., Kunert, N., Hölscher, D., 2015. Tree water uptake in a tropical plantation varying in tree diversity: interspecific differences, seasonal shifts and complementarity. Ecohydrology 8, 1–12.
Smith, D.M., Jarvis, P.G., Odongo, J.C.W., 1997. Sources of water used by trees and millet in Sahelian windbreak systems. J. Hydrol. 198, 140–153.
Stahl, C., Herault, B., Rossi, V., Burban, B., Brechet, C., Bonal, D., 2013. Depth of soil water uptake by tropical rainforest trees during dry periods: does tree dimension matter? Oecologia 173, 1191–1201.
Tan, Z.H., Zhang, Y.P., Song, Q.H., Liu, W.J., Deng, X.B., Tang, J.W., Deng, Y., Zhou, W.J., Yang, L.Y., Yu, G.R., Liang, N.S., 2011. Rubber plantations act a water pumps in tropical China. Geophys. Res. Lett. 38, L24406.
Tang, Y.K., Wen, X.F., Sun, X.M., Zhang, X.Y., Wang, H.M., 2014. The limiting effect of deep soil water on evapotranspiration of a subtropical coniferous plantation subjected to seasonal drought. Adv. Atmos. Sci. 31, 385–395.
Tang, Y.K., Wu, X., Chen, Y.M., Wen, J., Xie, Y.L., Lu, S.B., 2018. Water use strategies for two dominant tree species in pure and mixed plantations of the semiarid Chinese Loess Plateau. Ecohydrology 11, e1943.
Tobella, A.B., Hasselquist, N.J., Bazié, H.R., Nyberg, G., Laudon, H., Bayala, J., Ilstedt, U., 2017. Strategies trees use to overcome seasonal water limitation in an agroforestry system in semiarid West Africa. Ecohydrology 10, 1–10.
van Noordwijk, M., Lawson, G., Hairiah, K., Wilson, J., 2015. Root distribution of trees and crops: competition and/or complementarity. In: Ong, C.K., Black, C.R., Wilson, J. (Eds.), Tree-Crop Interactions: Agroforestry in a Changing Climate, 2nd ed. CAB International, Wallingford, UK, pp. 221–257.
Vandermeer, J., 1989. The Ecology of Intercropping Systems. Cambridge University Press, Cambridge.
West, A.G., Dawson, T.E., February, E.C., Midgley, G.F., Bond, W.J., Aston, T.L., 2012. Diverse functional responses to drought in a mediterranean-type shrubland in South Africa. New Phytol. 195, 396–407.
Wu, J.E., Liu, W.J., Chen, C.F., 2016. Can intercropping with the world's three major beverageplants help improve the water use of rubber trees? J. Appl. Ecol. 53, 1787–1799.
Yang, B., Wen, X.F., Sun, X.M., 2015. Seasonal variations in depth of water uptake for a subtropical coniferous plantation subjected to drought in an East Asian monsoon region. Agric. For. Meteorol. 201, 218–228.
Yang, B., Wang, P.Y., You, D.B., Liu, W.J., 2018. Coupling evapotranspiration partitioning with root water uptake to identify the water consumption characteristics of winter wheat: a case study in the north China Plain. Agric. For. Meteorol. 259, 296–304.
Zhu, X.A., Liu, W.J., Jiang, X.J., Wang, P.Y., Li, W.X., 2018. Effects of land-use changes on runoff and sediment yield: implications for soil conservation and forest management in Xishuangbanna, Southwest China. Land Degrad. Dev. 29, 2962–2974.