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Herbs perform better than woody plants at improving soil hydrological properties in rubber agroforestry systems

Enfu Lu · Bin Yang · Wenjie Liu · Xiai Zhu

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Abstract Soil hydrological properties play a key role in the balance of water and heat, as well as the stability of ecosystems. Understanding the differences in soil hydrological properties between rubber-woody plant and rubber-herb agroforestry systems (RW and RH) is important to construct suitable rubber-based agroforestry systems. Soil physical and hydrological properties from 105 soil cores were measured in three types of rubber plantations in Xishuangbanna, Southwest China. Results showed that at depth of 0–10 cm, the soil bulk density was highest in rubber monoculture (RM), which also had the lowest soil porosity. Soil initial gravimetric water content in different types of plantations followed the order RH > RW > RM at depth of 0–10 cm. Coefficient of variation among soil saturated water capacity, capillary holding capacity, field water capacity and initial gravimetric water content in different plantations followed the order RM > RW > RH. Correlation coefficients among soil saturated water capacity, capillary holding capacity and field water capacity were 0.882–0.990, whereas those between initial gravimetric water content and them were 0.290–0.547. These results indicate that the soil water retention capacity in different types of plantations followed the order RH > RW > RM. Intercropping can improve soil structure and hydrological properties of topsoil, particularly intercropping herbs with rubber was better than woody plants for improving the soil hydrological functions in rubber plantation.

Keywords Intercropping · Land degradation · Agroforestry system · Soil water content · Soil water retention capacity

E. Lu · B. Yang · W. Liu · X. Zhu (✉)
CAS Key Laboratory of Tropical Forest Ecology, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Menglun 666303, Yunnan, China
e-mail: zhuxiai@xtbg.ac.cn

E. Lu · B. Yang · W. Liu · X. Zhu
Center of Plant Ecology, Core Botanical Gardens, Chinese Academy of Sciences, Menglun 666303, Yunnan, China

E. Lu
University of Chinese Academy of Sciences, Beijing 100049, China

Introduction

Soil hydrological properties are essential ecological factors for plant growth (Pavlik 2001; Al-Seekh and Mohammad 2009). They affect the interaction between the soil and atmosphere, thus controlling the forest hydrological process and the stability of the whole ecosystem (Mallet et al. 2020). Understanding the temporal and spatial variation of soil water is very significant for comprehending hydrological processes (Cho and Choi 2014). Soil water can be changed by many factors, including climate conditions, soil physical properties, topographic features, and land use types (Jia et al. 2017; Mallet et al. 2020). Soil water

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temporal stability is an index reflecting the change of soil water spatial patterns over time, higher temporal stability indicating slower change. Xin et al. (2008) found that the soil water temporal stability tends to be low once it was disturbed (e.g., alternating wet and dry conditions). Soil water temporal stability can be determined using the Spearman rank correlation coefficient (Zhao et al. 2020).

In humid tropical areas, many forests are rapidly being converted into rubber plantations (Zeng et al. 2021). Rubber plantation area has been reported to have increased nearly 6-fold in southwest China from 1987 to 2018 (Xiao et al. 2019). Previous research indicated that rubber monoculture (RM) led to serious soil erosion, biodiversity loss, and increased diseases and pests (Li et al. 2007; Mann 2009; Zhu et al. 2018). Moreover, there are many large lactiferous vessels inside the rubber tree, which lead to its requirement for large amounts of water, having a negative impact on water resources (Isarangkool Na Ayutthaya et al. 2011). Qiu (2009) found that rubber tree can be regarded as a pump, increasing evapotranspiration and depleting soil water in the dry season, which can result in regional water shortages. Soil water deficit occurs once plant transpiration and soil evaporation exceed rainfall supply according to Jia et al. (2017). Due to the ecological problems caused by RM and the decline of the rubber price, the government and scientists have developed many agroforestry systems that intercrop rubber trees with economic crops or medicinal plants (Feng 2007; Hammond et al. 2015; Xiao et al. 2019). Rubber-based agroforestry systems have replaced around 5% of RM in Xishuangbanna, Southwest China (Liu et al. 2016). Previous studies have shown that intercropping can improve soil physico-chemical properties, maintain a high diversity of agricultural products, and ameliorate the ecological and environmental problems caused by rubber monoculture (Zhu et al. 2018; Chen et al. 2019).

There are many ecological differences between the woody and herbaceous plants used for intercropping. For instance, the root system of herbs is shorter than that of woody plants; also, herbs mainly utilize the sunlight of the understory and can coexist well with woody plants in natural ecosystems. Previous studies conducted at Xishuangbanna mainly focused on rubber-woody plant agroforestry systems (RW), such as rubber-*Camellia sinensis*, rubber-*Coffea arabica*, and rubber-*Rauvolfia verticillata*. However, few studies have looked at rubber-herb agroforestry systems (RH) (Liu et al. 2016; Zhu et al. 2018; Chen et al. 2019). Moreover, a comparison between RW and RH has rarely been carried out.

Previous studies have mainly focused on a single index of soil water content (initial gravimetric water content), and the different indexes of soil water content among different forest types have rarely been analyzed comprehensively (She et al. 2010; Yang et al. 2012; Jia et al. 2017; Yu et al. 2019). Studies conducted in this region mention soil water content briefly, but seldom refer to its internal mechanisms and potential impacts (Zhu et al. 2019; Zeng et al. 2021; Zou et al. 2021). Soil water retention capacity is very significant for plant growth and water resource regulation. This is especially true in Xishuangbanna, which suffers water scarcity in the dry season due to 87% of its rainfall occurring in the rainy season. The balance and stability of soil water content are crucial for rubber planting because of the high water dependence of the rubber tree (Zhu et al. 2019). Furthermore, a better intercropping pattern (e.g., rubber with herbs or woody plants) needs to be researched for recommendation to policy makers and land owners.

To estimate the variation and influencing factors in soil hydrological properties among the different types of plantations, an RM, two RH, and two RW were chosen for investigation of the soil physical and hydrological properties. Specifically, the aims of this study were: (1) to compare the difference in soil water content among different types of plantations. (2) to compare the soil water retention capacity among the different types of plantations; and (3) to evaluate the relationships between soil water content, bulk density, porosity, and composition of the soils' initial state, thus revealing the factors that affect soil water content in different types of plantations. We hypothesized that (1) the difference of initial gravimetric water content among different plantation types were greater than saturated water capacity, capillary holding capacity, and field water capacity. (2) the soil water retention capacity among the different types of plantations followed the order RH > RW > RM. (3) soil water content were affected by soil properties (e.g., texture, porosity) and other environmental factors (e.g., the evapotranspiration and water absorption rates of plants).

Materials and methods

Study site

The study site was located in the Xishuangbanna Tropical Botanical Garden (21°55′39″N, 101°15′55″E), Yunnan Province, southwest of China. This region has a tropical monsoon climate with two distinct seasons: November–April is the dry season and May–October is the rainy season with annual average temperature of 20–22.5 °C per year, and an average rainfall of 1200–1800 mm, 90% of which occurs in the rainy season (Xiao et al. 2019; Zou et al. 2021). The relative humidity of the region is 86%, and the dryness index is 1.01 (Hammond et al. 2015). The sample plots are adjacent to each other: the RM, rubber-*Alpinia oxyphylla* and rubber-*Alpinia officinarum* agroforestry systems are in one area, at a distance of 100 m from each other; the rubber-*Camellia sinensis* and rubber-*Coffea arabica* are in another area, at a distance of 50 m from each other. The distance between the above two areas is about 200 m. *Alpinia oxyphylla* and *Alpinia officinarum* are herbs; rubber (*Hevea brasiliensis*), *Camellia sinensis* and *Coffea arabica* are woody plants. The soil is a thick latosol, and the inter-cropped plants were grown under the rubber trees. There are no irrigation activities in the sample plots.

The plant height, first branch height, and stem diameter were measured using a measuring pole, tape, and caliper. The leaf area index and mean foliage tilt angle were measured using a plant canopy analyzer (LAI-2200; Li-Cor Inc., USA). More details can be found in Table 1.

Soil sampling and measuring methods

Soil samples were collected during the dry season, and there was no precipitation for half a month before the collection. The soil bulk density, porosity and soil water content were measured with a cutting-ring. Before the collection, an electronic balance was used to measure the weight of the hollow 200 cm^3 steel cylinders with a filter paper at the bottom (*Whsc*, g), then the undisturbed soil at depths of 10, 20, 30, 40, 60, 100, and 150 cm (each including three replicates) were collected using the cylinders. A total of 105 soil cores were thus collected. RM, RW and RH each collected 21, 42 and 42 soil cores respectively.

The specific method was as follows: the hollow steel cylinders were individually embedded into the excavated soil profile, then taken out. After flattening the surface of the soil cores, they were covered and brought back to the laboratory. The total weight of a steel cylinder containing soil (*Wscs*, g) was measured. The steel cylinders were then put into a water-filled container to absorb water for 24 h (the water level was nearly equal to the upper end of the steel cylinders, ensuring no water entered the soil samples from above). They were taken out and weighed (*Wsat*, g) after wiping off external water, then placed on dry sand and weighed again after 2 h (*W2h*, g). They were then put back on the dry sand for 5 days and weighed (*W5d*, g). Lastly, the steel cylinders were oven-dried

Table 1 General characteristics of the rubber trees and understory species in the different rubber plantations

Sample plot	*Hevea brasiliensis* (RM)	*Camellia sinensis*	*Coffea arabica*	*Alpinia oxyphylla*	*Alpinia officinarum*
Type	–	Woody plant	Woody plant	Herb	Herb
Height (m)	16.83 ± 0.11a	1.64 ± 0.06c	6.28 ± 0.50b	1.48 ± 0.08c	2.38 ± 0.05c
Basal diameter (cm)	65.87 ± 4.15a	1.98 ± 0.24b	8.85 ± 1.43b	0.95 ± 0.07b	1.78 ± 0.03b
Mean foliage tilt angle (°)	40.77 ± 0.17b	39.82 ± 0.3b	41.73 ± 0.22a	34.22 ± 0.43c	41.48 ± 0.19a
Leaf area index (m^2 m^{-2})	2.26 ± 0.02c	4.24 ± 0.13a	3.28 ± 0.02b	3.07 ± 0.12b	2.95 ± 0.05b
Crown base height (m)	12.33 ± 1.17a	0.27 ± 0.01b	2.20 ± 0.19b	0.00 ± 0.00b	0.00 ± 0.00b
Crown breadth (m)	9.67 ± 1.06a	1.34 ± 0.03b	2.79 ± 0.25b	1.68 ± 0.09b	–
Canopy cover (%)	64.83 ± 0.60d	93.00 ± 0.73a	80.50 ± 0.76c	87.00 ± 0.58b	80.67 ± 0.71c
Distance from rubber(m)	4.88 ± 0.17a	4.05 ± 0.81a	2.40 ± 0.04b	0.13 ± 0.04c	0.07 ± 0.03c

Data are expressed as the mean ± standard error (n = 6)

RM rubber monoculture

The different lowercase letters indicate significant differences between the different sites ($P < 0.05$)

(105 °C) to a constant weight ($Wscd$, g). The initial gravimetric water content (%), saturated water capacity (%), capillary holding capacity (%), field water capacity (%), bulk density (g cm^{-3}), capillary porosity (%), noncapillary porosity (%), total porosity (%), solid phase (%), liquid phase (%), and gas phase (%) were calculated using the following formulae (Chen 2005):

$$Initial\ gravimetric\ water\ content = \frac{W_{scs} - W_{scd}}{W_{scd} - W_{hsc}} \times 100\% \tag{1}$$

$$Saturated\ water\ capacity = \frac{W_{sat} - W_{scd}}{W_{scd} - W_{hsc}} \times 100\% \tag{2}$$

$$Capillary\ holding\ capacity = \frac{W_{2h} - W_{scd}}{W_{scd} - W_{hsc}} \times 100\% \tag{3}$$

$$Field\ water\ capacity = \frac{W_{5d} - W_{scd}}{W_{scd} - W_{hsc}} \times 100\% \tag{4}$$

$$Bulk\ density = \frac{W_{scd} - W_{hsc}}{200} \tag{5}$$

$$Capillary\ porosity = \frac{Capillary\ holding\ capacity \times Bulk\ density}{\rho_{water}} \times 100\% \tag{6}$$

$$Noncapillary\ porosity = \frac{(Saturated\ water\ capacity - Capillary\ holding\ capacity) \times Bulkdensity}{\rho_{water}} \times 100\% \tag{7}$$

$$Total\ porosity = Noncapillary\ porosity + Capillary\ porosity \tag{8}$$

$$Solid\ phase = 1 - Total\ porosity \tag{9}$$

$$Liquid\ phase = \frac{Initial\ gravimetric\ water\ content \times Bulk\ density}{\rho_{water}} \times 100\% \tag{10}$$

$$Gas\ phase = Total\ porosity - Liquid\ phase \tag{11}$$

Assessment of temporal stability of soil water content

Soil saturated water capacity, capillary holding capacity, field water capacity and initial gravimetric water content were the soil water content measured at four different times. Temporal stability of soil water content refers to the stability of soil water spatial patterns at these different times.

Spearman's rank correlation coefficient (rs) was used to reflect the temporal stability of soil water content at different spatial positions (Vachaud et al. 1985; Zhao et al. 2020), so as to evaluate the effects of environmental factors on soil water content. The calculation formula is as follows:

$$r_s = 1 - \frac{6\sum_{i=1}^{n}(R_{ij} - R_{il})^2}{n(n^2 - 1)} \tag{12}$$

where i, l (j) represent different locations and times, respectively; R_{ij} represents the rank of the soil water content at position i at measurement time j; R_{il} represents the rank of the soil water content at position i at measurement time l; n represents the number of positions for measuring the soil water content. The higher the value of r_s, the higher the temporal stability of soil water content.

Coefficient of variation of soil water content

Coefficients of variation (CV) were used to evaluate the changes in soil water content (Yang et al. 2014; Guo et al. 2020) and were calculated using the following formula:

$$CV = \frac{standard\ deviation}{mean} \times 100\% \tag{13}$$

where the higher the CV, the greater the level of difference. In this study, we defined CVs, CV_f, and CV_d as the CV of different soil water content types (saturated water capacity, capillary holding capacity, field water capacity, and initial gravimetric water content), different plantations (RM, RW, and RH), and different soil depths (10, 20, 30, 40, 60, 100, and 150 cm), respectively.

Statistical analysis

Statistical analyses were performed on the R platform, version 4.0.3. One-way ANOVA followed by the Tukey test was applied to assess the differences in general characteristics of the sample plots and the differences in soil physical and hydrological properties among different types of plantations. Spearman's rank correlation was applied to determine the correlation among the different soil physical and hydrological properties and the temporal stability of soil water spatial patterns. All statistical procedures were performed with an $\alpha = 0.05$ threshold for significance.

Results

Soil initial composition characteristics

Initial composition characteristics of soils are shown in Fig. 1. In general, solid phase significantly increased with soil depth across all types of plantations, whereas gas phase showed significant decreases with soil depth. The liquid phase significantly increased with soil depth in both RM and RW,

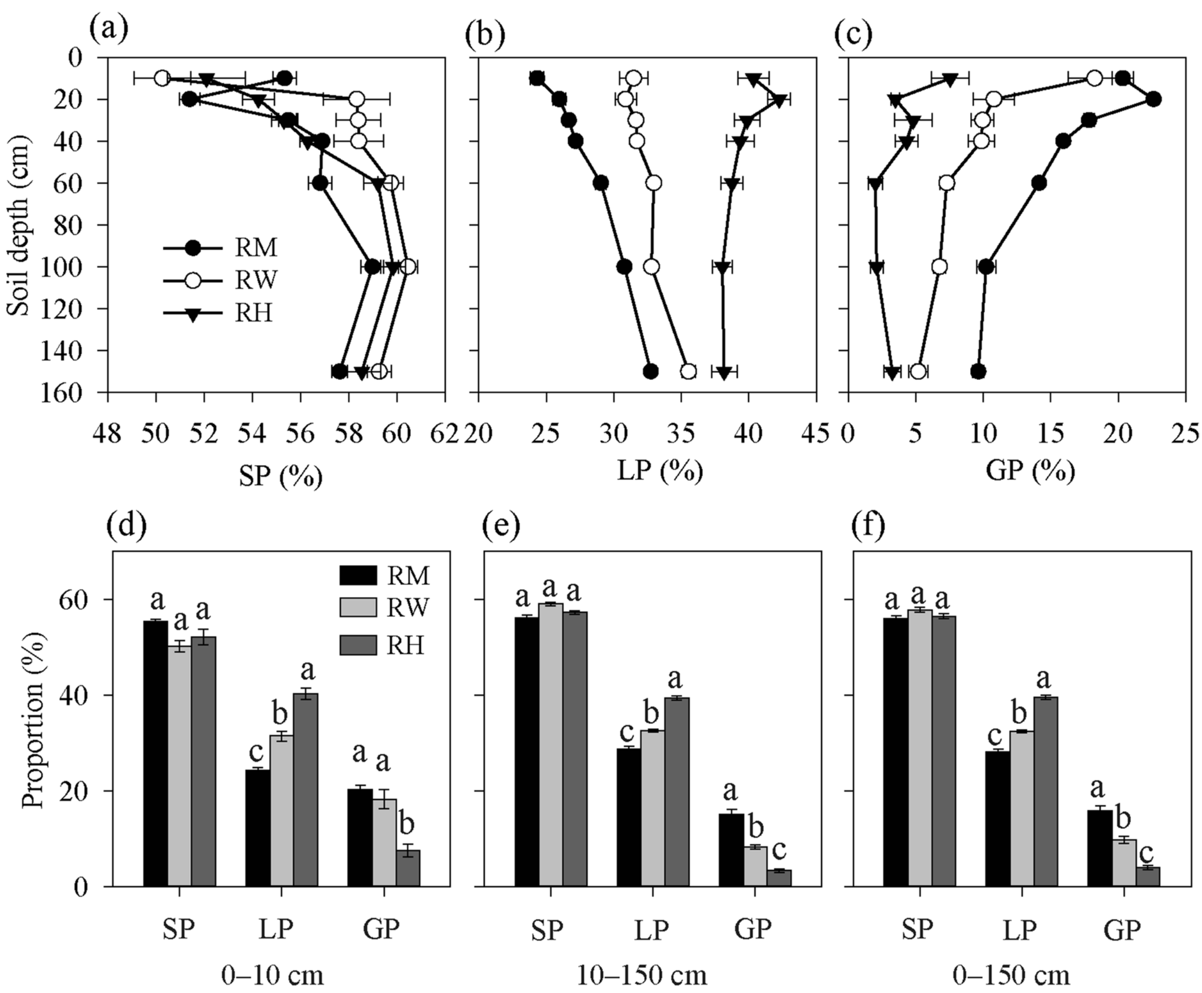

Fig. 1 **a–c** Variation in the *solid phase* (*SP*, %), *liquid phase* (*LP*, %), *gas phase* (*GP*, %) with soil depth, data are expressed as the mean ± standard error (n = 3–6). **d–f** *SP*, *LP* and *GP* of three types of plantations at different depth ranges, data are expressed as the mean ± standard error (n = 3–42); different lowercase letters indicate a significant difference at $P < 0.05$. *RM* rubber monoculture, *RH* rubber-herb agroforestry system, *RW* rubber-woody plant agroforestry system

whereas it decreased in RH (Fig. 1a–c). The solid phase in RM (55.34%) was higher than in the rubber-based agroforestry systems (RW: 50.26%, RH: 52.11%) at depth of 0–10 cm, whereas it was lower at depth of 10–150 cm (Fig. 1d–f). The liquid phase in the different plantations always followed the order RH (39.54%) > RW (32.42%) > RM (28.10%), whereas the gas phase followed the order RM (15.82%) > RW (9.74%) > RH (3.95%) at depth of 0–150 cm.

Soil bulk density and porosity

In general, the soil bulk density increased with soil depth, but clearly decreased at 10–20 cm in RM (Fig. 2a). There was no significant difference in soil bulk density across the three types of plantations at depth of 0–150 cm (Fig. 2b, $P > 0.05$). However, the soil bulk density in RM (1.40 g cm^{-3}) was significantly higher than in RW (1.22 g cm^{-3}) at depth of 0–10 cm, and it was significantly lower in RM (1.36 g cm^{-3}) than in RW (1.44 g cm^{-3}) and RH (1.43 g cm^{-3}) at depth of 10–150 cm ($P < 0.05$).

Soil porosity decreased with depth. No significant differences were revealed among the three types of plantations in each soil porosity type (Fig. 3, $P > 0.05$). The noncapillary porosity followed the order RM (1.66%) < RW (3.29%) < RH (3.42%) at depth of 0–10 cm, and the capillary porosity and total porosity followed the order RM < RH < RW. However, the noncapillary porosity, capillary porosity and total porosity followed the order RW < RH < RM at depth of 10–150 cm. Each soil porosity type in RM was lower than rubber-based agroforestry systems at depth of 0–10 cm, but an opposite trend was found at depth of 10–150 cm.

Soil water content characteristics

Generally, each soil water content type in RM increased at depth of 10–20 cm, then decreased, and then increased slightly (Fig. 4e–g). However, the different types of soil water content decreased initially and then increased slightly with soil depth in RW and RH. Each type of soil water content showed the same trend with soil depth in the same plantation type (Fig. 4e–g).

At a depth of 0–10 cm, the saturated water capacity, capillary holding capacity, and field water capacity in different types of plantations followed the order RM < RH < RW, and the initial gravimetric water content followed the order RM (17.33%) < RW (25.73%) < RH (30.58%, Fig. 4h, $P < 0.05$). At depth of 0–150, the saturated water capacity and capillary holding capacity followed the order RW < RH < RM, whereas the initial gravimetric water content followed the order RM (20.63%) < RW (23.16%) < RH (28.04%, $P < 0.05$). From saturated water capacity to field water capacity, the soil water content decline gradient in RM was the greatest, and the RH was lowest (Fig. 4e–j, $P < 0.05$).

The *CVs* in different types of plantations followed the order RM > RW > RH, which decreased with soil depth in each type of plantation. The sum of the *CVs* values of each soil layer was highest at 1.317 in RM, while the lowest value (0.308) was in RH (Fig. 5a). At depth of 0–10 cm, the CV_f followed the order: initial gravimetric water

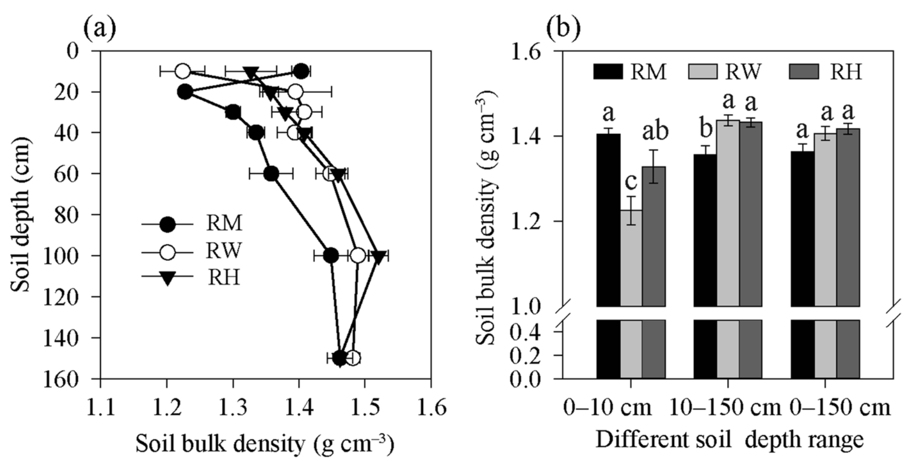

Fig. 2 **a** Variation in the soil bulk density (*BD*) with depth, data are expressed as the mean ± standard error (n = 3–6). **b** *BD* at different depth ranges, data are expressed as the mean ± standard error (n = 3–42); different lowercase letters indicate a significant difference at $P < 0.05$

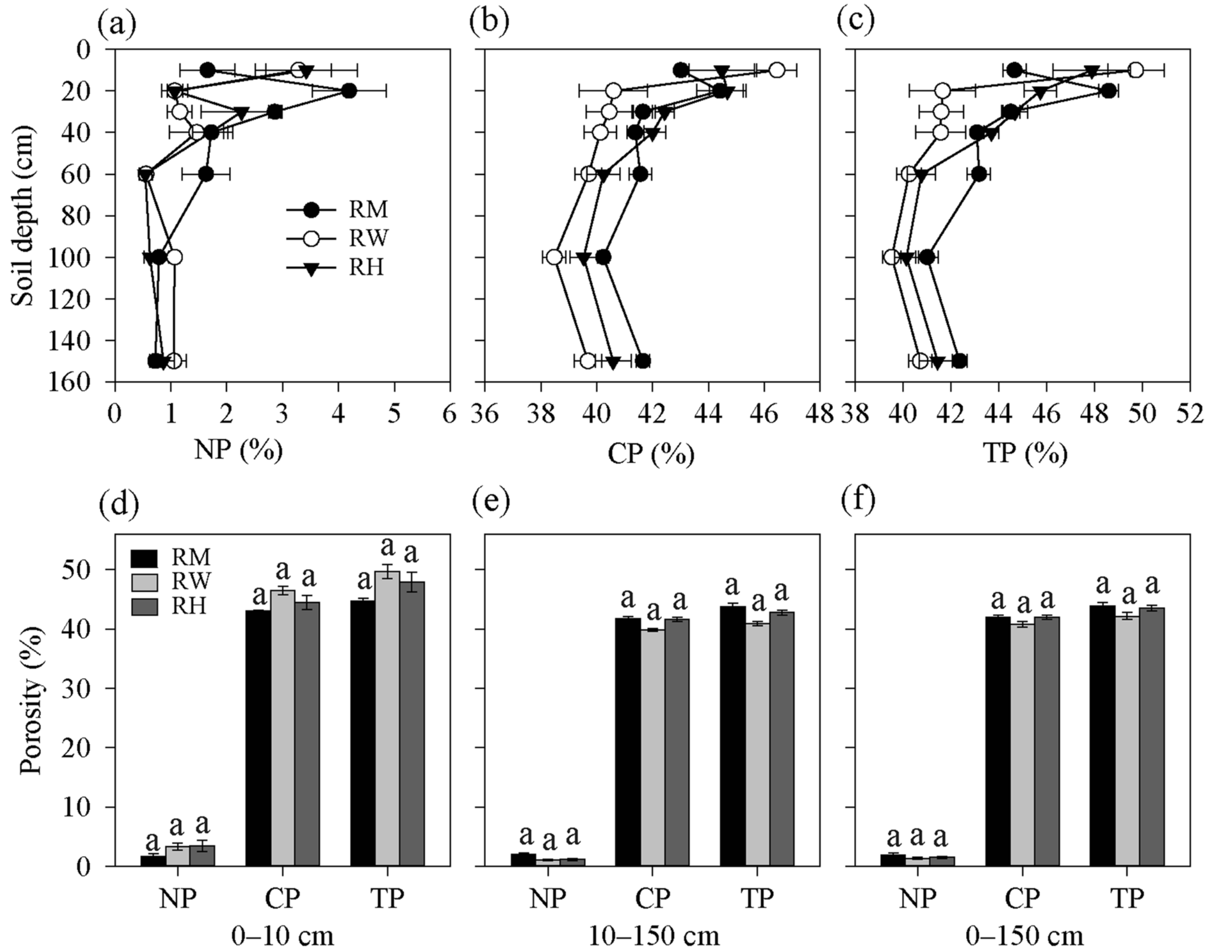

Fig. 3 **a–c** Variation in the capillary porosity (*CP*, %), non-capillary porosity(*NP*, %), total porosity (*TP*, %) with depth, data are expressed as the mean ± standard error (n = 3–6). **d–f** *NP*, *CP* and *TP* at different depth ranges, data are expressed as the mean ± standard error (n = 3–42). The same lowercase letters indicate that there are no significant differences among the three types of plantations in each soil porosity type at $P < 0.05$

content > saturated water capacity > capillary holding capacity > field water capacity. The CV_f also decreased with soil depth (Fig. 5b). The sum of the CV_f values for the initial gravimetric water content in each soil layer was highest (1.116), and for the field water capacity it was lowest (0.471). The CV_d in RW was relatively high, while in the RM and RH systems it was relatively low. The CV_d of saturated water capacity was the highest, but that of initial gravimetric water content was relatively low.

Relationship among soil properties, and soil water temporal stability

Spearman correlation analysis showed that there were significant positive correlations among saturated water capacity, capillary holding capacity, field water capacity and initial gravimetric water content (Table 2, $P < 0.01$). The correlation coefficients between saturated water capacity, capillary holding capacity and field water capacity were relatively high (ranging from 0.882 to 0.990), indicating high temporal stability of the soil water spatial pattern. The correlation coefficients between the initial gravimetric water content and other

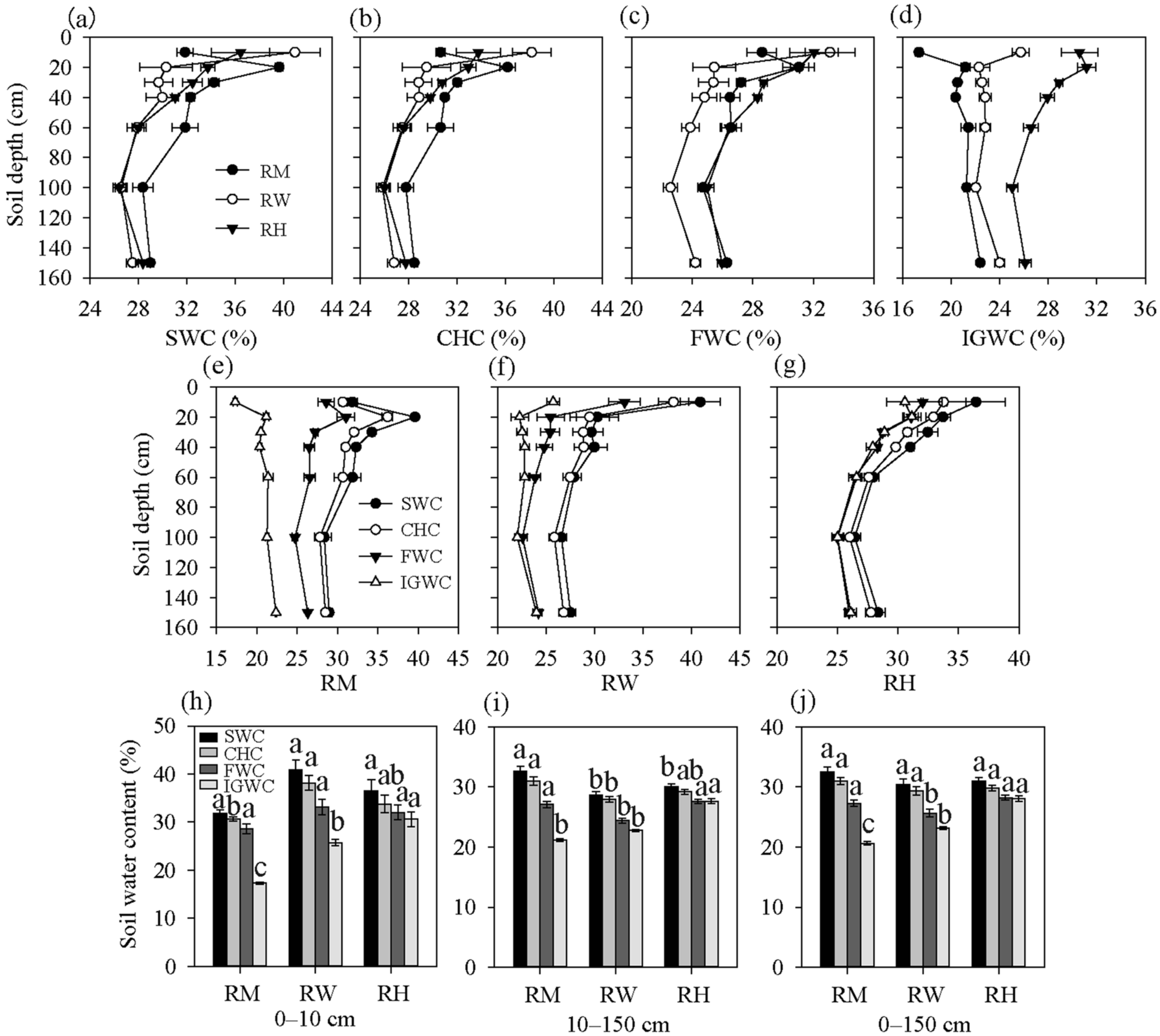

Fig. 4 **a**–**g** variation in the saturated water capacity (*SWC*, %), capillary holding capacity (*CHC*, %), field water capacity (*FWC*, %), initial gravimetric water content (*IGWC*, %) with depth, data are expressed as the mean ± standard error (n = 3–6). **h**–**j** *SWC*, *CHC* and *FWC* at different depth ranges, data are expressed as the mean ± standard error (n = 3–42); different lowercase letters indicate a significant difference at $P < 0.05$

types of soil water content were relatively low (ranging from 0.290 to 0.547), indicating low temporal stability of soil water spatial pattern. The soil water content was negatively correlated with the bulk density and solid phase but positively correlated with the soil porosity.

Discussion

Effects of intercropping on soil bulk density and soil porosity

Soil bulk density and soil porosity are essential indexes for evaluation of soil properties. Excessive

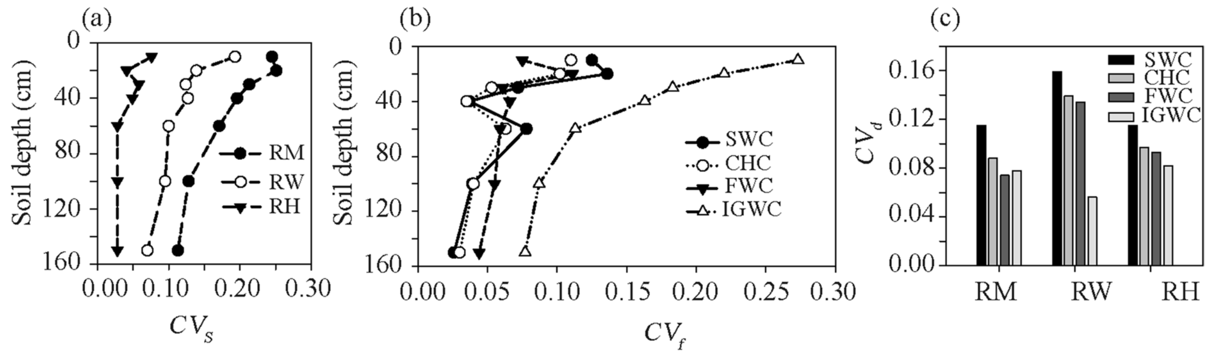

Fig. 5 Variation of the *CVs* (**a**), CV_f (**b**) with depth. CV_d (**c**) for three types of plantations and four different types of soil water content. Data are expressed as the mean. *CVs*: the coefficient of variation of soil water content among four soil water content types. CV_f: the coefficient of variation of soil water content among three types of plantations. CV_d: the coefficient of variation of soil water content among different soil depths

soil bulk density will hinder root penetration and thus plant growth (Burr-Hersey et al. 2020). The pore is an important storage space for soil water, and an essential channel for gas exchange between soil and atmosphere (Feiza et al. 2014). Good pore conditions are, therefore, conducive to the growth of plants (Passioura 2002).

In this study, soil bulk density in RM was significantly higher than in RW at depth of 0–10 cm ($P<0.05$). However, the bulk density in RM was significantly lower than in the intercropping systems ($P<0.05$) at depth of 10–150 cm. These results show that intercropping mainly reduced the bulk density of the topsoil. The capillary porosity and total porosity in different types of plantations followed the pattern RM < RH < RW at depth of 0–10 cm. However, they followed the pattern RW < RH < RM at depth of 10–150. These results indicate that intercropping can improve the porosity of the topsoil, especially intercropping with woody plants. Most plant roots are distributed in the topsoil, therefore covering with different plants has a greater impact on topsoil, and less on the deeper soil (Gao et al. 2010; Zhang et al. 2021). Moreover, the bulk density and porosity of topsoil in the agroforestry systems were lower and higher than in the RM, respectively, while those at the deeper layers were higher and lower than in the RM, respectively. These results indicate that the low topsoil bulk density and high topsoil porosity in the agroforestry systems were not inherent characteristics of the soil matrix itself, but were caused by intercropping. This is consistent with a previous study that found that the intercropping system can decrease topsoil bulk density and increase topsoil porosity (Su et al. 2022).

Impact of intercropping on soil water content

Previous studies have reported that intercropping can improve soil physical quality, such as temperature and water, and change the earthworm activities, fertility and ecosystem services (Olasantan et al. 1996; Jose 2009; Stöcker et al. 2020). Our study showed that the CV_f of initial gravimetric water content was higher than that of saturated water capacity, capillary holding capacity, field water capacity (Fig. 5b), demonstrating that hypothesis (1) was reasonable. This may be because the factors affecting initial gravimetric water content were more numerous than those affecting the other three soil water content types. The CV_f decreased with increasing soil depths, which indicated that the differences of soil water content among the three types of plantations were greater in the topsoil, and decreased with increasing soil depths, indicating that intercropping mainly had a greater impact on the soil water content of topsoil. This result was consistent with that found by Zhu et al. (2018) reported that initial gravimetric water content and field water capacity of topsoil in rubber monoculture were lower than in tropical seasonal rainforest.

In Xishuangbanna, the introduction of rubber has led to drought and water shortage (Qiu 2009; Tan et al. 2011). Furthermore, the soils in this study were sampled under relatively dry soil conditions, when the initial gravimetric water content was less

Table 2 Correlation coefficients of soil physical properties

Indicator	SWC	CHC	FWC	IGWC	BD	TP	NP	CP	SP	LP	GP
SWC	1	0.990***	0.882***	0.290**	−0.945***	0.958***	0.732***	0.887***	−0.958***	−0.102	0.528***
CHC		1	0.896***	0.307**	−0.936***	0.948***	0.655***	0.914***	−0.948***	−0.080	0.492***
FWC			1	0.547***	−0.764***	0.920	0.541***	0.916	−0.920***	0.212*	0.193*
IGWC				1	−0.149	0.394	0.046	0.453	−0.394***	0.882***	−0.588***
BD					1	−0.820	−0.700***	−0.726	0.820***	0.259**	−0.617***
TP						1	0.716***	0.951	−1.000***	0.048	0.402***
NP							1	0.509	−0.716***	−0.243**	0.583***
CP								1	−0.951***	0.138	0.281***
SP									1	−0.048	−0.402**
LP										1	−0.851***
GP											1

SWC saturated water capacity (%), *CHC* capillary holding capacity (%), *FWC* field water capacity (%), *IGWC* initial gravimetric water content, *BD* soil bulk density (g cm^{-3}), *TP* total porosity (%), *NP* noncapillary porosity (%), *CP* capillary porosity (%), *SP* solid phase (%), *LP* liquid phase (%), *GP* gas phase (%)

*$P<0.05$; **$P<0.01$; ***$P<0.001$

than the field water capacity. There was no significant difference in the field water capacity among the three types of plantation systems, but the initial gravimetric water content followed the order RH > RW > RM in the topsoil (Fig. 4h, $P<0.05$). This showed that agroforestry systems, especially RH, significantly improved the soil water retention capacity of topsoil. This is consistent with the findings of Cui et al. (2022) that mattic epipedon cover can improve soil water conservation. From saturated water capacity to capillary holding capacity, then to field water capacity, the water decline gradient of RH was the lowest at depth of 0–10 cm, which also showed that the soil water retention capacity of RH in the topsoil was the highest. It is significant for plant growth in the dry season when there is insufficient water (Tan et al. 2011).

In the entire soil profile, the difference among saturated water capacity, capillary holding capacity, and field water capacity in the RH was lower when compared with RW and RM (Fig. 4e–g), which also showed that the soil water retention capacity in RH was higher than RW and RM. The results were consistent with a previous study that the sandy initial gravimetric water content showed grassland > cropland > poplar land (Niu et al. 2015). Furthermore, there was no significant difference in each type of soil porosity among the three plantation types (Fig. 3d–f). However, the initial gravimetric water content was much greater in the RH than the other two plantation types (Fig. 4j, $P<0.05$). This demonstrated that the higher soil water retention capacity in RH than in RM and RW did not mainly depend on soil porosity but also depended on other environmental variables (e.g., evapotranspiration and the water absorption rates of plants). The CV_S in different types of plantations followed the order RM > RW > RH across the entire profile (Fig. 5a), indicating that the soil water retention capacity in different types of plantations followed the order RH > RW > RM. These above discussions verified that hypothesis (2) was reasonable. The liquid phase in different types of plantations showed the order RM < RW < RH ($P<0.05$), indicating that intercropping herbs with rubber can increase the proportion of liquid phase more than intercropping woody plants with rubber (Fig. 1d–f).

Relationships among soil properties, and soil water temporal stability

The saturated water capacity was negatively correlated with the soil bulk density but positively correlated with the soil porosity. It showed that a high pore space can store more soil water. The Spearman correlation coefficient among different types of soil water content reflected the temporal stability of the soil water spatial pattern. Temporal stability analysis of soil water showed that the correlation coefficients among saturated water capacity, capillary holding capacity and field water capacity were high, indicating that the temporal stability of soil water spatial pattern was high. The low correlation between initial gravimetric water content and other types of soil water content indicated low temporal stability of soil water spatial patterns between them. The initial gravimetric water content was affected by field factors (e.g., evapotranspiration and water absorption rates of plants), but the saturated water capacity, capillary holding capacity and field water capacity were types of soil water content produced in the laboratory, they were not affected by field factors. The above result, therefore, indicates that the temporal stability of the soil water spatial pattern was high when the soil water content was only affected by soil properties (e.g., texture, porosity). In contrast, when the soil water content was influenced by other field factors, the spatial pattern of the soil water content (initial gravimetric water content) was changed relative to the other types of soil water content that were produced indoors. This demonstrates that vegetation factors have a profound impact on the soil temporal stability. The result is consistent with the findings of Gómez-Plaza et al. (2000) that the soil water spatial pattern is relatively stable over time when only considering the geographical location and topography, but it becomes unstable when regarding the vegetation factors. Previous findings showed that trees consume more soil water through evapotranspiration than herbs (Cao et al. 2009), and the evapotranspiration in a rubber forest was higher than in tropical rain forest (Tan et al. 2011). Therefore, it is possible that the reason for the higher initial gravimetric water content in the RH was due to its lower evapotranspiration compared with the RM and RW because it has herbaceous plants under rubber tree. Intercropping herbaceous plants are expected to reduce the evapotranspiration in a rubber forest, which is of great significance to the protection of water resources in this region. The above discussions also verified that hypothesis (3) was reasonable. However, the specific mechanism needs to be clarified in future studies.

Implications and limitations

Xishuangbanna belongs to the tropical monsoon climate, which is characterized by non-uniform annual precipitation distribution. The plants here experience a long dry season (November–April). In addition, a large number of rubber plantations exacerbate the lack of water in the dry season (Qiu 2009; Tan et al. 2011; Liu et al. 2016). The high soil water retention capacity in this region is conducive to their survival. Moreover, the undergrowth vegetation is sparse in RM, with no blocking effect on throughfall/rainfall energy and surface runoff, thereby causing severe soil erosion in the RM (Zhu et al. 2018). In this study, intercropping reduced soil bulk density and increased all pore types in the topsoil (Fig. 2, 3d). This may result in more infiltration, reducing surface runoff and water erosion, as well as increasing recharge of groundwater in the agroforestry systems during the rainy season with concentrated rainfall (Olasantan et al. 1996). These results indicate that intercropping has a high potential value for sustainable water supply and rubber growth, thus promoting the production and may increase income (Mousavi and Eskandari 2011; Schwendenmann et al. 2015).

There are many differences in the characteristics of herbs and woody plants (Singleton et al. 2001; Liu et al. 2008). Our study has shown that there was a higher soil water retention capacity and initial gravimetric water content in the RH than in RW. This finding is consistent with that of Jia et al. (2017) who found that introducing exotic herbs to afforestation systems resulted in less soil drying than introducing exotic trees on the Loess Plateau. In addition, there is a long dry season in Xishuangbanna, and the combination of herbs with horizontal shallow roots and rubber trees with deep roots may help reduce the competition of plants for soil water. Thus, intercropping herbs with rubber may be more beneficial than intercropping woody plants with rubber in this region. It is still necessary to identify which herb intercropping system has better soil water retention capacity and additional economic benefits.

The higher initial gravimetric water content in RH was not only related to the soil properties (e.g., texture, porosity) but also closely related to other field factors (e.g., evapotranspiration and water absorption rates of plants). This aspect of the results still needs further research.

Conclusions

Rubber-based agroforestry systems continue to be a promising agricultural production mode in Xishuangbanna, SW China (Zhu et al. 2019). This study analyzed the differences in soil water characteristics (including related physical properties) in different types of rubber plantations in Xishuangbanna. We found that the soil bulk density in RM was higher than RW and RH at soil depth of 0–10 cm, whereas the soil porosity in RM was lower. The initial gravimetric water content in RM was lower than RW and RH in the entire profile. The CV_S in different plantations followed the order RH < RW < RM. The sum of the *CVs* values of each soil layer in the RM was 1.317, while in RH it was 0.308. The soil water retention capacity among different types of plantations followed the order RH > RW > RM. The CV_f of initial gravimetric water content was higher than that of saturated water capacity, capillary holding capacity, field water capacity. The CV_f decreased with soil depth, indicating that the difference in soil water content among different types of plantations decreased with soil depth. Correlation analysis between different types of soil water content showed that the initial gravimetric water content were not only affected by soil properties (e.g., texture, porosity) but also related to other factors. This was especially true of vegetation factors, which had a considerable influence on the spatial and temporal distribution of the soil water content. Intercropping herbs with rubber can improve soil hydrological properties, especially topsoil hydrological properties, better than intercropping with woody plants. From the perspective of hydrological properties, it is suggested that more consideration should be given to rubber-herb intercropping when establishing rubber-based agroforestry systems. This study supplements the knowledge about soil hydrological properties of rubber-based agroforestry systems by comparing the soil hydrological properties among RM, RW, and RH. More field factors that affecting soil hydrological properties in rubber plantations still need more research.

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Code availability Code available upon request.

Declarations

Conflict of interest The authors declare no competing interests.

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