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Conversion of primary tropical rainforest into rubber plantation degrades the hydrological functions of forest litter: Insights from experimental study

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ABSTRACT

Plant litter is an important component of forest ecosystems and has a key role in reducing soil and water loss. This study evaluated the effect of land use change on rainfall interception and other hydrological processes associated with the litter layer in the tropical region of Southwest China, where large areas of tropical rainforest (TR) have been converted into rubber monoculture (RM) in the past decades. Two litter types from the TR and RM were selected to determine the maximum water storage capacity (S), maximum and minimum interception storage capacities (i.e., C_{max} and C_{min}, respectively) and moisture dynamics under four litter masses and five simulated rainfall intensities. Results showed that the distribution of litter layer in the RM had a higher spatial variability than that in the TR. The average litter thickness in the TR and RM was 6.42 and 4.43 cm, respectively, and the S value of the litter layer in the TR and RM was 1.44 and 1.03 mm, respectively. Linear relationships among litter thickness, S, and litter mass were observed. The average C_{max} and C_{min} in the TR were respectively 1.25 and 1.30 times greater than that in the RM. Significant positive relationships among litter mass, rainfall intensity, and interception storage capacity were observed, indicating that litter mass and rainfall intensity played a critical role in determining rainfall interception of the litter layer. TR litter from mixed species had larger leaf surface area and higher water affinity, which resulted in 1.38 times greater litter interception (12.32%) than RM litter (8.96%). These results indicated that the conversion of TR into RM considerably weakened the hydrological functions of forest litter, such as water storage capacity and rainfall interception, and possibly subsequent erosion control. Introducing native rainforest species into rubber plantations can help improve the litter input and the hydrological attributes of forest litter.

1. Introduction

Plant litter not only participates in biogeochemical cycles directly, but also has important effects on the hydrological processes of forest ecosystems (Sayer, 2006; Carnol and Bazgir, 2013; Dunkerley, 2015; Zhao et al., 2019). The litter layer consisting of dead leaves, twigs, and other fragmented organic materials is recognized as the second most significant precipitation redistributor following the vegetation canopy (Liu et al., 2003; Sato et al., 2004; Gerrits et al., 2010; Li et al., 2013). The forest litter layer accumulates between vegetation and mineral soil to form a porous barrier that regulates water balance by intercepting and storing rainwater (Cuartus et al., 2007; Bulcock and Jewitt, 2012), increases water infiltration and limits soil evaporation and respiration (Sato et al., 2004; Marín-Castro et al., 2017; Magliano et al., 2017), and prevents soil erosion by absorbing the erosive power of raindrops and retarding surface runoff (Sepúlveda and Carrillo, 2015; Prosdocimi et al., 2016; Sidle et al., 2017). In addition, litter production and decomposition directly or indirectly improve soil structural stability and biological activity in the long term (Sayer, 2006; Bahnmann et al., 2018; Zhu et al., 2019), thus enhancing the resistance to rainfall–runoff–erosion processes. Although numerous researchers have focused increasing attention on the protective role of forest litter against

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soil erosion (Seitz et al., 2015; Liu et al., 2017; Cerdà et al., 2018; Zhao et al., 2019), the small but significant role of the litter interception process in the hydrological cycle is not often understood (Seitz et al., 2015; Li et al., 2017).

Litter interception is an important component of precipitation partitioning (Du et al., 2019). On the basis of simulated or natural rainfall experiments, several studies have explored the characteristics of water interception storage capacities of forest litter (Sato et al., 2004; Bulcock and Jewitt, 2012; Li et al., 2013; Kim et al., 2014). In general, litter interception loss accounts for 1–70% of gross rainfall because of the differences in climate conditions, species composition, litter characteristics, and spatiotemporal scales (Guevara-Escobar et al., 2007; Dunkerley, 2015; You et al., 2017). Litter interception is influenced by many factors, such as rainfall intensity, litter type, litter thickness, and leaf morphology (Walsh and Voigt, 1977; Marin et al., 2000; Sayer, 2006; Li et al., 2017). For example, Sato et al. (2004) noted that a high rainfall intensity increased the litter interception storage capacity of litter (*C*) and that needleleaf litter intercepted more rainwater than broadleaf litter. Putuhena and Cordery (1996) stated that litter interception increased linearly to litter mass under simulated rainfall. Accordingly, a thick litter layer in forest lands is expected to exhibit higher water interception capacity than an exiguous litter layer. In addition, the immersion test is commonly and conveniently used to determine the maximum water storage capacity of litter (*S*) to better understand the hydrological processes of litter. For instance, Helvey and Patric (1965) determined that hardwood litter in Eastern United States could retain water amounting to 135% to 170% of its dry weight. However, most studies compared the moisture dynamics of different litter types (i.e., broadleaf vs. needleleaf litter) in temperate climates only, and few studies have investigated the changes in the hydrological properties of litter layers in tropical forest ecosystems. Owing to high decomposition rates, many tropical soils often have thin litter layer, which is easily removed by surface flow during intense storms (Hartanto et al., 2003; Sidle et al., 2006). The sparse litter layer can promote more overland flow and subsequent erosion compared with vegetated temperate hillslopes (Bartley et al., 2006; Liu et al., 2017; Sidle et al., 2017). Extensive forest transitions and varying land use intensities have occurred, or are occurring in tropical areas (Park et al., 2010; Li et al., 2013; Drescher et al., 2016), but still little available information is obtained on the effects of these land use changes on forest litter and related hydrological functions.

Rubber plantations are expanding rapidly at the expense of primary and secondary forests in tropical Southeast Asia (Ziegler et al., 2009). In Xishuangbanna, Southwest China, dramatic land use/cover change occurred because of the massive transformation of tropical rainforest (TR) to rubber monoculture (RM) (Li et al., 2008; Qiu, 2009; Fox et al., 2014). From 1987 to 2018, the total area of rubber plantations increased by approximately 5.90 times (Xiao et al., 2019). The transformation of TR to RM has resulted in less litter accumulation (Li et al., 2012), faster litter decomposition, and severe water loss and soil erosion (Ziegler et al., 2009; Zhu et al., 2018). Furthermore, the terraced cultivation of rubber trees may lead to thick litter cover on terrace beds but sparse or no litter cover on terrace risers. The thin litter layer in rubber plantations is easily displaced by overland flow and eliminated by trampling because of regular latex tapping and herbicide application. These processes can increase the spatiotemporal heterogeneity of litter distribution, thereby influencing the moisture dynamics of forest litter. Are the changes of forest litter and associated hydrological attributes related to excessive water erosion in rubber plantations? Therefore, experimental analysis of litter layers from different land use systems is currently needed to clarify how they affect the hydrological processes.

In this study, we mainly focused on the effects of the conversion of TR into RM on the hydrological functions of the litter layer. Specifically, the objectives were to (a) investigate the differences in the characteristics of two types of leaf litter; (b) examine *S* under fully saturated conditions and the dynamics of litter interception under simulated rainfall; and (c) evaluate the relationships among rainfall condition, litter mass, and interception storage capacity.

2. Materials and methods

2.1. Study site

The study was conducted in the Xishuangbanna Tropical Botanical Garden (21°56′35″N, 101°16′12″E) in the Yunnan Province, Southwest China. The local climate is dominated by tropical southern monsoons from the Indian Ocean between May and October (rainy season) and by subtropical jet streams between November and April (dry season) (Zhang, 1988). The dry season includes a foggy cool sub-season (November to February) with dense fog in the morning and a hot dry sub-season (March to April) (Fig. S1). The mean annual air temperature is 21.6 °C with a maximum monthly temperature of 26.3 °C for the hottest month (June) and a minimum monthly temperature of 16.8 °C for the coldest month (January).

The mean annual rainfall (approximately 1431 mm) was monitored at a meteorological station near the study site. Of the total rainfall, 81% occurs during the rainy season and 19% occurs during the dry season. On the basis of the historical weather data (2009–2018), the rainfall intensities of most rainfall events were less than 8 mm h^{-1}, and more than 85% of the rainy days generated less than 20 mm day^{-1} (Fig. 1b and c).

Two forest ecosystems were selected as litter sampling plots. The first plot (20 m × 20 m) was established on a small hillslope (20°) within a seasonal TR formed in wet valleys, lowlands, and low hills (Cao et al., 1996). The age of TR is approximately 250–300 years (Tang et al., 2010). Soil under the forest is a yellow latosol developed from purple sandstone. This forest vegetation mainly consisted of *Terminalia myriocarpa*, *Barringtonia macrostachya*, *Pterospermum menglunense*, and *Pometia tomentosa* with different defoliation times. The second plot (10 m × 10 m) was established on a typical catchment covered with 31-year-old rubber trees (*Hevea brasiliensis*). The rubber trees were planted at 2.1 m × 4.0 m spacing on terrace beds on the slopes after clear-cutting the native rainforest completely in 1988. The rubber plantation plot was composed of a terrace bed (2°) and a terrace riser (23°) with the widths of 2 and 3 m, respectively (Liu et al., 2013; Zhu et al., 2018). This terraced micro-topography might result in non-uniform distribution of surface litter layer, such as less litter accumulation on terrace riser because of its greater slope. As a rubber plantation management measure, regular herbicide application was conducted to eliminate the understory vegetation. The distance between the two sampling plots was approximately 1000 m and there was no significant difference in the rainfall characteristics or geological properties between the two stands. Detailed information about the study site is shown in Table 1.

2.2. Litter sampling

Litter can be separated into three layers, which are labeled L, F, and H (Sato et al., 2004). The L layer was composed of relatively undecomposed material whose source could be easily identified, the F layer was composed of fragmented of decomposed material that could still be identified as plant material, and the H layer was composed of particles broken down to a certain level that its source could not be identified. Obviously, the upper undecomposed litter directly intercepts and holds rainwater. The upper undecomposed litter plays a more important role in the hydrological processes of the litter layer than the lower decomposed litter (Li et al., 2013). In addition, it is often very difficult to define boundary of each litter layer (Bulcock and Jewitt, 2012). It is also quite hard not to disturb field samples when taking all litter layers to lab (Gerrits et al., 2007). Accordingly, we mainly considered the moisture dynamics of the upper undecomposed litter in the present study.

On the basis of the availability and physical properties of ground litter, we investigated the litter thickness and litter mass (i.e., the mass

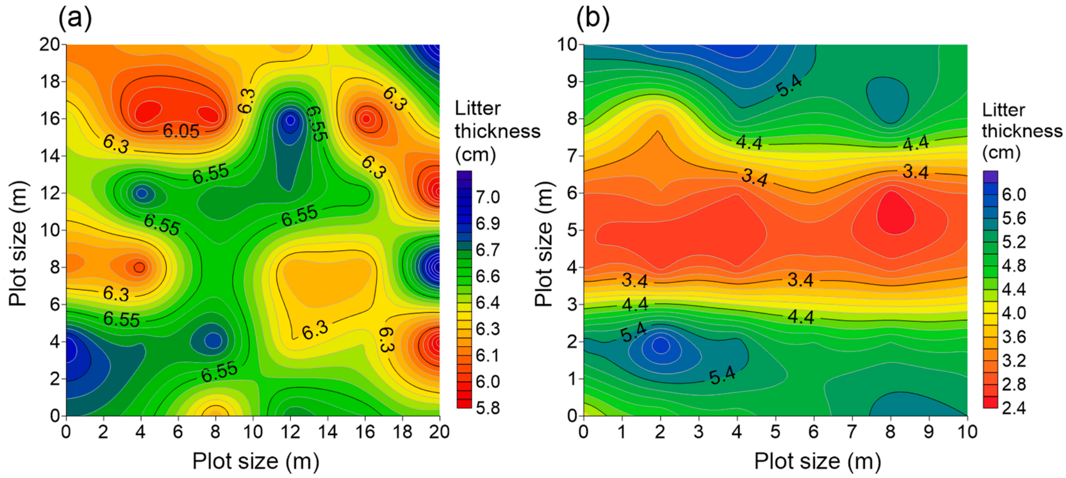

Fig. 1. Spatial distributions of the litter thickness in experimental plots of tropical rainforest (a) and rubber monoculture (b).

Table 1
General characteristics of the tropical rainforest (TR) and rubber monoculture (RM).

Study site	Age (y)	Plot area (m^2)	Density (trees ha^{-1})	Diameter at breast height (cm)	Height (m)	Canopy cover (%)	Leaf area index (m^2 m^{-2})	Stand litter (g m^{-2})
TR	250–300	400	730	26.77 ± 1.53	21.51 ± 3.96	85.67 ± 1.76	4.41 ± 0.19	820.08 ± 58.64
RM	31	100	526	25.42 ± 1.60	19.81 ± 1.54	66.43 ± 3.42	1.47 ± 0.21	406.62 ± 24.17

Data were expressed as the mean ± SE (n = 8).

per unit area of the litter layer) of two experimental plots in March 2019 when the rubber trees shed a large number of leaves. A total of 36 sampling points in the TR (4.0 m intervals) and RM (2.0 m intervals) were selected to determine litter thickness. Eight randomly selected 0.25 m^2 subplots were installed temporarily by inserting a sharp-edged iron frame into the ground to measure litter mass. Then, the material contained in the frame was collected by hand, placed in plastic bags, and brought back to the laboratory for further analysis. To fit into the sample tray (240 cm^2), all of the decomposed and large litter samples were eliminated before weighing. The remaining litter samples were divided into three components: (a) leaf, (b) branch and bark (diameter < 2 cm), and (c) reproductive unit (flower, fruits, and seed). The weight and percentage of these three components were measured after natural air-drying. We also measured the length, breadth, leaf area, dry weight, and leaf size to investigate the morphological differences of leaf litter from the TR and RM (Walsh and Voigt, 1977).

2.3. Interception facility

The interception facility was composed of an artificial rainfall simulator, a sample tray, a tipping bucket rain gauge, and a self-recording rain gauge (Fig. S2). The artificial rainfall simulator controlled the amount of rainfall and the rainfall intensity using a float flowmeter (LZB-3WB, YuYao WeiChuang Flowmeter Co., Ltd, China). One end of the float flowmeter was connected to a water pipe with silicon tube, and the other end of the float flowmeter was equipped with a sprinkler. Uniform artificial raindrops (approximately 1–2 mm in diameter) were produced by the sprinkler. A 40 × 60 cm^2 stainless steel rectangle sample tray was placed on a slightly gradient platform to facilitate the flow of water. A sieve support (0.3 × 0.3 cm^2 mesh) for the litter samples was placed on the sample tray, approximately 1 cm away from the bottom. The sample tray outlets were routed to the tipping bucket rain gauge (WatchDog 1120 Data-Logging Rain, Spectrum Technologies, Inc., Fort Worth, TX, USA) and recorded once per minute with a data logger. The rain gauge was calibrated to record 25.4 mm, which was equivalent to 100 tips of the tipping bucket.

2.4. Measurements of water storage capacity

(a) Maximum water storage capacity (*S*, mm): *S* is a critical indicator used evaluate the interception loss of the litter layer. The *S* values corresponding to the litter masses of 0.2, 0.4, 0.8, and 1.0 kg m^{-2} were calculated. The proportion of each litter component was different between the two forest ecosystems investigated in this study. Thus, the litter samples were composed of the following components: leaf (80%), branch and bark (15%), and reproductive parts (5%) for the TR and leaf (60%), branch and bark (15%), and reproductive parts (25%) for the RM. Given the complexity of field conditions, the litter was piled up in the sample tray as carefully as possible to simulate the field status of the litter layer. The sample tray was soaked in water for 24 h to saturate the litter completely. Then, the tray was taken out of the water and weighed when the drainage flow has ceased (approximately 30 min later). The *S* value was calculated as the difference in the litter mass of the litter samples before and after the soaking process. Each litter mass was replicated three times, and new litter samples were used each time.

(b) Water holding capacity (%): For measuring the water holding capacity of each litter component, 20 g litter samples were immersed in water for 24 h and subsequently determined their weight gain once gravity drainage was complete. Each litter component was conducted for three duplications. The water holding capacity was calculated as the percentage of the water content contained in litter samples to their dry weight.

(c) Interception storage capacity (*C*): The interception storage capacity of the litter layer needs to be examined to better understand its moisture dynamics. In this study, we used four litter masses (i.e., 0.2, 0.4, 0.8, and 1.0 kg m^{-2}) and applied five simulated rainfall intensities (i.e., 2.5, 10, 25, 50, and 100 mm h^{-1}) for a duration of 60 min to determine the difference in the litter interception storage capacity. We defined the amount of rainwater retained in the litter sample when the rainfall was stopped at 60 min as C_{max} (an instantaneous value) and the amount of rainwater retained in the litter sample after drainage flow from the litter layer ceased completely as C_{min} (a steady value).

2.5. Statistical analysis

One-way ANOVA, followed by Tukey's multiple comparison test, was used to estimate the differences in thickness, *S*, and water holding capacity of litter between TR and RM ($P < 0.05$). Prior to one-way ANOVA, the Levene and Shapiro–Wilk tests were used to check the homogeneity of variance and normal distribution. Linear and nonlinear models were applied to assess the relationships among litter thickness, *S*, rainfall conditions, interception storage capacity (i.e., C_{max} and C_{min}), litter interception percentage, and litter mass. All statistical analyses using the SPSS software package (Version 19.0, SPSS Inc., Chicago, IL, USA). The contour map of the spatial distributions of litter thickness was drawn using the Golden Software Surfer 12 (Golden software Inc., Golden, CO, USA) on the basis of ordinary kriging interpolation.

3. Results

3.1. Characteristics of the litter layer

The spatial distributions of litter thickness in each plot are shown in Fig. 1. The litter layer in the TR was uniformly distributed, and the litter mass varied from 0.46 kg m^{-2} to 1.27 kg m^{-2}, with the average of 0.82 kg m^{-2}. The litter layer in the RM had a high spatial heterogeneity with less litter on the terrace risers than on the terrace beds. The litter mass in the RM varied from 0.24 kg m^{-2} to 1.01 kg m^{-2}, with the average of 0.40 kg m^{-2}. The average litter thickness in the TR and RM was 6.42 and 4.43 cm, respectively. Similarly, litter was obviously thinner on the terrace risers than on the terrace beds in the RM.

The average length, breadth, and elongation ratio of leaf litter in the TR were greater than those in the RM (Fig. 2). The length of leaf litter was 5.40–41.00 and 5.81–19.10 cm in the TR and RM, respectively. The breadth of leaf litter was 4.00–8.00 cm in the TR and 4.00–6.40 cm in the RM. The average dry weight of leaf litter in the TR (0.55 g) was evidently higher than that in the RM (0.24 g). On average, the leaf area in the TR was 1.69 times larger than that in the RM, with a smaller fluctuation for the RM. More than 50% of leaves in the TR was mesophyll, whereas the largest proportion of leaves in the RM was notophyll (approximately 70%).

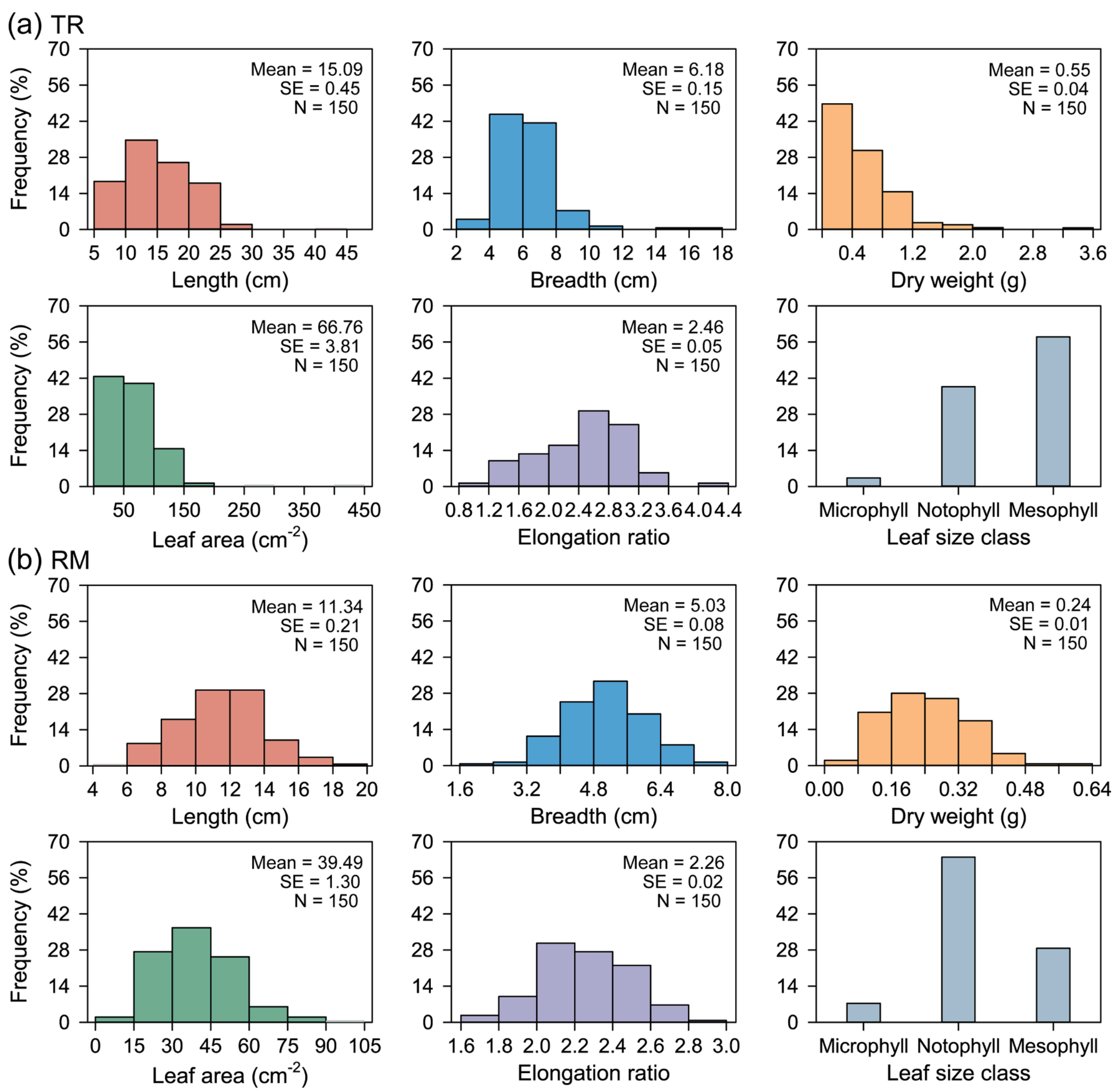

Fig. 2. Frequency distribution of the leaf litter morphology of the tropical rainforest (a) and rubber monoculture (b).

3.2. Maximum water storage capacity (S)

The changes in the *S* value exhibited an approximately positive linear relationship with the litter mass in the two study sites (Fig. 3b). As litter mass increased from 0.2 kg m^{-2} to 1.0 kg m^{-2}, the *S* of litter layer ranged from 0.27 mm to 3.01 mm and from 0.35 mm to 1.87 mm in the TR and RM, respectively. No significant difference in the *S* value between TR and RM was observed when the litter mass was less than 0.8 kg m^{-2}. The *S* value per unit area of litter mass (1 kg m^{-2}) was significantly higher in the TR than in the RM.

The water holding capacity of litter varied with the litter components (Fig. 4). Except for the reproductive unit in the TR, the water holding capacity showed the decreasing order of leaf > mixed > branch & bark > reproductive unit in the study forests. All litter components in the TR had significantly higher water holding capacity than those in the RM ($P < 0.05$). The water holding capacity of leaf litter was 1.16 times higher in TR than in the RM. The water retention of the mixed litter samples relative to their dry weight ranged from 151% to 168% for TR, and 110% to 123% for the RM.

3.3. Interception storage capacity (C)

The dynamics of cumulative rainfall interception of the litter layer is shown in Fig. 5. Over the entire observation period, the cumulative rainwater intercepted by the litter layer increased rapidly in the first 10 min of rainfall, increased slowly, and maintained a stable level at 45 min. The drainage stage was from the 60th minute when the rainfall ceased to the end of the experiment. The cumulative interception storage exhibited a small fluctuation at approximately 15 min after the cessation of rainfall. In general, the interception process slowed down earlier under high rainfall intensity than under low rainfall intensity. TR litter took a longer time to reach the steady state than RM litter.

Depending on the litter type and litter mass, C_{max} and C_{min} in the TR were 0.35–6.30 and 0.28–4.51 mm, respectively. By contrast, C_{max} and C_{min} in the RM were 0.28–5.88 and 0.18–4.27 mm, respectively (Table 2). On average, C_{max} and C_{min} in the TR were 1.07–1.71 and 1.06–1.85 times higher than that in the RM, respectively. Both C_{max} and C_{min} significantly increased with rainfall intensity. Compared with that between C_{min} and rainfall intensity ($P < 0.01$), more significant and stronger correlations between C_{max} and rainfall intensity were observed ($P < 0.001$; Fig. 6). The effects of rainfall intensity on *C* appeared to be similar between TR and RM. In addition, *C* was significantly positively correlated with litter mass regardless of rainfall intensity (Fig. 6c–d). For the two litter types, a stronger linear relationship between litter mass and C_{min} than between litter mass and C_{max} was observed.

When the litter mass increased from 0.2 kg m^{-2} to 1.0 kg m^{-2}, the percentage of litter interception of TR and RM varied from 0.80% to 56.70% and from 0.60% to 38.30%, respectively (Fig. 7). Certain relationships among simulated rainfall amount (*SRA*, mm), litter mass and percentage of litter interception (C_{min}/SRA) were observed, and the regression line equations can be expressed as follows:

$$TR : LI = 4.571 + 47.811e^{-0.215SRA}, R^2 = 0.649, P < 0.001, \quad (1)$$

$$RM : LI = 3.524 + 33.998e^{-0.219SRA}, R^2 = 0.607, P < 0.001, \quad (2)$$

$$TR : LI = 1.256 + 18.436LM, R^2 = 0.124, P = 0.07, \quad (3)$$

$$RM : LI = 0.172 + 14.654LM, R^2 = 0.159, P < 0.05, \quad (4)$$

where *LI* is the percentage of C_{min}/SRA (%) and *LM* is the litter mass (kg m^{-2}).

4. Discussion

4.1. Maximum water storage capacity (S) of the litter layer

Basically, *S* is an important parameter used to clarify the hydrological functions of the litter layer (Sato et al., 2004). *S* is reached only when litter is completely saturated after being immersed in water for a sufficient time. In general, 24–48 h is widely accepted in laboratory experiments. In our study, a period of 24 h was applied. TR litter showed consistently higher *S* than RM litter at the same litter mass (excluding at 0.2 kg m^{-2}). On average, *S* was 1.40 times higher in the TR (1.44 mm) than in the RM (1.03 mm). This finding can be mainly attributed to the TR litter having a larger leaf area that could absorb more water than the RM litter (Fig. 2). Moreover, the TR had looser and more porous litter layer than the RM because the litter layer in the TR was thicker than that in the RM at the same litter mass (Fig. 3a). This porous litter structure facilitated the increase in the *S* values. The *S* increased with the increase of litter mass in the study forests, which was consistent with the findings of Putuhena and Cordery (1996) and Sato et al. (2004). Specifically, the *S* exhibited significant exponential growth with increased litter mass in the TR, while no significant exponential relationship was tested in the RM (Fig. 3b); and a significant difference in *S* between TR and RM was

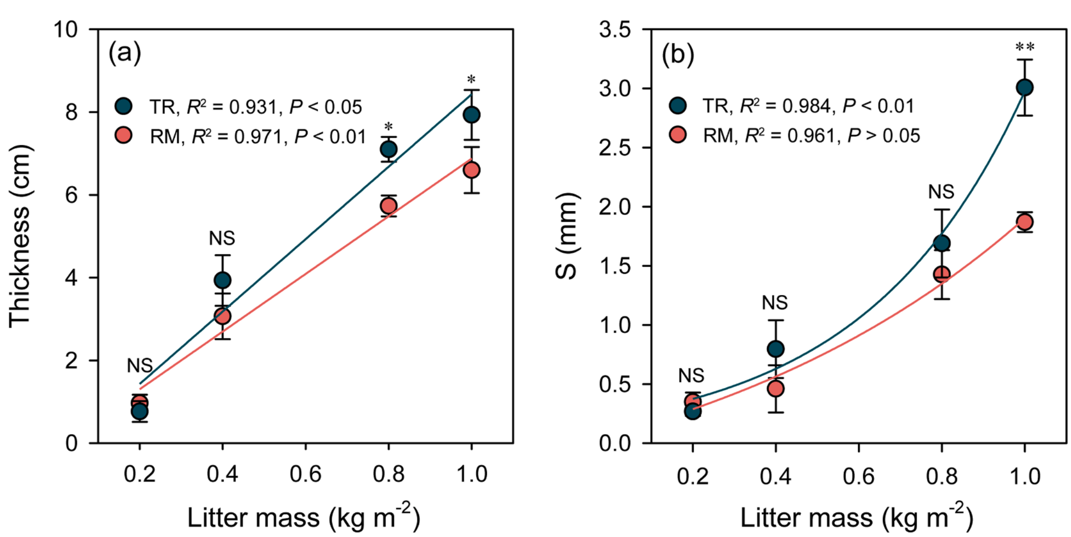

Fig. 3. Relationships (a) between litter mass and litter thickness and (b) between litter mass and maximum water storage capacity (S) of the tropical rainforest (TR) and rubber monoculture (RM). Data were expressed as the mean ± SE (n = 3). Differences in litter thickness and S between TR and RM were denoted as *$P < 0.05$, **$P < 0.01$, NS = not significant.

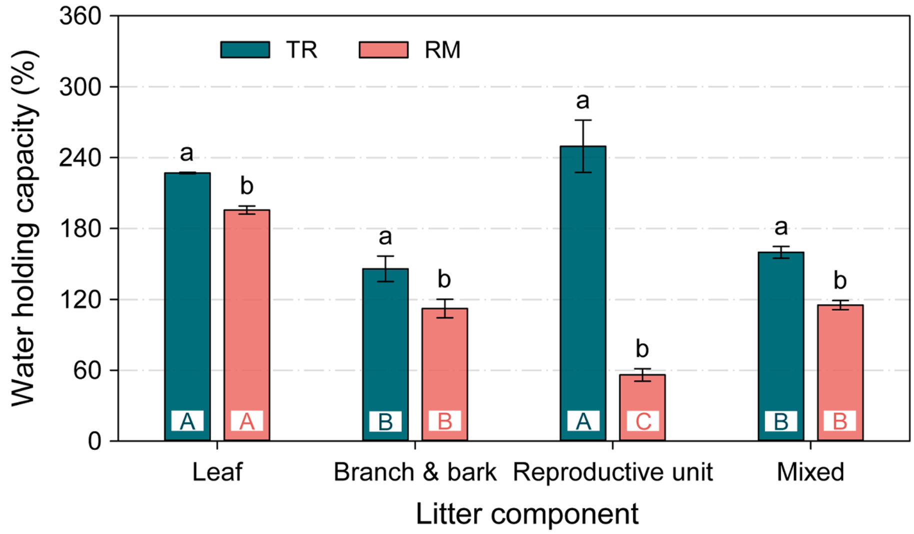

Fig. 4. Water holding capacity (%) of litter components from the tropical rainforest (TR) and rubber monoculture (RM). Data were expressed as the mean ± SE (n = 3). Different small letters above the bars indicate significant differences ($P < 0.05$) between forest types for each litter component. Different capital letters inside the bars indicate significant difference ($P < 0.05$) among litter components for each forest type.

observed when litter mass increased to 1.0 kg m^{-2}. These results indicated that the change of water storage capacity RM litter was quite insensitive to the increase of litter mass. Increasing litter accumulation would contribute to more improvement of water storage capacity of TR litter than RM litter.

The average *S* per unit area of litter mass (1.0 kg m^{-2}) in the TR and RM was 3.01 and 1.87 mm, respectively (Fig. 3). These *S* values fell within the range (i.e., 0.97–3.45 mm) reported in previous studies (Table 3). The *S* value of TR litter was similar to that of *Quercus variabilis* litter (3.45 mm) in a temperate forest in China (Li et al., 2013). On the basis of the results of this study shown in Table 3, we conclude that the *S* value of the litter layer differed depending on the species, leaf shape, and experimental conditions. In general, needleleaf litter had lower *S* than broadleaf litter under the same experimental conditions. The *S* values under immersion conditions were often higher than those under simulated or natural rainfall because the litter was not fully saturated in the short rainfall duration.

The litter components in the TR exhibited 1.16–4.45 times higher water holding capacity than those in the RM (Fig. 4). Excluding the reproductive litter, the leaf litter also showed higher water holding capacity than other litter components. In addition, the litter containing more leaf (i.e., TR litter) exhibited a higher *S* value than that containing less leaf (i.e., RM) despite having the same litter mass (Fig. 3). These results indicated that litter composition played a critical role in determining their water retention. Compared to the TR litter, the RM litter appeared a certain degradation of hydrological functions, such as lower *S* and lower water holding capacity.

4.2. Interception storage capacity (C) of the litter layer

Under field conditions, *C* of the litter layer during real rainfall events is different from *S* of the litter layer because of the unequal distribution of supplied rainwater within the litter layer (Sato et al., 2004). The litter may not be adequately immersed in rainwater in a relatively short period of time. The mechanisms of rainfall interception of the litter layer depend on vegetation type and surface tension, as well as rainfall intensity, amount, and duration (Zeng et al., 2000). Therefore, *C*, including C_{max} and C_{min}, is considered to change with these factors. In this study, significant linear relationships among C_{max}, C_{min} and rainfall intensity were observed regardless of litter mass (Fig. 6). This finding is consistent with the result of Sato et al. (2004) who tested litter samples under the rainfall intensities of 5–50 mm h^{-1} for a duration of 300 min.

However, some studies obtained different conclusions. For example, in the study of Putuhena and Cordery (1996), both C_{max} and C_{min} did not depend on the rainfall intensities under rainfall durations ranging from 30 min to 60 min, which could be attributed to the fact that their experiments were conducted within a narrow range of high rainfall intensities (i.e., 34–75 mm h^{-1}). Guevara-Escobar et al. (2007), Li et al. (2013) and Du et al. (2019) also noted that C_{max} increased with the rainfall intensities of 6.8–115.0 mm h^{-1} under a rainfall duration of 60 min, but C_{min} exhibited a fairly unclear relationship with rainfall intensity. These varying results indicated that rainfall intensity had complex effects on *C* of the litter layer. In general, C_{max} of the litter layer was positively correlated with rainfall intensity with a wide range.

With regard to the interception capacity of the litter layer in a forest landscape, C_{min} was more important than C_{max} because gravitational water was readily drained 30 min after the cessation of rainfall (Sato et al., 2004; Guevara-Escobar et al., 2007). In the present study, C_{min} per unit area of litter mass (mm kg^{-1} m^{-2}) ranged from 1.02 mm to 4.52 mm. These values were within the upper range reported in several previous studies. For instance, C_{min} of bracken litter was 1.67 mm (Pitman, 1989); C_{min} of *Pinus radiata* slash was 0.70 mm (Kelliher et al., 1992); C_{min} of *Pinus radiata* and eucalyptus litter was 0.96 mm and 1.12 mm, respectively (Putuhena and Cordery, 1996); C_{min} of coniferous and broadleaf litter was 1.44–1.74 mm (Sato et al., 2004) and 0.30–1.13 mm (Li et al., 2013), respectively; and C_{min} of poplar leaves and woodchips was 0.60–1.85 mm (Guevara-Escobar et al., 2007). The differences in C_{min} between previous studies and the present experiment can be explained by the fact that various rainfall conditions (i.e., rainfall duration, intensity, and range) were considered and different litter samples were used. In this study, the litter samples may not saturated within 60 min of rainfall and mainly composed of four components (i.e., broad leaves, branches, barks, and reproductive material). Sato et al. (2004) tested litter samples only containing broad leaves and shoot litter (twigs + needles) under 3 h of simulated rainfall. Therefore, prolonged rainfall might increase litter interception. Moreover, only the surface pits from broadleaf litter acted as vessels that could temporarily store additional water. The "loose" water might drain easily when the leaves are situated on an inclined surface (Crockford and Richardson, 2000; Zhao et al., 2019). This is why the litter layer frequently intercepted more water, with high *S* and the same litter mass (Table 2; Fig. 3). These results indicated that the morphology, type, and composition of litter may influence its capacity to catch rainwater during rainfall events.

As in the case of *S*, both C_{max} and C_{min} of the litter samples from the

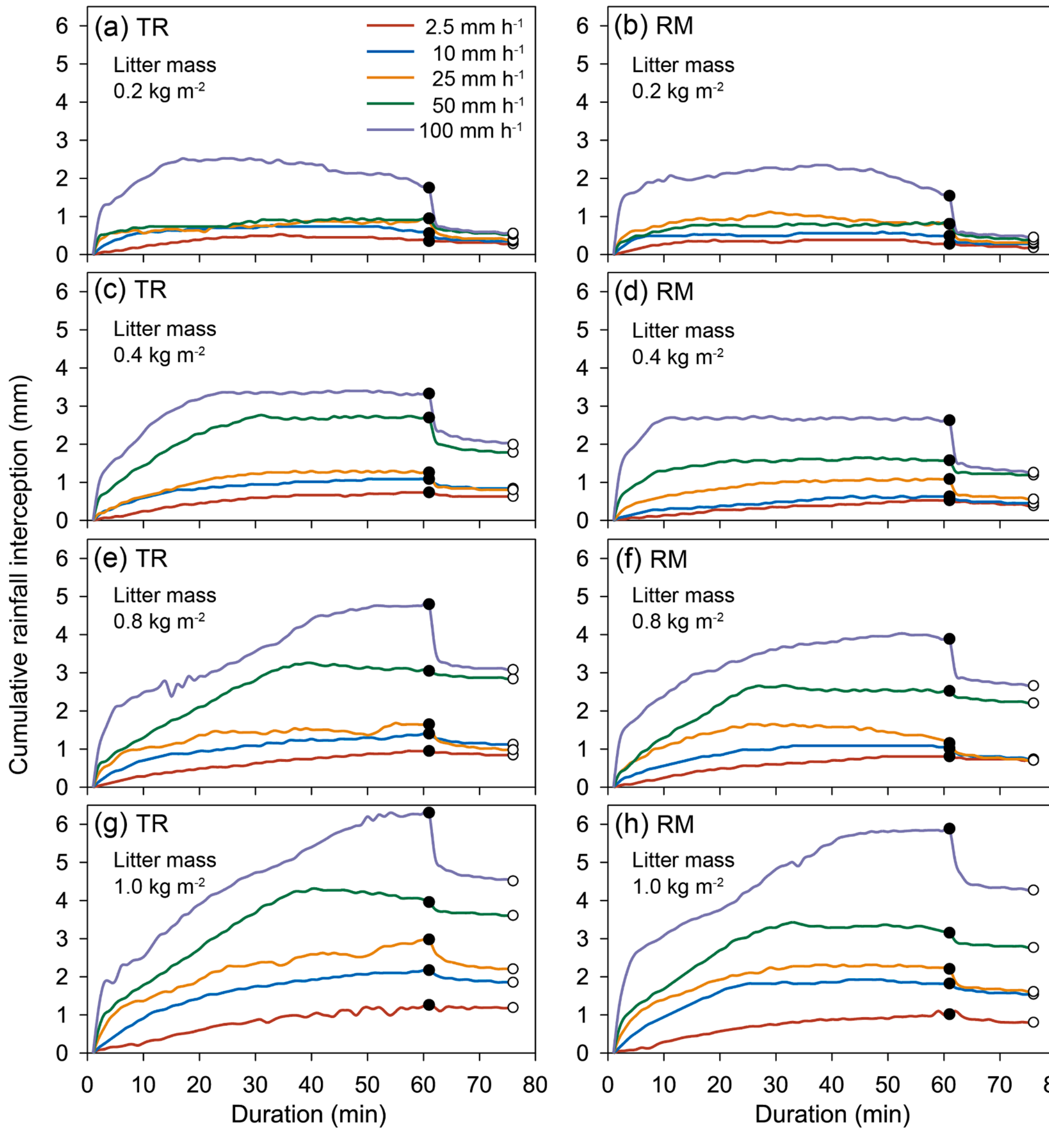

Fig. 5. Time series of the cumulative rainfall interception of the litter layer in the tropical rainforest (TR) and rubber monoculture (RM) under different rainfall intensities. Closed circles indicate C_{max} and open circles indicate C_{min}.

Table 2
Interception storage capacity (C_{max} and C_{min}) of the litter layer under different litter mass and rainfall intensities.

Litter mass (kg m^{-2})	Rainfall intensity (mm h^{-1})									
	2.5		10		25		50		100	
	C_{max} (mm)	C_{min} (mm)	C_{max} (mm)	C_{min} (mm)	C_{max} (mm)	C_{min} (mm)	C_{max} (mm)	C_{min} (mm)	C_{max} (mm)	C_{min} (mm)
Tropical rainforest										
0.2	0.35(0.03)	0.28(0.00)	0.56(0.02)	0.35(0.00)	0.95(0.03)	0.39(0.00)	0.96(0.07)	0.53(0.01)	1.75(0.05)	0.56(0.01)
0.4	0.74(0.05)	0.63(0.01)	1.05(0.01)	0.84(0.00)	1.26(0.07)	0.81(0.01)	2.70(0.10)	1.79(0.06)	3.33(0.06)	1.20(0.02)
0.8	0.95(0.04)	0.84(0.01)	1.40(0.05)	1.12(0.01)	1.65(0.02)	0.98(0.01)	3.05(0.24)	2.84(0.03)	4.80(0.12)	3.08(0.09)
1.0	1.26(0.10)	1.19(0.01)	2.17(0.16)	1.86(0.00)	2.98(0.12)	2.21(0.10)	3.96(0.20)	3.61(0.11)	6.30(0.20)	4.52(0.10)
Rubber monoculture										
0.2	0.28(0.01)	0.18(0.00)	0.49(0.01)	0.28(0.00)	0.81(0.02)	0.32(0.02)	0.81(0.02)	0.39(0.00)	1.54(0.03)	0.46(0.02)
0.4	0.53(0.02)	0.39(0.01)	0.63(0.00)	0.46(0.02)	1.05(0.04)	0.56(0.01)	1.58(0.01)	1.19(0.00)	2.63(0.11)	1.26(0.01)
0.8	0.81(0.06)	0.70(0.01)	1.02(0.08)	0.74(0.01)	1.16(0.10)	0.70(0.01)	2.52(0.05)	2.21(0.01)	3.89(0.10)	2.67(0.03)
1.0	1.02(0.12)	0.81(0.02)	1.82(0.10)	1.54(0.02)	2.21(0.14)	1.61(0.02)	3.15(0.13)	2.77(0.02)	5.88(0.16)	4.27(0.12)

Data were expressed as mean and standard error (n = 3).

TR and RM were significantly positively correlated with litter mass regardless of rainfall intensity (Fig. 6). This result is consistent with the findings of Putuhena and Cordery (1996) but contrary to that of Li et al. (2013) who revealed that no obvious linear relationships between litter mass and C_{max} of two broadleaf litters and two needleleaf litters were observed. Li et al. (2013) argued that the discrepancy was caused by the different litter masses used (i.e., 0.3–1 kg m^{-2}). Although we also used different litter masses (i.e., 0.2–1 kg m^{-2}), we still observed linear

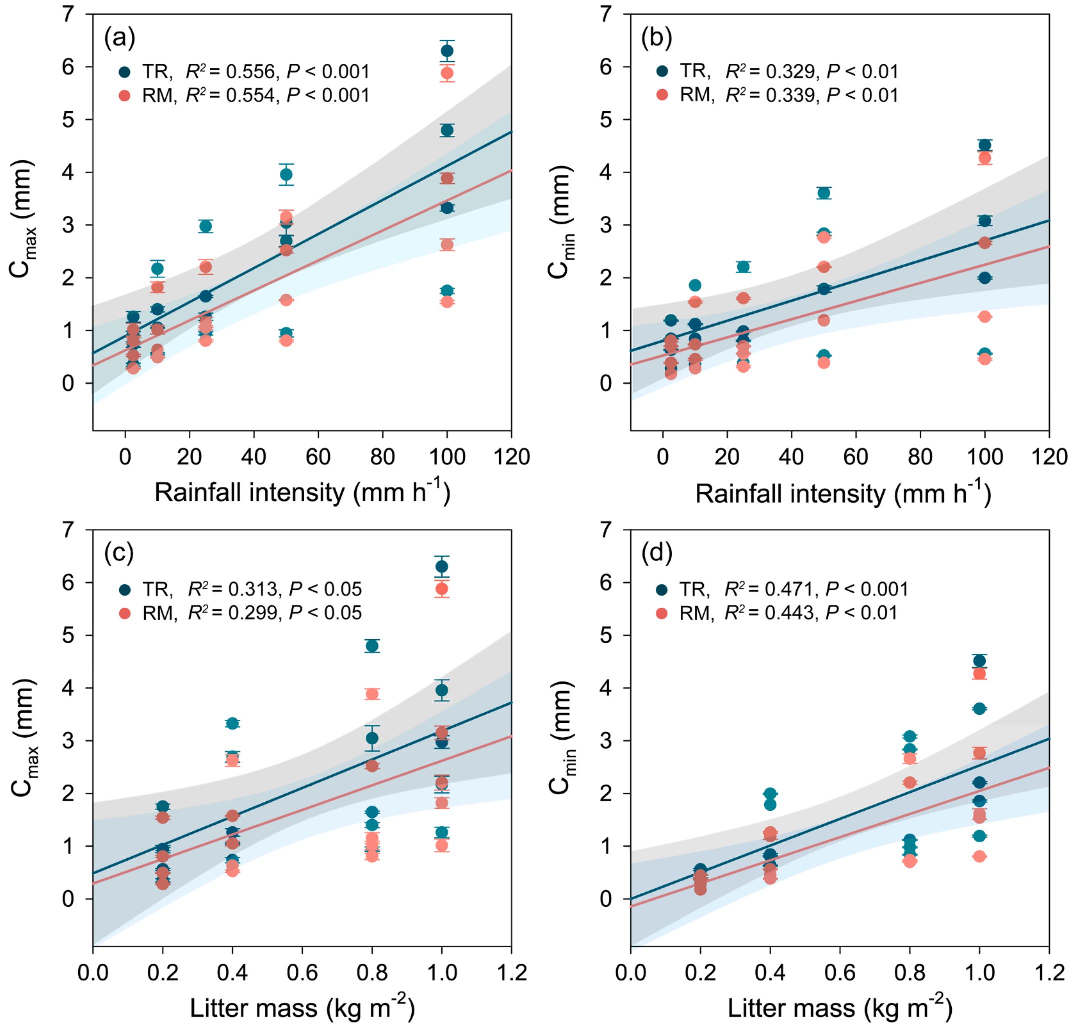

Fig. 6. R Relationships among rainfall intensity, litter mass, and interception storage capacity (C_{max} and C_{min}) of the tropical rainforest (TR) and rubber monoculture (RM). The shaded area denoted the 95% confidence interval.

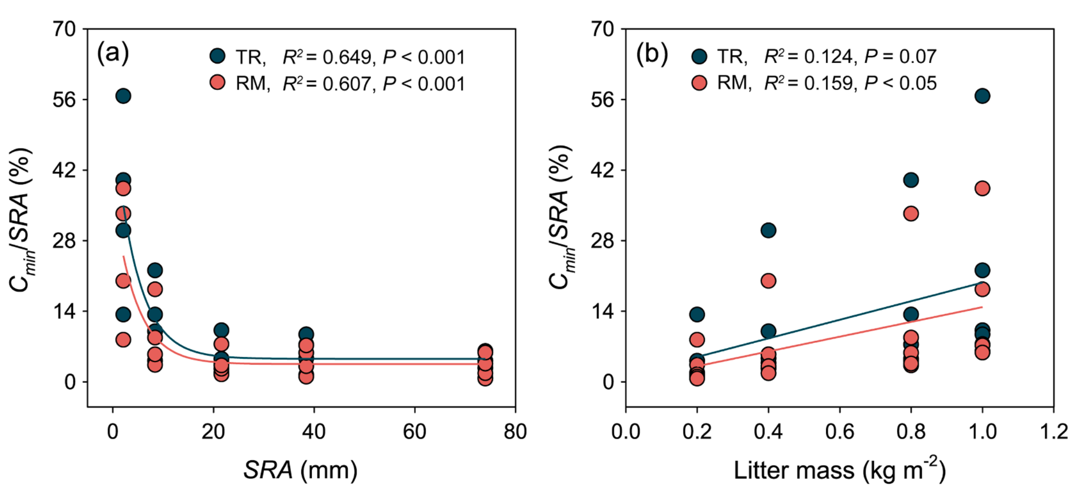

Fig. 7. Relationships among percentage of litter interception (C_{min}/SAR), simulated rainfall amount (*SRA*), and litter mass.

relationships between litter mass and C_{max}. Several researchers proposed that the dominant forces affecting the interception storage capacity of the litter layer were gravity and cohesion, which were associated with the physical characteristics of the litter components (Sato et al., 2004; Keim et al., 2006; Guevara-Escobar et al., 2007). With respect to the forest litter investigated in this study, both C_{min} and percentage of litter interception of TR litter were always higher than those of RM litter (Table 2; Fig. 7). This is probably due to the contact angle between rubber leaves (RM litter) and the surface slightly sloped, thereby inducing the formation of numerous macropores. Such a litter structure

Table 3
Maximum water storage capacity (*S*) per unit litter mass in several previous studies.

Site	Forest ecosystem	Litter type	Species	Experiment condition	*S* (mm kg^{-1})	Reference
China	Temperate forest park	Broadleaf litter	*Quercus variabilis*	Immersion test	3.45	Li et al. (2013)
			Acer truncatum	Immersion test	2.13	
		Needle leaf litter	*Pinus tabulaeformis*	Immersion test	0.95	
			Platycladus orientalis	Immersion test	1.25	
Japan	Evergreen coniferous forest	Needle leaf litter	*Cryptomeria japonica*	Immersion test	1.59	Sato et al. (2004)
	Commercial forest	Broadleaf litter	*Lithocarpus edulis*	Immersion test	1.56	
China	Tropical rainforest	Broadleaf litter	Mixed species	Immersion test	3.01	Present study
	Rubber plantation	Broadleaf litter	*Hevea brasiliensis*	Immersion test	1.87	
U.K.	Bracken forest	Bracken litter	*Pteridium aquilinum*	Simulated rainfall	1.67	Pitman (1989)
Australia	Eucalypt forest	Broadleaf litter	*Eucalyptus rossii* etc.	Simulated rainfall	1.13	Putuhena and Cordery (1996)
	Pine plantation	Needle leaf litter	*Pinus radiata*	Simulated rainfall	0.97	
Australia	Eucalypt forest	Broadleaf litter	*Eucalyptus rossii* etc.	Simulated rainfall	1.23	Crockford and Richardson (2000)
	Pine plantation	Needle leaf litter	*Pinua radiata*	Simulated rainfall	1.35	
Colombia	Amazonian rainforest	Broadleaf litter	Mixed species	Simulated rainfall	1.51	Marin et al. (2000)
India	Farm forest	Broadleaf litter	*Tectona grandis*	Natural rainfall	0.97	Pradhan (1973)

potentially enables the formation of a number of preferential litter flow channels for rainwater. Moreover, rubber leaves have a leathery texture with a layer of wax film after drying, resulting in a relatively low water affinity (Lu et al., 2011). Compared with the hairy leaves (with trichomes) from the TR, rubber leaves with glabrous surface resulted in low adsorption and cohesion of raindrops, i.e., water cannot easily penetrate the exterior of the leaf to reach the inner pores. Therefore, rainwater drains readily from the rubber leaf surface, leading to considerable water loss. Moreover, the RM litter more rapidly reached the interception equilibrium than the TR litter (Fig. 5). These results implied that the RM litter was less effective to retain rainwater and retard runoff generation compared with the TR litter.

In the current study, C_{min}/SRA ratios significantly decreased with the increase in *SRA*, which was similar to the findings of Du et al. (2019), because the maximum interception storage capacity of litter was soon reached under high rainfall intensity. Thus, excess rainwater was lost and C_{min}/SRA showed a strong inverse relationship with rainfall amount. Marin et al. (2000) observed that no litter drainage occurred when the rainfall amount was less than 5 mm. Thus, special attention should be focused on litter interception under low rainfall intensity. In addition, 0.60–56.70% (on average, 10.64%) of total rainwater was intercepted in our experiment (Fig. 7). Such range is consistent with the results obtained by several previous studies. For example, 25.67% and 3.59–44.58% of litter interception were reported by Li et al. (2013) and Du et al. (2019) under simulated rainfall, respectively. In the field, Gerrits et al. (2010) noted 15–50% litter interception in a temperate forest; Bulcock and Jewitt (2012) observed 8.5–12.1% of gross rainfall; Tsiko et al. (2012) reported 19% interception loss of Msasa leaf litter; and Brye et al. (2000) estimated up to 70% litter interception. Although in most cases litter interception with a high range of variability only accounted for a small portion of rainfall partitioning, its important role in the hydrological processes of forest ecosystems should not be neglected in long time scales.

4.3. *Implications and limitations*

Land use/cover change is widespread throughout the tropics. In the Xishuangbanna region of tropical China, the conversion of TR into RM has reduced litter accumulation (Li et al., 2012), increased litter decomposition (Zhu et al., 2018), decreased litter diversity, and modified litter distribution on the ground (Fig. 1). These variations in litter conditions, more or less, affected the hydrological functions of the litter layer (Fig. 8). Walsh and Voigt (1977) proposed that litter type and litter accumulation were chief factors determining the absolute amounts of rainfall interception. In this study, litter in the TR that came from multiple species had larger surface area and more leaf trichomes and were relatively thicker than litter in the RM that came from a single species. These characteristics of TR litter could contribute to the improvement of water storage and rainfall interception capacities. In addition, the intensities of most of the local real rainfall events were less than 8 mm h^{-1} (Fig. S1). Under such rainfall intensities, the two litter types investigated in this study had a relatively high rainfall interception

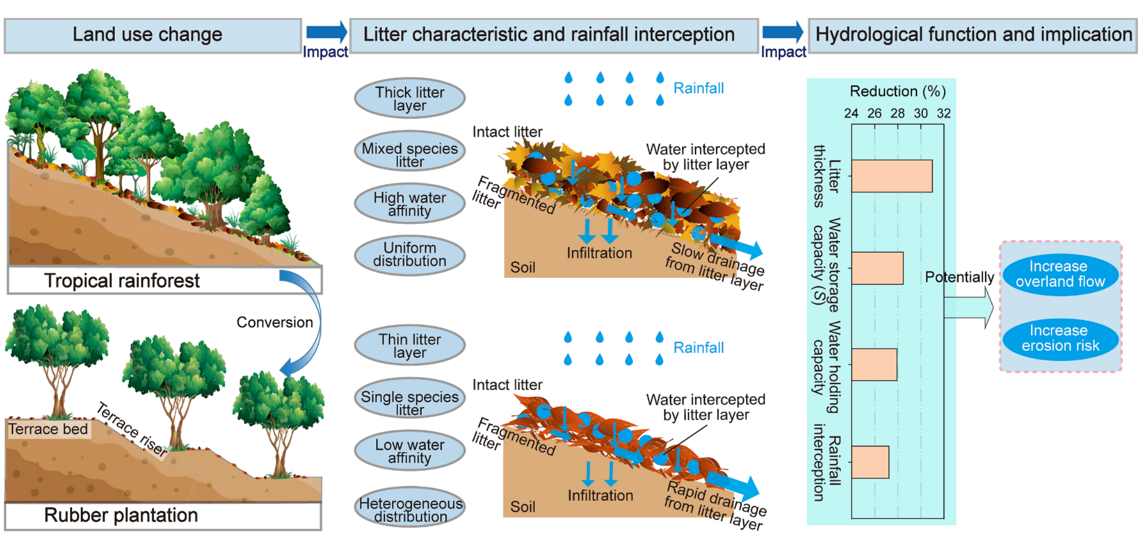

Fig. 8. Conversion of tropical rainforest into rubber monoculture modified the litter characteristics and subsequently degraded the hydrological functions of forest litter layer in Xishuangbanna, SW China. Reduction (%) = (LP_{TR}–LP_{RM})/LP_{TR}*100%, where LP_{TR} and LP_{RM} indicated litter parameters of TR and RM, respectively.

capacity (>10%, Fig. 7). Moreover, the rainfall interception capacity of TR litter was evidently higher than that of RM litter. This finding indicated that more rainfall and throughfall would reach the mineral soil in rubber plantations. Runoff generation will be enhanced when the moisture content of litter exceeds the storage capacity of litter (Bulcock and Jewitt, 2012), thereby possibly exacerbating subsequent water erosion. This viewpoint was substantially supported by Zhu et al. (2018) who observed that RM generated dramatically high surface runoff and sediment yield. Therefore, the degradation of the hydrological functions of forest litter was partly responsible for the negative hydrological consequences resulting from the conversion of TR into RM.

Du et al. (2019) determined that both C_{max} and C_{min} had a significant negative relationship with slope. Litter was uniformly distributed in the TR, whereas litter accumulation was evidently less on the terrace risers (slopes of 10–23°) than on the terrace beds (slopes of 0–5°) in the RM (Fig. 1). The thin litter layer on the terrace risers has low water storage capacity and low rainfall interception (Fig. 3; Fig. 6), potentially increasing surface runoff and erosion risk during rainfall events. Given the importance of the litter layer in erosion control, practical agricultural and forestry managements should pay more attention to the protection of litter layer on terrace risers. The government should encourage farmers to reduce herbicide application for maintaining rich ground cover of terrace risers. In addition, land holders can intercrop some deciduous species (or cash crops) with different defoliation times in the RM. This measure can not only increase income but also help improve the litter accumulation and litter diversity. For example, the litter layer from cacao trees (*Theobroma cacao*) could maintain a relatively long residence time in rubber-cacao agroforestry system (Zhu et al., 2018), which would be a promising intercrop in large area of RM. In addition, introducing native species of rainforests in abandoned rubber plantations is likely to help improve the litter input, litter accumulation and related ecohydrological functions.

Indeed, litter interception on a forested hillslope may be influenced by wind, atmospheric humidity, litter water content, decomposition level, plantation ages, and other factors (i.e., surface runoff and mineral soil). These effects were not considered in the present study. This is partly because of the technical difficulties inherent in interception measurements (Llorens and Gallart, 2000; Gerrits et al., 2007). It is also quite difficult to distinguish the boundary between the litter layer (H-layer) and mineral soil (Bulcock and Jewitt, 2012). In addition, the rainfall duration of 60 min may not be sufficient to saturate the litter, and the experimental litter in the tray may not be piled to the same thickness or density that was on forest floor. These study limitatioins means that the laboratory results were not applied strictly to field conditions. However, it is worth noting that the exclusion of these factors considerably clarified the effects of litter mass, litter morphology and rainfall conditions on the hydrological functions of forest litter during the conversion of TR into RM. Tree age is a variable of influence for litter accumulation. The aged rubber plantations might generate less plant materials than mature and young plantations. Long-term field experiments are needed to assess the differences in hydrological functions of litter layer among different plantation ages in future study. Hydrological attributes of plant litter in various rubber-crop agroforestry systems are also important for better understanding the significance of this management practice in water and soil conservation.

5. Conclusions

The effects of the conversion of TR into RM on the hydrological attributes of the litter layer were measured under simulated rainfall conditions. The results indicated that the average S was 1.40 times greater in the TR than in the RM. Significant linear relationships among litter mass, rainfall intensity and interception storage capacity (C_{max} and C_{min}) were observed in the two litter types. The average C_{max} and C_{min} in the TR were respectively 1.25 and 1.30 times greater than that in the RM. The RM litter was characterized by small leaf area, single species composition, leathery texture with a layer of wax film, glabrous surface, and nonporous litter structures, which resulted in high hydrophobicity and water loss during rainfall events. Therefore, the litter layer in the RM always intercepted and stored less rainwater (8.96%) than that in the TR (12.32%). These results indicated that the conversion of TR into RM inevitably modified the hydrological attributes of the litter layer by changing its composition and morphological characteristics. This conversion considerably impaired the hydrological functions of forest litter, such as lower water holding capacity and rainfall interception. This might increase runoff generation by reducing rainfall interception, potentially increasing soil erosion in rubber plantations. In view of the importance of forest litter, in practical management practices, special attention should be focused on the capacity of trees to increase litter accumulation and maintain soil surface cover in rubber plantations.

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. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2021.105172.

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