Isotope variations of throughfall, stemflow and soil water in a tropical rain forest and a rubber plantation in Xishuangbanna, SW China

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ABSTRACT

To assess the influence of vegetation structure on the isotopic composition of rainwater input during its passage through the canopy, rainfall, throughfall, stemflow and soil water were collected at a tropical seasonal rain forest (TSRF) stand and a rubber plantation (RP) stand for stable isotopic analysis during the 3 year period 2002–2004. The result clearly shows that the rainfall partitioning and the isotopic composition of throughfall, stemflow and soil water were strongly influenced by the forest canopy structure. Although the differences of overall mean isotopic composition of throughfall and stemflow between the two forests were small and not significantly different ($P > 0.05$), greater differences were found when only light rain events (≤ 10 mm) were taken into consideration. During the dry season, the enriched isotopic composition and the smaller slope of the regression line of $\delta^{18}O$ versus δD for soil water in the TSRF is not an indication that it lost significant water by evaporation, but a mixture of enriched fog drip, throughfall and stemflow. However, the soil in the RP stand showed significant evaporation. During the rainy season, the soil water for both stands did not appear to display considerable evaporation effects.

Key words | interception, rubber plantation, soil water, stable isotopes, throughfall, tropical rain forest

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INTRODUCTION

Vegetation cover has a profound influence on the hydrological cycle. A proportion of precipitation is intercepted by the vegetation, and some of this is lost to the atmosphere by evaporation (Tsujimura & Tanaka 1998; Aboal *et al.* 2000). As a result of difference in interception losses, forest canopy characteristics are a principal cause of hydrological differences between watersheds (Gash *et al.* 1980; Lloyd *et al.* 1988; Calder 1996; Hölscher *et al.* 1998; Crockford & Richardson 2000). Interception loss in dense forest not only affects streamflow and recharge, but through repeated rainfall–evaporation cycles, may significantly alter the rainfall climate (Lettau *et al.* 1979; Lawton *et al.* 2001; Hall 2003). An understanding of relationships between canopy characteristics and interception is thus essential for quantitative prediction of the effects of deforestation and changes in vegetation (Bosch & Hewlett 1981; Loescher *et al.* 2002; Dietz *et al.* 2006).

For isotope hydrology studies, isotopes of open rainfall samples rather than throughfall samples have often been used to represent the isotopic composition of water input into watershed, even if the watershed was entirely covered with forest. Thus, the effect of interception loss by the forest canopy on the isotopic composition of rainfall has often been neglected. It is, however, recognized that fractionation and selection processes lead to changes in the isotopic composition of rainwater on its passage through the vegetation canopy and soil (Gat & Matsui 1991; DeWalle & Swistock 1994; Gat 1996). For forested watershed, the

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water input into the system is throughfall, stemflow, dew and fog drip, a result of fog droplets impacting the vegetation (Bruijnzeel 2001; Scholl *et al.* 2002). Accordingly, the isotopic composition of throughfall, stemflow and soil water should be evaluated.

In Xishuangbanna, studies on rainfall partitioning into throughfall, stemflow and interception are available for a few primary and artificial forests (Zhang *et al.* 2003; Wang 2005). However, comparison of the influence of vegetation structure on the stable isotopic composition in throughfall, stemflow and soil water are lacking, although re-evaporation after interception may be different between primary forests and artificial types that replace them. As rubber plantation is a critical component of the local economy and is still a widespread practice in Xishuangbanna (Li *et al.* 2007), the hydrologic balance is an important topic regarding the search for sustainable agricultural uses.

In this study, we use seasonal isotopic composition variation in rainfall, throughfall, stemflow and soil water to compare the influence of stand structure on canopy hydrological behaviour in a primary rain forest and an artificial forest in Xishuangbanna, SW China. This study is a part of our previous study (Liu *et al.* 2004) on the hydrological and chemical effects of rainfall and fog drip on tropical seasonal rain forest (TSRF) and rubber plantation (RP). Isotopic analysis of fog drip and rainfall has previously been carried out to learn about the possible sources of the fog drip in TSRF (Liu *et al.* 2007). Seasonal variations in isotopic data in this study are compared with seasonal isotopic data of rainfall from the previous results.

MATERIALS AND METHODS

Study site

The experiment was carried out at a TSRF stand and a RP stand (21°55′39″ N, 101°15′55″ E) in Menglun town of Xishuangbanna Dai Autonomous Prefecture, Yunnan province (Figure 1), about 800 km from the Bay of Bengal on the northwest and 600 km from the Bay of Beibu on the east. The distance between the two forest stands is about 5 km. The TSRF site (dominated by *Pometia tomentosa* and *Terminalia myriocarpa*) is located on a small flat area between two hills extending from east to west and at an elevation of 750 m above sea level. Slopes to the south and north of the site are about 15°. The TSRF shows an intense

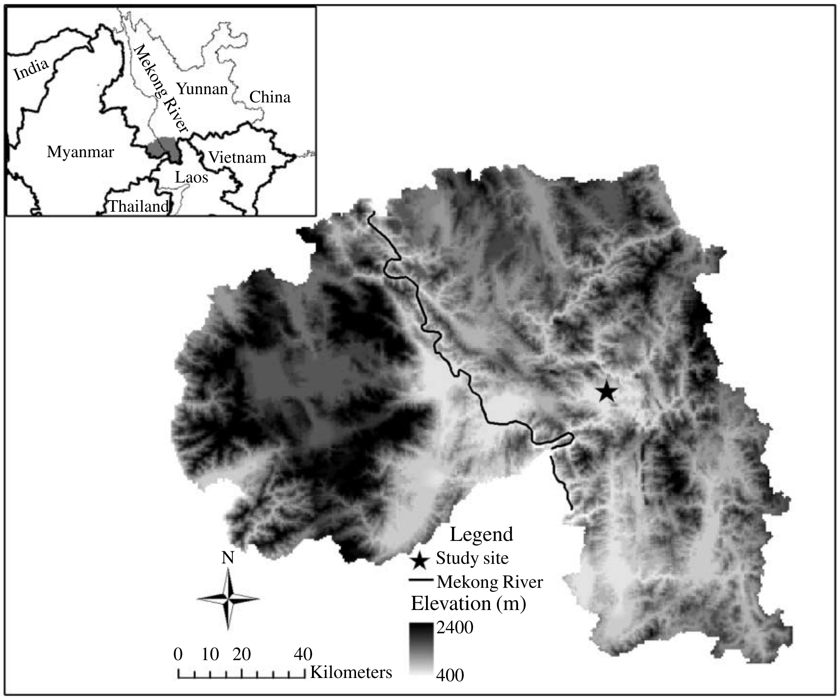

Figure 1 | Map showing location of the study site (21°55′39″N; 101°15′55″E; 750 m) in Yunnan Province, southwest China (indicated by a solid star).

tropical tendency in forest flora and is closely related to Malesian forests in flora. The forest canopy was about 36 m high. Detailed information of this forest structure can be found in Cao *et al.* (1996). Another site for this study was covered with a 37-year-old artificial forest of *Hevea brasiliensis Muell.-Arg.* or rubber tree (RP), which made up the forest canopy and was approximately 25 m high. This site was located at an elevation of 587 m above sea level. The rubber forest extended approximately 100 m in all directions, and was planted and cultivated for economic development purposes. The understory vegetation consisted of a mixture of agricultural plants such as *Camellia sinensis var.assamica (Masters) Kitamura* (tea plant).

The terrain is relatively flat to the north and south, and slopes upwards several degrees to the east. Cover-related variables of the two forests including mean diameter at breast height (DBH), mean DBH of dominant trees, stand tree density (DBH > 5 cm), mean height and top height, leaf area index (LAI) and fraction of the sky visible beneath the canopy are listed in Table 1. The soil under the two forests is lateritic soil developed from siliceous rocks, such as granite and gneiss. Both the experimental sites are permanent plots dedicated to the long-term ecological research managed by the Xishuangbanna Tropical Rain Forest Ecosystem Station, Chinese Academy of Sciences.

Xishuangbanna is situated on the northern edge of the tropical zone in southeast Asia contiguous to Laos to the south and Myanmar to the southwest. The region has mountain-valley topography with the Hengduan Mountains running north-south, and about 95% of the region is covered by mountains and hill. The Mekong River flows through the center of Xishuangbanna, and the region contributes more than 20 important tributaries, resulting in many river valleys and small basins (Cao *et al.* 1996).

Table 1 | Canopy structure characteristics of the tropical seasonal rain forest (TSRF) stand and the rubber plantation (RP) stand in Xishuangbanna, southwest China in 2004 (adapted from Wang 2005)

Items	TSRF	RP
Number of trees per ha	890	370
Mean DBH all trees (cm)	15.9	24.6
Mean DBH dominant trees (cm)	71.7	31.8
Top height (m)	36.0	25.2
Mean height all trees (m)	12.1	20.5
Fraction of the sky visible beneath the canopy (%)	2.0 ± 1.0	18.0 ± 15.0
LAI (m^2/m^2)	4.96 ± 0.80	2.40 ± 0.75

The Hengduan Mountains to the north of the region act as a major barrier keeping out cold air coming from the north in the winter. The climate is strongly seasonal with two main air masses alternating during the year. Between May and October (rainy season), the tropical southwest monsoon from the Indian Ocean delivers about 85% of the annual rainfall, whereas the dry and cold air of the southern edges of the subtropical jet streams dominate the climate between November and April (dry season). The dry season includes a cool sub-season from November to February and a hot sub-season from March to April. The cool sub-season is characterized by the highest frequency of heavy radiation fog during the night and morning. The hot-dry sub-season is characterized by dry and hot weather during the afternoon and with heavy radiation fog during the morning only. Radiation fog occurs almost every day from November to April and is heaviest from midnight (23:00–02:00) until mid-morning (09:00–11:00) when the daily temperature difference is greatest. This area has fog about 37% of the time during the dry season period, with a maximum of 46% during foggy season (Liu *et al.* 2005).

Long-term climate records measured at a weather station (560 m a.s.l.) nearby the RP site in the past 40 years shows that the mean annual air temperature is 21.7°C, with a maximum monthly temperature of 25.7°C for the hottest month (June) and a monthly minimum of 15.9°C for the coldest month (January). Temperatures exceeding 38°C often occur during March and April, and are always associated with a low relative humidity (less than 40%). The mean annual rainfall is 1487 mm, of which 1,294 mm (87%) occurs in the rainy season compared to 193 mm (13%) in the dry season. Class A pan evaporation varies between 1,000 and 1,200 mm/y. The mean monthly relative humidity is 87%. The prevailing wind direction is southwest, with a mean annual wind speed of 0.5 m/s and frequency of calm days of 75% (Liu *et al.* 2005).

Water sampling

Water samples for environmental isotope analysis were collected from throughfall, stemflow and shallow soil water.

Each of six V-shape troughs (each 0.3 m × 2.0 m) placed in random pattern were used to collect throughfall at the two forests. Each trough, connected to a plastic closed bottle, was mounted 0.7 m above the forest floor. The impacts of understory vegetation on the throughfall gauge measurements should be relatively low since sparse vegetation occurs below this height (Cao *et al.* 1996).

In the TSRF stand, stemflow was taken from 9 sample trees that were composed of three stems of small (<10 cm), moderate (10–30 cm) and larger (>30 cm) diameter classes for each of three dominant species (Liu *et al.* 2007). In the RP stand, stemflow was taken from 5 sample rubber trees with mean stem diameter of 31 ± 4 cm. Stemflow for each tree was measured using spiral polyethylene collars around the tree trunk, connected to a plastic closed bottle (Wang 2005). Volume of throughfall and stemflow were measured after each rain event. Stemflow per area was estimated by using the number of stems per area of the two forest stands (Wang 2005). Samples of throughfall and stemflow for isotope analysis were collected concurrently on each sampling date on an event basis at monthly intervals from January 2002 to December 2004. To reduce the number of samples for isotope analysis, volumes of water proportional to the volume collected by each trough or bottle for each collection event were combined after separate measurement of the volumes collected.

Six soil samples were obtained randomly within the two forest study sites from cores collected to a depth of 20 cm beneath the canopy on each sampling day. The soil samples were stored in 200 ml glass bottles, transported to the laboratory and immediately frozen for soil water extraction. The extracted soil waters of six soil samples from the same stand were combined. The sampling intervals were the same as for the throughfall and stemflow during the study period.

Throughfall and stemflow samples were collected in the 100 ml polysealed glass bottles, and transported to the laboratory and immediately frozen. Soil water was extracted from soil cores by vacuum distillation (Ingraham & Shadel 1992), and stored similarly. During the period of observation, a total number of 23 samples for throughfall, 17 for stemflow and 35 for soil water in TSRF and 27 for throughfall, 19 for stemflow and 33 for soil water in RP have been collected for isotope analyses.

Sampling for rainfall and fog drip at the TSRF stand and volume of each rain event at the RP stand were conducted during the same study period and analysed by Liu *et al.* (2007). Open precipitation samples were collected at a weather station near the RP on an event basis, by using a collector consisting of a stainless steel funnel (collecting area 314 cm^2) connected to a 2,000 ml plastic bottle. Previous study showed that no isotopically significant difference was found between the two forest stands in rainfall and fog samples (Liu *et al.* 2005). In this study, seasonal variations of throughfall, stemflow and soil water in isotopic data are compared with seasonal isotopic data from the previous results.

Isotopic analysis

The hydrogen- and oxygen-isotope analyses were performed at the Geochemistry Department, Test Centre of Lanzhou Branch, Chinese Academy of Sciences. The stable hydrogen and oxygen isotope composition was determined from a gas sample generated from pure liquid introduced into an isotope ratio mass spectrometer (Finnigan MAT252, Germany). The values are reported as the relative deviation of the isotope ratios (e.g. ^{2}H/^{1}H or ^{18}O/^{16}O) from that of V-SMOW. These are denoted as δD and δ^{18}O for the H and O isotope ratios, respectively (Dawson 1998). The precision (±S.D.) of oxygen and hydrogen isotope results are 0.2 and 2‰, respectively. The isotopic composition of each sample was analysed at least twice to check for repeatability of analysis, and standards were analysed to check for accuracy of analytical procedures.

Statistics

Volume-weighted mean isotopic composition were calculated for throughfall and stemflow samples, and time-averaged mean for soil water samples. Since very large variances are common, standard deviations are reported for isotopic composition. The Student t-test ($P < 0.05$ or <0.01) was used to test the significance of d values (deuterium excess; $d = \delta D - 8\delta^{18}O$; Gat & Matsui 1991) larger or small than 8.9 (i.e. d of the local meteoric water line (LMWL); Liu *et al.* 2007). It was also used to calculate the slope of best-fit regression line smaller than 7.96

(i.e. slope of the LMWL), and the different between the two forest stands in isotopic composition of throughfall, stemflow and soil water. If the slopes are significantly lower than 7.96, we conclude that a particular water, such as throughfall, stemflow and soil, has undergone considerable evaporation. If the *d* values are significantly smaller than 8.9, it can also be concluded that the measured water has undergone considerable evaporation (adapted from Gat & Matsui 1991; Ingraham & Shadel 1992; Martinelli *et al.* 1996). The LMWL was drawn through data collected at the same measurement site during the same study period (2002–2004) (Liu *et al.* 2007). SPSS 10.0 for Windows was used for all statistical calculations.

RESULTS

Rainfall, throughfall, stemflow and interception loss

On an annual basis, mean rainfall during the study period (2002–2004) was normal, with a value (mean ± 1 SD) of 1,509 ± 355 mm (Table 2). However, the value for 2002 (1,914 mm) was considerably greater than values of 2003 (1,253 mm) and 2004 (1,360 mm) (Figure 2(a)). The rainfall distribution pattern was strongly seasonal. Rainfall during the rainy season (from May to October) comprised 82% of total annual rainfall while it was 18% during the dry season (from November to April). The maximum monthly rainfall was 425 mm in August 2002 and the minimum monthly rainfall was 0 mm in November and December 2003.

The total volume of throughfall, stemflow and interception loss were significantly higher ($P \leq 0.05$) in the rainy season than in the dry season for each of the two forest stands (Table 2). The throughfall from the TSRF stand was 1,175 ± 259 mm or 78.1% of the total rainfall, which was significantly lower ($P < 0.05$) than value from the RP stand (1,254 ± 281 mm or 83.3%). For stemflow, the value from the TSRF stand was also significantly lower ($P < 0.05$) than the value from the RP stand. By subtracting the throughfall and stemflow from the rainfall, the interception loss from the two stands were estimated to be 17.1% and 9.4%, respectively, which were significantly different ($P < 0.05$).

The throughfall, stemflow and interception expressed as a percentage fraction of the total rainfall in the 36 months are shown in Figures 2((b)–(d)). As would be expected, the throughfall and stemflow were commonly lower, whereas the interception was significantly higher during the dry months than during the rainy months for each stand. Additionally, the values for the RP stand showed a higher variability than those for the TSRF stand. During January to February, when defoliation occurred for rubber trees, cover was still effective in preventing rainfall reaching the ground surface and interception loss was the highest (20–100%) compared with the other months, since rainfall was generally too small to saturate the canopy.

Isotopic composition of throughfall and stemflow

The stable isotope values in rainfall, throughfall, stemflow and soil water with their *d* values (deuterium excess) are given in Table 3. For both of the stands, volume-weighted means of isotopic composition and *d* value were higher (more enriched) than that of rainfall ($\delta D = -56.8$, $\delta^{18}O = -7.9$, $d = 8.9$; Liu *et al.*, 2007), although not significantly ($P > 0.05$), indicating that as rainfall travels

Table 2 | Summary of rainfall, throughfall, stemflow and interception at the TSRF and the RP during 2002–2004. For each water type, values within a row with different capital letters (A, B) are significantly different ($P < 0.05$; Student's *t*-test). Within one column, values with different lower-case letters (a, b, c) are significantly different from each other ($P < 0.05$; Student's *t*-test). Note that values are means ± SD, along with % of bulk rainfall in parentheses

		Throughfall (mm)		Stemflow (mm)		Interception (mm)	
Season	**Rainfall (mm)**	**TSRF**	**RP**	**TSRF**	**RP**	**TSRF**	**RP**
Dry	273 ± 84^{a}	180 ± 56^{Aa} (66.3)	208 ± 62^{Ba} (76.8)	11 ± 4^{Aa} (3.9)	19 ± 7^{Ba} (6.7)	81 ± 33^{Aa} (29.8)	45 ± 16^{Ba} (16.5)
Rainy	1236 ± 321^{b}	995 ± 252^{Ab} (80.6)	1046 ± 261^{Bb} (84.8)	62 ± 19^{Ab} (5.0)	91 ± 23^{Bb} (7.4)	179 ± 50^{Ab} (14.4)	99 ± 38^{Bb} (7.9)
Annual	1509 ± 355^{c}	1175 ± 259^{Ac} (78.1)	1254 ± 281^{Bc} (83.3)	73 ± 18^{Ac} (4.8)	110 ± 26^{Bc} (7.3)	260 ± 80^{Ac} (17.1)	144 ± 51^{Bc} (9.4)

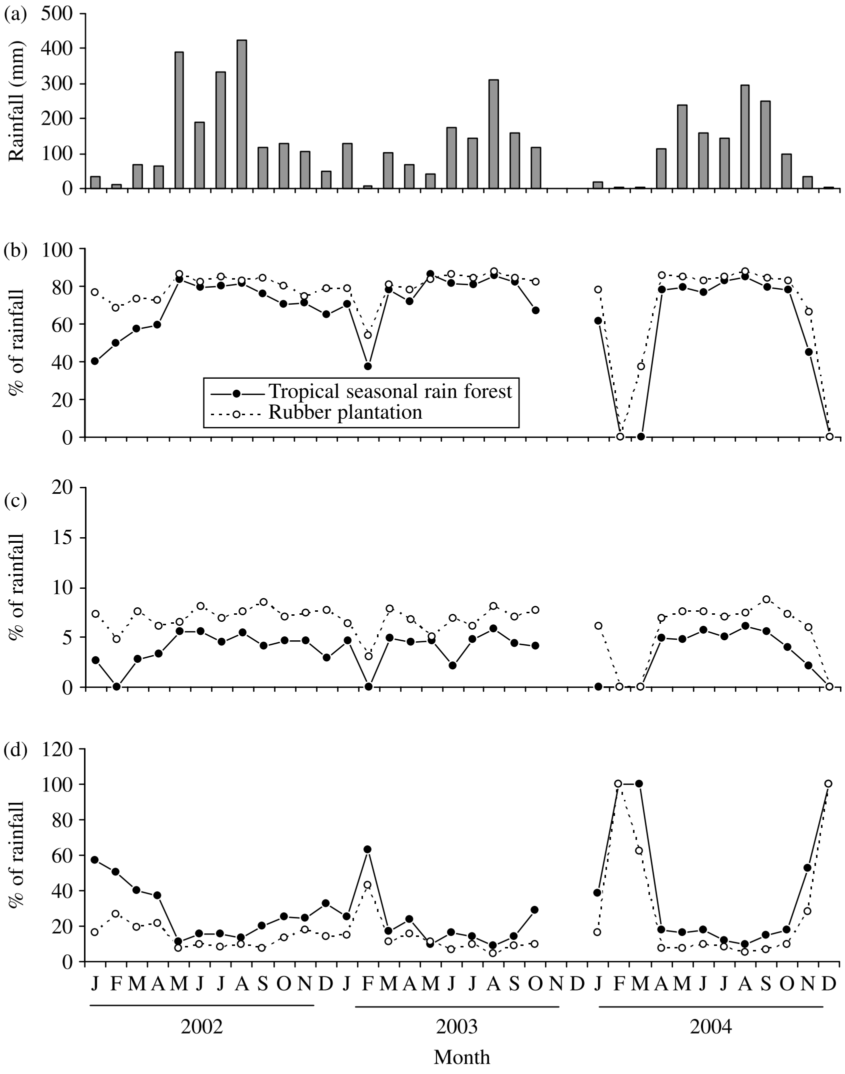

Figure 2 | The time series of monthly (a) rainfall, (b) throughfall, (c) stemflow, and (d) interception collected at the tropical seasonal rain forest (TSRF) and the rubber plantation (RP) during 2002–2004.

Table 3 | Summary of stable isotopic variability of waters by type at the TSRF and the RP during 2002–2004. Within one column, values with different lower-case letters are significantly different between site and sample type ($P = 0.05$; ANOVA followed by Tukey's comparison test)

Sample type	Site	δD (‰)	δ^{18}O (‰)	*d* (‰)	*n*
Rainfall	Open	-56.8 ± 15.1^a	-7.9 ± 4.7^a	8.9 ± 3.5^a	116
Throughfall	TSRF	-51.3 ± 13.7^b	-7.2 ± 3.3^a	7.5 ± 2.7^a	23
	RP	-52.7 ± 9.8^b	-7.4 ± 2.8^a	7.8 ± 3.3^a	27
Stemflow	TSRF	-52.4 ± 12.2^b	-7.3 ± 2.9^a	7.3 ± 4.0^a	17
	RP	-54.0 ± 11.6^b	-7.6 ± 1.7^a	7.6 ± 3.4^a	19
Soil water	TSRF	-41.2 ± 5.0^c	-5.9 ± 2.0^b	7.1 ± 3.5^a	35
	RP	-37.9 ± 5.8^d	-5.6 ± 3.5^b	$6.3 \pm 2.2^{b*}$	33

*The *d* (deuterium excess) is significantly lower than 8.9 (i.e. *d* of local meteoric water).

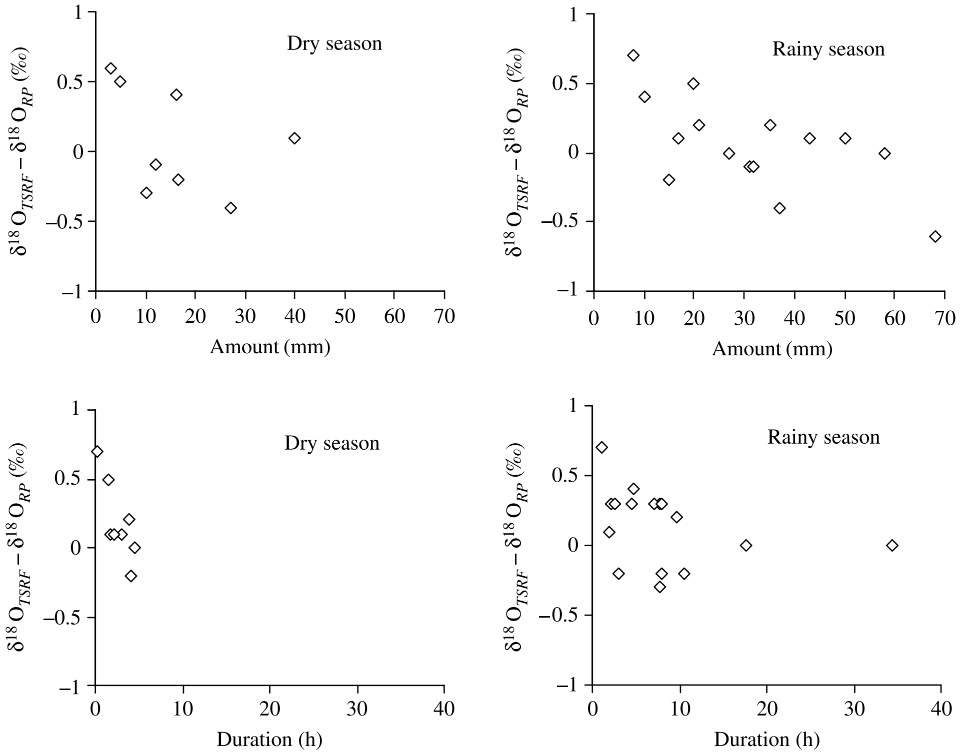

Figure 3 | Plot of throughfall δ^{18}O differences between the TSRF and the RP versus throughfall amount (upper) and rain duration (below) on the individual basis for the dry and rainy season during 2002–2004.

through the canopy some is loss by evaporation. The differences of overall mean δ^{18}O between TSRF and RP were +0.2‰ and +0.3‰ for throughfall and stemflow, respectively, while for the δD differences they were +1.4‰ and +1.6‰, respectively, which were not significantly different ($P > 0.05$, Table 3). The minor differences in the isotopic composition between the two stands in throughfall and stemflow may be attributed to volume-weighted calculation, which may reduce the deference (Kubota & Tsuboyama 2003; Liu *et al.* 2007). However, when only light rain events (≤10 mm or short rain duration, commonly occur during the dry season) are considered, apparently lower values were found at the RP stand, as shown in Figure 3 for throughfall δ^{18}O.

The slopes of δ^{18}O versus δD regression line for throughfall and stemflow by two rain size groups (≤10 mm and > 10 mm) are list in Table 4. In Xishuangbanna region, light rain events (≤10 mm) commonly occur during the dry season while heavy rain events (>10 mm) occur during the rainy season (Wang 2005). It can be seen that slopes of throughfall and stemflow for light rain (≤10 mm) were significantly different ($P < 0.05$) from those for heavy rain (>10 mm) and were significantly lower ($P < 0.05$ or < 0.01) than the slope (= 7.96) of local meteoric water line (LMWL, $\delta D = 7.96\delta^{18}O + 8.67$,

Table 4 | Values of slope with respective standard deviations, coefficient of best-fit regression and number of data points for the regression of δ^{18}O versus δD in throughfall and stemflow by two rain sizes (≤10 mm and > 10 mm) at the TSRF and the RP during 2002–2004. Within one column, means with different lower-case letters are significantly different between site and rain size ($P = 0.05$; ANOVA followed by Tukey's comparison test)

Sample type	Rain size	Site	Slope	R^2	n
Throughfall	≤10 mm	TSRF	$6.29 \pm 0.20^{a**}$	0.82	10
		RP	$6.68 \pm 0.35^{a*}$	0.65	12
	>10 mm	TSRF	7.55 ± 0.28^{b}	0.71	13
		RP	7.67 ± 0.29^{b}	0.69	15
Stemflow	≤10 mm	TSRF	$6.35 \pm 0.26^{a*}$	0.74	6
		RP	$6.84 \pm 0.34^{a*}$	0.80	8
	>10 mm	TSRF	7.69 ± 0.21^{b}	0.79	11
		RP	7.72 ± 0.57^{b}	0.66	11

*, ** Denotes that the slope is significantly smaller than 7.96 (i.e. slope of LMWL) at the 0.05 and 0.01 level, respectively.

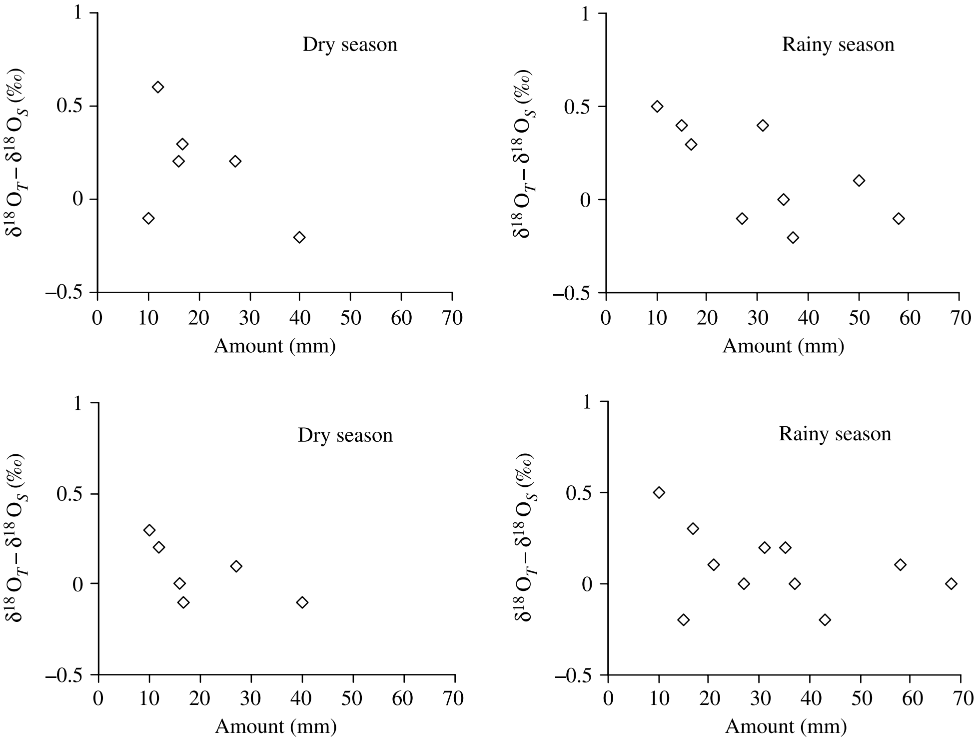

Figure 4 | Plot of δ^{18}O differences between throughfall *T* and stemflow *S* versus throughfall amount on an event basis at the TSRF (upper) and the RP (below) for the dry and rainy season during 2002–2004.

Liu *et al.* 2007). For each rain size group, slopes of throughfall and stemflow for the TSRF stand were slightly lower than those for the RP stand, but not significantly different ($P > 0.05$). In addition, large differences in isotopic fractionation between throughfall *T* and stemflow *S* were found in light rain events for each forest stand (Figure 4).

Isotopic composition of soil water

The isotopic composition of soil water for both stands is shown in Table 3, which were significantly higher ($P < 0.05$) than those for throughfall and stemflow. The *d* value for the TSRF stand was smaller than those of throughfall and stemflow, although not significantly different ($P > 0.05$), while for RP stand it was significantly smaller ($P < 0.05$) than 8.9 (i.e. *d* of local meteoric water) and those for throughfall and stemflow ($P < 0.05$).

The slopes of δ^{18}O versus δD regression line for soil water samples collected during the two distinct seasons (i.e. dry and rainy season) are list in Table 5. For the dry season, the slopes of soil water for both stands were significantly smaller ($P < 0.05$ or < 0.01) than 7.96 (slope of LMWL), which mean that the soil has undergone considerable evaporation during this period. However, during the rainy season the slopes were similar to that of rainfall. It is also seen that the slope of soil water under the RP stand was significantly smaller compared to that of the TSRF stand during the dry season ($P < 0.05$).

Table 5 | Values of slope with respective standard deviations, coefficient of best-fit regression and number of data points for the regression of δ^{18}O versus δD in soil water during the dry (November–April) and rainy (May–October) seasons at the TSRF and the RP during 2002–2004. Within one column, means with different lower-case letters are significantly different between season and site ($P = 0.05$; ANOVA followed by Tukey's comparison test)

Site	Season	Slope	R^2	n
TSRF	Dry	$6.14 \pm 0.16^{a*}$	0.65	17
	Rainy	7.96 ± 0.25^{b}	0.82	18
RP	Dry	$5.91 \pm 0.23^{c**}$	0.66	18
	Rainy	7.83 ± 0.19^{b}	0.72	15

*, ** Denote that the slope is significantly smaller than 7.96 (i.e. slope of LMWL) at the 0.05 and 0.01 level, respectively.

DISCUSSION

Throughfall, stemflow and interception loss

The throughfall from the TSRF stand was 78.1% of the annual rainfall, which falls in the lower range of values for other tropical montane and lowland rain forests (76–91%) reported by previous studies (Nye 1961; Manokaran 1979; Brasell & Sinclair 1983; Lloyd & Marques 1988; Veneklaas 1990; Bruijnzeel *et al.* 1993; Calder 1996; Crockford & Richardson 2000; Dietz *et al.* 2006). The throughfall from the RP stand was 83.3% of the annual rainfall. However, the interception loss in the TSRF (17.1% of rainfall) was larger than that of RP (9.4% of rainfall), which indicates that the re-evaporation after interception in the canopy of the TSRF was significantly higher than that for the RP.

The differences between our primary forest and artificial forest in throughfall and interception loss can be attributed to an apparently lower crown density and lower LAI in the RP stand (Table 1). As pointed out by many researchers (Aboal *et al.* 2000; Brodersen *et al.* 2000; Crockford & Richardson 2000; Hall 2003; Dietz *et al.* 2006), canopy structure had a clear effect on throughfall and interception loss, e.g., throughfall will increase and interception loss will decrease with decreasing LAI and decreasing crown density. In addition, canopy interception also varies with the climate conditions (Parker 1983; Lloyd *et al.* 1988). In our study, the interception loss was distinctly higher during the dry season (low humidity and low intensity storm) compared to the rainy season (high humidity and high intensity storm) for both stands (Table 2). The smaller the storm intensity, the greater is the interception loss (Figure 2). During January to February, even when defoliation occurred for rubber trees in RP stand, the proportion of interception still reached the highest value (20–100%) compared with the other months, since rainfall was generally too small to saturate the canopy.

As expected from Table 2 and Figure 2, the stemflow for both stands presented a similar pattern to the throughfall. The number of stemflow collectors in the TSRF stand was insufficient, because there was a large number of species in this forest. However, the friction of stemflow of dominated species in the TSRF was significantly lower compared to the value in the RP (Table 2, Figure 2). The reason for the high stemflow value for the RP stand could be the growth form and the crown morphology of rubber tree, which has inclined branches and high crown.

Isotopic composition of throughfall and stemflow

In a forest stand, part of the falling rainwater is stored in the canopy as interception. Before dripping down, this water is subjected to evaporation and isotopic exchange with the atmospheric water vapour. Commonly, this process will lead in most cases to an isotopic enrichment of throughfall and stemflow (Gat & Matsui 1991; DeWalle & Swistock 1994). The data observed in our study were in good agreement with this trend, as shown in Table 3.

Although the differences of overall mean isotopic composition between TSRF and RP were small and not significant, greater differences were found between the two stands when only light rain events were considered, as shown in Figures 3 and 4 using throughfall and stemflow δ^{18}O as an example. In this case, throughfall and stemflow in TSRF stand are isotopically more enriched compared to those for the RP stand. This indicates that during the course of light rain events, considerably more rain water was returned to the atmosphere through evaporation at the TSRF stand than at the RP stand.

These differences can be contributed to the differences in bark characteristics and leaf area index among tree species in the two stands (Wang 2005). The rubber trees have a smoother bark and a lower crown density while most of the trees in TSRF have a rough bark with some epiphytes and a higher crown density, which can greatly affect the stemflow and throughfall processing (Wang 2005). Moreover, large differences in isotopic fractionation between throughfall T and stemflow S were found in light rain events for each forest stand (Figure 4), which indicates that the small amount of stemflow occurred during the end of the light rain events when less rain water was returned to the atmosphere through canopy evaporation.

Clearly, the greater the storm intensity, the smaller is the interception loss, as pointed out by Williams *et al.* (1987). During the dry season (especially during the hot-dry season during March–April) the rain size is usually small (≤ 10 mm) and the air is quite dry and hot in Xishuangbanna region (Zhang 1986). Thus, more isotopic enriched throughfall and stemflow should be found during the dry season for both forest stands, especially for the TSRF stand. The slopes of δ^{18}O versus δD regression line for throughfall and stemflow by two rain size groups (≤ 10 mm and > 10 mm), as shown in Table 4, also reflected this trend. The slopes of throughfall and stemflow for light rain (≤ 10 mm) were significantly lower ($P < 0.05$) than those for heavy rain (> 10 mm) and were significantly lower ($P < 0.05$ or < 0.01) than the slope ($= 7.96$) of LMWL, indicating that rainwater has undergone considerably more evaporation during light rain events than during heavy rain events. Compared to the RP stand, the slopes of throughfall and stemflow for the TSRF stand were lower, although not significant, which also indicates that more evaporation of intercepted rainwater occurred in the TSRF stand. For heavy rain events, which commonly occurred during the rainy season, the slopes of throughfall and stemflow were slightly lower than that of LMWL, which suggests less rainwater also evaporated into the atmosphere through the two forest canopies.

It is also interesting to note that the throughfall δ^{18}O and its difference between the two forest stands tended to be smaller as the volume rainfall and rainfall duration increase (Figure 3). This indicates that larger and stronger rainfall tended to have a smaller effect on the isotopic composition in throughfall and on the isotopic difference between the two stands. As mentioned above, rainwater has undergone considerably more evaporation during light rain events than during heavy rain events before reaching the forest ground, which also confirms this finding.

The other major effect causing changes in the isotope composition of throughfall and stemflow is the selection process (Gat & Matsui 1991; DeWalle & Swistock 1994; Kubota & Tsuboyama 2003). This effect is especially important if the isotope composition of the rain changes significantly during the course of an event. The process can either result in enriched or depleted throughfall and stemflow, depending on whether the rain tends to be isotopically lighter or heavier at the end, as part of the end portion is held in the canopy (DeWalle & Swistock 1994). Results from Kubota and Tsuboyama (2003) showed that the overall difference between rainfall and throughfall was 0.4‰ in δ^{18}O, while the isotopic variations of rainwater in some individual rain event were more than 4‰. However, we did not measure and consider the selection process since our samples of rainfall, throughfall and stemflow for isotope analysis were collected concurrently on each sampling date on an event basis.

Isotopic composition of soil water

For the TSRF stand, the isotopic composition of soil water was significantly higher ($P < 0.05$) than those for throughfall and stemflow (Table 3), and the slope was significantly smaller ($P < 0.05$) than that for the LMWL ($= 7.96$) during the dry season (Table 5). These indicate that some water might be subjected to evaporation during the course of water infiltration into the soil. However, the difference in isotopic composition between the soil water and the rainfall could not be solely attributed to evaporation from the soil because of the frequent occurrence of the dense radiation fog (Liu *et al.* 2005) and of the litter layer. Water contained in the litter layer may be more enriched than the soil water, but this effect should not be considered since the litter was taken out prior to the soil samples collection. An alternative explanation is that the soil water contains some fog drip water during the dry season. Our previous study showed that under the TSRF canopy, the average amount of annual fog drip was 89.4 mm with 86% of the fog drip occurring in the dry season and representing 49% of total rainfall in the same period (Liu *et al.* 2004). Nearly every morning during the dry season (especially during the cool-dry season during November–February) the wetness inside the forest is similar to a light rain owing to the dense fog. During fog events, fog drops cover tree leaves and the soil is wet by fog drip in the morning. Our empirical observation also shows that some fog drip can infiltrate into the forest soil through the litter layer. The soil water which contained isotopically enriched fog drip, throughfall and stemflow could therefore still yield a slope significantly smaller than 7.96.

Another effect influencing the isotopic composition of the soil water is the mixing process with water that was previously stored in the soil (Brodersen *et al.* 2000; Gat 2000). However, this effect should be lower since the relatively large isotopic difference between the soil water and the throughfall existed. Martinelli *et al.* (1996) and Brodersen *et al.* (2000) also pointed out that isotopic changes in soil water resulting from direct evaporation can be neglected because evaporation is minimal in densely forested soil. In addition, the degree of soil saturation (soil moisture content) could affect the slope of the soil water evaporation line (Barnes & Alison 1988). However, this effect remains to be confirmed in further research since information of the soil moisture content is not available at present.

For the RP stand, the isotopic composition of soil water was significantly higher ($P < 0.05$) and the d value was significantly smaller ($P < 0.05$) than those for throughfall and stemflow (Table 3). Furthermore, the slope for the RP stand was significantly smaller ($P < 0.01$) than that for the TSRF stand and the slope of LMWL ($= 7.96$) during the dry season (Table 5). These suggest that the RP soil might have undergone considerably more evaporation than the TSRF soil during this period since the crown of this artificial forest was sparse, especially during January to February when defoliation occurred. However, we could not rule out the effect of fog drip on the isotopic content of the RP soil water since less fog drip also occurred in this stand. A previous study (Liu *et al.* 2003) showed that there was lesser annual fog drip (18.6 mm) in the RP stand compared to the TSRF stand (89.4 mm). The lower fog drip in the RP stand should be contributed to the lower crown density, lower LAI and lower surface roughness (as tree height variability) of the RP during the dry season (since reductions in these variables mean decreased surface area for fog entrapment). The greater amount of enriched soil water in the RP was therefore thought to be contained water that has undergone considerable evaporation from soil, plus the more enriched fog drip, throughfall and stemflow.

It is also interesting to note that the soil water for both stands had a similar slope to that of rainfall ($= 7.96$) during the rainy season (Table 5), showing that the soil did not appear to display considerable evaporation effects. In this season, dense fogs and fog drip amounts were not observed as much as in the dry season (only 13% of the annual total), and its effect on the soil δ^{18}O and δD values should be small. A previous study at this forest site also show that the soil water is not significantly different from the rainfall in mean δ^{18}O and δD values and hence can most reasonably be ascribed to that source (Liu *et al.* 2005). Study from Martinelli *et al.* (1996) in the Amazonian rain forest also pointed out that soil under the dense canopy in the rainy season has not undergone considerable evaporation.

CONCLUSIONS

It is believed that substituting tropical rain forest for rubber plantation might greatly alter the energy balance and consequently the water balance. To evaluate the hydrological effect of rubber plantation, rainfall, throughfall, stemflow and soil water were collected at a tropical seasonal rain forest (TSRF) stand and a rubber plantation (RP) stand for stable isotopic analysis during a period of 3 years. The result clearly shows that the rainfall partitioning and the isotopic composition of throughfall, stemflow and soil water were strongly influenced by the forest canopy structure. The fractions of throughfall and stemflow from the TSRF were significantly lower than values from the RP, while the interception loss from the TSRF (17.1%) was significantly higher than that from the RP (9.4%).

Although the differences of overall mean isotopic composition of throughfall and stemflow between the two forests were small and not significantly different, greater differences were found between the two stands when only light rain events were considerated. This indicates that during the course of light rain events, considerably more rainwater was returned to the atmosphere through evaporation at the TSRF than at the RP. The enriched isotopic contents and the lower slope for the regression lines of δ^{18}O versus δD for soil water in the TSRF indicates that some water might have evaporated significantly during the course of water infiltration into the soil. However, analysis suggests that the soil under this dense forest has not undergone considerable evaporation, and that the soil water appears to be a mixture of fog drip, throughfall and stemflow. While the RP soil showed significant evaporation, the more enriched soil water was thought to be produced through considerable evaporation from soil plus the enriched fog drip, throughfall and stemflow.

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