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Hydrologically transported dissolved organic carbon influences soil respiration in a tropical rainforest

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Abstract. To better understand the effect of dissolved organic carbon (DOC) transported by hydrological processes (rainfall, throughfall, litter leachate, and surface soil water; 0–20 cm) on soil respiration in tropical rainforests, we detected the DOC flux in rainfall, throughfall, litter leachate, and surface soil water (0–20 cm), compared the seasonality of $\delta^{13}C_{DOC}$ in each hydrological process, and $\delta^{13}C$ in leaves, litter, and surface soil, and analysed the throughfall, litter leachate, and surface soil water (0–20 cm) effect on soil respiration in a tropical rainforest in Xishuangbanna, southwest China. Results showed that the surface soil intercepted 94.4 ± 1.2 % of the annual litter leachate DOC flux and is a sink for DOC. The throughfall and litter leachate DOC fluxes amounted to 6.81 and 7.23 % of the net ecosystem exchange respectively, indicating that the DOC flux through hydrological processes is an important component of the carbon budget, and may be an important link between hydrological processes and soil respiration in a tropical rainforest. Even the variability in soil respiration is more dependent on the hydrologically transported water than DOC flux insignificantly, soil temperature, and soil-water content (at 0–20 cm). The difference in $\delta^{13}C$ between the soil, soil water (at 0–20 cm), throughfall, and litter leachate indicated that DOC is transformed in the surface soil and decreased the sensitivity indices of soil respiration of DOC flux to water flux, which suggests that soil respiration is more sensitive to the DOC flux in hydrological processes, especially the soil-water DOC flux, than to soil temperature or soil moisture.

1 Introduction

Dissolved organic carbon (DOC), the most active form of fresh carbon, stimulates microbial activity and affects CO_2 emissions from the surface soil (Bianchi, 2011; Chantigny, 2003; Cleveland et al., 2006). This indicates that the proportion of DOC that leaches from the soil is a crucial component of the carbon balance (Kindler et al., 2011; Stephan et al., 2001), which is also estimated as the high ratio of DOC flux to net ecosystem exchange (NEE) in forests, grasslands, and croplands (Sowerby et al., 2010). The DOC from water-extractable soil carbon is regenerated quickly and functions as an important source of substrate for soil respiration (SR), especially microbial heterotrophic respiration (HR) (Cleveland et al., 2004; Jandl and Sollins, 1997; Schwendenmann and Veldkamp, 2005), which contributes more to SR than does autotrophic respiration. Laboratory studies have shown that DOC also plays an important role in SR in the surface soil (De Troyer et al., 2011; Fröberg et al., 2005; Qiao et al., 2013). However the mechanisms underlying the effects of DOC on the carbon budget and SR in the field remain unclear.

Hydrological processes that transport DOC, such as throughfall and litter leachate, are important sources of DOC in surface soil water (De Troyer et al., 2011; Kalbitz et al., 2000, 2007; Kindler et al., 2011). The soil retains most of the DOC that reaches the soil surface from the throughfall and litter leachate (Chuyong et al., 2004; Dezzeo and Chacón,

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2006; Liu and Sheu, 2003; Liu et al., 2008; McJannet et al., 2007; Schrumpf et al., 2006; Zimmermann et al., 2007). Qiao et al. (2013) suggested that the addition of labile organic carbon increases the decomposition of the native soil organic carbon (SOC) by exerting a priming effect, and augments the CO_2 emissions in subtropical forests. Because of the massive rainfall in tropical rainforests, more DOC flux is transported to the soil by throughfall and litter leachate than in other forests. The high temperature and leaching in tropical forests may mean that the fresh DOC from hydrological processes affects SR differently in tropical rainforests than in boreal and temperate forests (De Troyer et al., 2011; Fröberg et al., 2005; Qiao et al., 2013). For this reason, research into the role of hydrologically transported DOC in the SR in tropical rainforest is essential.

The fate of DOC intercepted by the surface soil can be determined from variations in the DOC flux and $\delta^{13}C_{DOC}$ among soil water, soil, litter leachate, and throughfall. Based on the seasonal and source (canopy leaf, litter, or soil) differences in $\delta^{13}C$ (De Troyer et al., 2011), $\delta^{13}C_{DOC}$ studies have shown that DOC transported from aboveground water and from the desorption of soil aggregates is retained in the surface soil by soil absorption or is involved in surface carbon biochemical dynamics through soil-water leaching and microbiological activity (Comstedt et al., 2007; De Troyer et al., 2011; Fang et al., 2009; Kindler et al., 2011). This proposal has been confirmed in a laboratory leaching experiment simulating a temperate forest, as performed by Park et al. (2002), who reported that the cumulative amount of CO_2 evolved is positively related to the availability of carbon (Park et al., 2002). Furthermore, fresh DOC fed to the surface soil influences soil CO_2 emissions in both the short term (3–14 days) and long term (month to years) (Davidson et al., 2012). Therefore, several models of the surface soil carbon efflux indicate that DOC is a factor that influences CO_2 emissions (Blagodatskaya et al., 2011; Guenet et al., 2010; Yakov, 2010) based on recent research with controlled experiments. However, the natural mechanism underlying the effects of the hydrologically transported DOC flux on CO_2 emissions remains unclear. The precipitation rate, NEE, and litterfall are all high in tropical forests (Tan et al., 2010; Zhang et al., 2010), and several studies have shown that DOC plays an important role in the carbon balance in these settings (Fontaine et al., 2007; McClain et al., 1997; Monteith et al., 2007). Here, we investigate the relative contribution of hydrologically transported DOC to SR in a rainforest compared with the contributions of soil temperature and moisture, which has not been extensively studied until now.

Our study was performed in a tropical rainforest at Xishuangbanna in south-west China, on the northern edge of a tropical region. This forest has less annual rainfall (1557 mm), a smaller carbon sink ($1667\,kg\,C\,ha^{-1}$) (Tan et al., 2010; Zhang et al., 2010), lower SR ($5.34\,kg\,CO_2\,m^{-2}\,yr^{-1}$) (Sha et al., 2005), and less litterfall ($9.47 \pm 1.65\,Mg\,C\,ha^{-1}\,yr^{-1}$) (Tang et al., 2010) than typical rainforests of the Amazon and around the Equator. We hypothesized that throughfall and litter leachate DOC flux are important in the carbon budget, and that hydrologically transported DOC significantly affects SR in the tropical rainforest at Xishuangbanna. To test these hypotheses, we determined the SR, HR, and DOC fluxes in the rainfall, throughfall, litter leachate, and surface soil water (0–20 cm depth), the seasonal variability in $\delta^{13}C$ (isotopic abundance ratio of ^{13}C), in DOC ($\delta^{13}C_{DOC}$), and in the carbon pools in the soil, litter, and canopy leaves in this tropical forest.

2 Materials and methods

2.1 Study site

The study site is located at the centre of the National Forest Reserve in Menglun, Mengla County, Yunnan Province, China (21°56′ N, 101°15′ E), and has suffered relatively little human disturbance. The weather in the study area is dominated by the northern tropical monsoon and is influenced by the south-west monsoon winds, with an annual average temperature of 21.5 °C, annual average rainfall of 1557 mm, and average relative humidity of 86 %. Based on the precipitation dynamics, the rainy season occurs between May and October (with 84.1 % of the total annual precipitation) and the dry season between November and April.

The dominant trees are *Terminalia myriocarpa* and *Pometia tomentosa*, which are typical tropical forest trees. Canopy height is about 45 m, the land cover ratio is 100 %, there are 311 species whose diameter at breast height (DBH) is larger than 2 cm (Cao et al., 1996). The topographic slope is 12–18°, and the soil type is oxisol, formed from Cretaceous yellow sandstone, with a pH of 4.5–5.5 and a clay content ($d < 0.002$ mm) of 29.5 % in the surface soil (0–20 cm) (Tang et al., 2007).

2.2 Experimental set-up

At the study plot (a 23.4 ha catchment), three rainfall collectors were set above the canopy on a 70 m eddy-flux tower to collect rain samples. Each collector had a polytetrafluoroethylene (PTFE) funnel (2.5 cm diameter) connected to a brown glass bottle, which was rinsed with distilled water before each collection. There were four replicates of throughfall, litter leachate, and soil water (20 cm depth). All the collectors were set around the eddy-flux tower randomly. All the collectors were distributed randomly around the eddy-flux tower. The throughfall collectors were $200 \times 40\,cm^2$ V-shaped tanks made of stainless steel. A PTFE tube connected the collector to a polyethylene sampling barrel. The litter leachate was collected in 40 cm × 30 cm × 2 cm PTFE plates. In the plate, we layered 100-, 20-, and 1-mesh silica sand from the bottom to the upper edge, to a depth of 2 cm, to ensure that the litterfall fragments did not reach the bottom of the plate and to filter the leachate. The bottom of the plate was curved into an arc shape, causing the leachate to flow together at the bottom funnel. The funnel was connected by a PTFE tube to a 10 L bottle further down the slope. The soil-water collector was designed like the litter leachate collector. The collection system was buried in soil at a depth of 20 cm along the surface slope. To reduce the disturbance from digging as much as possible, all the soil collectors were placed in holes that were approximately the size of the PTFE collector, and all soil was added from the bottom to the surface, layer by layer. All the soil water and litter leachate collectors were set in place 3 months before the samples were collected, to minimize the influence of their installation.

The water fluxes from rainfall and throughfall were estimated with an installed water-level recorder. The recorder was set to measure the average discharge at 30 min intervals. The daily and weekly water fluxes from rainfall and throughfall were calculated from the data recorded automatically between 08:00 and 08:00 LT (local time) on the following day. The water fluxes from the litter leachate and soil water were determined daily by manual observation.

We set four 5 m × 5 m plots around the eddy-flux tower to measure SR and HR using the trenching method. In each plot, three paired trenches and control treatments were used to detect both HR and SR. Each treatment covered an area of 50 cm × 50 cm. Most fine roots occur in the first 0–20 cm of soil and few occur below a depth of 50 cm in the soil of tropical rainforests (Fang and Sha, 2005). In each trenched treatment, a polyvinyl chloride panel was installed, and a 50 cm deep trench was filled with in situ soil to protect root respiration during the trenching treatment.

The soil respiration was measured using a Li-820 system (Li-Cor Inc., Lincoln, NE, USA), which consisted of an infrared gas analyser with a polyvinyl chloride chamber (diameter of 15 cm and height of 15 cm). A polyvinyl chloride collar (diameter of 15 cm an height of 5 cm) was installed in the forest floor to a depth of ∼ 3 cm. All the leaf litter and small branches were left in the collar. Soil respirations were detected from 09:00 to 14:00 LT when a gas sample was taken to represent respiration in that day (Sha et al., 2005; Yao et al., 2012) biweekly from February 2008 to February 2009.

2.2.1 Soil temperature and moisture

From 2008 to 2011, soil temperature and moisture at a depth of 5 cm were measured every 15 min with a Campbell Scientific data logger (Campbell Scientific, North Longan, Utah, USA), which was fixed to the eddy-flux tower. The daily average soil temperature and moisture were calculated as the daily means of the data collected every 15 min.

During soil respiration observation period between February 2008 and January 2009, soil-water content (0–12 cm) was detected by time-domain reflectometry (TDR100, Campbell Scientific, USA) in the soil close to every chamber. At the same time, the soil temperature (0–10 cm) and the air temperature were recorded with a needle thermometer.

2.2.2 Soil, leaf, and litter sampling

Soil (0–20 cm depth) near the soil-water collectors, and leaf samples and litter samples from around the water collector were collected in August and October 2010, and in January, March, and May 2011. The leaves of the dominant species were randomly picked from the canopy around the plots, and litter samples were collected from around the plots. Soil samples were collected with a steel soil sampler (diameter is 5 cm; height is 20 cm). All the leaf and litter samples were oven dried to constant weight at 60 °C. After drying, the leaf and litter were ground and passed through a 1 mm screen. Wind-dried soil was manually broken by hand and sieved (100 mesh) to remove larger particles, roots, and visible soil fauna. Plant and soil samples were analysed for total C and δ^{13}C values with an elemental analyser (Elementar vario PYRO cube, Germany) coupled to an continuous flow system isotope ratio mass spectrometer (IsoPrime 100 Isotope Ratio Mass Spectrometer, Germany, EA-IRMS). Samples (1.00–3.00 mg plant samples and 10–40 mg soil sample dried and sieved through 100 mesh size) were wrapped in a tin boat and loaded into the auto-sampler (EA3000, Eurovector, Milan, Italy) coupled to the EA-IRMS. The sample was flash combusted in a combustion reactor held at 1120°. The produced CO_2 was separated by the CO_2 absorption column, and carried by helium to ion source for measurements. The reference CO_2 (> 99.999 %) flowed in at 420 s and lasted for 30 s. The isotopic results are expressed in standard notation (δ^{13}C) in parts per thousand (‰) relative to the standard Pee Dee Belemnite:

$$\delta^{13}\mathrm{C} = [^{13}R_{\mathrm{sample}} / ^{13}R_{\mathrm{standard}} - 1] \times 1000, \quad (1)$$

where R is the molar ratio ^{13}C / ^{12}C.

2.3 Water sampling and analysis

All the 24 h cumulative water samples were collected at the sampling sites between 08:00 and 10:00 LT, following the procedure outlined by Zhou et al. (2013), using high-density polyethylene bottles. The sampling bottles were completely filled, allowing no headspace. After the bottles were washed with 3 % HCl solution, they were rinsed with distilled water. Before sample collection, the bottles were pre-rinsed 3 times with the sample water. The study was performed over 3 full calendar years, from 1 January 2009, to 31 December 2011. The water samples were collected on the day following a rain event during the dry season and once a week during the rainy season in 2009, and once a week in 2010 and 2011. All the water samples were immediately transported to the laboratory in insulated bags to prevent DOC decomposition.

Based on the analytical method of Zhou et al. (2013), all the samples were vacuum-filtered through a 0.45 µm glass fiber filter (Tianjinshi Dongfang Changtai Environmental Protection Technology, Tianjin, China) and were prerinsed with deionized water and the sample water under vacuum. The filtered samples were analysed for DOC within 24 h of collection using a total organic carbon/total nitrogen (TOC/TN) analyser (LiquiTOC II, Elemental Analyses System GmbH, Germany).

To analyse the water DOC isotopic δ^{13}C-DOC ($\delta^{13}C_{DOC}$), the samples were collected on the same day as the leaves, litter, and 0–20 cm soil samples were collected. Subsamples (500 mL) of the rain, throughfall, litter leachate, and soil-water samples were passed through a 0.45 µm glass fiber filter and transferred to another 500 mL polyethylene terephthalate bottle. All the filtered water was frozen and placed in a freeze dryer until it was reduced to a fine powder. The δ^{13}C of the freeze-dried DOC was analysed with a method similar to that for the plant and soil samples. Considering the lower C content, more sample amount (20–60 mg) were weighted, the combustion temperature was set at 920°, and the reference CO_2 flowed in at 475 s, later than for the soil and plant samples. The sample δ^{13}C abundance were calculated according to Eq. (1).

2.4 Calculations and statistics

The correlations among the daily water flux and DOC concentration, SR, HR, soil moisture, and soil temperature from February 2008 to January 2009, as well as the weekly SR and HR rates and the amounts of DOC and water in 2009–2011, were tested with Pearson's correlation (two-tailed) and non-linear regression tests. One-way analysis of variance (ANOVA) was used to compare the hydrological DOC fluxes among different hydrological processes. The seasonal difference of hydrological DOC fluxes, $\delta^{13}C_{DOC}$ was tested by independent sample t test. The Statistical Program for Social Sciences (SPSS) 15.0 software was used for all calculations.

Because the individual correlations between the water flux and the DOC concentration in the throughfall, litter leachate, and soil water were significant (Fig. S1 in the Supplement), the regression equations used for the water flux and DOC concentration ($Y = ae^{bx}$) were as follows:

$$C_{TF} = 48.69e^{-0.097x} \text{ adjusted } r^2 = 0.3883,\ p = 0.002, \quad (2)$$

$$C_{LL} = 60.93e^{-0.048x} \text{ adjusted } r^2 = 0.4131,\ p < 0.001, \quad (3)$$

$$C_{sw20} = 6.78e^{-0.02048x} \text{ adjusted } r^2 = 0.5840,\ p < 0.001, \quad (4)$$

where C_{TF}, C_{LL}, and C_{sw20} are the DOC concentrations (mg L^{-1}) in the throughfall, litter leachate, and soil water (0–20 cm) respectively, and x is the water flux per day (mm d^{-1}).

We did not collect all the individual rainfall events, throughfall, litter leachate, and soil-water samples to analyse the DOC concentrations, but interpolated all the DOC concentrations and water fluxes according to Eqs. (2)–(4).

The daily DOC flux was calculated as

$$F = CV / 100, \quad (5)$$

where F is the daily DOC flux (kg C ha^{-1} d^{-1}), C is the DOC concentration (mg L^{-1}), and V is the water flux (mm d^{-1}) per day.

The weekly carbon flux (kg C ha^{-1} $week^{-1}$) was calculated as the sum of the daily DOC fluxes.

Soil temperature and soil-water content of eddy-flux tower explained 89.96 and 80.57 % dynamic of that of soil respiration observation plot from February 2008 to January 2009 respectively, and the correlations between soil temperature at a depth of 5 cm and both SR and HR were strong (Fig. S2 in the Supplement) between February 2008 and January 2009. SR and HR during the period from 1 January 2009 to 31 December 2011 were calculated based on the equation $Y = ae^{bx}$ from the data collected between February 2008 and January 2009 as follows:

$$SR = 46.37e^{(0.11T5)} r^2 = 0.8966,\ p < 0.0001, \quad (6)$$

$$HR = 18.90e^{(0.14T5)} r^2 = 0.8372,\ p < 0.0001, \quad (7)$$

where SR is total soil respiration (mg CO_2 m^{-2} h^{-1}), HR is heterotrophic respiration (mg CO_2 m^{-2} h^{-1}), and T5 is soil temperature at 5 cm depth.

2.4.1 Sensitivity indices calculations

First, weekly soil respirations fluxes, weekly average of soil temperature and soil-water content, weekly water and DOC fluxes were standardized by the ratio of measured value to the mean value during the observation period. Second, linear regression equitation was used between the standardized soil respirations values and T, SWC, water and DOC fluxes respectively. Third, we considered the slope of the linear regression as the sensitivity indices, which showed the soil respirations variation rate with soil temperature, soil-water content, water and DOC fluxes changing.

3 Results

3.1 Water and DOC fluxes in a tropical rainforest

The seasonal and annual water fluxes decreased from the rainfall to the surface soil (Fig. 1a). The interception rate of the water between hydrological processes was higher in the dry season than in the rainy season (Fig. 1a, Table 1). The highest annual interception rate was between the litter leachate and the surface soil (63.85 ± 7.98 %), which was 62.19 ± 15.07 % in the rainy season and 81.64 ± 23.38 % in the dry season.

The seasonal dynamics of the DOC flux were similar to those of the water flux (Fig. 1, Table 1). The annual DOC flux increased from rainfall (41.9 ± 3.8 kg C ha^{-1} yr^{-1}) to throughfall (113.5 ± 8.5 kg C ha^{-1} yr^{-1}) and to litter leachate (127.7 ± 8.5 kg C ha^{-1} yr^{-1}), and then decreased sharply to the surface soil at 0–20 cm (7.07 ± 1.4 kg C ha^{-1} yr^{-1}) (Fig. 1b). The surface soil

Table 1. The interception rate of the water between hydrological processes in the tropical rainforest at Xishuangbanna, south-west China.

	Interception %	Annual	Rainy season	Dry season
Water flux	Between TF and P	53.9 ± 11.7	43.1 ± 2.7	41.3 ± 14.8
	Between LL and TF	33.9 ± 6.6	33.9 ± 9.8	34.1 ± 27.6
	Between SW20cm and LL	63.8 ± 8.0	62.2 ± 15.1	81.6 ± 23.3
DOC flux	Between TF and R	137.0 ± 19.9	182.0 ± 16.0	170.8 ± 7.8
	Between LL and TF	1.1 ± 17.0	16.1 ± 9.4	12.7 ± 4.3
	Between SW20cm and LL	-96.7 ± 4.4	-93.9 ± 2.6	-94.4 ± 1.2

P indicates rainfall. TF indicates throughfall. LL indicates litter leachate. SW20 indicates soil water at a depth of 20 cm.

Table 2. DOC δ^{13}C dynamics along the hydrological processes (R, rainfall; TF, throughfall; LL, litter leachate) and the δ^{13}C in leaves, litter, and surface soil in the tropical rainforest at Xishuangbanna, south-west China.

Season	*P*	TF	LL	SW20	Leaves	Litter	Soil (0–20 cm)
Rainy season	-23.9 ± 3.3^{a}	$-28.7 \pm 1.7^{b,c}$	$-28.1 \pm 2.7^{b,c}$	$-23.9 \pm 1.6^{a*}$	-32.4 ± 0.6^{d}	$-30.4 \pm 0.2^{c,d}$	-27.3 ± 0.1^{b}
Dry season	-23.8 ± 1.3^{a}	$-29.1 \pm 1.6^{b,c}$	$-28.1 \pm 1.5^{b,c}$	-27.1 ± 2.2^{b}	-32.5 ± 0.5^{d}	$-30.2 \pm 0.1^{c,d}$	$-27.3 \pm 0.1^{b,c}$

P indicates rainfall, TF indicates throughfall, LL indicates litter leachate, SW20 indicates soil water at a depth of 20 cm.
Different subscript letters indicate significant differences between the treatments according to least significant difference (LSD) test ($P < 0.05$).
* indicates the significant seasonal difference according to independent sample *t* test ($p < 0.1$).

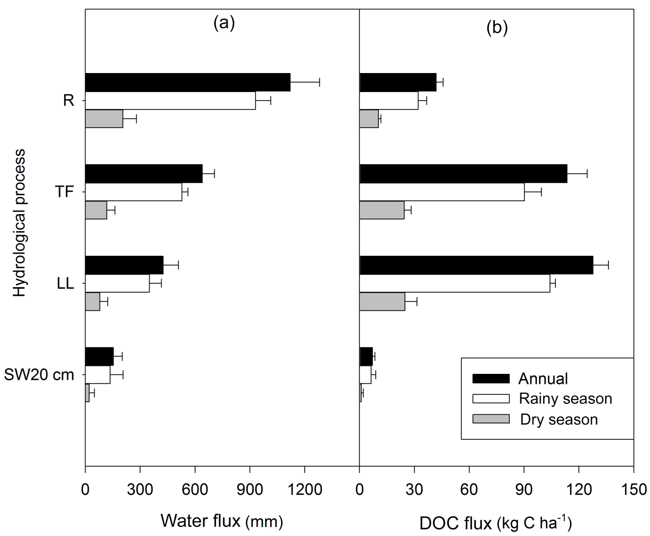

Figure 1. (a) Amount of water and **(b)** DOC flux along the hydrological processes in the tropical rainforest at Xishuangbanna, south-west China.

intercepted most of the DOC coming from the previous layer (annual: 94.4 ± 1.2 %; dry season: 96.7 ± 4.4 %; rainy season: 93.9 ± 2.6 %). That the interception rates for water and DOC were the greatest in the surface soil indicates that the surface soil is the most important water and DOC sink in this tropical rainforest (Table 1).

3.2 Isotopic characteristics of DOC in the hydrological processes of a tropical rainforest

During the transfer of rainfall to soil water (0–20 cm), $\delta^{13}C_{DOC}$ was highest in the rainfall DOC and lowest in the throughfall DOC in both the rainy and dry seasons (Table 2). The seasonal difference in $\delta^{13}C_{DOC}$ was the highest in the surface soil water (3.25 ‰) and lowest in the litter leachate (0.11 ‰). From the litter leachate to the surface soil water, $\delta^{13}C_{DOC}$ increased significantly by 4.26 ‰ ($p = 0.05$) in the rainy season, but increased by only 1.12 ‰ (not significant; $p = 0.39$) in the dry season. δ^{13}C increased from the canopy leaves to the soil and did not differ significantly between seasons (Table 2).

In both the dry and rainy seasons, $\delta^{13}C_{DOC}$ in water was higher than δ^{13}C in the corresponding element (comparing throughfall with leaves, litter leachate with litter, and soil water with soil at 20 cm depth) (Table 2). The smallest difference between $\delta^{13}C_{DOC}$ and δ^{13}C in each compartment occurred between soil-water DOC and soil carbon in the dry season, which was only 0.23 ‰. The greater difference between $\delta^{13}C_{DOC}$ and δ^{13}C in the rainy season than in the dry season for soil water and soil (Table 2) indicates that the biogeochemical dynamics of DOC are more active in the rainy season than in the dry season in soil.

3.3 Surface soil CO_2 flux dynamics in a tropical rainforest

In the tropical rainforest at Xishuangbanna, SR was dominated by HR (Fig. 2). HR contributed more to SR during

Table 3. Results of a regression analysis of the weekly water flux, DOC flux, soil respiration (SR), and heterotrophic respiration (HR) along the hydrological processes (TF, throughfall; LL, litter leachate) in the tropical rainforest in Xishuangbanna, south-west China.

		SR				HR			
		a	*b*	R^2	*p*	*a*	*b*	R^2	*p*
DOC flux	*T*	0.56	0.54	0.987	< 0.001	0.46	0.64	0.982	< 0.001
	SWC	0.65	0.41	0.558	< 0.001	0.53	0.52	0.568	< 0.001
	P	2.31	−1.17	0.423	< 0.001	1.86	−0.74	0.425	< 0.001
	TF	2.36	−1.25	0.429	< 0.001	1.91	−0.83	0.413	< 0.001
	LL	2.71	−1.57	0.355	< 0.001	2.21	−1.10	0.366	< 0.001
	SW20	3.57	−2.23	0.227	< 0.001	2.91	−1.62	0.240	< 0.001
	LL–SW20	2.66	−1.53	0.352	< 0.001	2.17	−1.07	0.363	< 0.001
Water flux	P	2.42	−1.35	0.323	< 0.001	1.96	−0.92	0.331	< 0.001
	TF	2.55	−1.44	0.316	< 0.001	2.06	−0.99	0.323	< 0.001
	LL	3.02	−1.83	0.301	< 0.001	2.46	−1.31	0.312	< 0.001
	SW20	3.70	−2.34	0.166	< 0.001	3.02	−1.71	0.178	< 0.001
	LL–SW20	2.64	−1.54	0.257	< 0.001	2.14	−1.08	0.267	< 0.001

Equations used to calculate the sensitivity indices: sensitivity index = *a*, where *b* is the constant of the regression equation for standardized soil respirations, and soil temperature, soil-water content, water flux, and DOC flux: $Y = aX + b$, where Y is the standardized soil respiration rate, and X is standardized soil temperature, soil-water content, water flux, or DOC flux.
T indicates soil temperature at a depth of 5 cm, SWC indicates soil-water content, TF indicates throughfall, LL indicates litter leachate, SW20 indicates soil water at a depth of 20 cm, LL–SW20 indicates the difference between litter leachate and soil water at a depth of 20 cm.

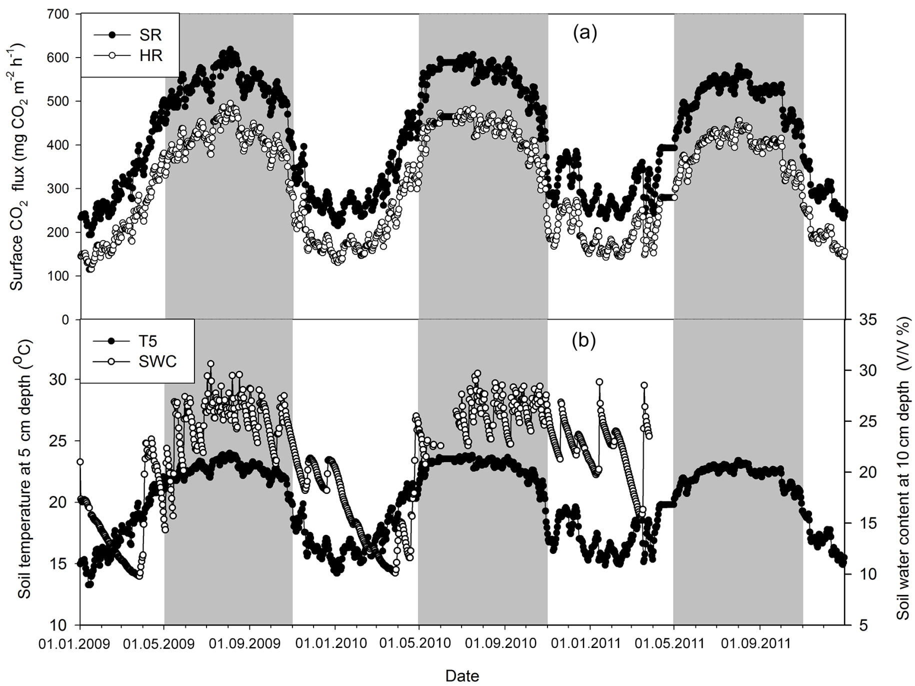

Figure 2. Dynamics of soil respiration (SR) and heterotrophic respiration (HR) **(a)** and soil temperature at 5 cm and soil-water content at 10 cm **(b)** in the tropical rainforest at Xishuangbanna, south-west China. The shaded area indicates the rainy season. ()

the rainy season (76.8 ± 0.8 %) than during the dry season (66.5 ± 0.5 %), and the annual contribution of HR to SR was 71.7 ± 0.7 %. SR and HR were higher in the rainy season than in the dry season, similar to the dynamics of the hydrological and DOC fluxes (Fig. 1).

Standardized soil temperature explained 98.7 and 98.2 % of the variation in standardized SR and HR respectively, and standardized soil moisture explained 55.8 and 56.8 % of the variation in standardized SR and HR respectively (Table 3). The sensitivity indices of SR and HR for soil temperature at a depth of 10 cm were 0.56 and 0.46 respectively, whereas their sensitivity indices for soil moisture were 0.65 and 0.53 based on observational data (Table 3, Fig. S2 in the Supplement).

3.4 Influence of DOC flux on soil CO_2 flux in a tropical rainforest

There were significant correlations between the standardized weekly SR and HR and the standardized weekly water fluxes and DOC fluxes through the hydrological processes (Table 3). Based on the definition of the temperature-dependent sensitivity index for soil respirations, which is the slope of standardized soil respirations caused by an increase in standardized temperature, we also defined a soil-water-content-dependent sensitivity index, a DOC-flux-dependent sensitivity index, and a water-flux-dependent sensitivity index in this study, analogous to the temperature-dependent sensitivity index for SR (Table 3). An independent t test showed that the DOC-flux-dependent sensitivity indices for SR (2.72 ± 0.51) and HR (2.21 ± 0.42) were significantly lower than the water-flux-dependent sensitivity indices for SR (2.87 ± 0.52, $t = -2.68$, $p = 0.06$) and HR (2.33 ± 0.43, $t = -2.57$, $p = 0.06$) respectively, which indicates that SR and HR were more sensitive to the water flux than to the DOC flux through the hydrological processes. The significant difference was observed between the water-flux-dependent indices ($t = 13.78$, $p < 0.001$) for SR (2.87 ± 0.52) and HR (2.33 ± 0.43), or between the DOC-flux-dependent indices ($t = 13.12$, $p < 0.001$) for SR (2.72 ± 0.51) and HR (2.21 ± 0.42).

The soil-water-content-dependent sensitivity indices for HR (0.53) and SR (0.65) were higher than the soil-temperature-dependent sensitivity indices (HR, 0.46; SR, 0.56), but less than all the water-flux-dependent and DOC-flux-dependent sensitivity indices for SR and HR (Table 3). This indicates that SR and HR are more sensitive to the hydrological water flux and DOC flux than to the soil-water content and soil temperature. A comparison of the sensitivity indices for water flux, DOC flux, soil temperature, and soil moisture in all the hydrological processes reveals that SR and HR were most sensitive to the water flux (3.70) dynamics, which is a little higher than DOC flux (3.57) in the soil water (0–20 cm depth) when weekly variations in the Xishuangbanna tropical rainforest were considered.

4 Discussion

Our results showed that the throughfall carried most of the DOC (113.5 ± 8.5 kg C ha^{-1} yr^{-1}) through the hydrological processes in the Xishuangbanna tropical rainforest, which amounted to 6.81 % of the NEE (1.67×10^3 kg C ha^{-1} yr^{-1}) (Tan et al., 2010) in this tropical rainforest in south-west China. The litter leachate DOC (127.7 ± 8.5 kg) accounted for 7.23 % of the NEE in this forest. This result indicates that the throughfall DOC is an important component of the tropical rainforest carbon budget. The litter leachate fed a great deal of DOC to the soil, but the surface soil intercepted 94.4 ± 1.2 % (127.7 ± 8.0 kg) of the DOC, and the surface soil-water DOC flux was only 7.1 ± 1.4 kg C ha^{-1} yr^{-1}, which was slightly less than that at the headwater stream outlet (10.31 kg C ha^{-1} yr^{-1}) (Zhou et al., 2013). The surface soil intercepted the bulk of the litter leachate DOC and transported little DOC to the deep layer, indicating that the surface soil is the DOC sink in the tropical rainforest in Xishuangbanna.

The small seasonal differences in $\delta^{13}C_{DOC}$ in the rainfall, throughfall, and litter leachate indicate that the DOC in the aboveground water is seasonally stable (Table 2). However, $\delta^{13}C_{DOC}$ in the soil water (at 0–20 cm) was higher in the rainy season (3.25 ‰) than in the dry season, indicating that the DOC reaction in the surface soil is seasonal. In the dry season, $\delta^{13}C_{DOC}$ in the surface soil water (-27.1 ± 2.2 ‰) was similar to $\delta^{13}C_{DOC}$ in the soil (-27.3 ± 0.1 ‰), indicating that the soil is the major source of soil-water DOC. This is attributable to the combined absorption effects of the high clay content (Fröberg, 2004; Lemma et al., 2007; Sanderman and Amundson, 2008; Tang et al., 2007) and the lack of water carrying DOC through the different compartments in the dry season. Therefore, most DOC is locally produced rather than transported. Less water and the lower DOC input from litter leachate and throughfall to the surface soil (Fig. 1) also contribute to a reduction in microbial activity, which contributes negligibly to the soil DOC when the soil moisture and soil temperature are low in the dry season (Wu et al., 2009). In the rainy season, the soil-water content and soil temperature are higher, so there is more vigorous biogeochemical activity in the surface soil (Bengtson and Bengtsson, 2007). Therefore, more DOC is released from the soil to be mineralized by microorganisms, and there is more ^{13}C in the soil-water DOC ($\delta^{13}C = -23.9 \pm 2.2$ ‰) than in the soil ($\delta^{13}C$, -27.3 ± 0.1 ‰). The relatively low $\delta^{13}C_{DOC}$ in the litter leachate ($\delta^{13}C_{DOC} = -28.1 \pm 2.7$ ‰) compared with the soil water indicates that the DOC from the litter leachate was active in the carbon cycle in the surface soil (Cleveland et al., 2006; De Troyer et al., 2011). Furthermore, most of the DOC from the throughfall, litter leachate, and litter was fed to the surface soil, and the soil-water $\delta^{13}C_{DOC}$ value was higher than that of the throughfall, litter leachate DOC, and $\delta^{13}C$ soil (0–20 cm) values (Table 2). These data indicate that all the DOC transported by the throughfall and litter leachate was ultimately involved in the surface soil carbon cycle (Fröberg et al., 2003, 2005; Kammer et al., 2012), and has also contributed to the SR because it is an important part of the surface soil carbon cycle in the tropical rainforest at Xishuangbanna.

Laboratory-based studies of tropical forests have shown that DOC primes the soil CO_2 flux (Qiao et al., 2013). A study of a temperate forest showed that the rate of DOC production is one of the rate-limiting steps for SR (Bengtson and Bengtsson, 2007). Comparative studies of ^{13}C and ^{14}C in DOC and SOC have also shown that fresh organic carbon stimulates the activity of old carbon, and increases the emission of CO_2 because DOC is the substrate of microbial activity (Cleveland et al., 2004, 2006; Hagedorn and Machwitz, 2007; Hagedorn et al., 2004; Qiao et al., 2013). Because the microbial biomass and potential carbon mineralization rates are higher in soils with higher DOC contents than in soils with lower DOC contents (Montaño et al., 2007), the DOC turnover rate (Bengtson and Bengtsson, 2007) is rapid and the transformation period is short (3–14 days) (Cleveland et al., 2006; De Troyer et al., 2011). This indicates that DOC is involved in the surface soil carbon cycle in the short term by affecting SR (Cleveland et al., 2004, 2006). Although we did not determine the period of the DOC turnover cycle, the weekly DOC flux passing through the hydrological processes (throughfall, litter leachate, soil water, and interception by the surface soil) significantly explained SR and HR, with higher sensitively indices than the indices for the soil-water content and soil temperature (Table 3), predicting that DOC has a significant impact on soil CO_2 emissions in this tropical rainforest.

It is important to consider which part of the DOC flux in the hydrological processes of this tropical rainforest most strongly influences SR. Previous studies have shown that of all the factors affecting SR, it is most sensitive to soil temperature (Bekku et al., 2003; Reichstein et al., 2003; Zheng et al., 2009), as in the tropical forest at Xishuangbanna (Sha et al., 2005). Although soil temperature better explained SR and HR than the DOC flux, the sensitivity indices for the soil-water DOC fluxes were higher than the sensitivity indices for soil temperature, although temperature explained the rate of SR better than the DOC flux (Table 3). At this study site, HR, which depends predominantly on microbial activity and substrates, contributed the major fraction of SR (Fig. S2 in the Supplement), so not only HR but also SR depends most strongly on the microbial and respiratory substrates in this tropical rainforest. Therefore, the DOC transported by the forest hydrological processes, from litter decomposition, root exudates, and the soil itself, will contribute to SR (Table 2). The bioavailability of the DOC transported by hydrological processes is greater than that of SOC (De Troyer et al., 2011; Kindler et al., 2011). The DOC from throughfall and litter leachate is also an important contributor because $\delta^{13}C_{DOC}$ differs between the surface soil water and the litter leachate and throughfall (Table 2). Although ectotrophic mycorrhizae contribute significantly to SR in the rhizospheres of some temperate and boreal forests (Neumann et al., 2014; Tomè et al., 2016), in this tropical rainforest, EMF: *Paraglomus*, a kind of endomycorrhiza, occupies more than 90 % of the mycorrhizal community (Shi, 2014). Together with roots, and root exudate, it contributes to the autotrophic SR, which is only 28.9 % of the total SR, so the mycorrhiza is not the dominant contributor to SR in this tropical rainforest. The other details of the biogeochemical processes affecting DOC in the surface soil are not obvious in this study. However, according to both laboratory and field studies, the DOC intercepted by the surface soil clearly affects HR (Table 3), together with the DOC from litter decomposition and the soil itself (Cleveland et al., 2004, 2006; Hagedorn and Machwitz, 2007; Hagedorn et al., 2004; Jandl and Sollins, 1997; Keiluweit et al., 2015; Montaño et al., 2007; Qiao et al., 2013; Schwendenmann and Veldkamp, 2005). Considering the effect of DOC on SR, the surface soil-water DOC is the most sensitive index of HR and SR (Table 3).

The DOC-flux-dependent sensitivity indices for the different parts of the hydrological processes in this tropical rainforest were a little less but insignificant in comparison with the amount of water-dependent sensitivity indices, which shows that the DOC flux affects SR less than the amount of water passing through the system, because of the combined effects of water and DOC on SR. According the DOC significant contribution of soil respirations (Cleveland et al., 2004, 2006; Hagedorn and Machwitz, 2007; Hagedorn et al., 2004; Qiao et al., 2013), the little difference mechanisms between DOC and water flux of tropical rainforest should be declared in the future study.

This study demonstrates that the surface soil is a sink for the DOC transported by hydrological processes (Fig. 1), and that HR and SR are sensitive to the DOC flux through these processes. The most sensitive indicator of SR is the soil-water flux (at 0–20 cm) and followed by soil-water DOC flux, both exceeding the sensitivity of the soil temperature, soil-water content, and other water flux, and DOC flux along all the hydrological processes (Table 3). The variations in $\delta^{13}C$ in DOC, soil, and plants also partly support the notion that the soil-water DOC flux is the more sensitive index of SR in this tropical rainforest. The results suggest that the DOC transported by hydrological processes plays the more important role in the SR processes. In the context of global climate change, more attention must be paid to the contribution of hydrologically transported DOC in future studies of the mechanisms of SR.

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