Soil & Tillage Research 203 (2020) 104686

Contents lists available at ScienceDirect

Soil & Tillage Research

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

# Effects of a funnel-shaped canopy on rainfall redistribution and plant water acquisition in a banana (*Musa* spp.) plantation

Bin Yang[a,b,1], Wanjun Zhang[a,b,c,1], Xianjing Meng[d], Ashutosh Kumar Singh[a,b], Sissou Zakari[a,b], Liang Song[a,b], Wenjie Liu[a,b,*]

[a] CAS Key Laboratory of Tropical Forest Ecology, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Menglun, Yunnan, 666303, China
[b] Center of Plant Ecology, Core Botanical Gardens, Chinese Academy of Sciences, Menglun, Yunnan, 666303, China
[c] University of Chinese Academy of Sciences, Beijing, 100049, China
[d] Thermo Fisher Scientific, Shanghai, 201206, China

ARTICLE INFO

*Keywords:*
Banana cultivation
Canopy interception
Soil management
Throughfall distribution
Water source partitioning

ABSTRACT

Most of the world's tropical landscapes are experiencing changes in land-use and land-cover. In Yunnan Province in southwestern China, land-use changes are widespread throughout the tropics, with large areas of tropical forests being converted to banana (*Musa* spp.) plantations. In this study, we explored the effects of banana trees' funnel-shaped leaves on rainfall redistribution and plant water acquisition during the 2017/2018 rainy season. Both the conventional and isotopic ($\delta$D and $\delta^{18}$O) methods were used to conduct rainfall partitioning, assess throughfall distribution, and predict plant water sources. We found that the mean contribution of throughfall, stemflow, and interception loss to gross rainfall (rainfall amount: 0.3–33.3 mm) were 71.8 ± 6.8 %, 17.6 ± 3.6 %, and 10.6 ± 3.8 %, respectively. The percentage of stemflow under the banana canopy was noticeably higher than previously reported for other species. The maximum amount of throughfall below the banana canopy was 1.4–4.4 times greater than the gross rainfall (rainfall amount: 14.7–70.5 mm). Soil water content and soil water $\delta$D and $\delta^{18}$O showed both horizontal and vertical heterogeneities within the banana plantation. Analysis of $\delta$D and $\delta^{18}$O indicated that banana trees absorbed 72.3 % of their water from the shallow soil stratum at 0 − 30 cm depth. In addition, the acquisition proportion of 0 − 80 cm soil water ranged from 10.2%–16.3% in the horizontal directions (0 − 360°). These findings indicated that banana trees' wide and long leaves considerably altered rainfall redistribution, which in turn affected their water acquisition characteristics. As banana plantations expand in this area, there is an urgent need to further examine environmental consequences such as soil erosion and surface runoff resulting from banana cultivation.

## 1. Introduction

Plant canopies have important effects on rainfall redistribution via canopy interception, stemflow, and throughfall (Marin et al., 2000; Limin et al., 2015). Throughfall variability is a potential key driver of soil erosion, nutrient cycling, and plant productivity (Nepstad et al., 2002; Liu et al., 2008; Orság et al., 2018). Over the last four or five decades, a large area of the world's tropical rainforest has been converted to farmland (Borrelli et al., 2015; Drescher et al., 2016), and anthropogenic forcing has triggered the intensification of extreme precipitation worldwide (IPCC., 2013). These changes have resulted in huge impacts on rainfall redistribution (Keim et al., 2005; Cattan et al., 2009; Liu et al., 2018), which may further affect water acquisition in plants with various canopy structures. Numerous studies have been conducted to better understand the process of rainfall redistribution (Loescher et al., 2002; Germer et al., 2006; Ramírez et al., 2018), but the influence of rainfall redistribution on plant water acquisition has received little attention.

Canopy structures in tropical landscapes are experiencing dramatic changes around the world (Islam and Weil, 2000; Mayes et al., 2015; Zhu et al., 2018). Banana trees (*Musa* spp.) are widely cultivated in tropical and subtropical areas, which carry considerable value for small holders in Central America and South-East Asia (FAO., 2012). However, banana' funnel-shaped canopy with long-wide leaves at large angles of

* Corresponding author at: CAS Key Laboratory of Tropical Forest Ecology, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Menglun, Yunnan, 666303, China.
*E-mail address:* lwj@xtbg.org.cn (W. Liu).
[1] The authors contributed equally.

https://doi.org/10.1016/j.still.2020.104686
Received 4 November 2019; Received in revised form 20 April 2020; Accepted 23 April 2020
Available online 01 June 2020
0167-1987/ 

inclination can have deleterious impacts on local agricultural development. Some studies have reported that throughfall under the margin of banana leaves is approximately six times higher than natural rainfall (Cattan et al., 2006, 2007, 2009). The architecture of the banana canopy also sharply increases the rainfall splash intensity (Bassette and Bussiere, 2008). In this case, water acquisition by banana trees might be limited by the rainfall redistribution.

Bananas are a globally popular fruit crop ranking alongside the three major grain crops (Singh et al., 2016), but their water sources have not yet been reported. Previous studies have successfully detected the water uptake zone for plants using hydrogen and oxygen stable isotopes (Zegada-Lizarazu et al., 2007; Brooks et al., 2010; West et al., 2012). An underlying assumption of this methodology is that there is no isotopic fractionation during the root water-absorbing process (Ehleringer and Dawson, 1992). In many cases, studies of water source partitioning have led to an enhancement of field water managements (Goebel and Lascano, 2014; Wu et al., 2019). For example, quantifying the water uptake depth for crops is useful for optimizing the irrigation schedules (Sekiya and Yano, 2002; Araki and Iijima, 2005; Yang et al., 2018). In addition, investigations of maize (*Zea mays*) and wheat (*Triticum aestivum*) indicate that shallow-rooted crops will prevailingly absorb surface soil water across the growing season (Asbjornsen et al., 2008; Zhang et al., 2011; Ma and Song, 2016). However, these isotope studies do not account for the horizontal heterogeneity of soil water status (Barnard et al., 2006; Yang et al., 2015; Wu et al., 2017; Muñoz-Villers et al., 2018).

Banana plantations in Yunnan Province account for over 1/5 of the total planted area of China, serving as a pillar industry for local farmers (Feng et al., 2019). In recent years, banana cultivation has become more widespread due to the falling price of natural latex (Fox et al., 2014; Zhang et al., 2019), after rubber trees' (*Hevea brasiliensis*) expansion caused severe land degradation in the region (Smajgl et al., 2015; Zhu et al., 2018). However, hydrological threats caused by the rapid expansion of banana agriculture have received little attention from the local government. Meanwhile, there is a dry season of approximately six months in this region (Liu et al., 2008; Wang et al., 2019), and sustainable agricultural development requires knowledge of drought stress on bananas' water acquisition. We therefore aimed to explore the characteristics of rainfall redistribution and plant water utilization in a banana plantation. We hypothesized that rainfall redistribution would be altered by the shape of banana leaves, and that the spatial variability of rainfall redistribution would affect the water acquisition by banana trees.

## 2. Materials and methods

### 2.1. Study site

The study was conducted at the Xishuangbanna Tropical Botanical Garden (XTBG) in Yunnan, southwestern China (21° 55′ 39″ N, 101° 15′ 55″ E, at 750 m elevation). Mean annual temperature and rainfall from 1965 – 2004 were 21.7 °C and 1487 mm (Liu et al., 2008; Wang et al., 2019). A rainy season occurs from May to October and a dry season occurs from November to April, which were distinguished in this study according to Budyko's aridity index (AI) (Budyko, 1974; for details see the supporting information). A 4.3 ha experimental field was located on a flat terrace (Fig. 1), with 2.0 m soil thickness and 1.25 g $cm^{-3}$ bulk density. The soil had a clayey texture with 23 % coarse sand (2.0 – 0.05 mm), 30 % silt (0.05 – 0.002 mm), and 47 % clay (< 0.002 mm).

Banana (*Musa* spp.) seedlings were planted in 2.0 × 2.0 m grids at the end of February 2016. After each 11 – 13-month growth cycle, one banana sucker was allowed to grow for the next harvest. In the rainy season, a few drainage ditches (0.5 m wide × 1.5 m depth) were arranged perpendicular to the Buyuan river (Fig. S1). In the dry season, a centrifugal water pump (IS-100 – 80-160A, KM Pump Factory Limited Inc., Kunming, CHN) was used for field irrigation. Maximum canopy height, mean diameter at breast height, and number of healthy foliage of the banana trees were 555.8 ± 16.8 cm, 55.4 ± 1.4 cm, and 8.8 ± 1.0 (n = 15). Maximum leaf length and leaf width of the banana trees were 195.7 ± 26.1 cm and 75.9 ± 10.4 cm, with a mean tilt angle (MTA) of 26.7 ± 6.2° (n = 49). The maximum leaf area index (LAI) in the banana plantation was 3.9 ± 0.1 $m^2$ $m^{-2}$ (LAI-2200, Li-Cor Inc., Lincoln, USA) during the study periods.

### 2.2. Measurements of rainfall components

An open site and two throughfall observation sites (each 5.0 × 5.0 m) were established at the experimental field. In the early rainy season, throughfall amount was measured during June 18-July 12, 2017. In total, five V-shaped troughs (0.1 m wide × 2.0 m length) were installed in the field. As described by Liu et al. (2017), one V-shaped trough was placed in the open site to record gross rainfall. The remaining four V-shaped troughs were placed in the observation sites. All troughs were connected to 25-L sealed plastic containers mounted 0.3 m above ground level with an inclination angle of 0.5°. Litterfall was discarded from the trough to avoid measurement errors.

Together with the throughfall measurements, stemflow amount was monitored using the P-shaped seal strips (0.9 cm wide × 1.2 cm length × 2.2 cm height; YC-895, YC Vehicle & Ship Parts Limited Inc., Xingtai, CHN). A total of eight P-shaped seal strips were embedded into the trees' pseudo stems. The ends of strips were also connected to 25-L containers. Interception loss ($I$) was estimated according to the following equation (Limin et al., 2015):

$$I = P - TF - SF \tag{1}$$

where $P$ is the gross rainfall amount (mm), $TF$ is the throughfall amount (mm), and $SF$ is the stemflow amount (mm).

### 2.3. Throughfall distribution measurements

In an independent site (3.0 × 3.0 m), throughfall amount was measured using handmade funnel-type rain gauges. These measurements were made to evaluate the effects of funnel-shaped canopy structure on throughfall distribution in the peak rainy season during August 3-September 5, 2017. The duration of these observations were about 48 – 72 h. A total of 49 rainfall gauges were arranged evenly (25 × 25 cm) below the banana canopy. The rainfall gauges were made from 6.0 cm diameter short-stemmed funnels and valve bags (7.0 cm wide × 35 cm length). The funnel and valve bag were connected using a binder clip. In case of the interference of splashing raindrops, some banana leaves were placed below the gauges. Throughfall ($TF$) amount in each valve bag was calculated as:

$$TF = (m_g - m_b)/\rho\pi r^2 \times 1000 \tag{2}$$

where $m_g$ is the gross weight of valve bag (g), $m_b$ is the net weight of valve bag (g), ρ is the density of water (1.0 g/$cm^3$), and $r$ is the semi-diameter of the funnel (mm).

### 2.4. Root excavation

Sampling of banana roots was performed in the late rainy season (September 15, 2017). A banana tree was randomly selected to represent the average growth state of banana plantation. It was supported by the fact that the banana trees received uniform management in term of fertilization, weeding, and irrigation (Fig. S1). Nine grids (25 × 25 cm) were horizontally arranged around the tree's pseudo stem. Then, the pseudo stem was removed from the experimental field. In an area of 625 $cm^2$, soil profiles of 0 – 30 cm, 30 – 50 cm, and 50 – 80 cm were excavated using spades and hand cutters. We sampled 27 soil cuboids in total for root investigation. After excavation, all living fine roots were manually collected, separated in 2 mm sieves, and oven dried at105 °C for 24 h.

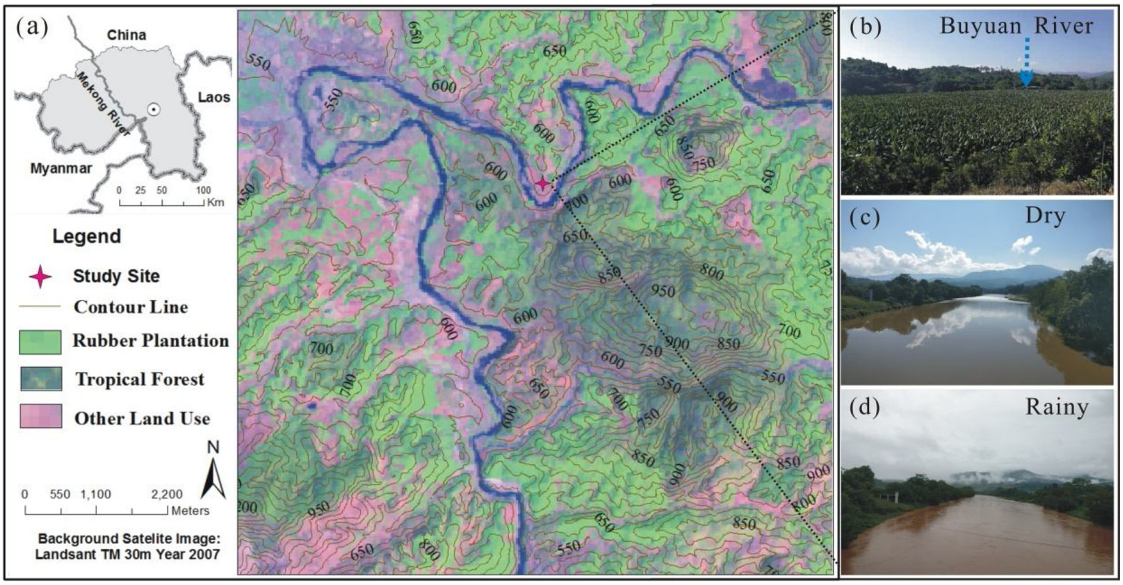


**Fig. 1.** The study site (a) of a banana plantation (b) was located in southwestern China near the Buyuan River (indicated with a blue arrow) in the peak dry season on February 23, 2017 (c) and the peak rainy season on July 9, 2017 (d).

### 2.5. Isotopic sampling and measurements

To determine the water sources for banana trees, water samples for isotopic analysis were collected from plant xylem and soil water on September 16, 2017. As suggested by Barnard et al. (2006), root crowns of the banana trees were sampled (n = 6) to reflect the isotopic composition of xylem water. The phloem tissues were removed from root crowns to avoid contamination by isotopically enriched water (Querejeta et al., 2007). Using a 4 cm diameter hand auger, soil profiles of 0 – 80 cm were sampled around the pseudo stem of banana tree. On a horizontal plane, five concentric circles at 10 cm, 20 cm, 30 cm, 50 cm, and 80 cm from the pseudo stem were drawn below the banana canopy. Seven radiating directions were evenly arranged on these concentric circles. At the intersection points, soil samples were collected from depths of 0 – 5, 5 – 30, 30 – 50, and 50 – 80 cm, yielding a total of 240 soil samples. Half the samples were used to determine the gravimetric soil water content (SWC) by drying at 105 °C for 24 h (~ 50 g each). The remaining samples were sealed (~ 12 g each) in 10-mL screw-cap glass vials.

Liquid water in the samples was cryogenically extracted (LI-2100, Lica United Technology Limited Inc., Beijing, CHN) in the XTBG central laboratory. Extraction parameters were 240 min for the extraction time, 105 °C for the heating temperature, and 400 Pa for the vacuum degree. Isotopic composition of the liquid water was analyzed using a high-temperature conversion elemental analyzer (TC/EA) coupled with a DELTA V Advantage isotope ratio mass spectrometer (Thermo Fisher Scientific, Bremen, GER). The deuterium and oxygen ratios in water samples are expressed in delta notation ($\delta$) as:

$$\delta\,\mathrm{D} = \left(\frac{R_{sample}}{R_{s\tan dard}} - 1\right) \times 1000 \tag{3}$$

$$\delta^{18}\mathrm{O} = \left(\frac{R_{sample}}{R_{s\tan dard}} - 1\right) \times 1000 \tag{4}$$

where $\delta$D and $\delta^{18}$O refer to the stable isotope composition of sample water, $R_{\mathrm{sample}}$ and $R_{\mathrm{standard}}$ are the D/H and $^{18}$O/$^{16}$O ratio of sample water and standard water (VSMOW, Vienna Standard Mean Ocean Water).

### 2.6. Calculations and statistical analyses

Because there is no isotopic fraction during the transportation of soil water from plant root to xylem sap (Ehleringer and Dawson, 1992), analysis of the $\delta$D and $\delta^{18}$O in xylem water reflects the water source in use by plants. MixSIAR is a Bayesian model that explicitly takes into account the uncertainties of isotope signatures and multiple sources (Stock and Semmens, 2013; Muñoz-Villers et al., 2018). This mixing model is based on the isotope mass conservation principles:

$$\delta\mathrm{D}_{\mathrm{xylem}} = \delta\mathrm{D}_{\mathrm{s1}} \cdot f_1 + \delta\mathrm{D}_{\mathrm{s2}} \cdot f_2 + \cdots + \delta\mathrm{D}_{\mathrm{si}} \cdot f_{\mathrm{i}} \tag{5}$$

$$\delta^{18}\mathrm{O}_{\mathrm{xylem}} = \delta^{18}\mathrm{O}_{\mathrm{s1}} \cdot f_1 + \delta^{18}\mathrm{O}_{\mathrm{s2}} \cdot f_2 + \cdots + \delta^{18}\mathrm{O}_{\mathrm{si}} \cdot f_{\mathrm{i}} \tag{6}$$

$$f_1 + f_2 + \cdots + f_{\mathrm{i}} = 1 \tag{7}$$

where $\delta\mathrm{D}_{\mathrm{xylem}}$ ($\delta^{18}\mathrm{O}_{\mathrm{xylem}}$) are isotope values of plant xylem water; $\delta\mathrm{D}_{\mathrm{s1}}$ ($\delta^{18}\mathrm{O}_{\mathrm{s1}}$), $\delta\mathrm{D}_{\mathrm{s2}}$ ($\delta^{18}\mathrm{O}_{\mathrm{s2}}$), and $\delta\mathrm{D}_{\mathrm{si}}$ ($\delta^{18}\mathrm{O}_{\mathrm{si}}$) are isotope values of soil water; and $f_1$, $f_2$, and $f_{\mathrm{i}}$ are contributions proportion of the i$^{\mathrm{th}}$ water source.

To facilitate water source partitioning, the soil profiles of 0 – 5, 5 – 30, 30 – 50, and 50 – 80 cm were first subdivided into two depth intervals (shallow: 0 – 30 cm, deep: 30 – 80 cm). We assumed that banana trees acquired water independently from each of the two soil layers. Meanwhile, the contribution of a potential water source (i.e., shallow or deep soil water) to banana trees would proportionally follow the fine root distribution in vertical soil stratum. Therefore, soil water $\delta$D and $\delta^{18}$O of these two depths were analyzed separately using the MixSIAR model. As an input item, standard deviations (SD) of soil water $\delta$D and $\delta^{18}$O were acquired from measuring repeatabilities (n = 6 with the first two injections being discarded to avoid possible "memory effects"). The fixed effect, SIAR (process + residual), No discrimination (0), and Markov-Chain-Monte-Carlo (normal) were specified (Wu et al., 2017; Yang et al., 2018). Finally, model outputs of the two soil strata were weighted by the coefficients of root amounts in the 0 – 30 cm and 30 – 80 cm layers.

All statistical analyses were performed using the SPSS Statistics (17.0, SPSS Inc., Chicago, USA). Comparisons of SWC between depths (n = 30) were made using a paired *t*-test at $\alpha$ = 0.05. One-way analysis of variance (ANOVA) including Tukey's HSD test was used to compare the $\delta$D and $\delta^{18}$O in different soil stratum (n = 30). Because both variables were random and subjected to measurement errors, geometric mean regression (GMR) was used to calculate regression parameters between throughfall and gross rainfall.

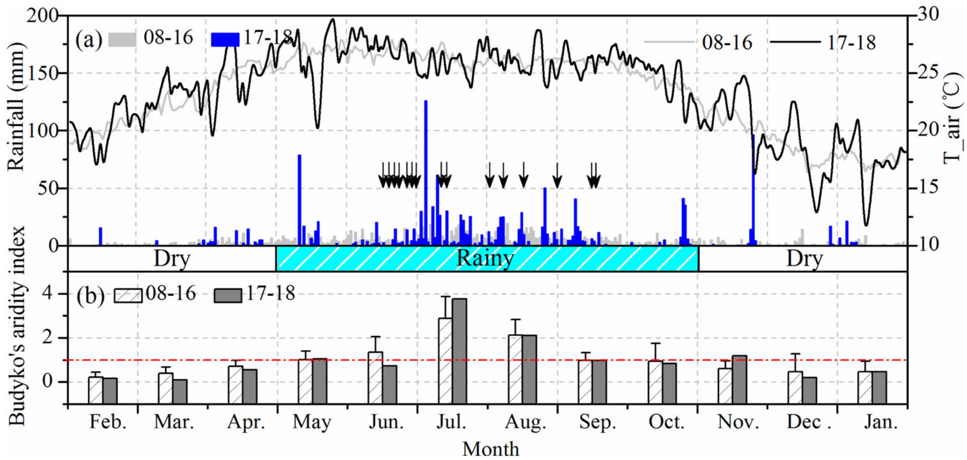


**Fig. 2.** Pattern of rainfall amount, air temperature (a), and Budyko's aridity index (AI) (b) at the experiment site. AI < 1 indicates a period of drought stress. Error bars represent 1 SD. The colored area indicates the rainy season (May-October). Arrows indicate sampling dates.

## 3. Results

### 3.1. Rainfall partitioning

There was relatively plentiful rainfall (AI = 1.6 ± 0.9) during the study period compared to the previous eight years (Fig. 2). Rainfall amount was 1208.5 mm in the rainy season of 2017/2018, accounting for 81.4 % of the total annual precipitation (1485.4 mm). Mean annual precipitation and air temperature of 2008–2016 in this area were 1403.3 ± 191.2 mm and 22.3 ± 0.2 °C. Correspondingly, mean AI for multiple years was 0.5 ± 0.2 in the dry season, and 1.5 ± 0.3 in the rainy season.

Throughfall and stemflow were measured during nine rain events in the early rainy season (Table 1). Throughfall amount gradually increased from 0.1 mm to 27.9 mm as gross rainfall increased from 0.3–33.0 mm. There was a positive correlation between throughfall and gross rainfall ($TF = 0.86P - 1.03$, $R^2 = 0.99$, $P < 0.001$). Contribution of throughfall to gross rainfall (*TF/P*) generally exceeded 50 %, with the exception of two small rain events. Mean value of *TF/P* was 66.5 ± 11.0 % for all rain events. In contrast, the amount of stemflow and interception loss changed slightly during different rain events, where stemflow increased irregularly from 0.6 mm to 3.5 mm. Meanwhile, interception loss also showed an irregular rise from 0.3 to 1.6 mm. This amount of stemflow was too small to be successfully monitored for the first rain event on June 22 − 24, 2017; and the contribution of interception loss to rainfall ($I/P$ = 24.3 %) seemed to be overestimated during the second rain event on June 21 − 22, 2017. When the first two rain events were excluded from analysis, mean contribution of each component to gross rainfall was 71.8 ± 6.8 % for throughfall, 17.6 ± 3.6 % for stemflow, and 10.6 ± 3.8 % for interception loss.

### 3.2. Throughfall distribution

The spatial distribution of throughfall was extremely heterogeneous beneath the banana canopy (Fig. 3). During the small rainfall events, the drip points of throughfall mostly occurred in the margins and tips of the banana leaves. With increasing rainfall amount, drip points gradually spread from leaf margins to the whole banana canopy. Maximum values of throughfall were 64.5 mm for rain event 1 (14.7 mm, Fig. 3a), 34.0 mm for rain event 2 (24.8 mm, Fig. 3b), 120.5 mm for rain event 3 (52.5 mm, Fig. 3c), and 118.5 mm for rain event 4 (70.5 mm, Fig. 3d). These amounts of throughfall were 4.4, 1.4, 2.3, and 1.7 times larger than the gross rainfall, respectively. Meanwhile, some rain gauges did not collect any throughfall even during the highest rain event (70.5 mm), indicating the essence of non-drip points. Minimum throughfall collected using the rain gauges were 2.1 mm for rain event 1, 0.1 mm for rain event 2, 0.1 mm for rain event 3, and 0.9 mm for rain event 4, which were only equivalent to 14.0 %, 0.6 %, 0.1 %, and 1.3 % of the gross rainfall, respectively.

### 3.3. Soil water characteristics beneath the canopy

Soil water content (SWC) varied both in vertical (0 − 80 cm) and horizontal (160 cm × 160 cm) spaces (Fig. 4). There was no significant difference in SWC between 0 − 5 cm and 5 − 30 cm ($P$ = 0.494). In the 0 − 5 cm soil layer, SWC increased sharply from 8.4%–26%, with a mean value of 15.7 ± 3.8 %. Meanwhile, SWC of 5 − 30 cm ranged from 11.0%–18.9%, with a mean of 15.2 ± 1.6 %. In both layers, SWC increased from the pseudo stem to the leaf tips. The shallow SWC (0 − 30 cm) differed markedly from SWC in 30 − 50 cm ($P \leq 0.004$) and 50 − 80 cm ($P < 0.001$). Moreover, SWC of 30 − 50 cm was lower than in

**Table 1**
Rainfall characteristic and its component in the early rainy season at the experimental site.

| Events | Rainfall (mm) | | Partitioning of rainfall (mm) | | | Proportion to rainfall (%) | | |
|---|---|---|---|---|---|---|---|---|
| | Periods | Precipitation (*P*) | Throughfall (*TF*) | Stemflow (*SF*) | Interception (*I*) | *TF/P* | *SF/P* | *I/P* |
| Event 1 | 22 − 24 Jun | 0.3 | 0.1 ± 0.0 | - | - | 46.4 | - | - |
| Event 2 | 21 − 22 Jun | 3.5 | 1.7 ± 0.0 | 0.9 ± 0.1 | 0.8 | 49.1 | 26.6 | 24.3 |
| Event 3 | 28 − 29 Jun | 4.2 | 3.2 ± 0.3 | 0.6 ± 0.2 | 0.4 | 75.0 | 14.4 | 10.6 |
| Event 4 | 11 − 13 Jul | 4.3 | 3.1 ± 0.2 | 0.9 ± 0.1 | 0.4 | 70.8 | 20.2 | 9.0 |
| Event 5 | 20 − 21 Jun | 6.1 | 4.7 ± 2.1 | 1.1 ± 0.3 | 0.3 | 76.5 | 17.2 | 5.7 |
| Event 6 | 29 June-01 Jun | 6.6 | 4.1 ± 1.1 | 1.2 ± 0.2 | 1.3 | 61.4 | 18.9 | 19.7 |
| Event 7 | 01 − 03 Jul | 10.3 | 6.1 ± 0.3 | 2.7 ± 0.3 | 1.5 | 59.2 | 26.2 | 14.5 |
| Event 8 | 18 − 20 Jun | 10.5 | 7.9 ± 0.9 | 1.6 ± 0.5 | 1.0 | 75.2 | 15.2 | 9.5 |
| Event 9 | 12 − 15 Jul | 33.0 | 27.9 ± 7.1 | 3.5 ± 0.6 | 1.6 | 84.4 | 10.7 | 4.9 |

Measurement of stemflow (*SF*) was failed in rain event 1because of its small amount of rainfall (0.3 mm).

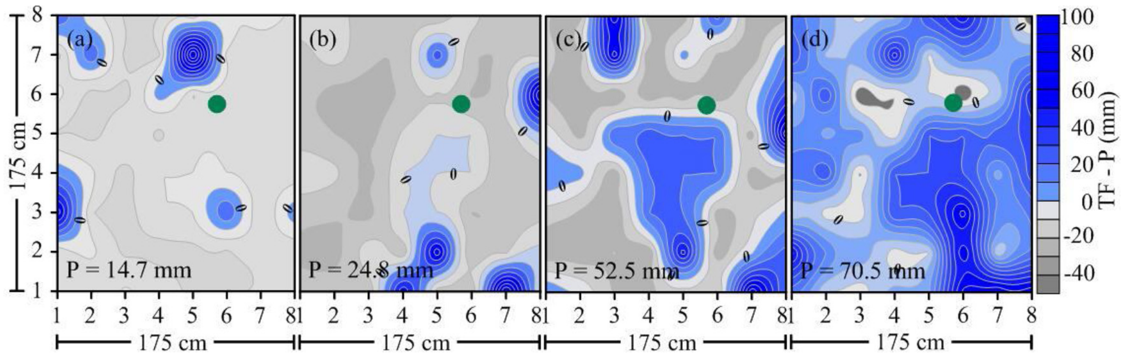


**Fig. 3.** Spatial distribution of throughfall (*TF*) below the banana canopy in the peak rainy season. Positive values (*TF-P*) indicate that the amounts of throughfall exceed the gross rainfall. Green solid circles indicate position of the banana pseudo stem.

50 − 80 cm ($P < 0.001$). Mean values of SWC were 17.6 ± 0.9 % (13.8 %–19.8 %) in 30 − 50 cm, and 21.1 ± 0.5 % (19.4 %–21.6 %) in 50 − 80 cm.

Similarly, soil water $\delta D$ and $\delta^{18}O$ underwent noticeable variation with depth and location (Fig. 4). Vertically, values of $\delta D$ and $\delta^{18}O$ in 0 − 5 cm were significantly higher than in 5 − 30 cm ($P < 0.001$). Values of $\delta D$ and $\delta^{18}O$ were − 69.8 ± 3.2‰ and − 8.38 ± 0.63‰ in 0 − 5 cm, − 78.4 ± 4.4‰ and − 10.04 ± 0.75‰ in 5 − 30 cm, respectively. In addition, values of $\delta D$ and $\delta^{18}O$ in 5 − 30 cm were more negative than in 30 − 50 cm and 50 − 80 cm ($P < 0.001$). There was no significant difference in $\delta D$ and $\delta^{18}O$ between 30 − 50 cm and 50 − 80 cm ($P \geq 0.033$). Values of $\delta D$ and $\delta^{18}O$ were − 68.3 ± 8.3‰ and − 8.99 ± 1.16‰ in 0 − 50 cm, − 62.0 ± 9.1‰ and − 8.34 ± 1.21‰ in 50 − 80 cm, respectively. On the horizontal planes, there was no homogeneous trend for soil water $\delta D$ and $\delta^{18}O$. Higher values of $\delta D$ and $\delta^{18}O$ normally appeared away from the pseudo stem of banana trees. Overall, values of $\delta D$ and $\delta^{18}O$ were − 74.1 ± 3.6‰ and − 9.21 ± 0.66‰ in the 0 − 30 cm stratum, − 65.2 ± 8.4‰ and − 8.66 ± 1.14‰ in the 30 − 80 cm stratum, respectively.

### *3.4. Water uptake pattern in the banana plantation*

The MixSIAR model predicted that banana trees acquired unevenly water from the shallow (0 − 30 cm) and deep (30 − 80 cm) soil strata (Fig. 5). Vertically, dry weights of fine roots were 0.64 kg $m^{-3}$ in 0 − 30 cm and 0.15 kg $m^{-3}$ in 30 − 80 cm. We therefore obtained a coefficient of 2.6:1, which was used to evaluate relative water contributions of the 0 − 30 cm and 30 − 80 cm strata. Based on this assumption, the overall soil water contributions were 72.3 % from the 0 − 30 cm layer and 27.7 % from the 30 − 80 cm layer. In the late rainy season, mean isotopic values of xylem water were − 72.0 ± 0.3‰ for $\delta D$, and − 9.59 ± 0.01‰ for $\delta^{18}O$. Combined with the root investigation, water contribution of the seven radiating directions increased from 8.5%–12.4% in the 0 − 30 cm stratum (Fig. 5b). Correspondingly, water contribution of the seven directions ranged from 1.7 % to 6.5 % in the 30 − 80 cm stratum. As summarized in Fig. 5c, water-absorbing proportion from horizontal directions (0 − 360°) fluctuated between 10.2 % and 16.3 % when the 0 − 30 cm and 30 − 80 cm soil strata were combined.

## 4. Discussion

### *4.1. Effects of banana canopy on rainfall redistribution*

Our results indicated that rainfall redistribution was greatly affected by banana trees (Table 1). Partitioning of rainfall revealed that throughfall rate (*TF/P*) in our banana plantation (71.8 ± 6.8 %,) was close to those in a clove (*Syzygium aromaticum*) plantation (62.9 %), a rubber monoculture (71–94 %), and a forest stand (70 − 80%) (Dietz et al., 2006; Limin et al., 2015; Liu et al., 2016). However, contribution of stemflow to gross rainfall (*SF/P*) in our banana plantation (17.6 ± 3.6 %) was noticeably higher than previously reported by Dietz et al. (2006) in forest stands (~ 1%), Liu et al. (2008) in a rubber plantation (~ 5%), and Limin et al. (2015) in a clove plantation (~ 0.98 %). This can be ascribed to the funnel-shaped canopy structure in banana plantations (Sansoulet et al., 2008; Cattan et al., 2009). Similarly, Cattan et al. (2007) found that stemflow can represent 18–26 % of the total rainfall during the different growing stages of banana trees. Cattan et al. (2009) further demonstrated that rainfall redistribution by the banana canopy will enhance runoff even on soil with a high infiltration rate. In the same region as this study, Zhu et al. (2018) showed that runoff from a rubber plantation is about 33.2 times higher than in a tropical rainforest. We therefore speculate that the considerable increase of stemflow in banana plantations might further aggravate runoff in southwestern China. It should be noted that the self-made stemflow collectors could not effectively capture rainwater in small rain events (see section 3.1), which would result in an underestimation of stemflow in the banana plantation. Furthermore, the limited measuring areas of the V-shaped troughs might also underestimate the amounts of throughfall during the partitioning of rainfall into its components.

Over the last few decades, the environmental impacts of rubber cultivation in southwestern China have received much attentions (Li et al., 2016; Jiang et al., 2017; Zhu et al., 2018), but the hydrological threats of banana cultivation expansion might be more serious. One reason for this could be the uneven distribution of throughfall in the banana plantation (Fig. 3). Throughfall amounts topped out at 140–440 % of the gross rainfall. At the same time, throughfall amounts in some drip points were only equivalent to 0.1–14.0 % of the gross rainfall. In addition, spatial heterogeneity of throughfall decreased with increasing rainfall amount. This trend is consistent with the findings from previous studies, which reported that the spatial variation of throughfall is highly dependent upon the volume of incident rainfall (Keim et al., 2005; Liu et al., 2017). They also suggested that the drip points of throughfall gradually extended from leaf edges in small rain events to plant stems during larger rain events. The coefficient of variation (CV) was used to identify the difference of throughfall between banana and rubber plantations. In our banana plantation, CV of throughfall increased from 52.7%–79.1% over 4 rain events (14.7–70.5 mm) in the peak rainy season. Accordingly, CV of throughfall was reported to range between 8.6 % and 22.9 % over 30 rain events (6.5–108.4 mm) in a rubber plantation (Liu et al., 2018). Although the observed maximum rainfall was lower in the present study, CV of throughfall in banana plantation was over three times larger than in the rubber plantation. We should note that the spatial variation of throughfall is also related to rainfall intensity (Keim et al., 2005; Kowalska et al., 2016; Liu et al., 2018), though we did not monitor this in this study. Further rainfall measurements with high temporal resolution can be expected to provide greater insight on this matter.

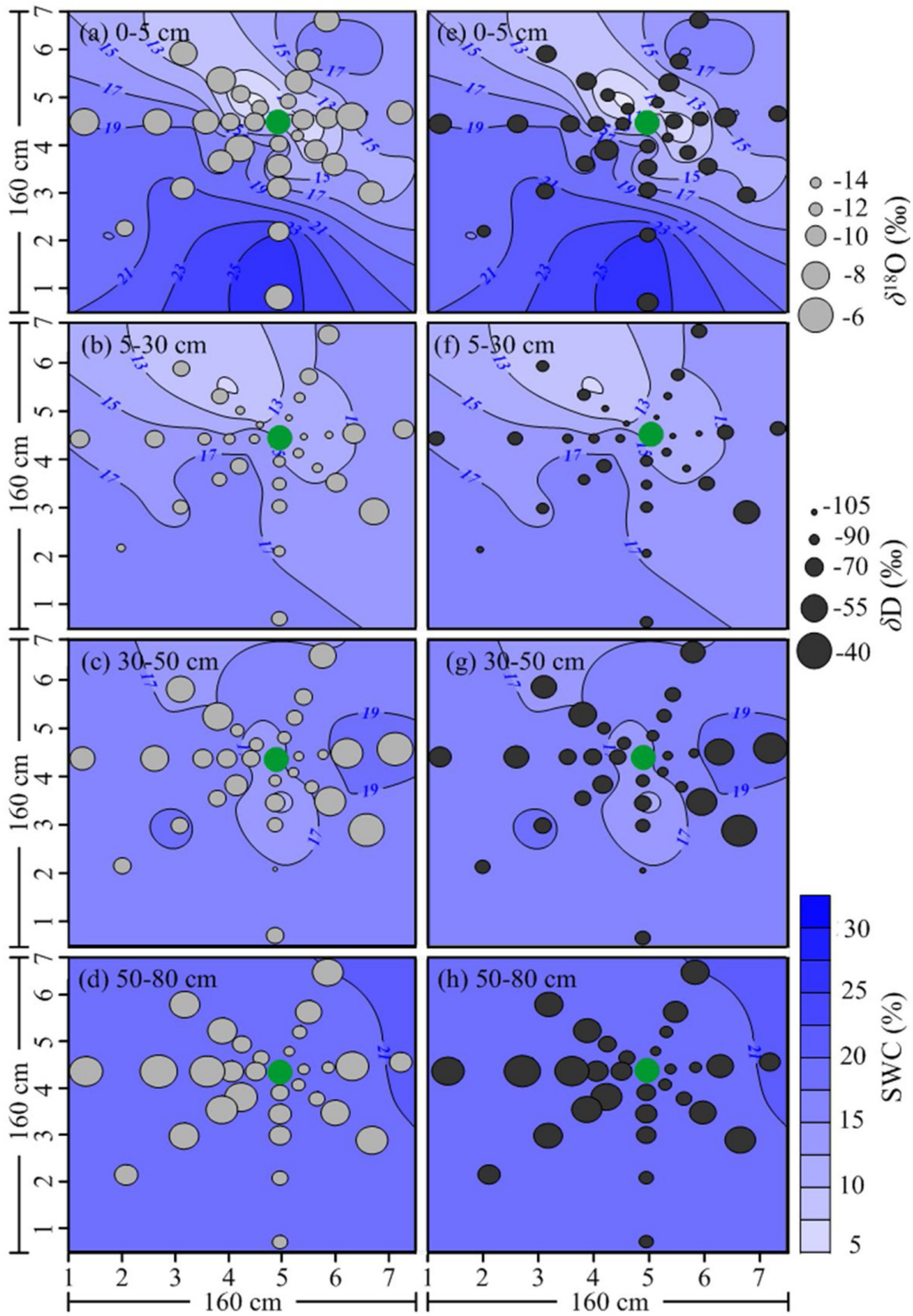


**Fig. 4.** Spatial pattern of the isotope composition ($\delta$D and $\delta^{18}$O) and soil water content (SWC) in 0-5, 5-20, 30-50, and 50-80 cm soil strata. Green solid circles indicate position of the banana pseudo stem.

### 4.2. Water source partitioning and uncertainties

Soil moisture is one of the most essential factors affecting plant water acquisition (Sekiya et al., 2002; Querejeta et al., 2007; Muñoz-Villers et al., 2018). Unsurprisingly, soil water content (SWC) exhibited vertical gradients in the 0 – 80 cm depth (Fig. 4). Horizontally, SWC fluctuated 17.6 % in 0 – 5 cm, 7.9 % in 5 – 30 cm, 6.0 % in 30 – 50 cm, and 2.2 % in 50 – 80 cm. Spatial variations in SWC also affected the isotopic composition of soil water. This could be due to the two independent processes of soil water evaporation and mixing with rainwater. Theoretically, the evaporation process will have an enriching effect on surface soil water $\delta$D and $\delta^{18}$O (Gat, 1996). This was confirmed by the co-variation between $\delta$D and $\delta^{18}$O in soil water (Fig. S2), which were plotted below the global meter water line (GMWL) due to Rayleigh distillation (Dawson and Simonin, 2011). Contrastingly, mixing with rainwater always leads to more negative $\delta$-values in deeper soil strata (McCole and Stern, 2007; Dawson and Simonin, 2011). Therefore, soil water $\delta$D and $\delta^{18}$O were more depleted in the middle (5 – 30 and 30 – 50 cm) soil layers in this study (Fig. 4b and c). This is the fundamental premise for identifying plant water source using stable isotopes (Ehleringer and Dawson, 1992). Based on these vertical gradients of $\delta$D and $\delta^{18}$O in soil layers, water source partitioning has been conducted in various ecosystems (Eggemeyer et al., 2009; Dawson and Simonin, 2011; Grossiord et al., 2017). However, we found that soil

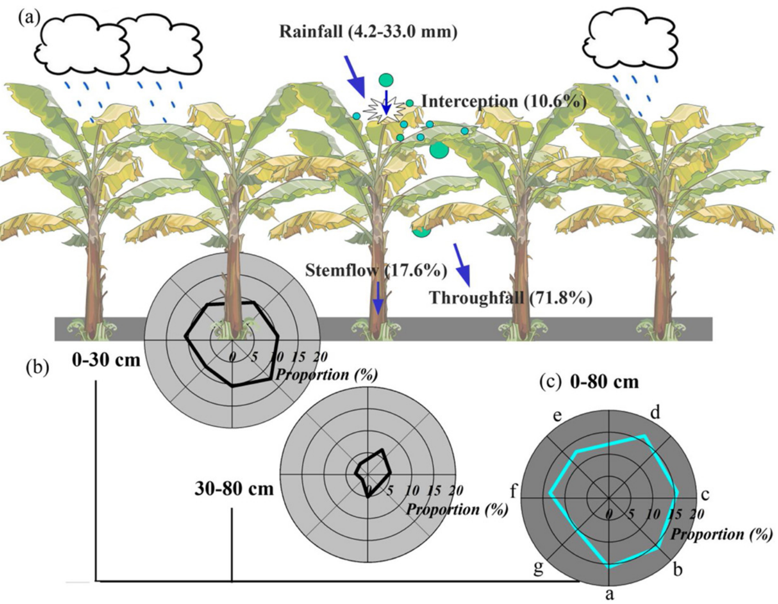


**Fig. 5.** Schematic representation of rainfall partitioning (a) and the absorbing proportion of soil water in different soil strata (b-c) during the study period.

water $\delta$D and $\delta^{18}$O also changed markedly in horizontal directions, providing an opportunity to re-examine the spatial utilization of soil water in banana plantations.

There is a common assumption of minimal horizontal variation in soil water $\delta$D and $\delta^{18}$O beneath plant canopies. Therefore, in most cases an increase in sampling replicates can effectively reduce uncertainties in water source partitioning (McCole and Stern, 2007; Querejeta et al., 2007; Muñoz-Villers et al., 2018). For example, our earlier research suggested that soil water $\delta$D and $\delta^{18}$O in $0-5$ cm, $5-20$ cm, and $20-45$ cm were almost unchanged horizontally ($P < 0.05$, unpublished data) in a Masson pine (*Pinus massoniana* Lamb.) plantation (Yang et al., 2015). However, this assumption was disproved in this study due to the non-homogeneous distribution of rainfall in the banana plantation (Figs. 3 and 4). Outputs of the MixSIAR model showed that acquisition proportion of soil water from $0-80$ cm to banana trees ranged from 10.2%–16.3% on the horizontal planes (Fig. 5c). These results were based on the assumption that source water contribution from the $0-30$ cm and $30-80$ cm depths to banana trees increased proportionally with their fine root distribution (see section 2.6 and 3.4). A few of the previous studies have mentioned that root distribution may not be a reliable indicator of plant water uptake (Ehleringer and Dawson, 1992; Sekiya et al., 2002; Zhang et al., 2011). However, shallow-rooted crops tend to utilize shallow soil water in accordance with their root distributions (Araki and Iijima, 2005; Zegada-Lizarazu et al., 2007; Asbjornsen et al., 2008). A sensitivity analysis implied that outputs of the MixSIAR model would be 78.8 ± 11.0 % for the $0-30$ cm soil stratum if we ignored the horizontal variability of soil water $\delta$D and $\delta^{18}$O. This proportion was quite close to the ratio of fine roots (72.3 %) in the $0-30$ cm soil layer. One possible explanation was that the field was well-watered in this region (Fig. S1), thereby, ensuring a sufficient water supply to the shallow root network of banana trees. Therefore, it is reasonable to associate banana trees' water acquisition with fine root distribution in this study.

### 4.3. Implications

As one of the 34 global biodiversity hotspots, Xishuangbanna region is known as the "Treasure House" of biological diversity in southwestern China (Myers et al., 2000). Nevertheless, a few of the tropical species now are on the verge of extinction due to the rapid expansion of various cash crops (Xu, 2011). The most important driver of the land-use change was believed to be the cultivation of rubber trees (Liu et al., 2008; Li et al., 2016), which resulted in excessive runoff, soil nutrient loss, and sediment yield (Chen et al., 2017; Jiang et al., 2017; Zhu et al., 2018). However, the expansion of rubber plantations has ceased since 2011 (Zhang et al., 2019). According to the latest Xishuangbanna Prefecture Report (Government of Xishuangbanna Dai Autonomous Prefecture (GXDAP, 2018), the area of banana plantations reached 26, 733 ha in 2015, with a yield of 846, 200 t. There is an urgent requirement for new data to explore ecohydrological processes in banana plantations. Our study was one of the first to investigate the effects of bananas' funnel-shaped canopy on rainfall redistribution and plant water acquisition, with the finding that the spatial distribution of rainfall would be directly affected, and indirectly affect the water source prediction. We hope that these findings will contribute to sustainable development of the banana industry in southwestern China. Further research into the effects of banana plantations on soil erosion and surface runoff would also be of use.

## 5. Conclusions

Our findings highlighted that the throughfall and stemflow accounted for 71.8 % and 17.6 % of the gross rainfall in a banana plantation. In the peak rainy season, the maximum amount of throughfall below the banana canopy was 1.4–4.4 times greater than the gross rainfall, while its minimum values were only equivalent to 0.1 %–14.0 % of the gross rainfall. This uneven distribution of throughfall has direct and indirect effects on soil water content and soil water $\delta$D and $\delta^{18}$O below the canopy. We also found that banana trees acquired 72.3 % of their water from the $0-30$ cm soil stratum. Meanwhile, the horizontal water-absorbing proportion from $0-30$ cm increased from 8.5%–12.4%. This water-absorbing proportion ranged from 1.7 % to 6.5 % in the $30-80$ cm soil stratum. Further studies are needed to improve our understanding of the influences of banana cultivation on ecohydrological processes.

## Declaration of Competing Interest

The authors declare that they have no competing financial interests that could influence the work reported in this paper.

## Acknowledgements

We thank Liu M.N., Li W.X., and Dao Y.Q. for their contribution to this work. The study was supported by Xishuangbanna Station for Tropical Rainforest Ecosystem Studies (XSTRE) and the Central Laboratory of XTBG. It was funded by the Natural Science Foundation of Yunnan Province (2018FB043), the National Science Foundation of China (31700560, 31670452), the CAS "Western Light Program", and the Chinese Academy of Sciences 135-Program (2017XTBG-F01).

## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.still.2020.104686.

## References

Araki, H., Iijima, M., 2005. Stable isotope analysis of water extraction from subsoil in upland rice (*Oryza sativa* L.) as affected by drought and soil compaction. Plant Soil 270, 147–157.
Asbjornsen, H., Shepherd, G., Herlmers, M., Mora, G., 2008. Seasonal pattern in depth of water uptake under contrasting annual and perennial systems in the Corn Belt Region of the Midwestern US. Plant Soil 308, 62–92.
Barnard, R.L., de Bello, F., Gilgen, A.K., Buchmann, N., 2006. The $\delta^{18}$O of root crown water best reflects source water $\delta^{18}$O in different types of herbaceous species. Rapid Commun. Mass Spectrom. 20, 3799–3802.
Bassette, C., Bussiere, F., 2008. Partitioning of splash and storage during raindrop impacts on banana leaves. Agric. For. Meteorol. 148, 991–1004.
Borrelli, P., Märker, M., Schütt, B., 2015. Modelling post-tree-harvesting soil erosion and sediment deposition potential in the Turano River Basin (Italian Central Apennine). Land Degrad. Dev. 26, 356–366.
Brooks, J.R., Barnard, H.R., Coulombe, R., McDonnell, J.J., 2010. Ecohydrologic separation of water between trees and streams in a Mediterranean climate. Nat. Geosci. 3, 100–104.
Budyko, M.I., 1974. Climate and Life. Academic Press, New York, NY.
Cattan, P., Cabidoche, Y.M., Lacas, J.G., Voltz, M., 2006. Effects of tillage and mulching on runoff under banana on a tropical Andosol. Soil Till. Res. 86, 38–51.
Cattan, P., François, B., Alban, N., 2007. Evidence of large rainfall partitioning patterns by banana and impact on surface runoff generation. Hydrol. Process. 21, 2196–2205.
Cattan, P., Ruy, S.M., Cabidoche, Y.M., Findeling, A., Desbois, P., Charlier, J.B., 2009. Effect on runoff redistribution by the impluvium-shaped canopy of banana cultivated on an Andosol with a high infiltration rate. J. Hydrol. 368, 251–261.
Chen, C.F., Liu, W.J., Jiang, X.J., Wu, J.E., 2017. Effects of rubber-based agroforestry systems on soil aggregation and associated soil organic carbon: implications for land use. Geoderma 299, 13–24.
Dawson, T.E., Simonin, K.A., 2011. The roles of stable isotopes in forest hydrology and biogeochemistry. In: Levia, D.F., Carlyle-Moses, D., Tanaka, T. (Eds.), Forest Hydrology and Biogeochemistry: Synthesis of Past Research and Future Directions. Springer, Heidelberg, pp. 137–161.
Dietz, J., Hölscher, D., Leuschner, C., 2006. Rainfall partitioning in relation to forest structure in differently managed montane forest stands in Central Sulawesi, Indonesia. For. Ecol. Manage. 237, 170–178.
Drescher, J., Rembold, K., Allen, K., Beckschäfer, P., Buchori, D., Clough, Y., Faust, H., 2016. Ecological and socio-economic functions across tropical land use systems after rainforest conversion. Philos. Trans. Biol. Sci. 371, 20150275.
Eggemeyer, K.D., Awada, T., Harvey, F.E., Wedin, D.A., Zhou, X.H., Zanner, C.W., 2009. Seasonal changes in depth of water uptake for encroaching trees *Juniperus virginiana* and *Pinus ponderosa* and two dominant $C_4$ grasses in a semiarid grassland. Tree Physiol. 29, 157–169.
Ehleringer, J.R., Dawson, T.E., 1992. Water uptake by plants: perspectives from stable isotope composition. Plant Cell Environ. 15, 1073–1082.
FAO, 2012. Crop Water Information for Banana. http://www.fao.org/nr/water/cropinfobanana.html.
Feng, Z.J., Zhao, J., Dai, J.J., 2019. Development present of banana planting industry in Yunnan Province: analysis of competitive advantages. Yunnan Agric. 1, 42–44 (In Chinese).
Fox, J.M., Castella, J.C., Ziegler, A.D., Westley, S.B., 2014. Rubber plantations expand in mountainous Southeast Asia: what are the consequences for the environment? Asia Pac. Issues 114, 1–8.
Gat, J.R., 1996. Oxygen and hydrogen isotopes in the hydrologic cycle. Annu. Rev. Earth Planet. Sci. 24, 225–262.
Germer, S., Elsenbeer, H., Moraes, J.M., 2006. Throughfall and temporal trends of rainfall redistribution in an open tropical rainforest, south-western Amazonia (Rondônia, Brazil). Hydrol. Earth Syst. Sci. Discuss. 10, 383–393.
Goebel, T.S., Lascano, R.J., 2014. Time for cotton to uptake water of a known isotopic signature as measured in leaf petioles. Agric. Sci. 5, 170–177.
Government of Xishuangbanna Dai Autonomous Prefecture (GXDAP), 2018. Development Actuality of Banana Plantation in Xishuangbanna. https://www.xsbn.gov.cn/index.dhtml.
Grossiord, C., Sevanto, S., Dawson, T.E., Adams, H.D., Collins, A.D., Dickman, L.T., Newman, B.D., Stockton, E.A., McDowell, N.G., 2017. Warming combined with more extreme precipitation regimes modifies the water sources used by trees. New Phytol. 213, 584–596.
IPCC, 2013. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Islam, K.R., Weil, R.R., 2000. Land use effects on soil quality in a tropical forest ecosystem of Bangladesh. Agric., Ecosyst. Environ. 79, 9–16.
Jiang, X.J., Liu, W.J., Wu, J.E., Wang, P.Y., Liu, C.A., Yuan, Z.Q., 2017. Land degradation controlled and mitigated by rubber-based agroforestry systems through optimizing soil physical conditions and water supply mechanisms: a case study in Xishuangbanna, China. Land Degrad. Dev. 28, 2277–2289.
Keim, R.F., Skaugset, A.E., Weiler, M., 2005. Temporal persistence of spatial patterns in throughfall. J. Hydrol. 314, 263–274.
Kowalska, A., Boczoń, A., Hildebrand, R., Polkowska, Ż., 2016. Spatial variability of throughfall in a stand of Scots pine (*Pinus sylvestris* L.) with deciduous admixture as influenced by canopy cover and stem distance. J. Hydrol. 538, 231–242.
Li, H.M., Ma, Y.X., Liu, W.J., 2016. Land use and topography as predictors of nitrogen levels in tropical catchments in Xishuangbanna, SW China. Environ. Earth Sci. 75, 539.
Limin, S.G., Oue, H., Sato, Y., Budiasa, I.W., Indra setiawand, B., 2015. Partitioning rainfall into throughfall, stemflow, and interception loss in Clove (*Syzygium aromaticum*) plantation in upstream Saba River Basin, Bali. Procedia Environ. Sci. 28, 280–285.
Liu, W.J., Liu, W.Y., Li, J.T., Wu, Z.W., Li, H.M., 2008. Isotope variations of throughfall, stemflow and soil water in a tropical rain forest and a rubber plantation in Xishuangbanna, SW China. Hydrol. Res. 39, 437–449.
Liu, W.J., Zhu, C.J., Wu, J.E., Chen, C.F., 2016. Are rubber-based agroforestry systems effective in controlling rain splash erosion? Catena 147, 16–24.
Liu, W.J., Luo, Q.P., Lu, H.J., Wu, J.E., Duan, W.P., 2017. The effect of litter layer on controlling surface runoff and erosion in rubber plantations on tropical mountain slopes, SW China. Catena 149, 167–175.
Liu, J.Q., Liu, W.J., Li, W.X., Zeng, H.H., 2018. How does a rubber plantation affect the spatial variability and temporal stability of throughfall? Hydrol. Res. 50, 60–74.
Loescher, H.W., Powers, J.S., Oberbauer, S.F., 2002. Spatial variation of throughfall volume in an old-growth tropical wet forest, Costa Rica. J. Trop. Ecol. 18, 397–407.
Ma, Y., Song, X.F., 2016. Using stable isotopes to determine seasonal variations in water uptake of summer maize under different fertilization treatments. Sci. Total Environ. 550, 471–483.
Marin, C.T., Bouten, W., Sevink, J., 2000. Gross rainfall and its partitioning into throughfall, stemflow and evaporation of intercepted water in four forest ecosystems in western Amazonia. J. Hydrol. 237, 40–57.
Mayes, M.T., Mustard, J.F., Melillo, J.M., 2015. Forest cover change in Miombo Woodlands: modeling land cover of African dry tropical forests with linear spectral mixture analysis. Remote Sens. Environ. 165, 203–215.
McCole, A.A., Stern, L.A., 2007. Seasonal water use patterns of Juniperus ashei on the Edwards Plateau, Texas, based on stable isotopes in water. J. Hydrol. 342, 238–248.
Muñoz-Villers, L.E., Holwerda, F., Alvarado-Barrientos, M.S., Geissert, D.R., Dawson, T.E., 2018. Reduced dry season transpiration is coupled with shallow soil water use in tropical montane forest trees. Oecologia 188, 303–317.
Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B., Kent, J., 2000. Biodiversity hotspots for conservation priorities. Nature 403, 853–858.
Nepstad, D.C., Moutinho, P., Dias-Filho, M.B., Davidson, E., Cardinot, G., Markewitz, D., Figueiredo, R., Vianna, N., Chambers, J., Ray, D., Guerreiros, J.B., Lefebvre, P., Sternberg, L., Moreira, M., Barros, L., Ishida, F.Y., Tohlver, I., Belk, E., Kalif, K., Schwalbe, K., 2002. The effects of partial throughfall exclusion on canopy processes, aboveground production, and biogeochemistry of an Amazon forest. J. Geophys. Res. 107, 8085.
Orság, M., Fischer, M., Tripathi, A.M., Žalud, Z., Trnka, M., 2018. Sensitivity of short rotation poplar coppice biomass productivity to the throughfall reduction-Estimating future drought impacts. Biomass Bioenerg. 109, 182–189.
Querejeta, J.I., Estrada-Medina, H., Allen, M.F., Jiménez-Osornio, J.J., 2007. Water source partitioning among trees growing on shallow karst soils in a seasonally dry tropical climate. Oecologia 152, 26–36.
Ramírez, B.H., Melsen, A.L., Ganzeveld, L., Leemans, R., Teuling, A.J., 2018. Tropical montane cloud forests in the Orinoco river basin: inferring fog interception from through-fall dynamics. Agric. For. Meteorol. 260-261, 17–30.
Sansoulet, J., Cabidoche, Y., Cattan, P., Ruy, S.Š, Cabi, J., 2008. Spatially distributed water fluxes in an Andosol under banana plants: experiments and three-dimensional modeling. Vadose Zone J. 7, 819–829.
Sekiya, N., Yano, K., 2002. Water acquisition from rainfall and groundwater by legume crops developing deep rooting systems determined with stable hydrogen isotope compositions of xylem waters. Field Crops Res. 78, 133–139.
Singh, B., Singh, J.P., Kaur, A., Singh, N., 2016. Bioactive compounds in banana and their associated health benefits-a review. Food Chem. 206, 1–11.
Smajgl, A., Xu, J.C., Egan, S., Yi, Z.F., Ward, Z., Su, Y.F., 2015. Assessing the effectiveness of payments for ecosystem services for diversifying rubber in Yunnan, China. Environ Modell. Softw. 69, 187–195.
Stock, B.C., Semmens, B.X., 2013. MixSIAR GUI User Manual. https://doi.org/10.5281/zenodo.56159. https://github.com/brianstock/MixSIAR.
Wang, P.Y., Liu, W.J., Zhang, J.L., Yang, B., Singh, A.K., Wu, J.E., Jiang, X.J., 2019. Seasonal and spatial variations of water use among riparian vegetation in tropical monsoon region of SW China. Ecohydrology 12, e2085.
West, A.G., Dawson, T.E., February, E.C., Midgley, G.F., Bond, W.J., Aston, T.L., 2012. Diverse functional responses to drought in a Mediterranean-type shrub land in South Africa. New Phytol. 195, 396–407.

Wu, J.E., Liu, W.J., Chen, C.F., 2017. How do plants share water sources in a rubber-tea agroforestry system during the pronounced dry season? Agric. Ecosyst. Environ. 236, 69–77.
Wu, J.E., Zeng, H.H., Chen, C.F., Liu, W.J., 2019. Can intercropping with the Chinese medicinal herbs change the water use of the aged rubber trees? Agric. Water Manage. 226, 105803.
Xu, J.C., 2011. China's new forests aren't as green as they seem. Nature 477, 371.
Yang, B., Wen, X.F., Sun, X.M., 2015. Seasonal variations in depth of water uptake for a subtropical coniferous plantation subjected to drought in an East Asian monsoon region. Agric. For. Meteorol. 201, 218–228.
Yang, B., Wang, P.Y., You, D.B., Liu, W.J., 2018. Coupling evapotranspiration partitioning with root water uptake to identify the water consumption characteristics of winter wheat: a case study in the north China Plain. Agric. For. Meteorol. 259, 296–304.
Zegada-Lizarazu, W., Kanyomeka, L., Izumi, Y., Iijima, M., 2007. Water acquisition from the seasonal wetland and root development of Pearl millet intercropped with cowpea in a flooding ecosystem of northern Namibia. Plant Prod. Sci. 10, 20–27.
Zhang, C.Z., Zhang, J.B., Zhao, B.Z., Zhu, A.N., Zhang, H., Huang, P., Li, X.P., 2011. Coupling a two-tip linear mixing model with a $\delta$D-$\delta^{18}$O plot to determine water sources consumed by maize during different growth stages. Field Crops Res. 123, 196–205.
Zhang, J.Q., Corlett, R.T., Zhai, D.L., 2019. After the rubber boom: good news and bad news for biodiversity in Xishuangbanna, Yunnan, China. Reg. Environ. Change 19, 1713–1724.
Zhu, X.A., Liu, W.J., Jiang, X.J., Wang, P.Y., Li, W.X., 2018. Effects of land-use changes on runoff and sediment yield: implications for soil conservation and forest management in Xishuangbanna, Southwest China. Land Degrad. Dev. 29, 2962–2974.