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Stable Isotopes Reveal the Effect of Canopy and Litter Layer Interception on Water Recharge in a Subtropical Manmade Forest of Southwest China

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Abstract: In areas completely covered by vegetation, the rainwater that passes through the canopy layer and litter layer is the source supplying surface runoff and seeping into the soil layer. To reveal the influence mechanisms of the canopy and litter layer on water supply in forest areas, this study conducted event-scale water sampling and hydrogen and oxygen isotopic comparison for the rainfall, canopy throughfall and litter layer throughfall in a manmade forest. The results show that canopy interception will lead to a more concentrated distribution and lower isotopic variability. The d-excess and the intercept and slope of the δD-$\delta^{18}O$ regression line of the canopy throughfall are slightly higher than those of rainfall, reflecting that the evaporation fractionation caused by canopy interception is weak, and the selection process may play a leading role. Compared with the canopy throughfall, the distribution of the $\delta^{18}O$, δD and d-excess in the litter layer throughfall is more dispersed, and the slope and intercept of the δD-$\delta^{18}O$ regression line are higher, indicating the strong influence of non-equilibrium fractionation on the water input caused by litter layer interception. The isotopic differences between the litter layer throughfall and canopy throughfall indicate that the water components of small-scale precipitation events (precipitation amount lower than 5 mm) and the early stage of large-scale precipitation events (precipitation amount higher than 25 mm) may be dissipated by litter layer interception, while that of the latter stage of large-size events is slightly affected. The findings of this study will be helpful to deeply understand the mechanisms of the water cycle in the forest ecosystem under the background of climate change and provide insights for the sustainable utilization of water resources.

Keywords: forest ecosystem; water recharge mechanisms; canopy interception; litter layer interception; isotopic tracers

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1. Introduction

In recent decades, concentrated human activities and intense climate change have led to frequent droughts and floods [1–3]. Under this background, it is of great significance to understand the recharge and evaporation process in the hydrological and ecohydrological cycle and the stress mechanism of excessive or deficit water on plants for sustainable water resources utilization and the maintenance of ecosystem function [4–6]. The forest plays an important role in climate regulation and soil-water conservation and is one of the most important terrestrial ecosystems. In forest areas, the dynamic interception and redistribution of precipitation by the canopy and litter layers will affect water cycle and water quality at different scales, which is important for the stability of the forest ecosystem [7–10]. As the first segment of precipitation redistribution, the canopy changes the amount and temporal distribution of the precipitation landing on the ground by intercepting the rain drops. This process weakens the precipitation intensity and then plays an extremely important role in regulating surface runoff and reducing soil erosion [11,12]. The rainwater that passes through the canopy is called the canopy throughfall, which is the main source of surface runoff in forest areas [13]. The litter layer is mainly composed of the dead and fallen organs of plants that are not completely decomposed and clearly visible and usually has a good capacity for water holding [14]. After the rainwater drops through the canopy, it will be intercepted again by the litter layer before reaching the soil. The interception of litter can greatly delay the runoff production, reduce the surface runoff, prevent the direct contact between raindrops and soil, and effectively control the soil erosion caused by splash erosion and slope flow [15]. Rainwater that contacts the soil layer through the surface litter is called the litter layer throughfall, which is the main water source for the growth of forest vegetation and affects the succession process of forest communities [16,17]. At present, the influence of canopy interception on precipitation has been widely considered, but few studies have focused on the impact of litter interception. The combined effects of canopy interception and litter interception on the forest hydrological cycle are usually ignored.

Stable isotope tracing is one of the modern technologies in global change research, and it is also an important tool in studies of the hydrological cycle [18,19]. Due to the stability of chemical properties, hydrogen and oxygen isotopes of water are widely used in the research of source identification, runoff segmentation, paleoclimate reconstruction and plant water utilization [20–26]. The hydrogen and oxygen stable isotopes in precipitation usually show a complex temporal and spatial distribution, which presents a sensitive response to the changes in atmospheric circulation patterns (such as air mass source and transport path) and local environmental factors (such as precipitation, relative humidity and air temperature) [27–31]. In forest areas, the isotopes of precipitation reaching the surface (or infiltrating into the soil) in forest are different from those in open lands, due to the water mixing and evaporation during the process of the interception of the canopy and litter layer. Comparing the stable isotope characteristics in open-land precipitation, the canopy throughfall and litter layer throughfall can reflect the redistribution, storage and evaporation of the precipitation caused by interception effects, which is helpful to understand the role of the canopy and litter layer in the forest hydrological cycle. In previous studies, the mechanisms of the canopy interception effect on forest precipitation have been revealed by isotope tracers in different regions, under different climate types and with different vegetation cover [32–34]. However, few studies have reported the application of hydrogen and oxygen isotopes to identify the role of the litter layer in the hydrological cycle, especially at the event scale. Therefore, in the summer months of 2019, 2020 and 2021, water samples of rainfall, canopy throughfall and litter layer throughfall were collected at an event scale in a manmade forest area in southwest China, and the composition of hydrogen and oxygen stable isotopes in water was analyzed. Through the isotopic comparison between different water types, the present study aims to preliminarily reveal the influence of the interception of canopy and litter on the precipitation migration process in the forest ecosystem.

2. Materials and Methods

2.1. Study Area

The manmade forest is located in the Ecohydrological Experimental Field of Sichuan University in Chengdu, southwest China (shown in Figure 1). The geographic coordinates are 30°33′ N, 103°59′ E, and the elevation is about 481 m. The study area belongs to a subtropical monsoon humid climate with abundant heat, abundant rainfall and a mild climate. According to the statistical yearbook of Chengdu City, the annual average temperature is 16.3 °C, the annual average precipitation is 855.8 mm, the annual average relative humidity is 83%, the annual sunshine hours are 957.6 h and the annual average evaporation is 907.5 mm. The average tree height, average canopy closure and leaf area index in the experimental forest land are about 9 m, 0.7 and 3.34, respectively. The main plant types are *Ficus virens* (i.e., *green fig*) and *Tenjikukatsura* (also known as *Cinnamomum japonicum Sieb*).

There are few herbaceous plants on the ground, and the thickness of litter layer was about 0.5 cm–1 cm during the observation period.

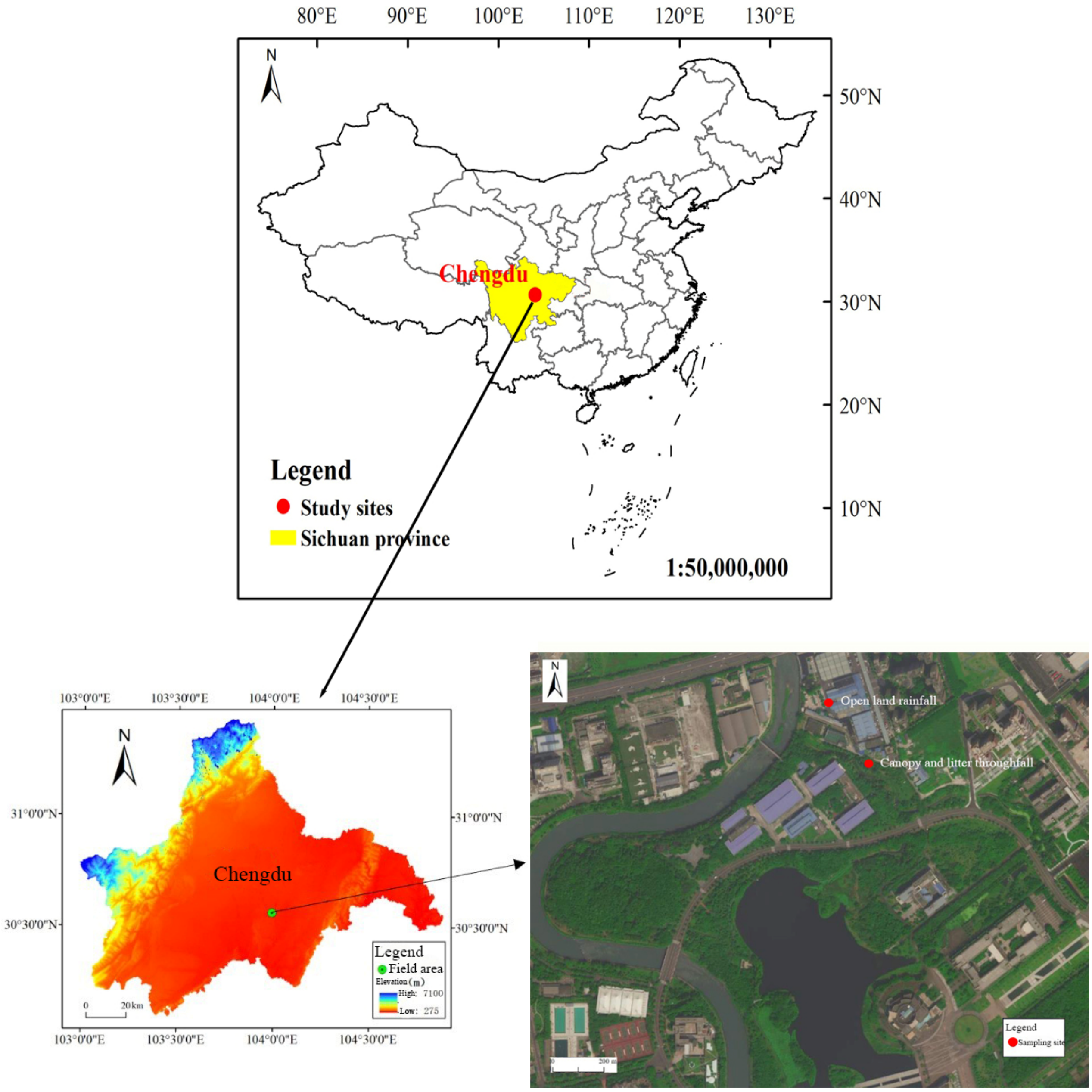

Figure 1. Geographical location of the study area.

2.2. Sampling Collection and Analysis

The rainfall (RF) sampling point is set in the open land next to the ecohydrological experimental field, the canopy throughfall (TF) sampling point is set in the manmade forest with a linear distance of about 150 m from the rainfall sampling point, and the litter layer throughfall (LF) sampling point is close to the sampling point of the canopy throughfall. For TF sample collection, 3 collectors were set under 3 trees with similar macroscopical canopy conditions. The rainwater collector was made of a plastic bucket with a diameter of 15 cm and a height of 21 cm, and a heavy block was placed inside the bucket to ensure its stability. A funnel with a diameter of 32 cm was placed on the mouth of the bucket, and a ping-pong ball was placed in the funnel to prevent rainwater from evaporating. A layer of plastic film was set on the sunken ground surface at the litter water sampling point, weights were put on the four corners of the plastic film, a layer of barbed wire was used to cover the plastic film, and finally the litter was put back to cover the barbed wire in a restored state. All the precipitation samples were collected within one hour after the events. Rainwater passed through the canopy drops onto the litter, and was collected by plastic film below the barbed wire. During the observation periods of July 2019, July–August 2020 and July–August 2021, a total of 84 precipitation and 78 canopy throughfall water samples were collected at the event scale. From July to August 2021, 32 samples of event-scale litter layer throughfall were collected.

The samples were measured in the Ecohydrological Laboratory of Sichuan University, and the Triple-Liquid Water Isotope Analyzer (T-LWIA-45-EP 912-0050) produced by Los Gatos Research Ltd. (LGR) was used for automatic and continuous measurement. The isotope content in water is expressed as the part per mil deviation ($\delta^{18}O$ and δD) from Vienna Standard Mean Ocean Water (VSMOW). The analytical errors of the instrument are $\delta^{18}O < 0.08‰$ and $\delta D < 0.3‰$, respectively.

The parameters of the linear regression model were solved by the ordinary least square (OLS) method, which was performed by Origin 2018 software. A sample t-test was used to evaluate the significance level of correlations between variables. Statistical product and service solutions (SPSS) software was used to analyze the significant difference (indicated by p).

3. Results and Discussion

3.1. Effect of Canopy Interception Revealed by RF-TF Isotopic Comparison

During the observation periods of three summers, 78 events of open-land rainfall and canopy throughfall were recorded simultaneously. As shown in Figure 2a, the variation range of $\delta^{18}O$ in rainfall events is $-17.27‰\sim-1.21‰$, with an average value of $-9.11‰$ and a standard deviation of 3.93‰. The variation range of δD is $-124.22‰\sim-0.80‰$, with an average value of $-63.48‰$ and a standard deviation of 31.59‰. The d-excess varies from 1.43‰ to 17.68‰, with an average value of 9.44‰ and a standard deviation of 3.72‰. In the canopy throughfall, the variation range of $\delta^{18}O$ is $-17.05‰\sim-1.57‰$, with an average value of $-9.14‰$ and a standard deviation of 3.90‰. The variation range of δD is $-124.63‰\sim-1.82‰$, with an average value of $-63.10‰$ and a standard deviation of 31.50‰. The d-excess varies from 4.27‰ to 16.80‰, with an average value of 9.99‰ and a standard deviation of 3.42‰. The variation range and standard deviation of the hydrogen and oxygen stable isotopes and d-excess of the canopy throughfall are slightly smaller than those of the rainfall, indicating that the interception of the canopy results in the concentrated distribution of $\delta^{18}O$, δD and d-excess. The average d-excess value of the canopy throughfall is higher than that of the event rainfall ($p < 0.01$), indicating that the canopy stores the rainwater at an early period with a low d-excess value caused by strong evaporation, and then makes it mix with the late-input rainwater with a higher d-excess value. With the increase in the water storage capacity of the canopy, part of the water falls directly on the surface, leading to the larger d-excess value of the collected water.

The isotopic differences between the rainfall and canopy throughfall ($\Delta D_{TF\text{-}RF}$, $\Delta\delta^{18}O_{TF\text{-}RF}$, Δd-excess $_{TF\text{-}RF}$) are shown in Table 1. About 50% of all events show that the isotopic values and d-excess of the canopy throughfall are higher than those of the rainfall, indicating that the canopy interception has no significant relationship with the enriched heavy isotopes or lower d-excess. Xu et al. (2014) reported similar results in the study of isotopic composition of canopy throughfall of manmade pine forest and natural eucalyptus forest in South Australia. It was pointed out that the isotopes of the canopy throughfall may be affected by evaporation fractionation, inter-event selection and intra-event selection processes [26]. Isotopic exchange and pre-event rainfall stored in canopy may also be the potential reasons for this result. When canopy water vapor and canopy water storage are in an unstable state, isotope exchange will occur, resulting in isotope deviation [35]. In the two precipitation events with a short time interval, the mixing of the rainfall input and the residual water components of the last event in the canopy will lead to a greater uncertainty in the stable isotopes in the throughfall.

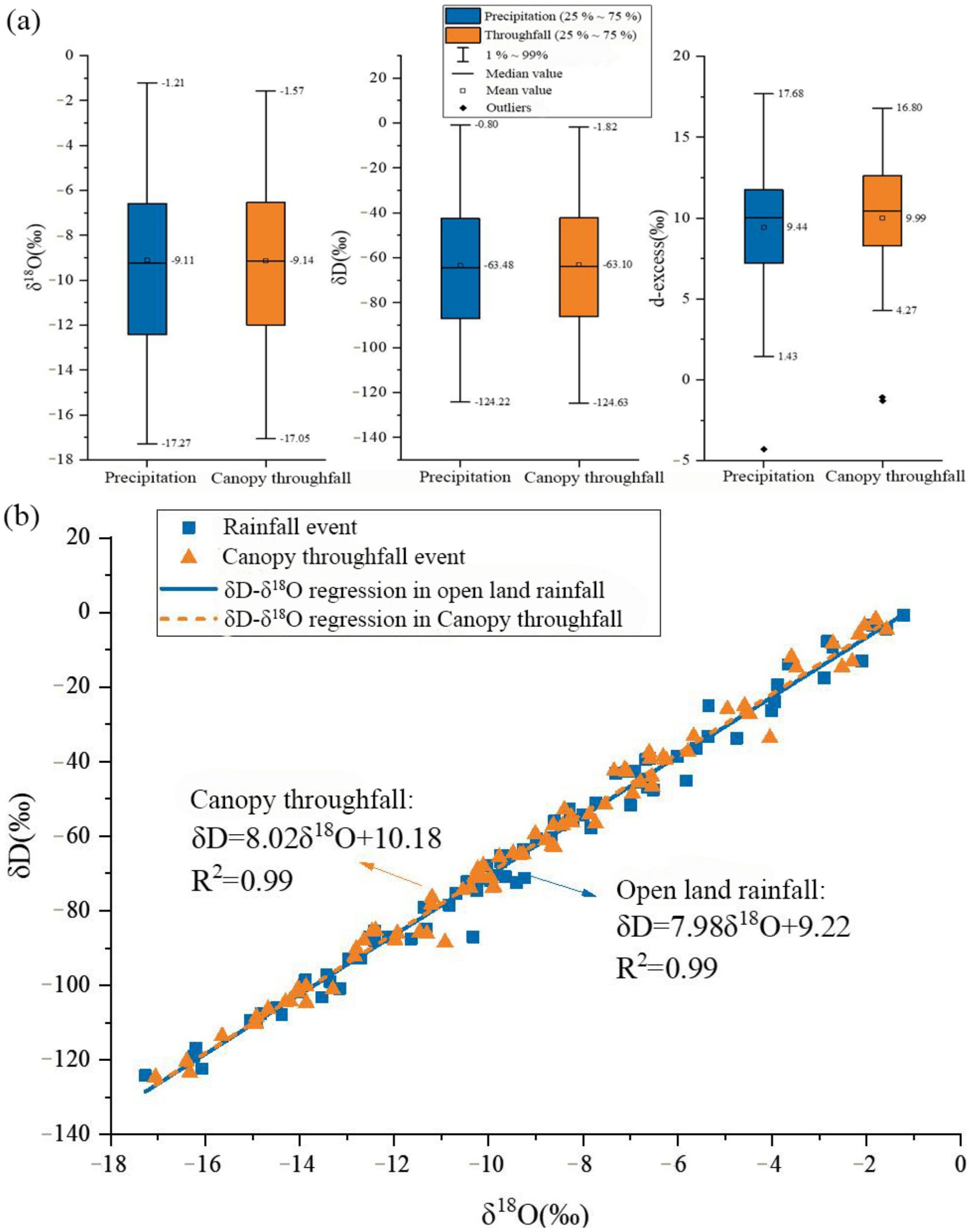

Figure 2. Isotopic comparison between open-land rainfall and canopy throughfall: (**a**) box-plot of δD, δ^{18}O and d-excess; (**b**) δD-δ^{18}O regression lines.

The relationship between δ^{18}O and δD in precipitation and the canopy throughfall is shown in Figure 2b. The δD-δ^{18}O linear regression equation in rainfall is δD = 7.98δ^{18}O + 9.22 (R^2 = 0.99, n = 78, p < 0.001) and that in the canopy throughfall is δD = 8.02δ^{18}O + 10.18 (R^2 = 0.99, n = 78, p < 0.001). The isotopic distribution of both water types is relatively similar, but the intercept and slope of the canopy throughfall are slightly larger, indicating that the interception of the forest canopy leads to a very weak isotope evaporation fractionation during the landing process. Based on the isotopic comparison between rainfall and canopy throughfall (Table 1), it is found that in this period with concentrated precipitation, the canopy has little effect on the evaporation of precipitation input, but it significantly changes the components of rainwater recharging the forest and leads to the redistribution of the precipitation through interception, storage and mixing. The complex water interaction in the forest canopy can reduce the kinetic energy of rainfall, change the distribution pattern of water below the forest and thus affect the water transport in the soil layer, plant water absorption and even groundwater level.

Table 1. Isotopic difference between rainfall (RF), canopy throughfall (TF) and litter layer throughfall (LF) and precipitation amount and intensity of events.

Sampling Date	Event Number	TF-RF Isotopic Difference (‰)			LF-TF Isotopic Difference (‰)			Precipitation Amount (mm)	Precipitation Intensity (mm/h)
		ΔD	$\Delta\delta^{18}O$	Δd-Excess	ΔD	$\Delta\delta^{18}O$	Δd-Excess		
2019/7/3	2	−1.02	−0.60	3.76	-	-	-	2.7	2.31
2019/7/3	3	1.97	0.67	−3.38	-	-	-	2.6	1.28
2019/7/4	1	−0.92	0.40	−4.08	-	-	-	15.4	1.60
2019/7/6	1	0.11	0.71	−5.55	-	-	-	0.5	0.50
2019/7/7	2	1.47	−0.01	1.55	-	-	-	13.8	2.24
2019/7/9	1	0.75	0.37	−2.20	-	-	-	31.4	5.32
2019/7/10	1	0.18	−0.30	2.59	-	-	-	2.4	1.11
2019/7/11	1	0.59	−0.05	0.97	-	-	-	62.2	8.20
2019/7/11	2	0.68	−0.04	0.97	-	-	-	8.5	3.21
2019/7/14	1	−0.96	−0.44	2.54	-	-	-	-	-
2019/7/15	1	0.54	0.21	−1.15	-	-	-	-	-
2019/7/16	1	1.29	0.36	−1.61	-	-	-	-	-
2019/7/21	1	1.35	0.10	0.56	-	-	-	2.9	0.97
2019/7/22	1	−2.31	−0.28	−0.09	-	-	-	41.5	7.18
2020/7/16	1	0.98	0.19	−0.51	-	-	-	36.8	3.07
2020/7/17	1	0.60	0.13	−0.45	-	-	-	2.6	0.95
2020/7/18	1	2.14	−0.37	5.07	-	-	-	2.8	3.73
2020/7/21	1	−1.04	−0.15	0.18	-	-	-	5.0	2.00
2020/7/22	1	3.42	0.29	1.10	-	-	-	2.6	0.61
2020/7/29	1	−0.28	−0.10	0.52	-	-	-	-	-
2020/7/29	2	0.17	−0.02	0.32	-	-	-	-	-
2020/7/29	3	−0.83	−0.24	1.07	-	-	-	2.6	1.30
2020/7/30	1	−0.13	−0.17	1.24	-	-	-	10.7	-
2020/7/31	1	0.16	−0.08	0.79	-	-	-	3.8	-
2020/7/31	2	3.38	0.23	1.57	-	-	-	0.2	0.30
2020/8/1	1	1.31	−0.02	1.50	-	-	-	-	-
2020/8/2	1	−0.64	−0.03	−0.43	-	-	-	1.8	0.32
2020/8/3	1	−0.30	−0.02	−0.18	-	-	-	2.0	4.00
2020/8/4	1	0.95	0.15	−0.27	-	-	-	6.6	1.69
2020/8/7	1	1.53	0.05	1.09	-	-	-	-	-
2020/8/7	2	−0.14	−0.22	1.61	-	-	-	0.4	0.15
2020/8/11	1	0.19	0.02	0.06	-	-	-	20.4	3.40
2020/8/11	2	−1.70	0.01	−1.82	-	-	-	12.8	2.74
2020/8/11	3	−2.92	−0.31	−0.40	-	-	-	43.8	3.13
2020/8/12	1	1.92	0.29	−0.36	-	-	-	4.8	1.20
2020/8/13	1	−1.00	−0.26	1.08	-	-	-	1.8	1.44
2020/8/13	2	−1.41	−0.33	1.22	-	-	-	2.5	-
2020/8/14	1	−0.41	0.22	−2.14	-	-	-	63.0	7.27
2020/8/16	1	−1.37	−0.15	−0.16	-	-	-	115.4	7.54
2020/8/16	2	−2.41	−0.55	1.97	-	-	-	0.4	0.53
2020/8/16	3	1.17	0.15	−0.02	-	-	-	78.2	7.11
2020/8/23	1	−1.49	−0.59	3.21	-	-	-	-	-
2020/8/28	1	0.40	0.10	−0.43	-	-	-	9.6	12.80
2020/8/29	1	−1.54	−0.72	4.19	-	-	-	2.8	1.40
2020/8/30	2	−0.91	−0.17	0.48	-	-	-	0.4	0.34
2020/8/31	1	−0.01	0.01	−0.09	-	-	-	36.4	3.64
2021/7/2	1	−0.71	−0.46	2.98	−1.71	−0.03	−1.49	23.4	9.96
2021/7/8	1	−1.64	−0.42	1.71	0.46	0.11	−0.43	4.0	1.33
2021/7/9	1	−0.66	−0.13	0.35	−1.79	−0.33	0.81	-	-
2021/7/10	1	−2.69	−0.67	2.67	2.62	0.93	−4.83	5.4	0.68
2021/7/11	1	−0.97	−0.49	2.91	2.34	0.97	−5.45	1.6	0.21
2021/7/15	1	5.33	0.49	1.44	−28.32	−3.41	−1.01	43.2	2.50
2021/7/16	1	5.00	0.73	−0.84	−6.14	−0.59	−1.43	0.8	2.18
2021/7/18	1	8.41	0.98	0.53	3.05	0.28	0.77	3.6	0.38
2021/7/19	1	−11.20	−1.60	1.64	14.44	2.44	−5.08	1.0	3.16
2021/7/21	1	0.26	0.14	−0.88	0.10	−0.12	1.03	18.2	2.21
2021/7/24	1	0.03	−0.15	1.26	2.63	0.62	−2.31	29.0	6.06

Table 1. *Cont.*

Sampling Date	Event Number	TF-RF Isotopic Difference (‰)			LF-TF Isotopic Difference (‰)			Precipitation Amount (mm)	Precipitation Intensity (mm/h)
		ΔD	$\Delta\delta^{18}O$	Δd-Excess	ΔD	$\Delta\delta^{18}O$	Δd-Excess		
2021/7/26	1	−0.53	0.20	−2.16	−1.49	−0.78	4.77	-	-
2021/8/5	1	2.05	0.06	1.59	1.84	0.79	−4.45	22.6	2.83
2021/8/8	1	0.89	0.00	0.87	1.79	0.11	0.87	2.4	2.40
2021/8/10	1	−1.01	−0.64	4.11	5.34	1.12	−3.64	-	-
2021/8/11	1	4.40	0.60	−0.40	−0.66	−0.04	−0.33	7.9	5.27
2021/8/12	1	−0.23	0.00	−0.23	−0.28	0.00	−0.26	-	-
2021/8/12	2	−0.15	−0.18	1.27	−0.11	0.12	−1.06	-	-
2021/8/12	3	4.58	0.40	1.37	3.89	0.46	0.20	2.2	0.80
2021/8/13	1	2.03	0.47	−1.75	1.18	0.27	−1.01	5.9	2.95
2021/8/15	1	0.83	−0.18	2.26	−0.83	−0.26	1.21	5.6	2.24
2021/8/15	2	0.77	0.13	−0.23	0.69	0.16	−0.59	4.8	0.45
2021/8/17	1	0.85	0.14	−0.27	0.13	0.04	−0.18	4.6	0.84
2021/8/17	2	−7.14	−1.04	1.17	6.28	1.39	−4.87	0.2	-
2021/8/17	3	−4.17	−0.59	0.57	−5.76	−0.69	−0.22	-	-
2021/8/18	1	−2.93	−0.70	2.65	1.40	0.03	1.13	18.4	2.94
2021/8/19	1	16.00	2.16	−1.32	−1.06	0.22	−2.81	1.0	3.53
2021/8/19	2	−0.26	−0.14	0.89	1.67	−0.23	3.50	2.4	1.62
2021/8/21	1	1.32	0.33	−1.33	0.21	−0.05	0.65	0.8	1.45
2021/8/22	1	−0.73	−0.14	0.43	−0.65	0.06	−1.11	1.0	1.94
2021/8/22	2	1.42	0.00	1.45	1.80	0.32	−0.73	17.0	1.77
2021/8/25	1	7.11	0.63	2.05	−13.20	−1.65	−0.03	35.2	2.27

3.2. Effect of Litter Layer Interception Revealed by TF-LF Isotopic Comparison

During the observation period in the summer of 2021, a total of 32 samples of canopy throughfall and litter layer throughfall were collected at an event scale. As shown in Figure 3a, the variation range of the $\delta^{18}O$ of the canopy throughfall is −15.64‰~−1.57‰, with an average of −8.62‰ and a standard deviation of 4.09‰; the variation range of δD is −113.56‰~−3.55‰, with an average of −59.59‰ and a standard deviation of 33.22‰. The d-excess varies from 4.27‰ to 16.8‰, with an average value of 9.35‰ and a standard deviation of 3.00‰. The variation range of the $\delta^{18}O$ of the litter layer throughfall is −16.34‰~−1.58‰, with an average value of −8.55‰ and a standard deviation of 4.36‰. The variation range of δD is −119.32‰~−3.66‰, with an average of −59.91‰ and a standard deviation of 34.95‰. The d-excess varies from 0.2‰ to 14.25‰, with an average of 8.46‰ and a standard deviation of 3.64‰. The variation range of the $\delta^{18}O$, δD and d-excess of the litter layer throughfall is slightly larger than that of the canopy throughfall, and the standard deviation is also larger, indicating that the water evaporation and (or) mixing in the litter layer are more changeable.

The isotopic differences ($\Delta D_{LF\text{-}TF}$, $\Delta\delta^{18}O_{LF\text{-}TF}$ and $\Delta d\text{-}excess_{LF\text{-}TF}$) between the canopy throughfall and litter layer throughfall are shown in Table 1. It can be observed that the $\delta^{18}O$ and δD are more enriched in about 60% of the event litter layer throughfall. Among these events, about 75% have a precipitation amount of less than 10 mm, which belongs to small-size precipitation. This reflects that the secondary interception of the litter layer to precipitation leads to a stronger evaporation fractionation of isotopes, especially for small-size precipitation. In the remaining events (about 40%), the $\delta^{18}O$ and δD of the litter layer throughfall are more depleted than those of canopy throughfall. Among them, two events are characterized with the highest deviations (Event 1: $\Delta\delta^{18}O_{LF\text{-}TF}$ = −3.41‰ and $\Delta D_{LF\text{-}TF}$ = −28.32‰, precipitation amount = 43.2 mm; $\Delta\delta^{18}O_{LF\text{-}TF}$ = −1.65‰, $\Delta D_{LF\text{-}TF}$ = −13.2‰, precipitation amount = 35.2 mm), which correspond to the events with the largest precipitation and the longest duration. The depleted heavy isotopes in the litter layer throughfall may be related to the distribution of the precipitation intensity in the event. At the early period of an event, the precipitation intensity is relatively weak, the air humidity is low, and the heavy isotopes are generally enriched. The water input during this period may be totally dissipated after being intercepted by the canopy and litter layer. As the rain lasts for some time, the heavy isotopes in the precipitation gradually become depleted, and the influence of the litter layer interception on the precipitation gradually decreases with the increase in precipitation intensity and air humidity. The average d-excess value of the litter layer throughfall is smaller than that of the canopy throughfall, and the d-excess of the litter layer throughfall is smaller in about 70% of events, reflecting that the interception of the litter layer promotes the evaporation fractionation of isotopes.

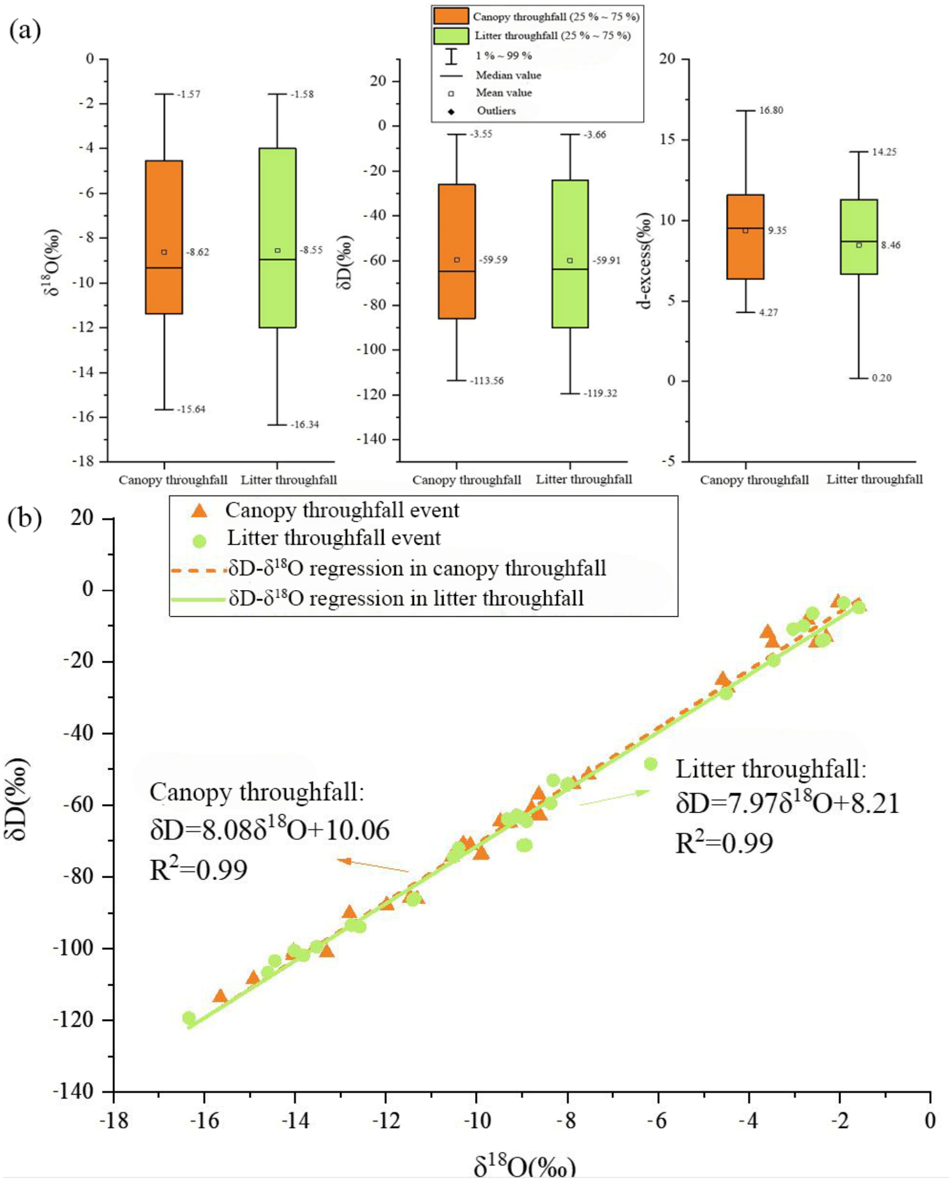

Figure 3. Isotopic comparison between canopy throughfall and litter throughfall: (**a**) box-plot of δD, δ^{18}O and d-excess; (**b**) δD-δ^{18}O regression lines.

The relationship between the δ^{18}O and δD in the canopy throughfall and litter layer throughfall collected in July-August 2021 is shown in Figure 3b. The δD-δ^{18}O linear regression equation of the canopy throughfall is as follows: $\delta D = 8.08\delta^{18}O + 10.06$ ($R^2 = 0.99$, $n = 32$, $p < 0.001$). That of the litter layer throughfall is as follows: $\delta D = 7.97\delta^{18}O + 8.21$ ($R^2 = 0.99$, $n = 32$, $p < 0.001$). The distribution of the isotopic scatters in the canopy throughfall and litter layer throughfall is relatively even, and their "water lines" are similar. The intercept and slope of the litter layer throughfall are slightly smaller, indicating the evaporation fractionation caused by litter layer interception.

For most of the observed events, the non-equilibrium fractionation caused by the litter layer interception took place when the rain passed through the litter layer, due to the small amount of precipitation, leading to enriched stable isotopes and a lower d-excess value. In a small number of events, intra-event selection may occur when the precipitation passes through the litter layer, leading to a depleted composition of heavy isotopes. During the travelling process, before recharging into the soil layer, the rainwater will be redistributed due to the interception of litter layer, by which the spatial distribution of water as well as the hydrological cycle will be changed in the forest area.

3.3. Relationship between Interception Effect and Characteristics of Precipitation

As shown in Figure 4, the LF-TF isotopic differences ($\Delta\delta^{18}O_{LF\text{-}TF}$ and $\Delta\delta D_{LF\text{-}TF}$) can be significantly fitted by a cubic curve ($p < 0.001$), but no significant statistical relationship exists between the $\Delta\delta^{18}O_{LF\text{-}TF}$ (and $\Delta\delta D_{LF\text{-}TF}$) and precipitation intensity. The d-excess difference between the two types of throughfall (Δd-excess$_{LF\text{-}TF}$) has no significant statistical relationship with the precipitation amount or intensity. The equations of the cubic curve between the $\Delta\delta^{18}O_{LF\text{-}TF}$ (and $\Delta\delta D_{LF\text{-}TF}$) and precipitation amount are $\Delta\delta^{18}O_{LF\text{-}TF} = -2.23P^3 + 0.01P^2 - 0.15P + 0.67$ ($R^2 = 0.64$, $n = 26$, $p < 0.001$) and $\Delta\delta D_{LF\text{-}TF} = -0.001P^3 + 0.05\ P^2 - 0.68P + 3.04$ ($R^2 = 0.76$, $n = 26$, $p < 0.001$). When the precipitation amount is less than 5 mm, the isotopes in the litter layer throughfall are more enriched than those in the canopy throughfall. When the precipitation amount is about 5–15 mm, the isotopes in the two types of throughfall are similar. When the precipitation is greater than 25 mm, the isotopic composition in the litter layer throughfall is more depleted. The different effect of the litter layer on the precipitation with a different size explains the dispersed distribution patterns of the isotopes and d-excess in the litter layer throughfall.

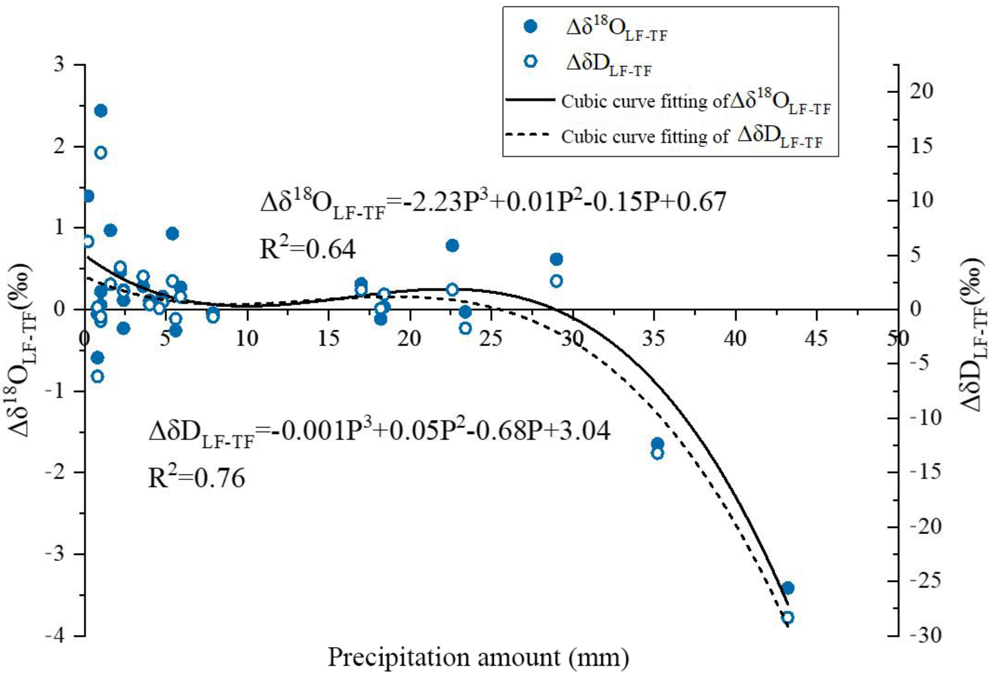

Figure 4. Relationship between isotopic difference between LF and TF ($\Delta\delta^{18}O_{LF\text{-}TF}$ and $\Delta\delta D_{LF\text{-}TF}$) with precipitation.

The relationship between the LF-TF isotopic difference and the precipitation amount reflects that the litter layer redistributes the penetrating water in the forest when the precipitation is small, which prevents the direct water recharge into the soil layer, slowing down the scouring effect of the throughfall on the surface soil and reducing the rainfall amount inputting the soil layer. With the increase in the precipitation amount, the water redistribution by the litter layer weakens, and more rainwater recharges the soil through litter layer. The litter layer loses its function of water redistribution when the precipitation continues to increase.

4. Conclusions

In this study, the characteristics and influencing factors of hydrogen and oxygen isotopes in open-land rainfall, canopy throughfall and litter layer throughfall were analyzed based on event-scale water observation and collection during three summers. The influence of the interception of the canopy and litter layer on the precipitation recharge in forest was preliminarily indicated by isotopic tracing. The results indicate that the precipitation experienced a selective interception and mixing effect in the canopy. Compared with the precipitation, the higher average d-excess value and intercept and slope of the δD-$\delta^{18}O$ relations of the canopy throughfall reflect the weak evaporation fractionation effect caused by the canopy interception. Compared with the canopy throughfall, the isotope and d-excess distribution of the litter layer throughfall are more dispersed, the $\delta^{18}O$ and δD are more enriched, and the intercept and slope of δD-$\delta^{18}O$ regression are lower, indicating the selective effect of the litter layer on the precipitation input and the influence of non-equilibrium fractionation. The isotope differences ($\Delta\delta^{18}O_{LF\text{-}TF}$ and $\Delta\delta D_{LF\text{-}TF}$) between the litter layer throughfall and canopy throughfall present a cubic curve relation with the precipitation amount, but it shows no significant statistical relationship with the precipitation intensity. The variations of $\Delta\delta^{18}O_{LF\text{-}TF}$ and $\Delta\delta D_{LF\text{-}TF}$ under events with different sizes reflect the different mechanisms of the litter layer interception effect on the precipitation recharge with different sizes, which may cause the water components of small-size precipitation and the early stage of large-size precipitation to be dissipated before reaching the soil layer. Generally, isotopic evidence shows that the precipitation input into the forest is intercepted and stored by the canopy and litter layer, in which water mixing and evaporation happens, resulting in the redistribution of the recharge of water resources to the forest area. However, in this study, water samples were collected without referring to plant species or physiological age and only the influence of the precipitation amount (and intensity) was considered. In the future studies on this topic, the evapotranspiration rate of the forest species needs to be analyzed along with more data on the quantification of the water balance, and the influence of the surrounding circumstances on the water cycle should be further explored.

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