

Article

# Rainfall Partitioning in Chinese Pine (*Pinus tabuliformis* Carr.) Stands at Three Different Ages

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**Abstract:** Chinese pine (*Pinus tabuliformis* Carr.) is the main forest species in northern China, with the potential to dramatically affect biotic and abiotic aspects of ecosystems in this region. To discover the rainfall partitioning patterns of different growth periods of Chinese pine forest, we studied the throughfall (*T<sub>f</sub>*), stemflow (*S<sub>f</sub>*) and canopy interception (*I*) in three stand ages (40-, 50-, 60-year-old) in Liaoheyuan Natural Reserve of Hebei Province during the growing seasons of 2013 and 2014, and analyzed effect of rainfall amount, rainfall intensity, and canopy structure on rainfall partitioning in Chinese pine forest. The results showed that throughfall decreased with the stand age, accounting for 78.8%, 74.1% and 66.7% of gross rainfall in 40-, 50- and 60-year-old Chinese pine forests, respectively. Canopy interception, on the other hand, increased with the stand age (20.4%, 24.8%, and 32.8%, respectively), while the pattern in stemflow was less clear (0.8%, 1.1%, and 0.6%, respectively). As rainfall intensity increased, the *T<sub>f</sub>* and *S<sub>f</sub>* increased and *I* declined. Additionally, our results showed that leaf area index (LAI) and the diameter at breast height (DBH) increased with age in Chinese pine stands, probably explaining the similar increase in canopy interception (*I*). On the other hand, the mean leaf angle, openness, gap fraction all decreased with the stand age. Stepwise regression analysis showed that the rainfall amount and LAI were the major determinants influencing the rainfall partition. Our study highlights the importance of stand age in shaping different forest canopy structures, and shows how age-related factors influence canopy rainfall partitioning. This study also significantly adds to our understanding the mechanisms of the hydrological cycle in coniferous forest ecosystems in northern China.

**Keywords:** *Pinus tabuliformis*; age; forest structure; rainfall partitioning

## 1. Introduction

Forests can influence hydrological processes and alter soil conditions due to their many impacts on water purification, runoff regulation and water and soil conservation [1]. In this capacity, forests can also serve to improve water availability at watershed, regional and worldwide levels [2]. The forest canopy plays an important role in this process, by partitioning rainfall and affecting additional hydrological processes [3], not only changing the spatial distribution of rainfall in the forest [4,5], but also affecting the chemical composition of the falling rain [6,7]. Previous studies of forest stands indicated that forest rainfall interception led to heterogeneous water distribution [8–10] and showed a large range of spatial variation relating to different forest structures [11].

Rainfall is redistributed through a forest canopy by throughfall, stemflow and canopy interception. Throughfall is the total volume of raindrops that penetrate through the forest canopy and reach to the ground. Stemflow is the part of rainfall flowing down from stems or trunks, and the amount intercept by the vegetation canopy and evaporate is the interception loss [12]. Throughfall accounts for the

highest proportion of rainfall, and it is the main source influencing the spatial distribution of water within the soil [13]. The proportion of stemflow is small, but it can be an important source of ground water [14] and benefit to forest regeneration. Canopy interception returns to the atmosphere through evaporation [15]. Given their importance in ecosystem function and hydrology, many studies about the rainfall partitioning for several vegetation types in different places have conducted [16–18].

Rainfall redistribution in forests is a complex process, directly influenced by rainfall characteristics such as amount, intensity and duration [19], as well as environmental factors including wind speed, air humidity and air temperature. Studies have shown that rain events with high rainfall volume are known to induce higher throughfall [20]. In addition, the rainfall amount and the rainfall intensity are positively correlated with the canopy interception [5]. Interannual and intraseasonal variability of rainfall significantly influences the interception loss. Raindrop size and velocity diameter have been shown to influence the throughfall of the maize canopy [21]. Fog in a forest can also increase water input below the canopy [1,15].

Multiple plant characteristics are also important factors in rainfall redistribution. Shrubs present higher stemflow than trees [17]. Branching angle and canopy volume also influence the rainfall distribution in Turkish oak forests, where slender trees with upward thrusting branches producing more stemflow [6]. Stand density is an important factor for all rainfall partitioning elements in coniferous forests [22]. Campo et al. found stemflow ratios decreased with tree density [23]. Tree size, branching angles and bark roughness are the main factors controlling stemflow volumes [24,25]. Spatial variation of canopy interception has a significant relationship with the plant area index, but not with the leaf area index [11]. Other factors including the gap fraction, horizontal and vertical distribution of foliage, present of epiphytes and species composition also influence the interception [26].

Little is known, however, about the relationship between rainfall redistribution patterns and forest stand age in temperate forests especially in a Chinese pine forest, which could represent an important interaction in forest ecosystems. There were some reports on different succession in various places and different forest types. For example, a previous study has shown that stand age, as an indicator of forest successional status, plays a vital role in canopy interception loss in a range of age class of deciduous forest in the southern Appalachian Mountains [27]. In tropical dry forests net rainfall showed an obviously declined trend across successional stages in Costa Rica, but in Brazil no clear trend was found [28]. The annual interception ratio showed dominantly larger in mature stands in Chinese fir stands [29]. Many experiments have been conducted on rainfall partition worldwide, but few consider both stand age and rainfall redistribution patterns.

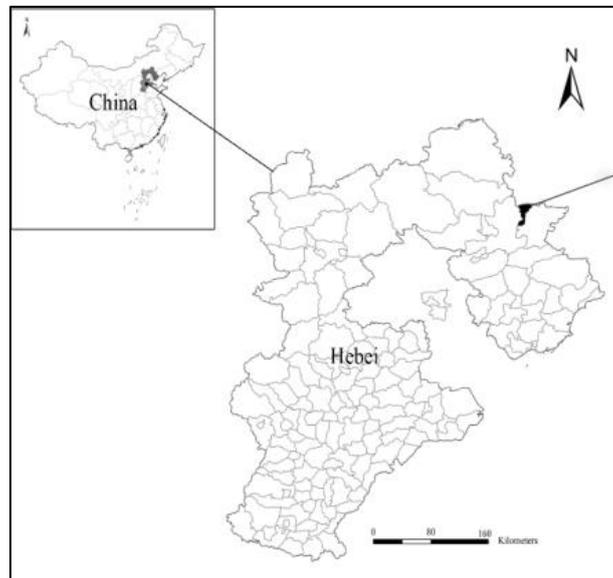
Liaoheyuan Natural Reserve is the origin of the Liaohe River. Within the reserve, there are large areas of Chinese pine natural forests, which play an important role in water and soil conservation for the Liaohe River Basin. Liaoheyuan Natural Reserve is also an important ecological barrier of wind and sand fixation for Beijing and Tianjin. In this study, we targeted three Chinese pine stand ages in Liaoheyuan Natural Reserve and monitored the precipitation, throughfall and stemflow in two consecutive growing seasons. The objectives of this study were: (1) to study the dynamic rainfall redistribution patterns for different stand ages of Chinese pine forests, and (2) to evaluate the rainfall characteristics and forest structures that affected rainfall partitioning in these pine forests. This study provided basic data for hydrological effects of forest vegetation in Liaoheyuan and a theoretical basis for the construction, management, and protection of water source conservation in Liaoheyuan.

## 2. Materials and Methods

### 2.1. Study Site

This study site was located in Liaoheyuan Nature Reserve, Pingquan County, Hebei Province, China (Figure 1) (latitude 41°01′–41°21′ N, longitude 118°22′–118°37′ E, elevation 625–1738 m a.s.l.). This area is a transition zone from warm to cold temperate zones with a typical continental monsoon climate, and has a humid and warm summer and snowy and cold winter. The average temperature

of a year is 7.7 °C and the mean precipitation of a year is 516.9 mm (1980–2018), according to data from Pingquan County Meteorological Bureau, with most rainfalls occurring from May to August. The soil is a typical brown forest soil, 0–100 cm thick [30]. The dominant tree species is the evergreen conifer *P. tabuliformis*, or Chinese pine, which is widely distributed in north China. *Spiraea pubescens* and *Lespedeza bicolor* are the main shrub species. *Carex rigescens*, *Saussurea nivea*, and *Dianthus chinensis* are major herbaceous plant species.



**Figure 1.** Location of Liaoheyuan Natural Reserve, Hebei Province, China.

In July 2012, we established three 20 m × 30 m study plots, each of which consisted of Chinese pine forest of a different age, namely the 40-year-old stand (latitude 41°18.522 N, longitude 118°31.169 E, elevation 1004 m a.s.l. (Above sea level)), the 50-year-old stand (latitude 41°18.572 N, longitude 118°31.188 E, elevation 998 m a.s.l.), and the 60-year-old stand (latitude 41°18.585 N, longitude 118°31.301 E, elevation 997 m a.s.l.). We got the plot basic information on vegetation and site characteristic data by field investigation. Species name, height, crown breadth, diameter and density of trees with DBH ≥ 5 cm were recorded for each plot. Nine digital hemispherical photographs (WinScanopy 2010a) were taken for each plot to get LAI and other structure information on overcast days or near sunrise or sunset. The camera was adjusted to horizontal position at 1.3 m above ground [31]. Photographs were analyzed using WinScanopy software for calculating LAI, the gap fraction, the openness, and the mean leaf angle [26]. Our study was conducted based on the National Standards of the People’s Republic of China or “Methodology for field long-term observation of forest ecosystem research” (GB/T 33027-2016). Data for each site are shown in Table 1.

**Table 1.** Basic structural characteristics of the three sampling plots of the Chinese pine forest of 40, 50 and 60 years old of age.

Age (Years)	Slope (°)	Density (Trees hm <sup>-2</sup> )	Mean DBH (cm)	Mean Height (m)	LAI (m <sup>2</sup> /m <sup>2</sup> )	GapFraction (%)	Openness (%)	Mean Leaf Angle (Degree)
40	27	1017	16.1	11.3	2.5	14.1	15.1	30.6
50	17	634	20.6	15.6	2.6	13.3	14.2	27.2
60	18	434	30.4	20.7	2.8	11.0	11.6	24.1

## 2.2. Collection of $P$ , $Tf$ , and $Sf$

Precipitation ( $P$ ), throughfall ( $Tf$ ) and stemflow ( $Sf$ ) were collected from May to September of 2013 and 2014. Precipitation was recorded by an automated tipping-bucket gauge (resolution 0.2 mm) at a meteorological station (CR1000, Campbell Scientific Inc., Logan, UT, USA), installed in an open hillside 1000 m away from the plots (Figure 2a). A single rainfall event was classified as rain exceeding 0.5 mm during a period with more than 6 h from the last rainfall event [32]. Rainfall events were divided into 4 intensity classes, including light rain ( $0.2 \text{ mm/d} \leq P < 10 \text{ mm}$ ), middle rain ( $10 \text{ mm/d} \leq P < 25 \text{ mm}$ ), heavy rain ( $25 \text{ mm/d} \leq P < 50 \text{ mm}$ ), rain storm ( $50 \text{ mm/d} \leq P < 100 \text{ mm}$ ), according to Criteria for Classification of Rainfall Intensity (Inland) produced by China's Meteorological Administration.



**Figure 2.** The photos for the experiment plot, (a): the auto precipitation gauge in the study, (b): throughfall gauge used in this study, (c): stemflow gauge in this study.

Throughfall ( $Tf$ ) was monitored manually by using 3 homemade plastic rain gauges ( $200 \times 10 \text{ cm}$ ) randomly placed in each plot, which were set on a bracket 50 cm above the ground (Figure 2b). Each gauge kept an angle of  $5^\circ$  above ground to make drainage easily, the end of the gauge connected to a plastic tank (16 L), which was in a hole below the ground covered with plastic sheeting to avoid evaporation and splash. The volume of water in the tank was measured soon after each rainfall event by using a graduated cylinder with the resolution of 1 mL. The throughfall depth was calculated by the rain volume divided by the area of the gauge. The average of the three throughfall depths was adopted as the throughfall amount for each plot.

The stemflow ( $Sf$ ) was collected by using a 5 mm thick white halved rubber hose, which was spirally wrapped around tree trunk and used Vaseline to create a water-tight environment between the stem and the hose. The lower side of the hose was 30 cm above the ground and connected to a plastic bucket (16 L), after each rainfall event the rain volume in the bucket was measured (Figure 2c). Trees for stemflow experiments were selected according to the diameter at breast height (DBH) within the plot. In each plot all the trees were divided into five groups by DBH. DBH groups for three stands were divided as follows: the 40-year-old stand ( $11 \leq d < 15$ ,  $15 \leq d < 19$ ,  $19 \leq d < 23$ ,  $23 \leq d < 27$ ,  $27 \leq d < 31$ ), the 50-year-old stand ( $5 \leq d < 10$ ,  $10 \leq d < 16$ ,  $16 \leq d < 22$ ,  $22 \leq d < 28$ ,  $28 \leq d < 34$ ), the 60-year-old stand ( $20 \leq d < 25$ ,  $25 \leq d < 30$ ,  $30 \leq d < 35$ ,  $35 \leq d < 40$ ,  $40 \leq d < 45$ ). Then one tree was chosen in each group as the standard tree to monitor stemflow for each plot in the studied forest. A total of five trees in each plot were selected as standard trees, information of which was shown in Table 2.

The depth of the stemflow is calculated by the following equation [14].

$$Sf = \sum_{i=1}^n \frac{C_i \times M_i}{S \times 1000}$$

where  $Sf$  is the stemflow amount (mm),  $n$  is the number of stem groups in this study;  $C_i$  is the stemflow amount of monitored tree in  $i$ th group (mL);  $M_i$  is the number of trees in the  $i$ th group ( $n$ );  $S$  is the plot area ( $600 \text{ m}^2$ ).

If total precipitation ( $P$ ), throughfall ( $Tf$ ), and stemflow ( $Sf$ ) are known, canopy interception amount ( $I$ ) can be measured according to the following equation [33]:

$$I = P - Tf - Sf$$

where  $I$  is interception amount (mm),  $P$  is the precipitation (mm),  $Tf$  is the throughfall amount (mm),  $Sf$  is the stemflow amount (mm).

Canopy interception ratio ( $R$ ) is then calculated as:

$$R = \frac{I}{P}100\%$$

where  $R$  is interception ratio (%),  $P$  is the precipitation (mm),  $I$  is the interception amount (mm).

**Table 2.** Basic information of 15 monitored trees for stemflow in 40-, 50-, 60-year-old Chinese pine stands.

Stand Age (Years)	Stemflow Tree Number (n)	DBH (cm)	Crown (m × m)
40	1	13.8	3.5 × 3.9
	2	17.8	4.5 × 4.8
	3	20.6	4.8 × 5.6
	4	24.6	4.9 × 5.5
	5	29.8	4.9 × 6.0
50	1	7.5	2.0 × 1.5
	2	14.2	3.4 × 2.8
	3	20.1	5.1 × 5.8
	4	26.2	5.6 × 9.2
	5	32.4	7.5 × 8.9
60	1	24.8	5.8 × 5.4
	2	27.7	4.8 × 6.3
	3	33.5	6.3 × 6.8
	4	36.2	7.9 × 7.2
	5	40.8	10.3 × 5.8

### 2.3. Data Analysis

Throughfall depth under each rainfall event for each stand was average amount of the three gauges. We used cumulative data during the study period to reflect the overall rainfall partitioning pattern, and used mean values to distinguish the difference between stand ages and months.

All data preparations including the total precipitation, amount and ratio data were done by Microsoft Excel (2010 version, Microsoft Corporation, Redmond, Washington, USA). A one-way analysis of variance (ANOVA) by SPSS (IBM SPSS Statistics 19 version, and ratio data were done by Microsoft Excel (2010 version) was used to compare the statistical difference between different Chinese pine stand ages. Stepwise multiple linear regression was conducted with SPSS to find out significant factors for Chinese pine rainfall partitioning.

## 3. Results

### 3.1. Rainfall Pattern During the Study Period

During May–September of 2013 and 2014, a total of 64 rainfall events produced 857.4 mm of precipitation ( $P$ ), each event ranging from 0.6 to 58.8 mm of rain with an average of 13.4 mm. The number of rainfall events and amount of precipitation varied across months and years, with 30 total rainfall events and 380.2 mm of rain in 2013, and 34 events and 477.2 mm of rain in 2014. The maximum rainfall amount for a single rainfall event was 58.8 mm, which occurred on 28 June 2013. In 2014, the maximum amount of rain from a single event was 42.6 mm on 5 June.

According to the classification of the “precipitation intensity classification standard (inland part)” of China’s Meteorological Administration, the precipitation events in the study area during the observation period were most often light rain, with 40 times total and rainfall amounting to 194.4 mm, accounting for 22.7% of total rainfall in growing seasons of 2013 and 2014 (Table 3). Increasingly intense rainfall events were less frequent. Rain storms occurred just twice, both in 2013. The gross rainfall amount of heavy rain was the largest, followed by middle rain, light rain, and rain storm.

**Table 3.** The total rainfall from May to September of 2013–2014 according to four rainfall classes.

Rainfall Intensity Class (mm d <sup>-1</sup> )	2013		2014		2013–2014	
	Amount (mm)	Frequency (N)	Amount (mm)	Frequency (N)	Amount (mm)	Frequency (N)
$0.2 \leq P < 10$	113.4	23	81	17	194.4	40
$10 \leq P < 25$	117.8	6	120.8	8	238.6	14
$25 \leq P < 50$	129.4	3	178.4	5	307.8	8
$50 \leq P < 100$	116.6	2	0	0	116.6	2
Total rainfall	477.2	34	380.2	30	857.4	64

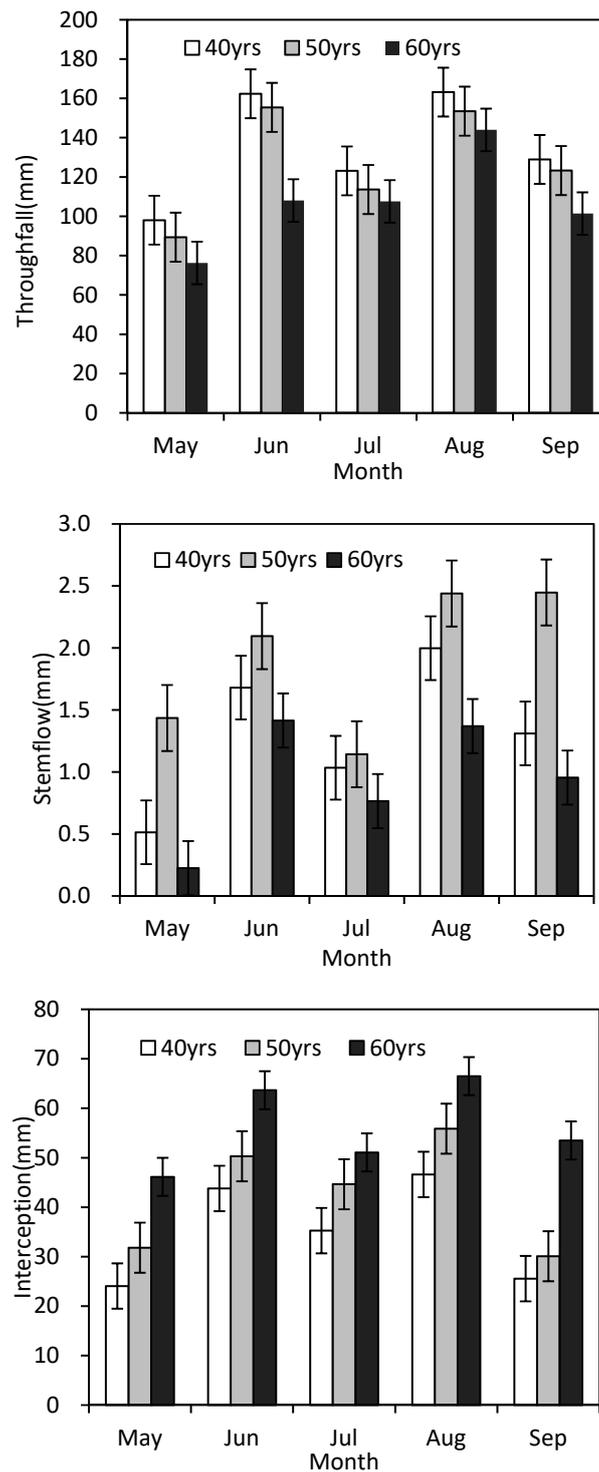
### 3.2. Rainfall Partitioning Pattern Across Chinese Pine Stand Age

During the two years of the observation period, the accumulated rainfall division in (mm) and (%) showed different results among the three forest stands (Table 4). In each plot, *Tf* corresponded to the highest proportion of the total rainfall, while *Sf* was always the lowest proportion. *Tf* showed an expected decrease from 40 to 60 years. Stemflow (*Sf*), on the other hand, did not show an obvious trend, since the 50-year-old stand resulted in the highest value among the three stands. Total interception (*I*), on the other hand, behaved similarly to *Tf*. An additional analysis, based on 64 sampled rainfall events (mm), showed *I* was the only variable that proved to have a significant statistical difference among the three forest stands, being the 60 years plot significantly greater than that of 40 and 50 years.

**Table 4.** Cumulative of throughfall, stemflow and interception in mm and percentages with concerning gross precipitation of three stand ages of Chinese pine forest from May to September of 2013 and 2014.

Stand Age (Years)	<i>Tf</i> (mm)	<i>Tf</i> %	<i>Sf</i> (mm)	<i>Sf</i> %	<i>I</i> (mm)	<i>I</i> %
40	675.6	78.8	6.5	0.8	175.3	20.4
50	635.1	74.1	9.6	1.1	212.7	24.8
60	571.8	66.7	4.7	0.6	280.8	32.8

Monthly rainfall distribution patterns for two years (Figure 3) showed that throughfall, stemflow and interception amount of three stand ages in June and August were larger than the other three months. The *Tf*, *Sf*, and *I* of three stands presented the same trend across five months and the trend among three stands varied. Throughfall in each month decreased as the stand age increases, whereas interception increased with the stand age. The stemflow was largest in the 50-year-old stand in each month.

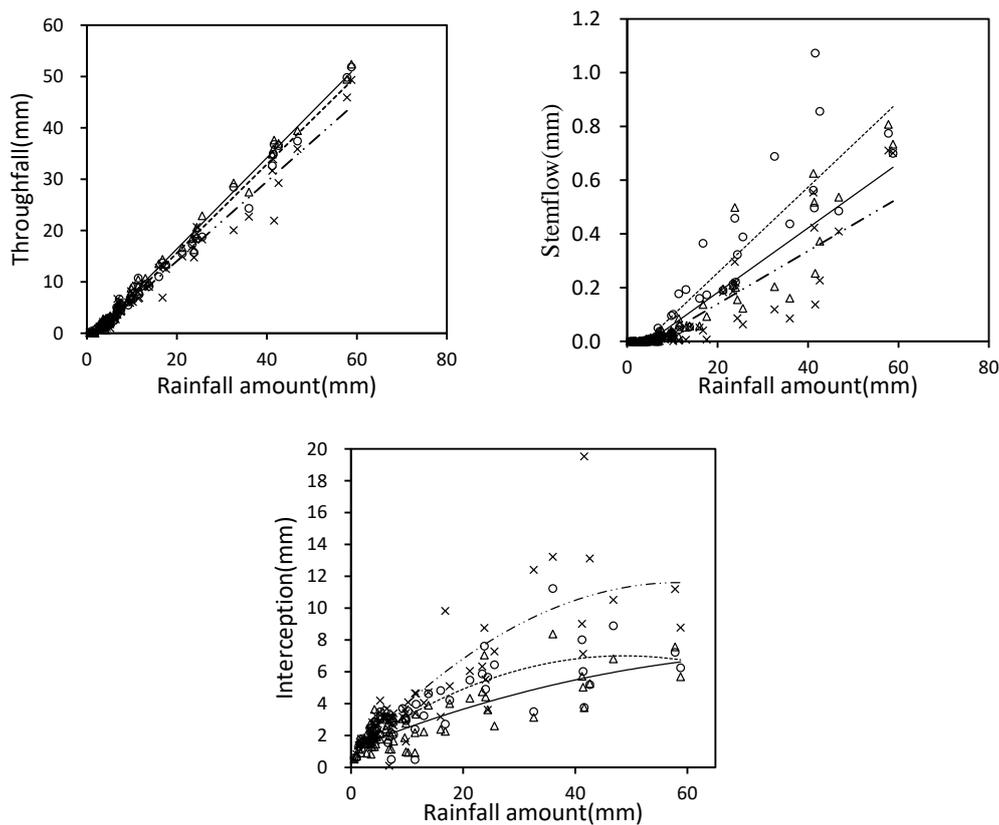


**Figure 3.** The amount of throughfall, stemflow and interception in five different months during the study period.

### 3.3. Dependence of Rainfall Partitioning on Rainfall Amount

The relationships between rainfall amount and throughfall, stemflow and canopy interception were examined (Figure 4), with the best fitting model and parameters of the model listed in Table 5. Throughfall and stemflow were positively related to the rainfall amount. According to the simulated model, throughfall would generate in the 40-year-old stand when rainfall amount reached more than 1.5 mm, and that for the 50-year-old and the 60-year-old stand was 1.9 and

1.86 mm, respectively. The stemflow occurred when rainfall was more than 4.9 mm for the 40-year-old stand, and the corresponding value for the 50-year-old, and the 60-year-old stand was 4.0 and 5.9 mm, respectively. That meant for 40-year-old stand, in general, the canopy was wetting under rainfall less than 1.5 mm. Forest canopy was saturated and could not hold more water when the rainfall reached 1.5 mm, after that throughfall occurred, and when the rainfall more than 4.9 mm, the water flowed down from the stem namely stemflow. This progress was basically consistent with monitored data. The interception and rainfall had binominal function relationship, with coefficient of determination > 0.67. Interception amount increased with the rainfall amount at first, after that reached to a maximum value then declined as shown in figures.



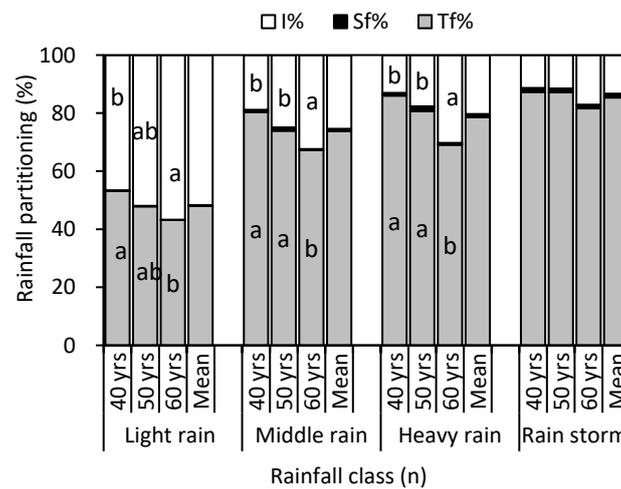
**Figure 4.** Linear relationship between throughfall, stemflow, interception with gross rainfall for three Chinese pine forest stands. Total of 64 rainfall events.  $\Delta$ : 40-year-old stand,  $\circ$ : 50-year-old stand,  $\times$ : 60-year-old stand. —: 40-year-old, - - -: 50-year-old, - · - · -: 60-year-old.

**Table 5.** Linear relationship between throughfall, stemflow, interception with gross rainfall in three Chinese pine forest stands, with a total of 64 rainfall events.

Item	Model	Regression Parameters			
		F	P	SE	R <sup>2</sup>
Tf	$y_{40} = 0.8880x - 1.3413$	9778.122	0.000	1.027	0.997
	$y_{50} = 0.8639x - 1.6400$	6188.525	0.000	1.256	0.995
	$y_{60} = 0.7744x - 1.4400$	2168.431	0.000	1.903	0.972
Sf	$y_{40} = 0.0120x - 0.0589$	360.983	0.000	0.072	0.851
	$y_{50} = 0.0159x - 0.0642$	361.028	0.000	0.096	0.851
	$y_{60} = 0.0099x - 0.0582$	232.573	0.000	0.074	0.786
I	$y_{40} = -0.0008x^2 + 0.1406x + 1.1676$	65.793	0.000	1.004	0.673
	$y_{50} = -0.0025x^2 + 0.2468x + 0.9891$	75.555	0.000	1.174	0.703
	$y_{60} = -0.0032x^2 + 0.3765x + 0.5784$	95.650	0.000	1.830	0.750

### 3.4. Effect of Rainfall Intensity on Rainfall Partitioning

Relative throughfall, stemflow and interception to gross rainfall varied with the rainfall intensity in three Chinese pine stand ages (Figure 5). On the whole, as the rainfall intensity increased, the average *Tf*% and *Sf*% for all three stands increased, but *I*% decreased. The largest interception ratio was under the light rain level for all three stands. Except for rainfall storm class *I*% of the 60-year-old stand was dominantly larger than the 40-year-old stand, and *Tf*% was opposite.



**Figure 5.** Relative throughfall, stemflow, and interception categorized by rainfall classes for three Chinese pine stand ages. Different letters meant the significant difference ( $p < 0.05$ ) among the three stand ages, and the alphabetical order showed the values from the largest to the smallest.

### 3.5. Effect of Canopy Features on Rainfall Partitioning

The rainfall redistribution of the three stands was also affected by the canopy structure (Table 1). As the age of Chinese pine forests increased, the DBH, the tree dimension and the LAI increased, whereas the forest gap fraction, openness and the mean leaf angle decreased. The canopy interception ability of the 60-year-old stand is higher than that of 40- and 50-year-old stand, probably caused by the discrepancy of above mentioned structural characteristics. This result demonstrated that the stand structure in different growing stage of the Chinese pine forest was an important factor for rainfall partitioning.

### 3.6. Comprehensive Analysis of Factors

A stepwise regression analysis was conducted to understand key factors influencing the rainfall redistribution pattern. We used the measured factors including rainfall amount, rainfall intensity, LAI, density, average tree height, DBH, dimension, and mean leaf angle as independent variables, and used *Tf*, *Sf* and *I* as dependent variables, respectively. Results (Table 6) showed rainfall amount and structural properties (LAI) were dominant factors for *Tf* and *I*, while rainfall amount, density and mean leaf angle were dominant factors for *Sf*.

**Table 6.** Stepwise analysis of rainfall partitioning factors.

Item	Influencing Factor	Model	N
<i>Tf</i>	Rainfall amount(x1), LAI(x2)	$y = 12.574 + 0.842x1 - 5.335x2$	192
<i>Sf</i>	Rainfall amount(x1), density(x2), mean leaf angle(x3)	$y = 0.013x1 - 0.001x2 + 0.075x3 - 1.567$	192
<i>I</i>	Rainfall amount(x1), LAI(x2)	$y = 0.145x1 + 5.472x2 - 12.871$	192

## 4. Discussion

### 4.1. Age Dependence of Rainfall Partitioning

Our results showed a rainfall partitioning pattern in Chinese pine stand ages (40, 50 and 60-year-old). We found that throughfall decreased while the canopy interception increased with increasing age, this pattern was in accordance with conifer species rainfall partitioning trend from young to adult in temperate boreal forests [13] and with deciduous forest *A. altissima* [31]. The study on a series of succession stands of *Liriodendron tulipifera* forest in the southern Appalachian Mountains also found that canopy interception increased rapidly with the forest age until reaching a maximum of 21% [27]. Another study on different Chinese fir stand ages got the similar trend that interception ratio in mature stands significantly higher [29]. There seems to be a clear pattern, therefore, that in mature forests of many species the canopy interception ability is higher than that in young forests.

Throughfall, stemflow and interception ratio varied among the three stand ages of Chinese pine forests, all of which were within the range of results of Sun et al. reported [14]. The throughfall in our study was higher than that of *A. altissima* [31], although lower than redcedar in the USA with an average annual throughfall of 57.3% [8]. We suspect that the discrepancy among different plants is due to differences in climate, tree species characteristics and stand structure.

Compared with previous studies of Chinese pine forest on rainfall partitioning (Table 7), including reports at Miyun [34], at Daqingshan [35], at Hebei [36], at Taiyue Mountain [37] and Yeheshan [38]. 1% in this study were higher than Taiyue Mountain reflected the young stand age had less canopy interception ability. Throughfall, stemflow and interception ratio of 33 years old Chinese pine forest in Miyun was similar to corresponding values for the 60-year-old stand in this paper, and Yeheshan result was similar to the 40-year-old forest in our study.

Compared with other coniferous forests worldwide (Table 7), the interception ability in our result was higher than that in mixed forests [39] and *P. cembroides* forest [9], lower than *P. eldarica* [40], *Pinus nigra* in Slovenia [41] and *Larix gmelinii* forest [42], and similar with other reports listed in the table [43,44]. Throughfall in this paper was higher than *P. nigra* and *Chamaecyparis obtuse* forest, but smaller than *P. cembroides* and mixed (upland) forest, within results range of other reports. The stemflow in the 50-year-old stand was larger than in the other two stand ages, though stemflow accounted for a small part of the rainfall (<2%) in all stands. This low percentage is consistent with the results of Chinese fir plantations that stemflow was the highest in the middle age category (12 years old forest). Stemflow of Chinese pine forest in our study was lower than most of the reports listed in the table, much lower than *C. obtuse* (22.6%), and higher than *L. gmelinii* and *P. nigra* forest. The low stemflow in this study may due to climate and also the accuracy of the experimental device of the stemflow in this study. Previous research confirmed that stemflow was the most variable part of the canopy partitioning (coefficient of variation = 107.8%) [17]. Furthermore, it is known that shrubs generate more stemflow than trees, which has been demonstrated in our results comparing with the results of stemflow in shrub species [45,46].

**Table 7.** Rainfall partitioning characteristics of conifer forests in different locations.

Location	Forest Type	Age (Years)		Study Period	Tf%	Sf%	I%	Literature
Boreal and temperate biogeographical zones	conifers	-	-		64.50	4.10	28.70	Barbier et al. 2009
Taiyue Mountain, China	<i>Pinus tabulaeformis</i>	20		May to September 2011	77.89	2.30	19.92	Zhou et al. 2013
Miyun Reservoir, China	<i>Pinus tabulaeformis</i>	33		2004–2006	67.65	0.68	31.67	Xiao et al. 2007
Yeheshan watershed, China	<i>Pinus tabulaeformis</i>	17		January–December 2016	75.40	0.70	23.90	Ma et al. 2019
Chitgar Forest Park, Iran	<i>Pinus eldarica</i>	42		30 January 2011 to 30 January 2012			44.20	Sadeghi et al. 2014
urban area of Ljubljana, Slovenia	<i>Pinus nigra</i>	-		January 2014 to June 2017	28.00	0.02	72.00	Zabret, Rakovec and Šraj 2018
Bezirgan Basin, Turkey	<i>Pinus nigra</i>	-		2012–2014	69.80	2.60	27.70	Aydm, Şen and Celik 2018
Bezirgan Basin, Turkey	<i>Pinus sylvestris</i>	-		2012–2014	73.9	5.90	20.20	Aydm, Şen and Celik 2018
Bezirgan Basin, Turkey	mixed <i>Pinus nigra</i> – <i>Pinus sylvestris</i>	-		2012–2014	77.70	3.10	19.20	Aydm, Şen and Celik 2018
Daxing’anling, China	<i>Pinus sylvestris</i> var. <i>mongolica</i>	32		18 May–September 11 2007	68.51	0.54	31.00	Jiang et al. 2008
Sierra San Miguelito, Mexico	<i>Pinus cembroides</i>	81		June 2006 to July 2009	92.23	3.76	18.95	Pérez-Suárez et al. 2014
Daxing’anling, China	<i>Picea koraiensis</i>	20		18 May–11 September 2007	66.00	1.04	33.50	Jiang et al. 2008
Daxing’anling, China	<i>Larix gmelinii</i>	32		May 18–September 11 2007	59.76	0.35	40.20	Jiang et al. 2008
Fukuoka, Japan	<i>Chamaecyparis obtusa</i>	33		April to October 2017	49.40	22.60	28.00	Jeong, Kyoichi and Farahnak, 2019
Fukuoka, Japan	<i>Chamaecyparis obtusa</i>	41		5 June 2010 to 31 December 2011	65.30	9.10	25.50	Saito et al. 2013
Fukuoka, Japan	<i>Cryptomeria japonica</i>	41		5 June 2010 to 31 December 2011	67.90	6.60	25.50	Saito et al. 2013
Tsukuba Experimental Watershed, Japan	<i>Cryptomeria japonica</i>	50		2008 and 2010	76.90	3.20	19.90	Iida et al. 2017
Changbai Mountains, China	mixed forest of broad-leaved and <i>Pinus koaiensis</i>	-		growing seasons in 2010 and 2011			21.95	Sheng and Cai 2019
Ljubljana, Slovenia	mixed (upland) forest including <i>Picea abies</i>	-		1 January 2008 to 31 December 2013	94.1	2.00	3.90	Kermavnar et al. 2017
Chitgar Forest Park, Iran	<i>Cupressus arizonica</i>	42		30 January 2011 to 30 January 2012			34.40	Sadeghi et al. 2014

#### 4.2. Effect of Rainfall Characteristic on Rainfall Partitioning

Rainfall directly influences the rainfall redistribution pattern, in redcedar forest rainfall amount accounts for 60–70% of the variation of the percentage of throughfall and stemflow [8]. In our study rainfall amount is also a dominant factor. According to Table 5, linear regression equations between the rainfall amount (x) and throughfall amount (y) showed positive coefficients of determination ( $R^2$ ) > 0.97, whereas for stemflow coefficients of determination were  $R^2$  > 0.79. This result was consistent with previous studies [47,48]. In a single rainfall event canopy gradually becomes moist, until rainfall amount reaches a threshold above which throughfall and stemflow are generated. Binominal function model fitted in this study accurately capture the relationship between the canopy interception and rainfall amount, which was different from previous study result that either the power [19] or the linear [49] relationship. The interception amount increased with rainfall until it reached plateaus. Some previous studies showed different best fit models probably due to the experiment designs and the vegetation features.

Rainfall intensity is also an important factor for the rainfall partitioning pattern. On the whole our results showed that throughfall and stemflow increased with rainfall intensity, while the canopy interception decreased, which meant that rainfall intensity could make more net rainfall under the canopy. The larger interception under light rainfall events in this study demonstrated that forest canopy had a strong interception effect under light rainfall events. Some reports reveal that rainfall partitioning was most influenced by rainfall intensity. For example, Nytch et al. [16] reported that rainfall intensity had a significant effect on delay in  $T_f$  reaching the ground and Li et al. found that the maximum and minimum interception storage were only correlated with rainfall intensity in Chinese pine forest [50]. However, Liang et al. found that stemflow generation was mainly affected by canopy structure not by rainfall intensity [51], and Li et al. [46] showed the rainfall intensity increased stemflow with which less than  $2 \text{ mmh}^{-1}$  and decreased with which greater than  $2 \text{ mmh}^{-1}$ . In light of this variation among studies, more research should be done to understand the impact of rainfall intensity on rainfall redistribution.

#### 4.3. Forest Structure Dependence of Rainfall Partitioning

Our results showed that the rainfall partitioning pattern in stands with three different stand ages was correlated with the canopy structure. Under the same rainfall events, the variation of throughfall, stemflow and interception were caused by the difference in the crown structure at different growth stage. The LAI of the 60-year-old stand were larger than the 40-year-old stand, meaning that older trees had larger crowns than younger trees, and are therefore able to intercept more water. Previous studies also analyzed forest structural parameters including basal area, bark sickness, leaf area index across the forest, which can contribute to the rainfall redistribution [52–54]. For example, larger canopy surface increases interception ratio, and a denser mid-canopy and taller trees can increase cloud interception [1]. Some studies have found that forest structure and meteorological events importantly influence interception ratios, especially in drier sites [23]. Structural properties including LAI and aggregation index were correlated with canopy interception [14]. Stand density is an informative structural factor for all the rainfall partitioning components in coniferous plantations [22]. Smooth barks in some species perform higher stemflow than with rough bark [13]. Significant changes in rainfall partitioning across an invasive chronosequence of *A. altissima* were underpinned by canopy structure and trunk parameters [31]. Fang et al. deemed canopy structure as a key element for spatial variation of throughfall in small rainfall events [55]. Our results also revealed that forest structure was an important factor influencing rainfall redistribution as shown in previous studies. Through this study, we show that stand age is a determining factor, causing the divergence of canopy structures that lead to differences in rainfall distribution patterns. Further work should be done to discover the rainfall partitioning laws in a large range of forest ages. Above all, both the rainfall amount and stand structure significantly influenced rainfall partitioning.

The last point, we simulated the relationship between the rainfall amount with  $T_f$ ,  $S_f$  and  $I$ , and calculated the tipping points, this is very useful and convenient. But advanced methods should be used like rainfall interception modeling, which includes more intercept progresses and can give deep insight to interception mechanisms [56]. Liang et al. concluded that the revised gash model was able to accurately simulate the weekly canopy interception of Chinese pine forest [36]. The results of canopy interception of Chinese pine from model [36,38] were compared with our results, a similar pattern was found, but more useful information from the models that should be our future work.

## 5. Conclusions

Our study monitored rainfall partitioning pattern of Chinese pine forest at three stand ages and provided deep insights to understand the rainfall interception dynamics. Specifically, we analyzed the dynamics of three rainfall partitioning aspects (throughfall, stemflow, and interception) reflecting the relationship with rainfall amount and intensity, which helps to better understand the progress and relevant facets. Across three stand ages, the majority of rainfall became throughfall, though this decreased with increasing stand age. We attribute this decrease in throughfall to an increase in interception as canopy structure changes with forest age. Our results also highlighted that the rainfall amount is also an important factor affecting the rainfall partitioning across different stand age of Chinese pine. This study provides insight into how rainfall amount, stand age and elements of forest structure affect rainfall partitioning, which has important implications for water conservation and forest management.

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