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Rainfall Partitioning by Evergreen and Deciduous Broad-Leaved Xerophytic Tree Species: Influence of Rainfall, Canopy Characteristics, and Meteorology

Changkun Ma [1,*], Qian Yao [1], Haobo Meng [1], Beibei Zhou [1], Quanjiu Wang [1] and Yi Luo [2]

[1] State Key Laboratory of Eco-Hydraulics in Northwest Arid Region, Xi'an University of Technology, Xi'an 710048, China
[2] Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
* Correspondence: mack@xaut.edu.cn; Tel.: +86-18792709639

Abstract: Understanding how rainfall is partitioned into throughfall, stemflow, and interception losses by xerophytic trees is important for evaluating afforestation projects and modeling hydrological budgets in semi-arid regions. However, information regarding rainfall partitioning by xerophytic trees and the controlling factors in semi-arid regions remains underrepresented in the literature. We examined whether plant functional groups have a significant impact on rainfall partitioning in two xerophytic trees (evergreen species: *Pinus tabuliformis* (Pinales:Pinaceae) hereafter called *P. tabuliformis*, deciduous species: *Robinia pseudoacacia* L. (Fabales:Fabaceae) hereafter called *R. pseudoacacia*) commonly used for afforestation on the semi-arid Loess Plateau of China, and evaluated the effects of rainfall, canopy characteristics and meteorological variables on rainfall partitioning. The event-based gross rainfall, throughfall and stemflow were measured during both growing (May–October) and dormant (January–April and November–December) seasons in 2015 and 2016 within an afforested watershed in semi-arid Loess Plateau of China. During our study period, the average rainfall depth for growing season and dormant season was 8.4 mm (varied from 0.2 to 57.6 mm) and 5.6 mm (varied from 0.2 to 41.6 mm), respectively. On average, the measured throughfall, stemflow and interception loss for *R. pseudoacacia* accounted for 81.8%, 1.4% and 16.8% of gross rainfall, respectively. Corresponding values for *P. tabuliformis* were 75.1%, 0.7% and 24.1%, respectively. Significant differences ($p < 0.05$) in stemflow were detected between *R. pseudoacacia* and *P. tabuliformis* during both the growing and dormant seasons. The rainfall partitioning components were significantly positively correlated with individual rainfall amounts. The minimum rainfall required to generate stemflow was 5.2 mm for *R. pseudoacacia* and 5.9 mm for *P. tabuliformis* during the growing season, and 3.1 mm for *R. pseudoacacia* and 6.0 mm for *P. tabuliformis* during the dormant season. Smaller rainfall events contributed to a lower percentage of rainfall amount, throughfall and stemflow but higher percentage of canopy interception loss. The percentage of throughfall and stemflow showed an increased tendency with increasing rain-fall characteristics, while the increasing rainfall characteristics resulted in a decrease in relative interception loss. During the growing season, leaf area index is significantly correlated with throughfall and interception loss of *R. pseudoacacia*, while there were no significant correlation between meteorological variables and rainfall partitioning. In general, the depth of rainfall partitioning can be predicted reasonably well by using the developed multiple regression models, but the proportions of rainfall partitioning had a relative lower accuracy using the developed models, especially for relative interception loss. To better predict canopy interception loss, other plant morphological and meteorological variables should be considered.

Keywords: rainfall partitioning; semi-arid region; throughfall; stemflow; interception loss; xerophytic species

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1. Introduction

In arid and semi-arid regions, large scale afforestation and reforestation activities have been carried out in order to tackle soil desertification, biodiversity loss and poverty, as trees and forests are vital for averting desertification and providing woods for local people [1,2]. For example, in dryland regions of the world, ~49 billion ha of land were reforested or afforested with trees between 2000 and 2010, resulting in a 0.8% increase in forest cover [3,4]. In fact, as these forest plantations are becoming increasingly important for providing ecological services (woody products, soil retention, habitat provisioning services and carbon sequestration), they have also become increasingly criticized for their hydrological impact [5,6]. As the area of forest plantations increases, the water consumption (transpiration and interception) of these planted trees would also increase [7]. There would be a decrease in the amount of water entering rivers and groundwater, which would increase the risk of water scarcity in local ecosystems and adversely affect the ecological security of the region [7]. In these water-limited arid and semi-arid regions, discrete rainfall is always the sole source of soil water replenishment, thus a better understanding of the ecohydrological processes induced by these forest plantations is essential for effective water resources management and land use planning [6,8]. One such process is rainfall partitioning by canopies of these forest plantations.

The partitioning of gross rainfall by vegetation into throughfall, stemflow and interception loss is a hydrological process in forest ecosystems necessary for the modification of evaporation and the redistribution of incident rainfall [9]. This results in a spatial variability of soil moisture under vegetation [10]. Interception loss is the amount of rainwater temporarily captured on the forest canopy and subsequently evaporates into the atmosphere during and after rainfall [11]. The remaining incident rainfall (net rainfall) reaches the forest floor either as throughfall or stemflow. Throughfall is the fraction of rainfall that reaches forest floor directly and/or dripping through the forest canopy and it accounts for 60–86% of gross rainfall in forest regions [12]. Stemflow is the fraction of rainfall intercepted by the canopy and reaches the ground by funneling down the trunks/stems and contributes little (2.0–10.0%) to gross rainfall in arid and semi-arid forests. Studies have shown that tree plantations have greater interception: gross rainfall ratio and lower stemflow: gross rainfall ratio than shrubs and grasses, because they have lower albedo and have taller and rougher canopies [9]. Therefore, the impact of plantations on net rainfall is highly dependent on the type of vegetation. For instance, broad-leaved forest stands have higher net rainfall than needle-leaved stands [5].

The literature reviews suggest that there are considerable variabilities in rainfall partitioning across different forest types [13]. This is mainly because partitioning of gross rainfall in forest eco-systems is affected by both intrinsic structural properties (e.g., leaf area index, branch inclination, density and rigidity), external meteorological variables (e.g., rainfall characteristics, relative humidity and etc.) and by the possible interactions between these two factors [14]. As an example, trees with small canopy surface areas can increase throughfall by intercepting a small portion of gross rainfall, while trees with dense, rigid, steeply inclined branches can divert a greater amount of gross rainfall into stemflow [15]. Additionally, the interchange between throughfall, stemflow, and interception can also be influenced by leaf seasonality and meteorological conditions [5,16]. Numerous studies have quantified rainwater partitioning in forest ecosystems [10,17,18]. However, systematic reports examining the relationships between rainfall partitioning and meteorological, canopy and rainfall characteristics are limiting in arid and semi-arid forest ecosystems, especially with respect to forest plantations for balancing forestation goals with water resource management needs [5].

In semi-arid regions of the Loess Plateau, as in many other dryland regions throughout Asia and central Europe, exotic *R. pseudoacacia* and *P. tabuliformis* have been widely planted in order to control soil and water erosion, prevent desertification, and produce timber and fuel wood [7,19,20]. Tree species of this type are commonly chosen for their greater tolerance of drought, as well as their faster rate of growth as compared to native tree species [1,9]. *R. pseudoacacia* is a medium-sized deciduous tree species with netted cracking cortical bark and odd-pinnate leaves constituted of elliptic leaflets, while *P. tabuliformis* is a medium-sized evergreen tree species with fissures bark and needle leaves. The morphological differences are larger, which may result in larger differences in both evaporation and rainfall partitioning processes [21,22]. Therefore, quantifying and comparing rainfall partitioning by these two widely planted tree species (as well as their structural variables) in this region are necessary, which may have greater implications for forest managers and policymakers to exploit canopy hydrological processes to societal benefit. However, to the best of the authors' knowledge, no such examination or comparison has been conducted. Therefore, the objectives of this study were: (i) to quantify rainfall partitioning into throughfall, stemflow and interception by two tree species at individual rainfall event scale, (ii) to explore the underlying causes of differences in rainfall partitioning between the two tree species, and (iii) to evaluate the influences of rainfall, canopy characteristics, and meteorological variables on rainfall partitioning. The results of the study could be useful in evaluating the hydrological consequences of large-scale vegetation rehabilitation programs in the study area. With the hydrological consequences, forest management practices which support sustainable rehabilitation and hydrological modeling can be implemented.

2. Materials and Methods

2.1. Site Description

Field measurements were carried out during two growing (May–October) and two dormant (January–April and November–December) seasons in 2015–2016 in the Yeheshan watershed (YHS, 34°31′ N, 107°54′ E) in the National Nature Reserve of Fufeng County in Shaanxi Province, China. The study area has a monsoon-influenced semi-arid continental climate characterized by a hot/humid summer (June–August) and cold/dry winter (December–February). The mean annual precipitation and temperate are 580 mm and 12.7 °C, respectively, as obtained at the nearest national meteorological station (<10 km to the study region). Rainfall mainly occurs in the growing season from May to October (80% of the annual total) and has a larger inter-annual variation (coefficient of variation of 30%).

YHS is a typical area of the hilly and gully region of the Loess Plateau. According to the soil map and filed investigations, the main soil type is silt loam soil with mean particle-size distribution of 73% of silt, 21% of clay and 6% of sand. The groundwater table is over 50 m below the ground surface according to the water level data of eight ground water observation wells, indicating that plant roots hardly reach the groundwater and therefore all plants relay on rainfall for their growth and development.

Larger-scale vegetation restoration effort has been widely implemented since 1970s in the area to protect soil and water erosion. The forest of YHS is dominated by *R. pseudoacacia* and *P. tabuliformis* according to our field investigation. Two representative experimental plots of size of 50 × 50 m^2 were established in the adjacent *R. pseudoacacia* and *P. tabuliformis* woodlands in October 2014. These two experimental plots were established to be representative of each forest site with tree diameter distribution and slope characteristics taken into consideration. A more detailed description of these two experimental plots are available in [23].

2.2. Meteorological and Canopy Characteristics

Within the *R. pseudoacacia* forest site, an automated weather station tower (15 m in height and ~2 m above tree canopy) was installed next to the experimental site in June 2014 and meteorological variables were measured above the stand. Relative humidity (RH, %) and air temperature (Ta, °C) were measured using a HMP155A type thermohygrometer (Vaisala, Finland). Wind speed (WS, $m \cdot s^{-1}$) was measured using a CSAT3 type 3-D sonic anemometers/thermometer (Campbell Scientific Inc., Logan, UT, USA). Meteorological values were automatically recorded and stored using a CR1000 data logger (Campbell Scientific Inc., Logan, UT, USA) and the data were measured every 10 s and stored every 10 min. Missing gaps in the data were filled using data from the nearby weather station. Due to their proximity (<200 m apart), the measured meteorological variables were regarded as being consistent between the two forest experimental plots.

Plant area index (PAI cm^2 cm^{-2}) and leaf area index (LAI cm^2 cm^{-2}) are two important indicators of canopy structure and may thus play a significant role in rainfall partitioning. In this study, LAI and PAI were measured three times each month using the plant canopy analyzer (LAI-2200C, LI-COR, Lincoln, NE, USA). During measurement, the instrument utilized five concentric rings centered at angles of 7°, 22°, 38°, 52°, and 68° to observe below-canopy radiation levels in the blue range (320–490 nm). Data from these sensors are combined with readings from the canopy to estimate the gap fraction (transmittance). Moreover, PAI and LAI were then estimated by inversion of the Beer-Lambert law (LICOR, [24]). The measurements were carried out close to the time of sunrise in order to obtain nearly uniform sky illumination, and they were repeated three times in order to reduce the measurement error.

2.3. Measurement of Gross Rainfall, Throughfall and Stemflow

Gross rainfall at each site was measured using an automatic rain gauge (30 cm diameter) and a weighing-bucket rain gauge (T-200B, Geonor, Eiksmarka, Norway) installed in a clearly open area adjacent to the two experimental sites (<30 m away), following the method utilized by Ma et al. [23]. Gross rainfall measured with the manual rain gauge was used to check the data obtained from the weighting gauge. During our study period, the mean relative error between the manual rain gauge and the weighting rain gauge was less than 5%, indicating the variation of gross rainfall over the two experimental plots were not significant ($p < 0.05$); therefore, the mean value of gross rainfall from these two types of rain gauges was used for further analysis.

Throughfall was measured following the method utilized by Ma et al. [23]. At each forest site, throughfall was measured using 30 rain gauges made from 25 L plastic buckets fitted with 30 cm diameter plastic funnel. Litter was prevented from entering into the funnel by fitting plastic net across the funnel and a pingpong ball placed on the funnel to limit evaporation between sampling periods. At each measurement plot, throughfall collectors were installed along 30 m transects. Three transects, each 10 m apart, were established beneath the canopy. The minimum distance between each set of collectors was 2 m and ten collectors were installed along each transect. To accurately determine throughfall at each measurement, two-thirds of throughfall collectors were replaced to a new random location after every three rain events [22,23]. Throughfall (mm) was calculated by dividing the measured throughfall volume with the orifice area of the funnel, which was 706.5 cm^2.

Stemflow (mm) was measured following the method utilized by Ma et al. [23]. During measurement, a total of 13 trees at each forest site, covering the whole diameter at breast height (DBH) range, were selected. Stemflow was sampled using spiral-type stemflow collars constructed from plastic hoses. Plastic hose collars with a diameter of 20 mm were cut in half lengthwise, attached to the stems, and sealed with silicon sealant in an upward spiral pattern to divert water into a reservoir of 50 L. Each collar gauge was checked during each collection period to ensure that it was properly fitted. SF volume was converted into stemflow by dividing by the canopy area (m^2) of the sampled trees.

Throughfall and stemflow were collected within four hours after a rainfall event. In this study, a rainfall event was defined as a period with more than 0.2 mm of total rainfall, separated by at least 6 h without rain [23]. The time intervals in each forest site were sufficient for residual rainwater to completely evaporate from tree crowns, as determined by measuring leaf wetness with a Campbell Scientific 237 L type leaf wetness sensor (Logan, UT, USA). The measurements were conducted during the growing season (May–October) and the dormant season (January–April and November–December) of 2015 and 2016, respectively.

Interception loss (mm) for each rainfall event was calculated as the difference between gross rainfall and the sum of throughfall and stemflow: interception = gross rainfall − (throughfall + stemflow) (Gash et al. [25]).

2.4. Statistical Analysis

Analysis of variance (ANOVA) was used to determine the statistical differences in throughfall, stemflow and interception between the growing and dormant seasons and between forest stands. The relationships between meteorological variables, canopy characteristics and rainfall partitioning components were analyzed using the Pearson correlation. Multiple linear regression analysis was used to evaluate the interactions between rainfall characteristics with rainfall partitioning components. The level statistical significance was $p < 0.05$ and all the statistical analyses were conducted in SPSS 19.0 software (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Rainfall Characteristics

During the two years study period in 2015 and 2016, a total of 163 rainfall events were measured, with gross rainfall of 1242.2 mm: 1002.1 mm in growing season (120 rainfall events) and 240.1 mm in the dormant season (43 rainfall events). The average rainfall depth of the 120 rainfall events in growing season was 8.4 mm, which ranged from 0.2 to 57.6 mm. The corresponding value in the dormant season was 5.6 mm, with individual rainfall depth varying from 0.2 to 41.6 mm. The individual rainfall intensity ranged from 0.1 to 6.4 mm h^{-1} during growing season, with a mean rainfall intensity of 1.3 mm^{-1}. The corresponding value in the dormant season was 0.6 mm^{-1}, with individual values ranging from 0.02 to 3.7 mm^{-1}. For individual rainfall duration, the observed mean value was 7.2 h and 10.8 h in growing and dormant seasons, respectively.

The frequency distribution of rainfall amount, intensity and duration during growing and dormant seasons of 2015 and 2016 are shown in Figure 1. Generally, low rainfall events were more frequently distributed but contributed less to gross rainfall amount than high rainfall events, and vice versa (Figure 1a,d). The distribution of rainfall intensity was highly positively skewed in the growing season rather than in the dormant season, implying that lower individual rainfall intensity apparently had higher frequency of occurrence but lower percentage contribution to gross rainfall amount in growing season and vice versa (Figure 1b). During the dormant season, rainfall intensity was also positively distributed among all rainfall intensity range, but it distributed evenly in the low intensity range (0–1.5 mm h^{-1}) (Figure 1e). For rainfall duration, short duration events always corresponded to high rainfall frequency, but low rainfall amount and vice versa in both growing and dormant seasons (Figure 1c,f).

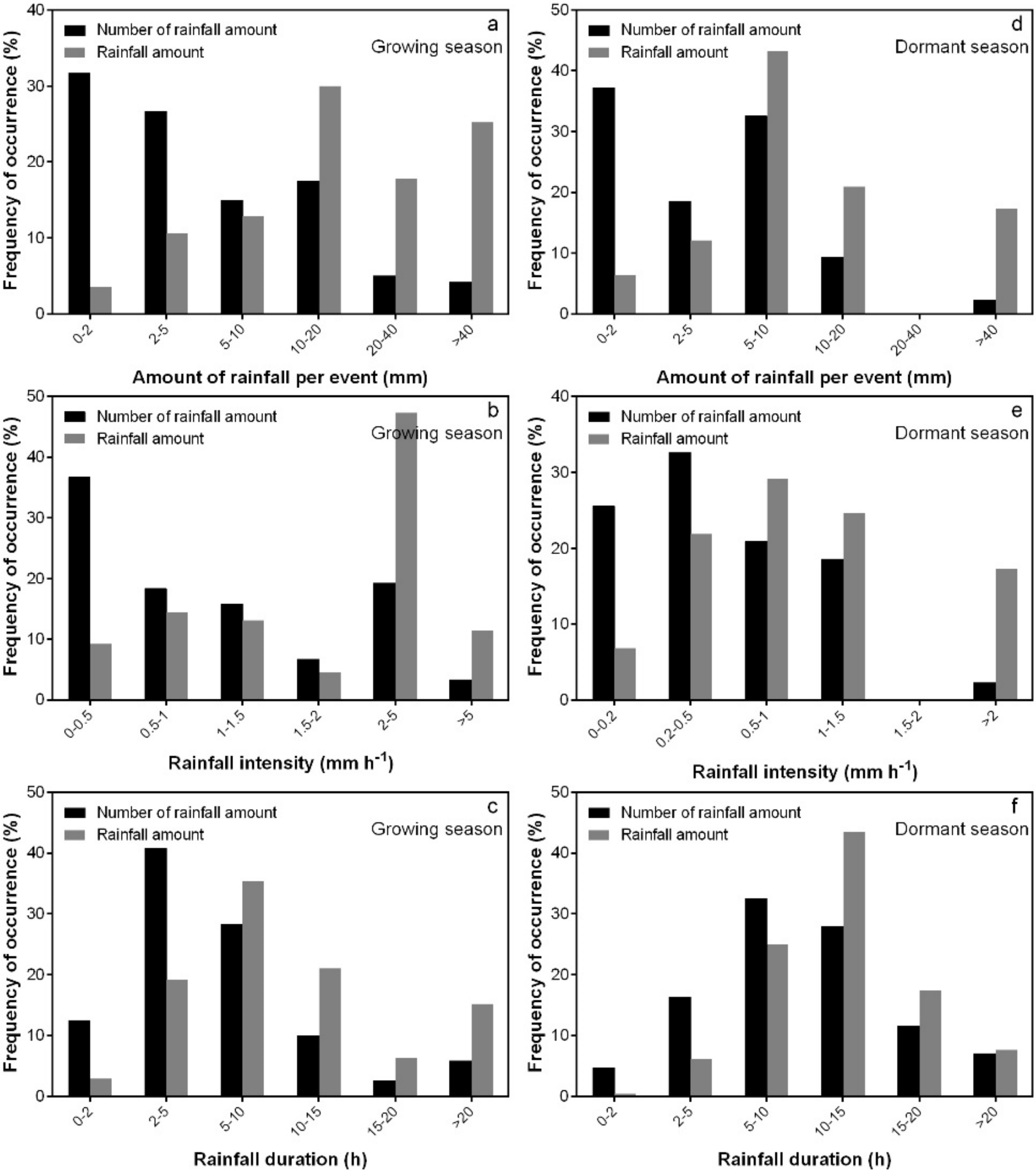

Figure 1. The frequency distribution of rainfall events in 2015 and 2016, along with the amount of rainfall depth and events in different ranges of event size (**a**,**d**), intensity (**b**,**e**) and duration (**c**,**f**).

3.2. Rainfall Partitioning Characteristics

For *R. pseudoacacia*, the cumulative annual throughfall was 1016.1 mm, while for *P. tabuliformis*, it was 933.4 mm, which accounted for 81.8% and 75.1%, respectively, of gross rainfall. In the growing season, throughfall for *R. pseudoacacia* was 801.7 mm (80.0% of gross rainfall), while in the dormant season, it was 214.4 mm (89.3% of gross rainfall). For *P. tabuliformis*, the corresponding values were 752.6 mm (75.1% of gross rainfall) during the growing season and 180.8 mm (75.3% of gross rainfall) during the dormant season (Table 1).

Table 1. Summary of gross rainfall (Pg), throughfall (TF), stemflow (SF), interception loss (I) and relative rainfall partitioning for *R. pseudoacacia* and *P. tabuliformis* during both growing and dormant seasons in 2015 and 2016.

Tree Species	Study Period	Pg (mm)	TF (mm)	SF (mm)	I (mm)
R. pseudoacacia	Growing season	1002.1 ± 1.6	801.7 ± 1.5 (80.0%)	14.0 ± 0.03 (1.4%) a	186.4 ± 0.1 (18.6%)
	Dormant season	240.1 ± 1.0	214.4 ± 0.9 (89.3%)	3.8 ± 0.02 (1.6%) a	21.8 ± 0.1 (9.1%)
	Annual	1242.2 ± 1.1	1016.1 ± 1.0 (81.8%)	17.8 ± 0.02 (1.4%) a	208.2 ± 0.1 (16.8%)
P. tabuliformis	Growing season	1002.1 ± 1.6	752.6 ± 1.3 (75.1%)	7.2 ± 0.01 (0.7%) b	242.3 ± 0.2 (24.2%)
	Dormant season	240.1 ± 1.0	180.8 ± 0.8 (75.3%)	1.8 ± 0.01 (0.7%) b	57.6 ± 0.2 (24.0%)
	Annual	1242.2 ± 1.1	933.4 ± 0.9 (75.1%)	9.0 ± 0.01(0.7%) b	299.9 ± 0.2 (24.1%)

Values are total values ± SEM. Parameters in parentheses indicate the percentage to the gross rainfall. Different letters in the table indicates significant differences between treatments ($p < 0.05$).

The results of our study indicated a significant difference ($p < 0.05$) in stemflow and relative stemflow (stemflow: gross rainfall ratio) between *R. pseudoacacia* and *P. tabuliformis*. The total stemflow for *R. pseudoacacia* was 17.8 mm, accounting for an average of 1.4% of gross rainfall; the corresponding values for *P. tabuliformis* was 9.0 mm and 0.7% of gross rainfall, respectively. For *R. pseudoacacia*, the cumulative stemflow was 14.0 mm in growing season and 3.8 mm in dormant season, occupying 1.4% and 1.6% of gross rainfall, respectively; as for *P. tabuliformis,* the corresponding values were 7.2 mm (0.7% of the gross rainfall) and 1.8 mm (0.7% of the gross rainfall) for the growing season and the dormant season, respectively.

As with stemflow, this study also found that there was a significant difference ($p < 0.05$) in interception loss between *R. pseudoacacia* and *P. tabuliformis* stands. The total interception was 208.2 mm for *R. pseudoacacia*, accounting for 16.8% of gross rainfall; the corresponding value for *P. tabuliformis* was 299.9 mm and 24.1% of gross rainfall, respectively. For *R. pseudoacacia*, the measured interception was 186.4 mm in the growing season and 21.8 mm in the dormant season, accounting for 18.6% and 9.1% of gross rainfall, respectively. As for *P. tabuliformis*, the corresponding values were 242.3 mm (24.2% of gross rainfall) and 57.6 mm (24.0% of gross rainfall), respectively.

3.3. Rainfall Partitioning in Relation to Rainfall Amount

The individual rainfall amount was significantly ($p < 0.05$) correlated with throughfall for both growing (Figure 2a) and dormant (Figure S1a) seasons. The relative throughfall (throughfall: gross rainfall ratio) leveled off after an almost linear initial increase with increasing rainfall amount, giving an exponential function (Figures 2d and S1d). According to the fitted curves, *R. pseudoacacia* had a significantly ($p < 0.05$) higher throughfall and relative throughfall than that of *P. tabuliformis* during both growing and dormant seasons.

Stemflow was also significantly correlated with rainfall amount for the two forest stands (Figures 2b and S1b). Based on the line of goodness-of-fit, the rainfall threshold for stemflow generation was 5.2 mm for *R. pseudoacacia* and 5.9 mm for *P. tabuliformis* in the growing season, and 3.1 mm for *R. pseudoacacia* and 6.0 mm for *P. tabuliformis* in the dormant season. For most cases, *R. pseudoacacia* had larger stemflow depth than *P. tabuliformis* for a given rainfall amount. Relative stemflow (stemflow: gross rainfall ratio) increased linearly with increasing rainfall amount for the two forest stands (Figures 2e and S1e).

There was a significant correlation between rainfall amount and interception loss for the two forest stands (Figures 2c and S1c). The amount of interception increased linearly with increasing rainfall amount during both growing and dormant seasons, while relative interception decreased linearly and exponentially with increasing rainfall amount for growing and dormant seasons, respectively (Figures 2f and S1f).

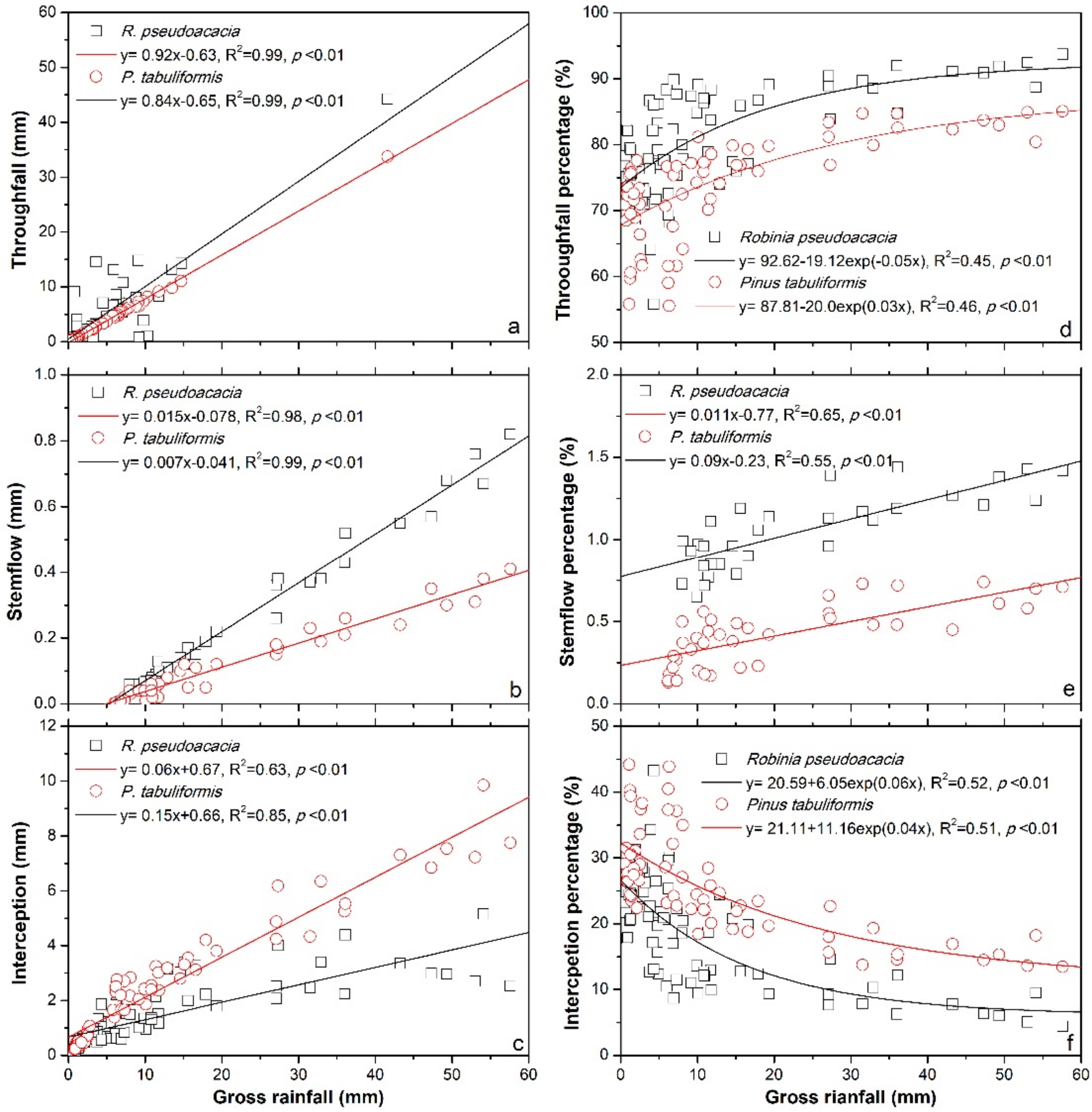

Figure 2. Relationships between individual rainfall amounts and rainfall partitioning components for *R. pseudoacacia* (**a**–**c**) and *P. tabuliformis* (**d**–**f**) during the growing season of May–October in 2015 and 2016.

3.4. Rainfall Partitioning in Relation to Rainfall Intensity

Generally, throughfall, stemflow, interception and corresponding relative values varied markedly with individual rainfall intensity, with exponential function for throughfall and linear function for stemflow and interception as the goodness-of-fit. For throughfall and relative throughfall, the measured values initially increased with rainfall intensity and then leveled off after reaching the threshold. Based on the equation of the goodness-of-fit, the leaved-off values for throughfall was 33.4 mm for *R. pseudoacacia* and 31.1 mm *P. tabuliformis* during growing season (Figure 3a). The relative throughfall at the leveled-off point was 90.8% for *R. pseudoacacia* and 82.9% for *P. tabuliformis* during the growing season (Figure 3d); the corresponding values was 92.3% for *R. pseudoacacia* and 77.1% for *P. tabuliformis* during the dormant season (Figure S2d). Unlike throughfall, stemflow and relative stemflow increased linearly with individual rainfall intensity during both growing and dormant seasons (Figures 3b–e and S2b–e). Over the whole study period, interception increased with individual rainfall intensity for both *R. pseudoacacia* and *P. tabuliformis*, while relative interception decreased linearly with rainfall intensity for both forest stands during growing and dormant seasons.

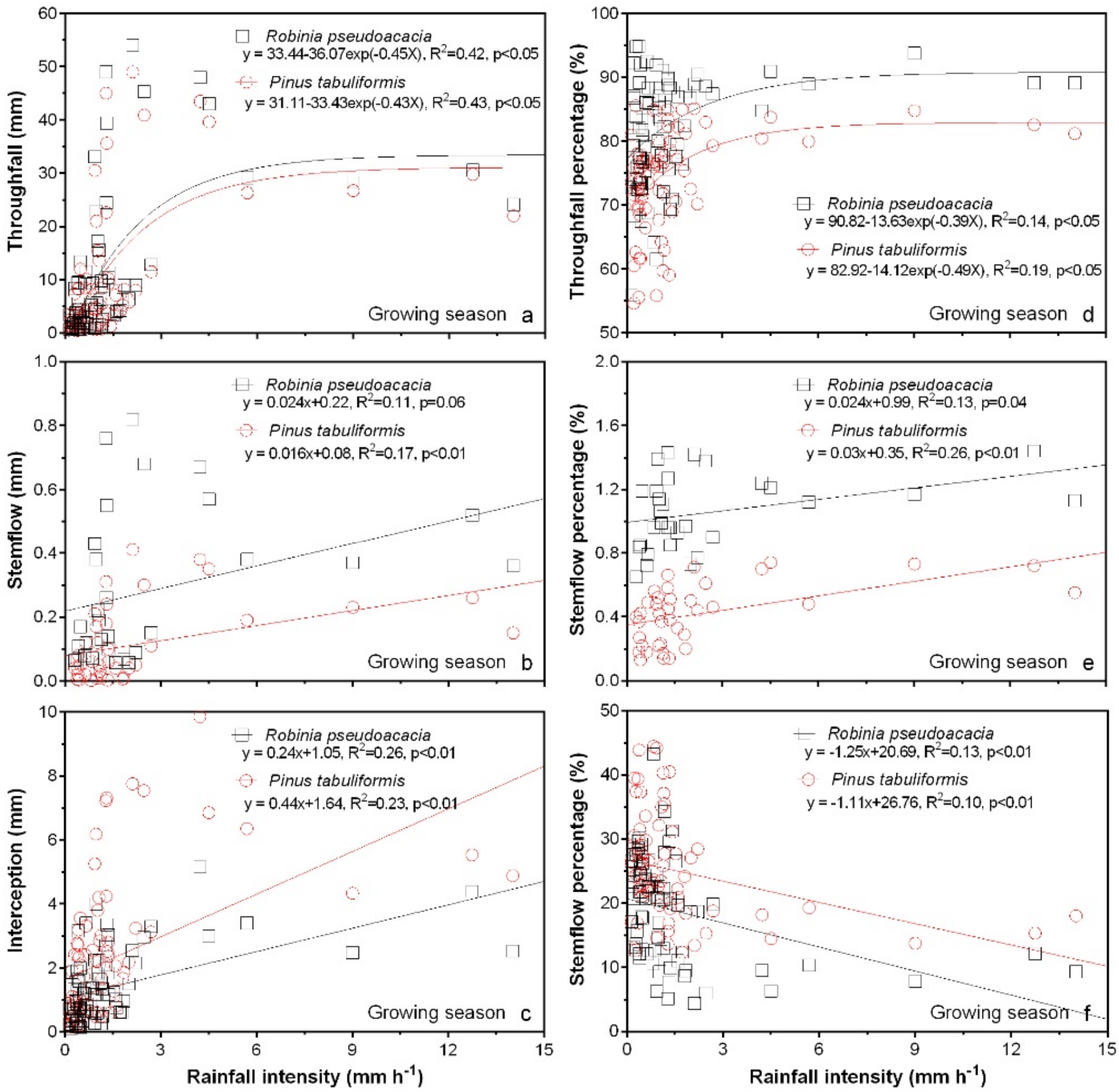

Figure 3. Relationships between individual rainfall intensity and rainfall partitioning components for *R. pseudoacacia* (**a**–**c**) and *P. tabuliformis* (**d**–**f**) rowing season in 2015 and 2016.

3.5. Rainfall Partitioning in Relation to Rainfall Duration

Throughfall was significantly ($p < 0.01$) correlated with individual rainfall duration for the two forest species during both growing and dormant seasons (Figures 4a and S3a). While for relative throughfall, it showed a weak linear correlation ($p > 0.05$) with individual rainfall duration for both forest stands (Figures 4d and S3d). Stemflow increased markedly with individual rainfall duration for *R. pseudoacacia* and *P. tabuliformis* but had much weaker correlations in the growing season than that in the dormant season (Figures 4b and S3b). For relative stemflow, it showed a weak linear correlation ($p > 0.14$) with rainfall duration, in which the trend increased insignificantly for the two forest stands during growing and dormant seasons (Figures 4e and S3e). Interception had a positive linear relationship with rainfall duration and was statistically significant ($p < 0.01$) for the two tree species during growing and dormant seasons (Figures 4c and S3c), while for relative interception, it decreased significantly ($p < 0.01$) with increasing rainfall duration during the growing season but decreased insignificantly ($p > 0.07$) with rainfall duration during the dormant season for *R. pseudoacacia* and *P. tabuliformis* (Figures 4f and S3f).

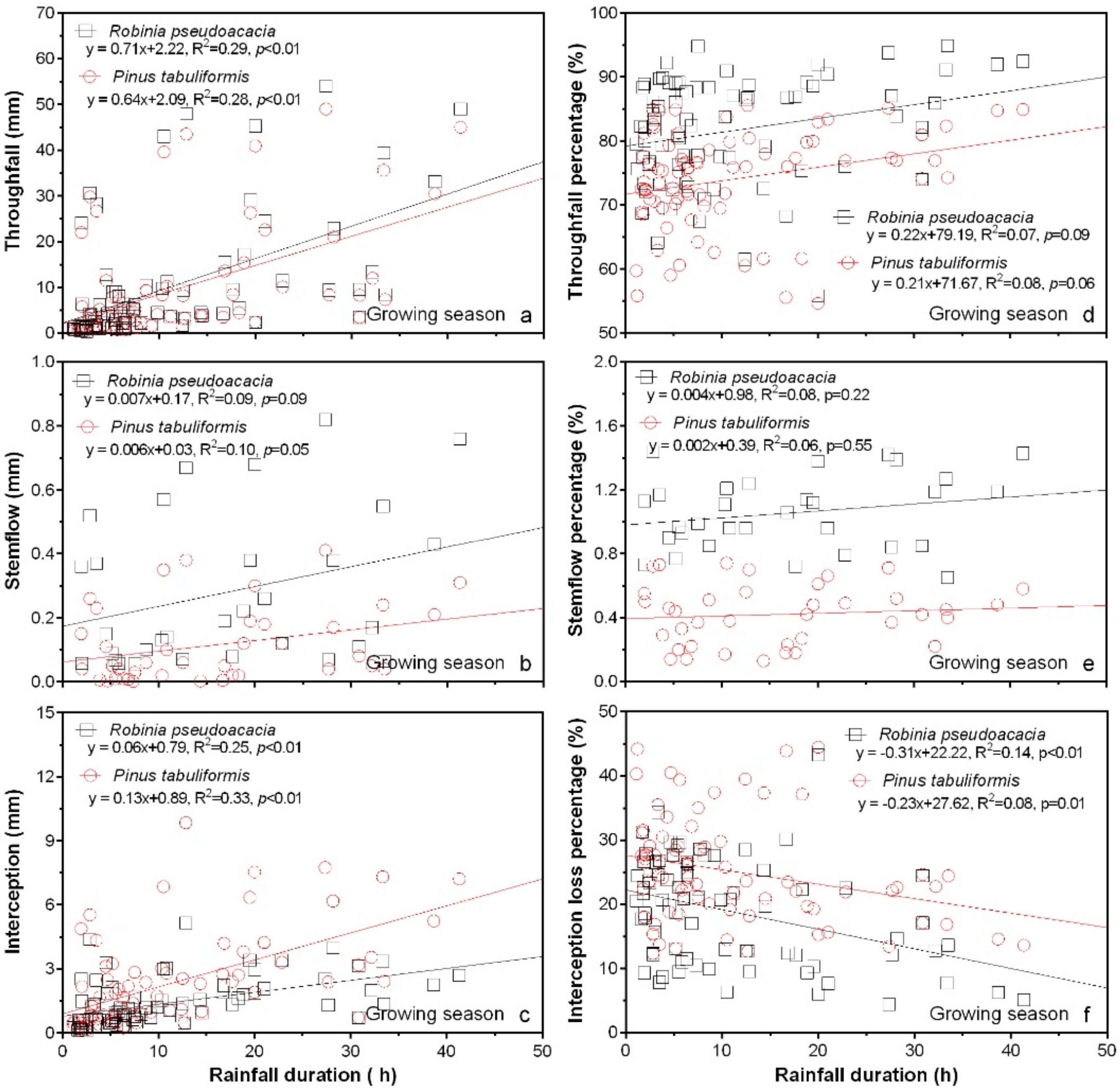

Figure 4. Relationships between individual rainfall duration and rainfall partitioning components for *R. pseudoacacia* (**a**–**c**) and *P. tabuliformis* (**d**–**f**) during the growing season in 2015 and 2016.

3.6. Relationship between Canopy Characteristics, Meteorological Variables and Rainfall Partitioning

Table 2 shows the correlations between canopy characteristics, meteorological variables and rainfall partitioning components for *R. pseudoacacia* and *P. tabuliformis* during both growing and dormant seasons in 2015 and 2016. It was found that throughfall and interception loss was significantly corelated with canopy characteristics for *R. pseudoacacia* during the growing season, while there was no statistically significant (p > 0.05) relationship between meteorological variables and rainfall partitioning components for both forest stands.

Table 2. Correlations between meteorological variables, leaf/plant area index (LAI/PAI, cm^2 cm^{-2}) and rainfall partitioning components for *R. pseudoacacia* and *P. tabuliformis* forest stands during the growing and dormant seasons in 2015 and 2016.

Rainfall Partition Components		**Growing Season (May–October)**								**Dormant Season (November–April)**							
		T_a (°C)		**RH (%)**		**WS (m s^{-1})**		**LAI**		**T_a (°C)**		**RH (%)**		**WS (m s^{-1})**		**PAI**	
		r	***p***	**r**	***p***	**r**	***p***	**r**	***p***	**r**	***p***	**r**	***p***	**r**	***p***	**r**	***p***
TF (mm)	*R. pseudoacacia*	0.1	0.46	0.39	0.09	0.05	0.69	0.61	0.04	0.19	0.22	−0.2	0.21	0.09	0.56	0.32	0.23
	P. tabuliformis	0.26	0.11	0.23	0.15	0.05	0.75	0.15	0.32	0.18	0.21	−0.19	0.23	0.1	0.53	0.18	0.42
TF (%)	*R. pseudoacacia*	0.27	0.14	0.55	0.12	0.09	0.52	0.58	0.03	−0.03	0.81	0.02	0.91	0.04	0.81	0.04	0.33
	P. tabuliformis	−0.02	0.89	0.3	0.06	0.02	0.93	0.29	0.34	−0.05	0.73	−0.22	0.15	0.29	0.06	0.08	0.51
SF (mm)	*R. pseudoacacia*	0.19	0.16	0.3	0.13	0	0.99	0.3	0.18	0.2	0.33	0.11	0.6	−0.1	0.62	0.29	0.23
	P. tabuliformis	0.33	0.11	0.09	0.55	0.03	0.86	0.26	0.42	0.33	0.17	−0.04	0.88	−0.02	0.93	0.21	0.62
SF (%)	*R. pseudoacacia*	0.35	0.08	0.09	0.5	−0.02	0.88	0.03	0.31	0.11	0.61	0.17	0.43	−0.15	0.47	0.11	0.41
	P. tabuliformis	0.45	0.07	−0.16	0.33	0	0.99	0.19	0.42	0.35	0.14	−0.28	0.25	0.13	0.59	0.17	0.52
I (mm)	*R. pseudoacacia*	0.27	0.06	0.25	0.07	0.08	0.58	0.54	0.02	0.14	0.36	−0.09	0.59	0.05	0.75	0.31	0.41
	P. tabuliformis	0.36	0.22	0.18	0.26	0.12	0.47	0.33	0.18	0.13	0.42	−0.1	0.51	−0.05	0.98	0.29	0.14
I (%)	*R. pseudoacacia*	0.24	0.07	0.55	0.08	0.08	0.54	0.55	0.04	0.12	0.46	0.31	0.06	−0.07	0.68	0.18	0.35
	P. tabuliformis	−0.08	0.96	−0.29	0.07	−0.01	0.93	0.55	0.23	−0.24	0.13	0.21	0.18	−0.33	0.06	0.08	0.29

Note: Ta (°C) is air temperature; RH (%) is relative humidity and WS (m s^{-1}) is wind speed. LAI (cm^2 cm^{-2}) is leaf area index and PAI (cm^2 cm^{-2}) is plant area index. TF (mm) is throughfall; TF (%) is throughfall percentage; SF (mm) is stemflow; SF (%) is stemflow percentage; I (mm) is rainfall interception loss; I (%) is rainfall interception percentage. Bold value indicates significant correlation at $p < 0.05$.

3.7. Multiple Linear Regression Analysis

In order to make a better prediction of rainfall partitioning, multiple linear regression analysis between rainfall characteristics, leaf area index and rainfall partitioning were performed in 2015. The analysis showed that the variability of rainfall partitioning can be largely ($p < 0.001$) explained by all of those variables (Tables 3 and 4). For *R. pseudoacacia*, the explained variability of all the regression models was 53–99% in the growing season and 36–99% in the dormant season. The explained variability for *P. tabuliformis* was 55–99% in the growing season and 37–99% in the dormant season. To test the applicability of the developed models in our study, we further compared the predicted values from regression models and observed rainfall partitioning for growing and dormant seasons in 2016. It was found that the predicted and observed rainfall partitioning were close to unity, indicating generally satisfactorily performance of these developed models (Figures 5 and 6). However, the coefficients of determination (R^2) between the simulated and observed relative rainfall partitioning were lower than that of rainfall partitioning depth, indicating a less prominent agreement between relative rainfall partitioning and selected influential factors.

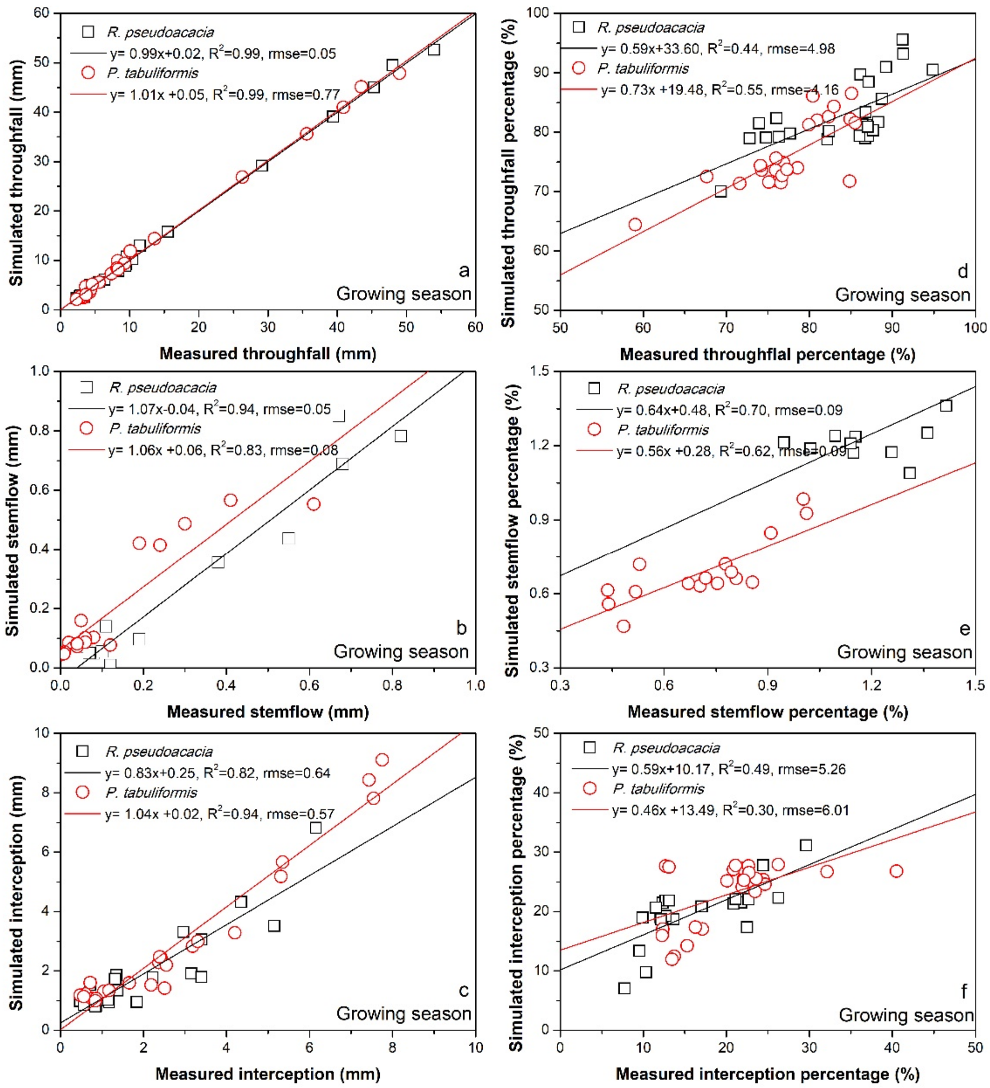

Figure 5. Comparison between the measured and simulated rainfall partitioning components for *R. pseudoacacia* (**a**–**c**) and *P. tabuliformis* (**d**–**f**) during the growing season of 2016.

Table 3. Results of multiple line regression analysis of rainfall partitioning components with rainfall characteristics and canopy characteristics for *R. pseudoacacia* and *P. tabuliformis* forest stands during the growing season in 2015.

Tree Species	Variable	Fitted Equation	p	P_{Pg}	P_{RD}	P_{RI}	P_{LAI}	R^2
R. pseudoacacia	TF (mm)	y = −0.38 + 0.94Pg − 0.03RD − 0.14RI − 0.26LAI	<0.001	0.000	0.02	0.00	0.01	0.99
	TF (%)	y = 78.08 + 0.31Pg − 0.02 RD + 0.10RI − 0.08LAI	<0.001	0.002	0.89	0.84	0.05	0.53
	SF (mm)	y = −0.09 + 0.02Pg − 0.01RD − 0.003RI	<0.001	0.000	0.34	0.17	-	0.94
	SF (%)	y = 0.75 + 0.01Pg + 0.002RD − 0.01RI	<0.001	0.000	0.61	0.30	-	0.67
	I (mm)	y = 0.42 + 0.04Pg + 0.03RD + 0.13RI + 0.05LAI	<0.001	0.000	0.01	0.05	0.03	0.77
	I (%)	y = 23.87 − 0.34Pg − 0.05RD − 0.34RI + 0.41LAI	<0.001	0.000	0.59	0.41	0.02	0.47
P. tabuliformis	TF (mm)	y = −0.41 + 0.85Pg − 0.02RD − 0.05RI	<0.001	0.000	0.04	0.26	-	0.99
	TF (%)	y = 70.25 + 0.26Pg + 0.02RD + 0.36RI	<0.001	0.004	0.82	0.42	-	0.55
	SF (mm)	y = −0.03 + 0.01Pg − 0.01RD + 0.001RI	<0.001	0.000	0.16	0.84	-	0.96
	SF (%)	y = 0.23 + 0.01Pg − 0.01RD +0.01RI	<0.001	0.000	0.67	0.13	-	0.59
	I (mm)	y = 0.39 + 0.14Pg + 0.02RD +0.05RI	<0.001	0.000	0.02	0.21	-	0.93
	I (%)	y = 29.17 − 0.27Pg − 0.03RD − 0.41RI	<0.001	0.004	0.77	0.37	-	0.29

Note: Pg is individual rainfall amount; RD is individual rainfall duration; RI is individual rainfall intensity, LAI is leaf area index.

Table 4. Results of multiple line regression analysis of rainfall partitioning components with rainfall characteristics for *R. pseudoacacia* and *P. tabuliformis* forest stands during the dormant season in 2015.

Tree Species	Variable	Fitted Equation	p	P_{Pg}	P_{RD}	P_{RI}	R^2
R. pseudoacacia	TF (mm)	y = −0.03 + 0.92Pg − 0.02RD + 0.02RI	<0.001	0.000	0.25	0.43	0.99
	TF (%)	y = 90.48 + 0.01Pg + 0.02 RD + 0.55RI	0.015	0.912	0.59	0.28	0.23
	SF (mm)	y = −0.07 + 0.02Pg + 0.01RD + 0.008RI	<0.001	0.000	0.38	0.67	0.97
	SF (%)	y = 0.53 + 0.05Pg + 0.02RD − 0.17RI	0.005	0.191	0.50	0.61	0.38
	I (mm)	y = 0.16 + 0.06Pg − 0.01RD + 0.10RI	<0.001	0.000	0.18	0.47	0.81
	I (%)	y = 8.77 − 0.11Pg + 0.01RD + 0.08RI	0.003	0.151	0.93	0.92	0.25
P. tabuliformis	TF (mm)	y = −0.14 + 0.78Pg − 0.01RD + 0.27RI	<0.001	0.000	0.39	0.10	0.99
	TF (%)	y = 75.17 + 0.55Pg − 0.21RD − 2.32RI	0.010	0.012	0.11	0.24	0.31
	SF (mm)	y = −0.04 + 0.01Pg + 0.001RD + 0.01RI	<0.001	0.000	0.62	0.09	0.99
	SF (%)	y = 0.11 + 0.01Pg − 0.002RD + 0.05RI	0.010	0.294	0.79	0.59	0.58
	I (mm)	y = 0.58 + 0.21Pg − 0.04RD + 0.01RI	<0.001	0.000	0.23	0.98	0.75
	I (%)	y = 24.67 − 0.16Pg + 0.11RD − 1.88RI	<0.001	0.42	0.39	0.33	0.32

Note: Pg is individual rainfall amount; RD is individual rainfall duration; RI is individual rainfall intensity.

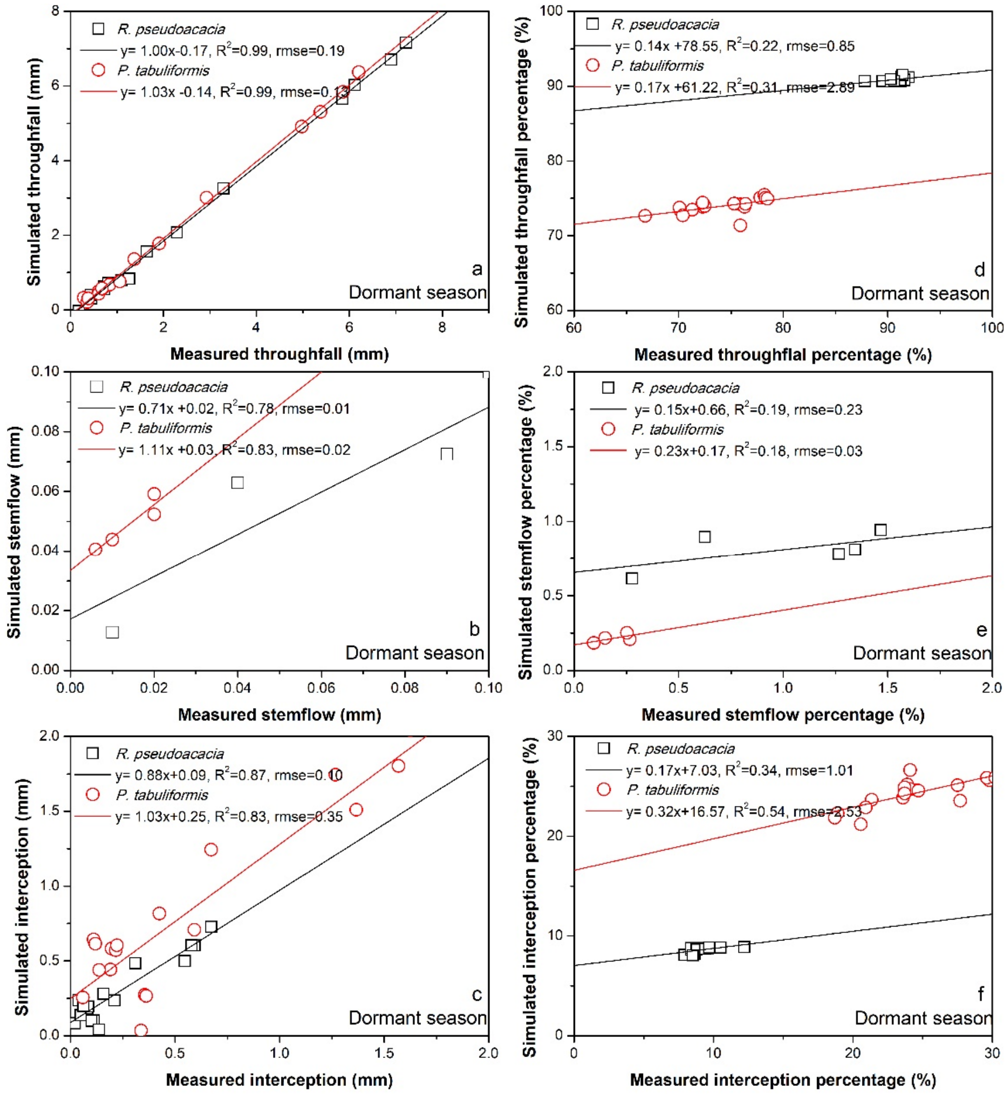

Figure 6. Comparison between the measured and simulated rainfall partitioning components for *R. pseudoacacia* (**a**–**c**) and *P. tabuliformis* (**d**–**f**) during the dormant season of 2016.

4. Discussion

4.1. Difference in Rainfall Partitioning between Two Study Forest Species

During the two-year experimental period, the observed interception was 16.8% of gross rainfall for *R. pseudoacacia*, which was similar to the reports (17.6–20% of gross rainfall) by Ma et al. [23] and Sadeghi et al. [5]. For *P. tabuliformis*, the measured interception in our study was 24.1% of gross rainfall, which was slightly higher than previously findings in other pine forests with low stem density (TD) and tree basal area (TBA), e.g., 22.3% of gross rainfall by Byrant et al. [26], 19.2% of gross rainfall by Silva et al. [27]. and 14.2% of gross rainfall by Shi et al. [28]. The higher relative interception values in our study could be attributed to higher tree density, basal aera, and LAI, which may have led to a higher rate of evapotranspiration during rainfall [23]. Overall, *P. tabuliformis* had higher relative interception than *R. Pseudoacacia*, as expected, because coniferous forests appear to have higher interception than deciduous forests [29]. Since environmental conditions around these two forest stands were comparable during study period, the relative higher interception for *P. tabuliformis* can therefore be attributed to its higher canopy storage capacity as well as its high rate of evaporation during rainfall [23]. Furthermore, the deeper crown of *P. tabuliformis* may also contribute to its higher relative interception values. With a thicker crown depth, *P. tabuliformis* is likely to increase the length of interaction between raindrops and canopy surfaces, thereby retaining and evaporating more water from the canopy [29].

Among the deciduous tree species *R. pseudoacacia*, the relative interception was significantly higher during the leafy season (18.6% of gross rainfall) than during the leafless season (9.1% of gross rainfall), which are in agreement with the findings for other *R. pseudoacacia* stands and deciduous trees [6,13,30]. The decreased interception in leafless season is likely to be caused by the reduction in LAI and leaf amounts, as previously reported (e.g., between seasons, Deguchi et al. [30] by thinning, Molina and del Campo. [31]). Decreased interception will increase net rainfall reaching forest floor and subsequent soil water content, which would benefit tree development during the next growing season. Therefore, forest managers and policymakers are recommended to implement water-oriented forest management, such as thinning, to increase net rainfall and soil water content in arid and semi-arid forests.

The components of net rainfall also varied significantly between the two forest stands (Table 1). For *R. pseudoacacia*, the measured throughfall was 81.8% of gross rainfall, which was similar to the findings by Ma et al. [23], but lower than the values reported by Wang et al. [17] in a 27-year-old forest with lower basal area and leaf area index in the central of Loess Plateau. Similar to *R. pseudoacacia*, the observed value of relative throughfall for *P. tabuliformis* in our study was lower than the values reported by Shi et al. [28] and Molina and del Campo. [31] in two pine plantations with a much lower basal area, but consistent with the findings by Fan et al. [32] in a pine plantation forest with similar tree basal area. This may imply that tree basal area is an important tree structural variable controlling the variation of relative throughfall, the lower relative throughfall in our study relative to other studies can thus be ascribed to their higher tree basal area. Studies indicated that forests with higher relative throughfall tend to have higher gap fraction and lower canopy thickness (i.e., canopy height Sadeghi et al. [5]. Therefore, the thicker canopies and lesser gap fraction of *P. tabuliformis* had a lower relative throughfall because they had more surface area or biomass to retain rainwater.

The measured stemflow represented a lower percentage of gross rainfall, 1.4% and 0.7% of gross rainfall for *R. pseudoacacia* and *P. tabuliformis*, respectively. Since the environmental conditions around these two forest stands were similar, the differences in stemflow can therefore be attributed to the differences in morphological characteristics. *R. pseudoacacia* is a medium-sized deciduous tree with loose and open canopy. The stem of *R. pseudoacacia* is lengthy and columnar, with only the upper part splits into branches. The bark is smooth and the leaves are odd-pinnate, constituted by 13–21 opposite standing elliptic leaflets, which can change their position depending on the environmental circumstances. All of these characteristics are helpful for stemflow generation. While for *P. tabuliformis*, a medium-sized evergreen tree species with flat-topped dense canopy, the stem is lengthy with numerous horizontal-oriented branches around the stem and the leaves are needle-like and dense. The bark was rough and fissures, which would reduce stemflow generation by absorbing a large amount of rainwater potential for stemflow production. The relative stemflow of *P. tabuliformis* in our study was lower than the findings by Molina and del Campo. [31], with a relative higher tree basal area, but it was similar to other studies: 0.7% of gross rainfall by Ma et al. [23], 0.9% of gross rainfall by Shi et al. [28] and 1.0% of gross rainfall by Fan et al. [32]. It may be possible that the lower stemflow fraction observed in *P. tabuliformis* in comparison with other studies is due to the lower basal area of the trees. The relative stemflow of *R. pseudoacacia* was slightly greater in the leafless season (1.6% of gross rainfall) than in the leafy season (1.4% of gross rainfall), a finding similar to Herbst et al. [33] and Muzylo et al. [13], and the reason for this is its lower leaf area and amount during the leafless season compared with the leafy season.

4.2. Rainfall Partitioning in Relation to Rainfall, Canopy Characteristics and Meteorological Variables

There was a significant correlation between throughfall and rainfall amount for *R. pseudoacacia* and *P. tabuliformis* during both growing and dormant seasons. However, there was a less strong correlation between rainfall amount and interception than there was between rainfall amount and throughfall, with correlation coefficients of 0.63 for *R. pseudoacacia* and 0.85 for *P. tabuliformis*, respectively, during the growing season, and 0.79 for *R. pseudoacacia* and 0.75 for *P. tabuliformis* during the dormant season. The differences in the correlation between rainfall amount and throughfall, interception loss were in consistent with the findings by Siles et al. [34] for *C. Arabica* and Wang et al. [17] for *R. pseudoacacia*. It may imply that throughfall is more predictable at high accuracy from rainfall amount than that for interception. This is because interception is not a directly measured quantity, but as the calculated residual of gross rainfall, throughfall and stemflow.

There was a significant positive linear correlation between stemflow and rainfall amount for both tree species, which was in agreement with the results of Fang et al. [35], Gomez et al. [36] and Herbst et al. [33]. However, different form of correlations between rainfall amount and stemflow were also reported in other studies by Siles et al. [34] and Fan et al. [32]. The variations in the relationship between rainfall amount and stemflow reflects species-specific differences, necessitating further studies for more conclusive correlations. Based on the best fitted linear regression equations, individual rainfall threshold value required to generate stemflow for *R. pseudoacacia* was 5.2 mm and 3.1 mm during growing and dormant seasons, respectively. For *P. tabuliformis*, the corresponding values were 5.9 mm and 6.0 mm, respectively, during the growing and dormant seasons. The average value threshold value (=4.2 mm) of *R. pseudoacacia* was similar to the values (=4.4 mm) reported by Ma et al. [23], but slightly larger than that of 0.3–2.7 mm reported for other arid and semi-arid forests [10,37] and also larger than that of 1.0–3.0 mm for forest in Mediterranean regions [9,35]. The calculated mean rainfall threshold value for stemflow generation of *P. tabuliformis* was 6.0 mm, which was similar to the findings (=5.9 mm) by Ma et al. [23], but slightly lower than the values (=7–10 mm) reported from sub-tropical forests [38]. Relative throughfall leveled off after rising almost linearly with increasing gross rainfall during both growing and dormant seasons (Figures 2d and S1d), and it was higher in *R. pseudoacacia* than that in *P. tabuliformis* for a given rainfall amount. These differences in relative throughfall could be explained by the differences in canopy morphology between the two tree species. For relative interception, the measured values initially decreased with gross rainfall and then relatively stabilized despite increasing gross rainfall, which agrees well with the findings of Gomez et al. [36], Siles et al. [34] and Zhang et al. [10]. This suggested that small rainfall events resulted in higher relative interception than large rainfall events. With increasing individual rainfall amount, canopy saturation gradually occurred while throughfall and stemflow increased markedly. This in turn reduced relative interception in the two tree species.

Throughout the measurement period, it was found that individual rainfall events of higher intensity were usually shorter in duration than those of lower intensity ($r = -0.33$, $p = 0.01$, $n = 163$). This negative relationship between individual rainfall intensity and duration was also reported by Owens et al. [39]. and Zhang et al. [10]. With increasing rainfall intensity, relative throughfall and relative stemflow increased while relative interception decreased in both growing and dormant seasons (Figures 3 and S2). Relative throughfall leveled off at rainfall intensity threshold, after initial increase during both growing and dormant seasons. The threshold values of relative throughfall in *R. pseudoacacia* were different from those in *P. tabuliformis* due mainly to the morphological differences. Moreover, the driving factors of evaporation during individual rainfall events also contributed to the observed differences. When rainfall intensity was high, water pathways along the branches changed as the water flow capacity of the branches were exceeded. This resulted in more release of rainwater from the branches to the ground, thus contributing larger to throughfall generation [12]. Furthermore, high intensity rainfall with high terminal velocity and kinetic energy can increase rainwater splashes against canopy surfaces, thereby reducing the amount of rainwater available for interception loss [16]. On the other hand, high rainfall intensity apparently induced high-efficiency canopy saturation in the two tree species, which favored the generation of throughfall and stemflow and in turn relatively reduced relative interception [10,40].

Studies indicated that rainfall events are always characterized by greater interactions among rainfall amount, intensity and duration [10]. It was also demonstrated in our study that rainfall events that were more intense were also shorter in duration ($r = -0.33$, $p = 0.01$, n = 163) as well as a greater amount of rainfall ($r = 0.10$, $p < 0.01$, n = 163). This interaction between rainfall intensity, duration, and amount makes it more likely that the results of the multiple regression will be more accurate than those of a single regression in explaining rainfall partitioning [41–43]. In order to improve the prediction of rainfall partitioning by the two trees species, multiple linear regression analyses relating rainfall partitioning to rainfall characteristics and leaf area index were carried out in both the growing and dormant seasons of 2015. It was found that the depth of rainfall partitioning components was highly ($R^2 > 0.71$) and significantly ($p < 0.01$) correlated with rainfall characteristics for the two tree species, which agrees well with the findings by Staelens et al. [42] and Zhang et al. [10]. To test and verify the applicability of these developed models, we further compared the predicted and measured rainfall partitioning components for growing and dormant seasons in 2016. The modeling results showed that the depth of rainfall partitioning components can be accurately predicted in the growing and dormant seasons using those developed models, with the coefficient of determination (R^2) larger than 0.76 and p value smaller than 0.001. However, the relatively lower R^2 values (=0.36–0.61) between the observed and predicted values for relative rainfall partitioning components indicated a less prominent agreement between these relative rainfall partitioning components and rainfall characteristics. The prediction of relative rainfall partitioning components may be improved by incorporating other canopy structure variables (e.g., leaf area index, canopy cover, bark area and etc.) and other meteorological variables such as wind speed, air temperature and relative humidity, although they were not significantly correlated with the rainfall partitioning in our study.

5. Conclusions

In this study, we examined whether plant functional groups have a significant impact on rainfall partitioning in two xerophytic trees (evergreen species: *Pinus tabuliformis*, deciduous species: *Robinia pseudoacacia*) commonly used for afforestation on the semi-arid Loess Plateau of China, and evaluated the effects of rainfall characteristics, canopy characteristics and meteorological factors on rainfall partitioning. We found that the measured throughfall, stemflow and interception loss for *R. pseudoacacia* accounted for 81.8%, 1.4% and 16.8% of gross rainfall, respectively. Corresponding values for *P. tabuliformis* were 75.1%, 0.7% and 24.1%, respectively. This may suggest that *R. pseudoacacia* has an advantage of receiving more net gross rainfall over *P. tabuliformis* in the semi-arid regions of Loess Plateau. The rainfall partitioning components were significantly positively correlated with individual rainfall amounts. The minimum rainfall required to generate stemflow was 5.2 mm for *R. pseudoacacia* and 5.9 mm for *P. tabuliformis* during the growing season, and 3.1 mm for *R. pseudoacacia* and 6.0 mm for *P. tabuliformis* during the dormant season. Smaller rainfall events contributed to a lower percentage of rainfall amount, throughfall and stemflow but higher percentage of canopy interception loss. For the two tree species, rainfall characteristics (i.e., gross rainfall, duration and in-tensity) exerted a significant ($p < 0.05$) influence on rainfall partitioning, while meteorological variables such as temperature, relative humidity and wind speed had no significant ($p > 0.05$) correlations with rainfall partitioning. Based on these significant factors (i.e., rainfall characteristics and leaf area), multiple regression models of rainfall partitioning were well-established during both the growing and dormant seasons. With these developed regression models, the amount and proportions of rainfall partitioning components during both seasons can be predicted reasonably well, except for relative interception loss. To better predict canopy interception loss, other plant morphological and meteorological variables should be considered.

The results presented in this paper highlight that the morphological characteristics of xerophytic tree species play an important role in determining the way rainfall partitioning. Different rainfall partitioning patterns between these two tree species will result in different local hydrologic budgets. These differences may have implications for the dynamics of soil water, erosion, runoff, and the composition of plant communities in afforested semi-arid areas of the Loess plateau. As such, when selecting trees for afforestation in semi-arid regions, it is recommended that rainfall partitioning characteristics be considered as a factor to take into account.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w14223723/s1, Figure S1. Relationships between individual rainfall amount and rainfall partitioning components (i.e., throughfall, stemflow and interception loss) for R. pseudoacacia and P. tabuliformis forest stands during the dormant season (November–April) in 2015 and 2016. Figure S2. Relationships between individual rainfall intensity and rainfall partitioning components (i.e., throughfall, stemflow and interception loss) for R. pseudoacacia and P. tabuliformis forest stands during the dormant season (November–April) in 2015 and 2016. Figure S3. Relationships between individual rainfall duration and rainfall partitioning components (i.e., throughfall, stemflow and interception loss) for *R. pseudoacacia* and *P. tabuliformis* forest stands during the dormant season (November–April) in 2015 and 2016.

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Conflicts of Interest: Not applicable.

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