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Rainfall interception by tree crown and leaf litter: An interactive process

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Abstract

Rainfall interception research in forest ecosystems usually focuses on interception by either tree crown or leaf litter, although the 2 components interact when rainfall occurs. A process-based study was conducted to jointly measure rainfall interception by crown and litter and the interaction between the 2 interception processes for 4 tree species (*Platycladus orientalis* and *Pinus tabulaeformis* represented needle-leaf species, and *Quercus variabilis* and *Acer truncatum* represented broadleaf species) at 3 simulated rainfall intensities (10, 50, and 100 mm hr^{-1}). Results indicated that (a) crown and litter interception processes incorporated 3 phases: the dampening phase, the steady saturation phase, and the postrainfall drainage phase, but the dampening phase for litter interception usually lasted 30 min longer than for crown interception; (b) the maximum and minimum interception storage (C_{max} and C_{min}) for the crown were 0.63 and 0.36 mm on average, and litter C_{max} and C_{min} were 5.38 and 2.36 mm, respectively; (c) generally, crown and litter C_{max} and C_{min} increased when gross precipitation increased significantly ($p < .05$) from 10 to 100 mm; and (4) crown C_{max} and C_{min} for needle-species were 1.8 and 1.2 times larger than broadleaf species, whereas broadleaf litter showed the opposite, its C_{max} and C_{min} were 2.0 and 1.6 times larger than needle-leaf litter on average; however, no significant differences were observed in crown and litter C_{max} and C_{min} between species on per leaf area and litter thickness basis. Results were normalized by total leaf area and litter thickness to provide a way to scale up from young trees to mature forests. Overall, rainfall interception was affected by biotic and abiotic factors together and could be quantified via multiple linear regression functions.

KEYWORDS

crown interception, gross precipitation, interception process, leaf area, litter interception, litter thickness

1 | INTRODUCTION

Rainfall interception, defined as rainwater that is temporarily intercepted and stored on vegetation surfaces (e.g., trees, shrubs, grass, and leaf litter) during rainfall and evaporates into the atmosphere or drains to the soil surface afterwards as either throughfall (*TF*) or stemflow (*SF*; Savenije, 2005), has been widely accepted as a major hydrologic process in forest ecosystems (Savenije, 2004; Gerrits, Savenije, Hoffmann, & Pfister, 2007). Past studies of rainfall mainly focused on crown interception (I_C), and results showed that it generally ranges from 10% to 30% of gross precipitation (P_g) (Gerrits, Pfister, & Savenije, 2010; Klaassen, Bosveldb, & Waterc, 1998; Llorens &

Domingo, 2007). Meanwhile, I_C significantly affects subsequent hydrological and erosional processes such as evaporation, transpiration, run-off (even peak flows and floods), infiltration, and water erosion (Morgan, 2005; Xiao & McPherson, 2003; Xiao, McPherson, Ustin, Grismer, & Simpson, 2000). Additionally, I_C impacts chemical and pollutant deposition, water availability, and even climate change (Aston, 1979; Arnell, 2002; Xiao & McPherson, 2011; Murray, 2014). Climate characteristics (i.e., air temperature, relative humidity, wind speed, and wind direction), rainfall characteristics (i.e., rainfall intensity, rainfall duration, gross precipitation, and rainfall interval), and tree crown characteristics (i.e., leaf morphology, branch inclination, leaf area and roughness, and leaf area index) have all been shown to play a relevant role in determining I_C (Rutter, Kershaw, Robins, & Morton, 1971; Rutter, Morton, & Robins, 1975; Xiao, McPherson, Ustin, & Grismer, 2000; Crockford & Richardson, 2000; Xiao & McPherson, 2015).

Compared with I_C, leaf litter interception (I_L) has rarely been investigated because I_L is often regarded as a minor component of the hydrologic process and proper I_L measurement has been difficult (Llorens & Gallart, 2000; Sato, Kumagai, Kume, Otsuki, & Ogawa, 2004). However, the litter layer may have a larger interception storage capacity and smaller evaporative potential compared to the crown (Baird & Wilby, 1999; Gerrits et al., 2010; Bulcock & Jewitt, 2012a). As a result, I_L also plays a vital role in shaping subsequent hydrological processes (Sayer, 2006). For instance, litter absorbs raindrop energy to prevent splash erosion and soil compaction, thereby reducing surface run-off and sedimentation (Benkobi, Trlica, & Smith, 1993; Miyata, Kosugi, Gomi, & Mizuyama, 2009; Li, Niu, & Xie, 2014). Acting as a buffer for the soil, the litter layer can increase infiltration and soil water content and decrease soil respiration and evaporation (Walsh & Voigt, 1977). Generally, I_L is less than 20% of P_g (Dunkerley, 2015) but can reach up to 40–70% in some cases (e.g., Price, Rochefort, & Quinty, 1998; Brye, Norman, Bundy, & Gower, 2000).

Challenges remain when measuring and analysing I_C and I_L. First, very few studies have measured I_C and I_L jointly despite the inevitable interaction of these two processes during rainfall. Particularly, I_L has been measured without crown cover in some of these experiments, leaving litter directly exposed to simulated rainfall (e.g., Putuhena & Cordery, 1996; Sato et al., 2004; Guevara-Escobar, González-Sosa, Véliz-Chávez, Ventura-Ramos, & Ramos-Salinas, 2007; Mo et al., 2009; Lu, Li, & Liu, 2011; Li, Niu, & Xie, 2013; Dunkerley, 2015). This is rarely the case in forest stands, where litter intercepts *TF* more frequently than direct rainfall. Given the differences between rainfall and *TF* in raindrop diameter and kinetic energy, intensity, and spatial variability, I_L may have been miscalculated (Nanko, Onda, Ito, & Moriwaki, 2011; Fathizadeh et al., 2014). Second, joint interception (I_C + I_L) has been widely recognized as a flux or stock rather than an interactive process in several studies (Gerrits & Savenije, 2011). As a consequence, the continuous interaction between the crown and litter have not been captured (e.g., Helvey & Patric, 1965; Gerrits et al., 2010; Tsiko, Makurira, Gerrits, & Savenije, 2012). In particular, the rate at which litter is wetted and saturated under crown cover during rainfall, and the volume of temporarily intercepted water that drains from the crown and litter after rainfall remains unclear. However, these processes and interactions are critical to fully understand mechanisms of interception, and the role of crown and litter in the water budget, run-off delay, and erosion control (Morgan & Duzant, 2008; Beven, 2011; Bulcock & Jewitt, 2012b; Dunkerley, 2015). Meanwhile, depicting joint interception as a flux measurement may have introduced several unexpected errors. I_C is generally determined by calculating the difference between P_g and net precipitation P_n (P_n = *TF* + *SF*). Accurately measuring *TF* may require numerous gauges located under the crown to overcome wind disturbance and the inherent spatial variation (Kimmins, 1973; Xiao, McPherson, Ustin, Grismer, et al., 2000). Few studies have adequately sampled *TF*, particularly in China (e.g., Zhang, Luo, & Jing, 2007; Chen, Zhang, Yu, Shi, & Huang, 2013; Fang, Zhao, Jian, & Yu, 2013; Peng et al., 2014). On the other hand, I_L has been misinterpreted as the maximum water storage capacity of the litter (*S*) and is measured by immersing the leaf litter in water for hours, which totally dampens and even saturates the leaves (e.g., Zhang et al., 2005; Qi, Shi, Yu, Zheng, & Li, 2011). This approach may overestimate I_L when leaves are partially wetted during light rainfalls. Moreover, the effect of litter thickness on I_L and evaporation has been rarely addressed (but see Park et al., 1998; Guevara-Escobar et al., 2007).

Direct measurement of the interactive interception process by tree crown and leaf litter is needed to better understand how these components contribute to the hydrologic cycle. This is especially important in China, where joint interception has not been thoroughly studied and where environmental problems such as severe water scarcity and soil erosion are becoming an increasing threat to sustainable development (Ministry of Water Resources of P.R.China, 2011, 2013; Yang & Lu, 2014; Wang, Shang, Wang, Zhao, & Yin, 2015).

The objectives of this study are to (a) depict the dynamics of the joint interception (I_C + I_L) and postrainfall drainage processes and (b) determine how abiotic factors (e.g., rainfall characteristics) and biotic factors (e.g., crown and litter traits) affect joint interception under simulated rainfall.

2 | MATERIALS AND METHODS

2.1 | Tree species and leaf litter

Four common species were selected to be representative of the trees in Northern China (China Forest Editorial Committee, 2001). Needleleaf trees were represented by *Platycladus orientalis* (*PO*) and *Pinus tabulaeformis* (*PT*), and broadleaf trees were represented by *Quercus variabilis* (*QV*) and *Acer truncatum* (*AT*). Two 5-year-old trees for each species were selected and then removed from four 25 × 15 m^2 experimental forest stands in Jiufeng National Forestry Park, Beijing, China (116°28′E, 39°34′N). Tree traits such as height, basal diameter, and crown height were measured before removal (Table 1). After the initial measurement, each tree was transplanted with intact roots and soils into a plastic cylinder 2.0 m in diameter and transported to the rainfall simulation lab (Key Laboratory of Soil and Water Conservation of State Forestry Administration, Beijing, China). Several other crown structure metrics were measured before rainfall simulation. As there were few secondary branches, only primary branch inclination was measured using a protractor. Leaf area index (*LAI*) was measured using an *LAI*-2200 Plant Canopy Analyzer (LICOR Inc., Lincoln, NE, USA). Crown

TABLE 1 Traits of the experimental tree crown and leaf litter

Tree species	*TH* (m)	*BD* (cm)	*CH* (m)	*LAI*	*CPA* (m^2)	*TLA* (m^2)	*MLL* (cm) ± STD	*MLW* (cm) ± STD	H_L (cm)
QV-1	3.36	3.0	2.64	1.33	1.36	1.81	9.5 ± 1.2	3.5 ± 0.3	3.7
QV-2	3.81	4.1	3.01	1.12	1.74	1.95	10.1 ± 0.8	4.2 ± 0.6	4.5
AT-1	2.77	4.2	1.85	1.56	2.23	3.48	6.5 ± 2.3	5.5 ± 2.1	5.5
AT-2	3.33	3.8	2.93	1.35	4.89	6.60	7.7 ± 1.5	6.7 ± 2.6	6.1
PO-1	2.45	2.1	1.96	1.44	1.01	1.45	6.7 ± 1.6	4.2 ± 1.3	4.4
PO-2	2.83	2.0	1.77	1.99	1.11	2.21	8.3 ± 1.8	3.3 ± 1.2	4.7
PT-1	1.66	3.1	1.52	2.83	1.95	5.52	11.1 ± 1.7	0.4 ± 0.1	3.5
PT-2	1.84	3.7	1.78	2.65	1.63	4.32	10.8 ± 1.1	0.3 ± 0.1	3.1

Note. PO = Platycladus orientalis; *PT = Pinus tabulaeformis*; *QV = Quercus variabilis*; *AT = Acer truncatum*; *TH = tree height*; *BD* = basal diameter; *CH* = crown height; *LAI* = leaf area index; *CPA* = crown projected area; *TLA* = total leaf area, which was calculated by *LAI* times *CPA*; *MLL* = mean litter length; *MLW* = mean litter width; H_L = litter layer thickness; STD = standard deviation.

projection area (CPA) was determined via photographs taken from above at a height of 15 m; these were further analysed using Photoshop software (Adobe System Inc., San Jose, USA). Before each simulation, tree roots were enclosed with plastic bags and were positioned below the two half-circle tray to ensure that no water was intercepted by the roots (the roots and plastic bags were not shown in the diagram given the limited space). The trees were replanted in the cylinder after each simulation. As a result, no foliage wilting was observed before or during the experiment.

Leaf litter conditions of the selected trees were also investigated. Only the relatively undecomposed leaf litter (L layer) was included in the experiment because it was the dominant component of the litter layer for that season and played a larger role in rainfall interception at the ground surface compared with the decomposed litter. No burning or human disturbance on the litter had been allowed once the trees were planted, indicating that the undecomposed litter with both fresh and nonfresh foliage had accumulated over 3–4 years. Therefore, the two kinds of foliage were selected for each species to exclude the effect of litter age difference on the result. The thickness of the undecomposed litter was measured. To reconstruct the litter arrangement in the lab to its original shape, the natural arrangement of the leaf litter under the selected trees was documented by pictures taken from four aspects at 20 cm above the ground surface before the trees were removed from the forest (June 2014). Afterwards, litter was carefully collected into several boxes by hand and taken back to the lab for 24-hoven–drying at 70 °C. The length and width of 50 randomly selected leaves and needle-leaves were measured as well. The litter mass for all the species was weighed after drying and ranged from 0.78 to 1.31 kg per CPA (m^2). The experimental mass for each species under simulated rainfall was 1.0 kg m^{-2} to reflect the typical litter characteristics in the field for comparison with previous studies.

2.2 | Rainfall simulation system

Measurements were conducted under simulated rainfall scenarios in the lab. The rainfall simulation system QYJY-503C was equipped with almost 200 rotation nozzles (Qingyuan Measurement Technology, Co. Ltd, Xi'an, China) and was able to simulate a wide range of rainfall intensities (10 to 300 mm hr^{-1}) controlled by a computer system. The rainfall simulation height was up to 18 m to allow raindrops to reach terminal velocity prior to hitting a vegetative surface. Rainfall uniformity was above 80%, and the median diameters of the simulated raindrops ranged from 0.2 to 5 mm, which ensured that the simulated rainfall was similar to the natural rainfall with respect to raindrop distribution and size (Huo et al., 2015).

Based on the precipitation data over the past 50 years in Beijing (Zhong, Jia, & Li, 2013), each tree was subjected to rainfall at intensities of 10, 50, 100 mm hr^{-1} for 1 hr to represent natural rainfall conditions. Rainfall intensities were re-calibrated prior to every simulation.

2.3 | Interception measurement set-up

Because the experiment was carried out at a single tree level, a new approach was developed to directly and independently measure the tree crown and leaf litter interception. Cumulative crown interception (I_C) for each tree was measured using a suspended electronic weighing balance system (WH-A08, ZK&E Co. Ltd, Shandong, China; minimum graduation: 0.2 g). The bottom section of the tree trunk was separated from the litter sample tray surface, and as a result, cumulative I_C was recognized as the difference in tree weight during the rainfall period (Figure 1).

For the cumulative litter interception (I_L), the measurement system consisted of two half-circle trays, a plastic barrel, a funnel, and an electronic balance (EP-500, E&C Co. Ltd, Shanghai, China; minimum graduation: 0.1 g). The diameter of the tray was dependent on the crown diameter and outline and ranged from 2 to 3 m. The two half-circle trays were composed of 2 × 2 cm^2 stainless-wire-mesh with 3-mm-diameter strands to allow the water temporarily intercepted by leaf litter to drip to the funnel. The half-circle trays were assembled to prevent contact with the tree bole and litter so that the *SF* drained directly to the funnel. Afterwards, the oven-dried litter was manually distributed onto the tray according to the crown outline and the original arrangements (based on the photos taken in the field). When rainfall began, the raindrops dripped from the litter and flowed into the drainage collector through the funnel and the tube. Cumulative I_L was recorded as the fluctuation of the litter weight shown in the electronic balance. Drainage water (*D*) was weighed by another electronic balance so that cumulative I_L could be recalculated as the difference between *TF* and *D*, which enhanced data accuracy. Nevertheless, as Gerrits et al. (2010) and Bulcock and Jewitt (2012a) suggested, the interface between the mesh and litter may prevent water drainage in time due to the cohesion. This may have caused an overestimation of

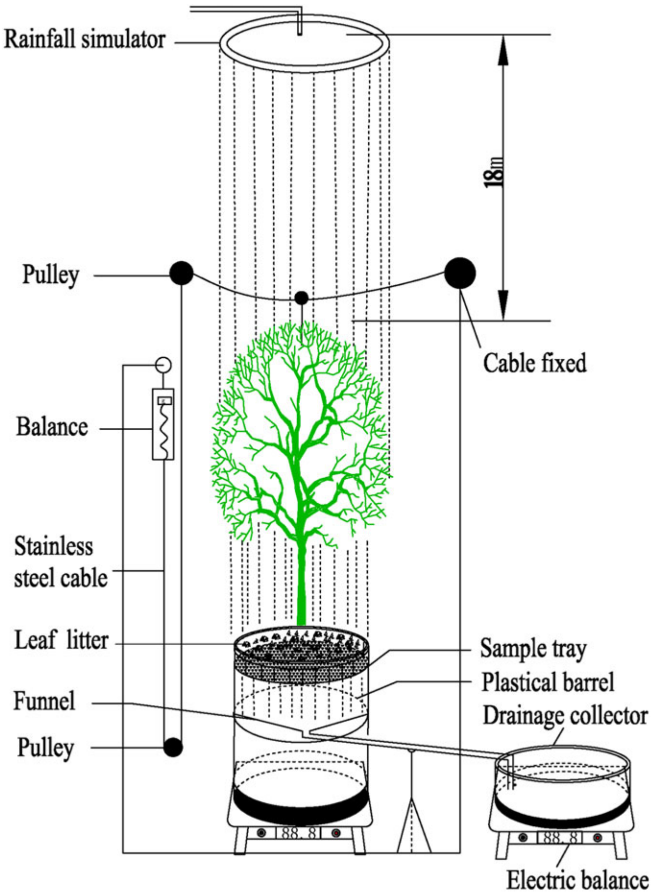

FIGURE 1 Schematic of the joint rainfall interception measurement set-up

cumulative I_L, particularly for broadleaf litter under rainfall intensity (*RI*) of 10 mm hr^{-1}. Miscalculations may have occurred due to the way *SF* was collected. Several water droplets were observed remaining on the plastic bag (not shown in Figure 1) after rainfall simulations, particularly for *RI* of 10 mm hr^{-1}, which may have overestimated crown interception. However, given that the bag surfaces were relatively smooth, the overestimation was relatively minor compared to the interception by dense roots without the cover bags.

2.4 | Experimental procedure

Besides cumulative I_C and I_L, two types of interception storage for crown and litter, C_{max} and C_{min}, were recorded. C_{max} is the maximum or dynamic interception storage and is the amount of rainwater intercepted and stored by the crown and leaf litter immediately before rainfall cessation. C_{min} is the minimum or static interception storage and is the amount of rainwater stored by the crown and leaf litter when drainage ceases postrainfall, this water can only be removed by evaporation (Putuhena & Cordery, 1996; Sato et al., 2004). Generally, C_{min} is regarded as more crucial than C_{max} because it is the ultimate interception lost to the atmosphere (Guevara-Escobar et al., 2007). However, C_{max} represents the largest amount of water that can be returned to the ground surface by crown and litter and is therefore meaningful for analysing the rainfall–run-off–erosion relationship.

Each tree and its underlying leaf litter were subjected to simulated rainfall for 1 hr. Once rainfall began, the weight of individual tree and corresponding leaf litter were recorded at a 10-s interval for the first minute, a 30-s interval for the next 9 min, and a 1-min interval for the next 50 min. The stable moment for the weight of tree and litter were noted, and C_{max} was recorded as the difference in tree and litter weight before and after the simulation. Tree and leaf litter weight were recorded immediately following rainfall cessation every 10 s for the first min, every 30 s for the next 9 min, and every minute for the remaining time until a weight change <0.2 g was obtained. C_{min} was calculated as the difference in weight for tree and litter before the rainfall simulation and after the drainage. Each tree was returned to the plastic cylinder to be watered to prevent wilting after every test run and set outside to dry the wetted crown for 24 hr. Meanwhile, leaf litter was collected and oven dried at 70 °C for 10 hr. Severely damaged leaves were replaced by the intact litter. Evaporation (*E*) was not measured and neglected in subsequent analysis because of limited wind and solar radiation in the laboratory. Relative humidity (*RH*) was monitored by a *RH* hand-held meter (RH820 series, OMEGA Corporation, USA) and was maintained at a regular level of 60–70% before rainfall simulation, which was in accordance with typical *RH* in Beijing′s summer. Every test was replicated once, indicating that four replications were employed for each tree species at each rainfall intensity, and thereby, 48 simulations were performed on eight trees over three rainfall intensities from June to August 2014 with a mean air temperature of 26.7 °C in the lab.

2.5 | Statistical analysis

Cumulative I_C and I_L, crown and litter C_{max} and C_{min} data were averaged by species and used in subsequent analysis. The two-tailed test of Pearson′s correlation coefficient (*r*) was used to describe the correlation of crown and litter C_{max} and C_{min} with P_g. Significant correlation was defined at or above the 95% confidence level ($p \le .05$). One-way analysis of variance with the Fisher LSD (Least Significant Difference) test at $p \le .05$ was used to determine if there were significant differences in crown and litter C_{max} and C_{min} between needle-leaf species and broadleaf species. Multiple linear regression analysis was employed to analyse how combining biotic and abiotic factors such as P_g, *LA*, and H_L affected crown and litter C_{max} and C_{min}. Equations with the least Akaike information criterion values were selected. All statistical analyses were performed using IBM SPSS Statistics 20.0 software.

3 | RESULTS AND DISCUSSION

3.1 | The joint interception process

Generally, both I_C and I_L processes were composed of three phases: the wetting phase, the saturation phase, and the postrainfall drainage phase (Figure 2). However, I_C and I_L duration and amount were different in each phase. I_C showed a short wetting phase (lasting 10–20 min) and a long saturation phase (lasting 40–50 min). By comparison, the wetting phase for I_L was much longer, lasting 40–50 min, and the saturation phase was relatively shorter, lasting only 10–20 min.

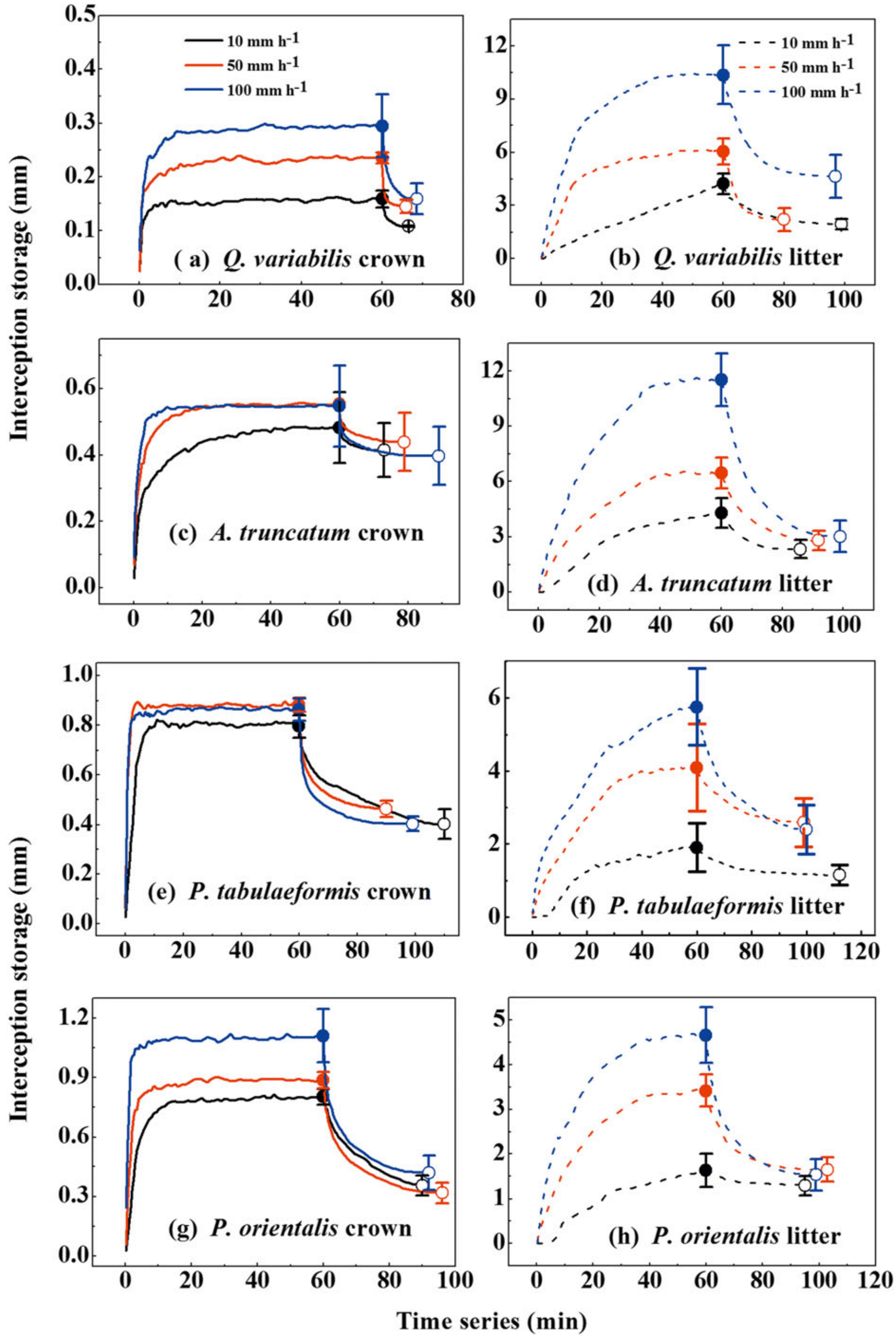

FIGURE 2 Time series of average cumulative interception storage of tree crown (represented by dash line) and leaf litter (represented by straight line) for (a, b) *Q. variabilis*; (c, d) *A. truncatum*; (e, f) *P. tabulaeformis*; and (g, h) *P. orientalis* at three rainfall intensities (magnitude of each rainfall intensity is shown in different colour). C_{max} and C_{min} are represented by closed and open symbols respectively. Error bars indicate standard deviation

This scenario indicated that the crown was wetted and saturated faster than the litter.

Specifically, both I_C and I_L increased dramatically in the wetting phase. For instance, average increment of I_C was 0.64 mm in the first 10 min of rainfall, which was 16 times larger than that in the following 50 min with an increase of 0.04 mm regardless of species and *RI*s. Similarly, average increase of I_L in the first 40 min (6.07 mm) was approximately 18 times larger than that in the remaining 20 min (0.34 mm) of rainfall. In addition, there was a transition between I_C and I_L in the wetting phase. I_C was larger than I_L only at the early period of rainfall. The transition occurred after 4 min of the wetting phase on average across species and *RI*s, when I_L began to surpass I_C. The threshold precipitation for the transition ranged from 0.14 to 4.17 mm for different species and *RI*s, with an average of 1.52 mm.

After 10–20 min of rainfall, I_C became relatively steady while I_L continued to rise until saturation for almost 30 min. By the end of rainfall, mean C_{max} of the litter for four species was 5.38 (±2.81) mm, which was 8.5 times larger than crown C_{max} (0.63 mm on average). In the postrainfall drainage phase, however, as much as 42.6% and 51.9% of the crown and litter C_{max} dripped off in 25 (±13) and 37 (±8) min, respectively (Figure 2). As a result, crown and litter C_{min} were 0.40

and 2.32 mm on average and mean C_{min} for the litter was 5.8 times larger than the crown.

The results demonstrate that litter intercepted and stored rainwater more effectively than the crown. There are two likely reasons for this. First, the crown scattered and softened the rainfall. At least 7–12 m in tree height is required for intercepted drops to reach terminal velocity before striking the litter layer surface (Wang & Pruppacher, 1977), but the average tree height in this study was only 2.72 m. Second, the relatively thick litter layer (4.4 cm on average, Table 1)was composed of a multi-sublayer of leaves, which could effectively retain the raindrops through cohesion (Sato et al., 2004).The relatively flat (rather than gradient) surfaces of the foliage in the litter layer may also contribute to its capacity to hold droplets, especially for the broadleaf species.

Previous studies draw different conclusions about crown and litter C_{min}. Some found that litter played a larger role than the crown in the joint interception process, ranging from 1.8–4.5 mm. By comparison, crown C_{min} varied from 0.4 to 1.2 mm (Gerrits et al., 2010; Bulcock & Jewitt, 2012a). Yet other studies showed the opposite, crown C_{min} was 0.24–2.70 mm, which was 1.6–6.2 times larger than litter C_{min} (range of 0.04–1.80 mm) (Helvey & Patric, 1965; Owens, Lyons, & Alejandro, 2006; Tian, 2009; Li, Rao, Lu, & Jin, 2012; Neto et al., 2012; Tsiko et al., 2012; Zhang, 2013). The divergence can be explained by rainfall pattern and litter thickness. Large and mature crowns tended to intercept much more water in small rainfall events (e.g., Owens et al., 2006; Tsiko et al., 2012; Zhang, 2013); very little *TF* was observed in such events. Litter thickness was another major reason. For instance, Bulcock and Jewitt (2012a) reported an extreme litter thickness of 9.7 cm, which enabled a multi-sublayer interception as occurred in the present study. However, I_L should not be neglected even in the crown-dominant interception process. Cumulative I_L during rainfall, litter C_{max}, and postrainfall drainage were all neglected in those studies. In mature forests, the litter layer is typically thick and dense, resulting in higher litter C_{max} and a longer drainage phase. Consequently, I_L would likely have been a major process if those measurements were taken into consideration.

3.2 | Effect of rainfall characteristics on joint interception

P_g had an impact on interception as well. Generally, average crown C_{max} and C_{min} increased 0.010 and 0.003 g cm^{-2} when P_g increased from 10 to 100 mm for all the species (Figure 3). Whereas the interception—P_g—showed different trends for specific species, only C_{min} increased significantly with P_g for *P. tabulaeformis* (r = 0.95, p < .05, Table 2). These scenarios indicate that the interception and drainage process may have been controlled by not only rainfall traits but also crown traits such as leaf morphology, leaf area, texture, and roughness.

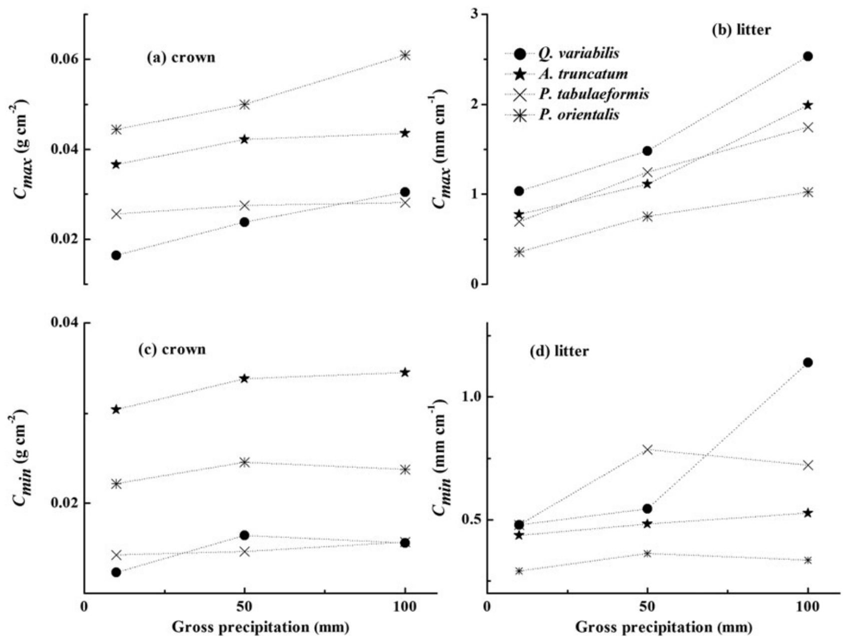

FIGURE 3 Relationships between rainfall intensity and (a) crown C_{max}; (b) litter C_{max}; (c) crown C_{min}; (d) and litter C_{min} on average for each species

TABLE 2 Pearson's rank correlation coefficients between gross precipitation (P_g) and normalized C_{max} and C_{min} for crown and litter for the 48 rainfall simulations

	Crown C_{max} (g cm^{-2})	Crown C_{min} (g cm^{-2})	Litter C_{max} (mm cm^{-1})	Litter C_{min} (mm cm^{-1})
P_g (*Quercus variabili*)	0.96	0.54	0.99*	0.97
P_g (*Acer truncatum*)	0.92	0.80	0.98*	0.95
P_g (*Pinus tabulaeformis*)	0.98	0.95*	0.95	0.39
P_g (*Platycladus orientalis*)	0.94	0.40	0.92	0.54

Note. Two-tailed test of significance is used. Significant correlations (p < .05) are labelled with asterisks. P_g (*Q. variabili*) indicated gross precipitation for *Q. variabili*, same to the following phrase.

In contrast, litter C_{max} and P_g were significantly correlated with a mean r of 0.985 for *Q. variabili* and *A. truncatum* (p < .05, Table 2). The average increment of litter C_{max} was 1.11 mm cm^{-1} for all species (Figure 3b), which was slightly larger than 0.09–0.80 mm cm^{-1} reported in previous studies, as P_g increased from 10 to 250 mm (Sato et al., 2004; Guevara-Escobar et al., 2007; Mo et al., 2009; Lu et al., 2011). One possible explanation for this discrepancy could be that litter was more easily saturated without crown cover in these experiments. This approach to I_L measurements enabled litter leaves in upper layers to be evenly and constantly dampened, while excluding the softening, scattering, and lagging effects of tree crown on rainwater, effects that were evident in our study: The litter along the edge of the tree crowns was wetter than the litter positioned around the tree bole, particularly for the P_g of 10 mm.

On the other hand, litter C_{min} insignificantly (p > .05) fluctuated with P_g (Table 2, Figure 3), and even decreased when P_g increased from 50 to 100 mm for *P. tabulaeformis* (Figure 3d). This effect may be due to its periodic release of rainwater that has accumulated in litter layer gaps during rainfall. The litter's porous structure may result in a cascade effect, as the stored water is released to layers below. This process becomes more pronounced as more water accumulates. This phenomenon has also been reported by Dunkerley (2015). Other studies reported the opposite conclusions. They found that litter C_{min} increased with P_g when ranging from 25 to 250 mm (Putuhena & Cordery, 1996; Sato et al., 2004; Guevara-Escobar et al., 2007; Gerrits et al., 2010; Bulcock & Jewitt, 2012a). The reason for the difference is probably due to difference in *TF* patterns of different tree species and litter structure. Most *RI*s in other studies were less than 50 mm hr^{-1} with small raindrops, which may have settled on crowns to forge large *TF* drops. By comparison, the raindrop diameters in the present study were 1.50–2.98 mm at *RI*s of 50 and 100 mm hr^{-1} (Huo et al., 2015). At those sizes, the raindrops were probably dismantled by the crown or coalesced to constitute large drops. Therefore, *TF* patterns such as median diameter of *TF* drops, distribution, and kinetic energy should be taken into consideration to further address the difference in C_{min} under various rainfall conditions.

3.3 | Effect of crown and litter traits on joint interception

Total leaf area and litter thickness are easily measured structure parameters that can be helpful for scaling up the experimental results to mature forests. Results indicated that crown C_{max} and C_{min} were at the range of 0.01–0.06 g cm^{-2} on a per leaf area basis (Figure 4). which was in agreement with Keim, Skaugset, and Weiler (2006), who reported a C_{max} variation of 0.01–0.08 g cm^{-2} for eight species. On the other hand, mean litter C_{max} and C_{min} varied five-fold on a per litter thickness (H_L) basis, ranging from 0.33 to 1.68 mm cm^{-1} (Figure 4). which was slightly larger than the 0.10–1.54 mm cm^{-1} reported in previous studies (Marin, Bouten, & Dekker, 2000; Sato et al., 2004; Guevara-Escobar et al., 2007; Mo et al., 2009; Bulcock & Jewitt, 2012a; Tsiko et al., 2012).

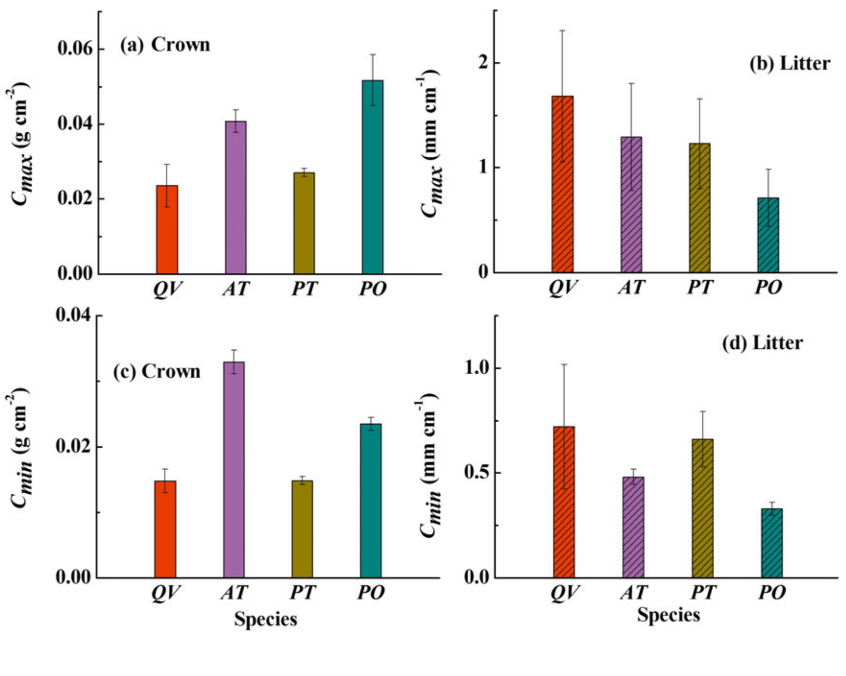

FIGURE 4 Average crown and litter C_{max} and C_{min} for each species regardless of rainfall intensities. *PO* = *Platycladus orientalis*; *PT* = *Pinus tabulaeformis*; *QV* = *Quercus variabilis*; *AT* = *Acer truncatum*. Error bars indicate standard deviation

TABLE 3 Mean crown and litter C_{max} and C_{min} for each species (values without normalization)

	Crown C_{max} (mm)	Crown C_{min} (mm)	Litter C_{max} (mm)	Litter C_{min} (mm)
Quercus variabili	0.29	0.18	6.89	2.95
Acer truncatum	0.59	0.48	7.49	2.79
Pinus tabulaeformis	0.74	0.41	4.05	2.18
Platycladus orientalis	0.86	0.39	3.24	1.50

Furthermore, the impact of leaf morphology on both crown and litter interception was examined. Generally, the responses of needle-leaf trees were different than broadleaf trees, and crown responses differed from litter (Table 3). The crown of needle-leaf trees (*P. orientalis* and *P. tabulaeformis*) generated the largest C_{max} and C_{min}: Needle-leaf crown C_{max} and C_{min} were 1.83 and 1.22 times larger than broadleaf ones, respectively. Conversely, broadleaf litter showed the greatest C_{max} and C_{min}, which were 1.97 and 1.55 times larger than the needle-leaf ones with significant differences observed (p = .002 and .015, respectively). These results agree with previous findings; Barbier, Balandier, and Gosselin (2009) reviewed 20 related studies and found that needle-leaf crown C_{min} was 1.15 times larger than for broadleaf species. Sato et al. (2004) and Li et al. (2013) reported that broadleaf litter C_{max} and C_{min} were 1.3–1.5 and 1.8–2.7 times larger than those for needle-leaf species.

On the per leaf area (*LA*) basis, although needle crown C_{max} and C_{min} were still slightly larger (1.22 and 1.04 times) than broadleaf C_{max} and C_{min}, no significant differences were found (p = .35 and .56). *A. truncatum* showed the greatest crown C_{min} of 0.33 g cm^{-2} among all the species. Similarly, C_{max} and C_{min} for broadleaf litter on a per litter thickness (H_L) averaged 1.49 and 0.60 mm cm^{-1}, respectively, and were not significantly different with needle litter C_{max} and C_{min} of 0.97 and 0.50 mm cm^{-1} (p = .15 and 0.46).

The contrary results obtained on divergent basis indicated that the differences of needle and broadleaf species in interception were the result of differences in *LA* and H_L, yet leaf morphology and surface texture (hairy or smooth), crown structure (open or tight), and litter layer shape (porous or overlapped) may have an impact on interception as well. Thus, more researches is needed to concentrate on how the above co-varieties interact.

3.4 | Effect of biotic and abiotic traits on joint interception

The combining effect of abiotic (e.g., P_g) and biotic traits (e.g., *LA* and H_L) affected joint interception were further studied. Multiple linear regression analysis showed that crown and litter C_{max} and C_{min} were significantly co-determined by P_g, *LA*, and H_L (Equations 1—4) for the four species.

$$\text{Crown } C_{max} = 0.003\ P_g + 0.12\ LA, R = 0.94, p = .0002 \quad (1)$$

$$\text{Crown } C_{min} = 0.001\ P_g + 0.08\ LA, R = 0.96, p = .00003 \quad (2)$$

$$\text{Litter } C_{max} = 0.05\ P_g + 0.62\ H_L, R = 0.96, p = .00004 \quad (3)$$

$$\text{Litter } C_{min} = 0.01\ P_g + 0.36\ H_L, R = 0.95, p = .0007 \quad (4)$$

Generally, the equations highlighted the importance of the co-variables on interception and may have generated rough estimations of C_{max} and C_{min} in future studies. Evidently, the interception processes are complicated and affected by many different biotic and abiotic factors, some of which are difficult to quantify (e.g., leaf and branch surface texture), more importantly, these factors interact with one another. Thus, more measurable variables including varying rainfall intensity (not constant in a rainfall event), rainfall duration, crown height, and branch angle, and related interactions should be taken into account in future interception studies.

4 | CONCLUSIONS

This research focused on the interaction of two interception processes (cumulative I_C and I_L, crown and litter C_{max} and C_{min}). Both I_C and I_L processes consisted of three phases, the dampening phase, stable saturation phase, and postrainfall drainage phase. Although the duration and amount for I_C and I_L were different in each phase, tree crowns dominated during the first 10 min, and litter played the primary role in joint interception during the remaining time. Almost one half of the joint C_{max} drained after rainfall, and the drainage amount may be larger in mature forests given that young trees were used in our study. Overall, litter C_{max} and C_{min} were much larger than crown C_{max} and C_{min}.

Both biotic and abiotic factors impacted interception, which has been proved in multiple linear regression equations. Crown and litter C_{max} and C_{min} increased with increasing rainfall intensity (*RI*) and gross precipitation (P_g), whereas significant correlations between interception amount and P_g were only found for specific species. In general, when comparing the absolute values, needle-leaf species generated larger crown C_{max} and C_{min}, and broadleaf species showed the greatest litter C_{max} and C_{min}. Nevertheless, on per leaf area and litter thickness basis, no significant differences in crown and litter C_{max} and C_{min} were observed between needle-leaf and broadleaf species, indicating that the differences in leaf morphology are also related to the differences in leaf area and litter thickness. In addition, leaf area (or *LAI*) and litter thickness can be used as parameters to scale up experimental results from small trees in the present study to mature forests.

Findings from this research enhance our understanding of the interactive processes that influence crown and litter interception. A more complete understanding of these complex processes will require field experiments under various rainfall (especially under varying and light rainfall), throughfall, and meteorological conditions, with a variety of vegetation types and sizes.

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