Quantifying the effect of non-spatial and spatial forest stand structure on rainfall partitioning in mountain forests, Southern China

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ABSTRACT

Forest stand structure plays an important role in rainfall interception and is a focal point in forest hydrology. Previous studies mainly looked at the effect of non-spatial attributes of stands while a few studies addressed the influence of spatial features. The aim of this study was to quantify the effect of stand structure on rainfall partitioning using diameter, height, leaf area index (LAI), neighbourhood comparison, mingling index and uniform angle index. The results revealed that the average accumulative throughfall, stemflow and interception loss accounted for 72.8%–83.2%, 0.5%–11.3% and 13.3%–26.2% of total precipitation, respectively, and significant differences existed in rainfall partitioning. The accumulative interception loss was negatively related to uniform angle index (a measure of tree spatial distribution patterns) as stand structure attribute was not available at each rainfall event. The effects of stand structure on throughfall, stemflow and interception loss varies considerably under different rainfall conditions. The LAI was significantly associated with interception loss for heavy rainfalls. The mingling index was negatively related to stemflow; however, significant relationships existed between mingling index, throughfall, and interception loss for light rainfall (drizzle). Significant positive relationships existed between uniform angle index and stemflow, while significant relationships existed for interception loss for light and heavy rainfalls. The results highlight that stand structure in combination with rainfall patterns influence rainfall partitioning.

Keywords: rainfall partitioning, LAI, mingling index, uniform angle index, rainfall patterns

RÉSUMÉ

La structure des peuplements forestiers influence grandement l'interception des précipitations et est au cœur même de l'hydrologie forestière. Les études antérieures ont porté principalement sur l'effet des éléments non spatiaux des peuplements et il y a eu peu de travaux sur l'influence des éléments spatiaux. Cette étude avait pour but de quantifier l'effet de la structure du peuplement sur la répartition des eaux de pluie en fonction du diamètre, de la hauteur, de l'indice de surface foliaire (LAI), des comparaisons avec les voisins, de l'indice de mélange (*mingling index*) et de l'indice d'angle uniforme (*uniform angle index*). Les résultats ont montré que la moyenne cumulée de l'égouttement, du ruissellement le long des troncs et des pertes par interception représentaient respectivement 72,8 %–83,2 %, 0,5 %–11,3 % et 13,3 %–26,2 % de toute la précipitation et qu'il y avait des différences significatives dans la répartition de l'eau de pluie. La perte cumulée par interception montrait une corrélation négative avec l'indice d'angle uniforme (une mesure de la distribution spatiale des arbres) puisque nous ne disposions pas d'une mesure de la structure du peuplement pour chaque épisode de pluie. L'effet de la structure du peuplement sur l'égouttement, le ruissellement le long des troncs et les pertes par interception varie considérablement sous différentes conditions de précipitations. Le LAI était étroitement corrélé aux pertes par interception durant les fortes précipitations. Une hausse de l'indice de mélange se traduisait par une diminution du ruissellement le long des troncs; il y avait toutefois une relation significative entre l'indice de mélange, l'égouttement et la perte par interception lors des épisodes de pluie légère (bruine). On a noté des relations positives entre l'indice d'angle uniforme et le ruissellement sur les troncs et des relations significatives avec la perte par interception pour les précipitations légères et fortes. Les résultats montrent clairement que c'est la structure du peuplement combinée à l'intensité des précipitations qui influence la répartition de la précipitation.

Mots-clés : répartition de l'eau de pluie, LAI, indice de mélange, indice d'angle uniforme, intensité des précipitations

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Introduction

Rainfall interception is essential in the water cycle and has been a research topic in forest hydrology for many years (Cui *et al.* 1980; Bosch and Hewlett 1982; Dunkerley 2000; Llorens and Domingo 2007; Tanaka *et al.* 2017). It may be estimated by determining the difference between total precipitation above the canopy and the sum of throughfall and stemflow (Llorens and Domingo 2007; Liang *et al.* 2011; Shinohara *et al.* 2013; Carlyle-Moses *et al.* 2014). Previous studies have shown that the canopy can intercept as much as 10 to 50% of the total precipitation (Roth *et al.* 2007; Carlyle-Moses and Gash 2011). The characteristics of the forest can affect the amount of interception loss (Crockford and Richardson 2000; Xiao *et al.* 2000; Park and Cameron 2008), and rainfall interception by the canopy depends on the amount and intensity of individual rainfall events (Staelens *et al.* 2008; Li *et al.* 2016b). This suggests that the proportion of rainfall separated by canopy interception, throughfall, and stemflow depends to a certain extent on the structure of the forest stand and rainfall patterns.

Rainfall interception is closely related to not only stand structure but meteorological factors (Crockford and Richardson 2000; Xiao *et al.* 2000; Pérez-Suárez *et al.* 2014). These factors relate to the amount and intensity of rain, as well as wind speeds, air humidity deficits and net radiation (Xiao *et al.* 2000; Staelens *et al.* 2008). Canopy cover, leaf characteristics (area, biomass, morphology), and branch traits (densities, number, lengths) are thought to be key factors dominating canopy water storage capacity (Levia *et al.* 2015; Li *et al.* 2016a). Tree height also affects canopy roughness and energy exchange with the atmosphere (Dietz *et al.* 2006). Basal area has a large impact on throughfall (Ponette-González *et al.* 2010; Molina and Del Campo 2012; Zimmermann *et al.* 2013). Stem density (Hölscher *et al.* 2005) and tree diameter (Li *et al.* 2015) may be important for stemflow generation. However, it is still difficult to assess the relative importance of stand structure attributes for rainfall partitioning in the canopy. If a single stand characteristic is analyzed separately, there may be conflicting results. For example, some studies found that throughfall decreases with LAI (Ponette-González *et al.* 2010; Tian *et al.* 2011; Molina and Del Campo 2012; Li *et al.* 2015b), while Dietz *et al.* (2006) and Teale *et al.* (2014) found that LAI has little influence on throughfall. Furthermore, Dietz *et al.* (2006) found that diameter and crown extension were significantly correlated to throughfall for rain > 10 mm d⁻¹ but not for < 10 mm d⁻¹. Peng *et al.* (2014) found the increased extent of interception loss varies with canopy cover and plant area index and depends on rainfall conditions. The two reports highlight the correlation between the effects of stand structure on rainfall partitioning and rainfall conditions.

Structural characteristics of forest stands may be qualitatively represented by non-spatial parameters such as leaf area and biomass, and branch density and inclination (Crockford and Richardson 2000; Levia *et al.* 2015). These parameters represent the canopy structure and not the whole stand. In fact, spatial structure of the stand is more complex than that of the canopy and is rarely examined (Gadow and Hui 2002). Some parameters such as the neighbourhood comparison, mingling index, and uniform angle index (Gadow and Hui 2002; Zhao *et al.* 2012) are commonly used in forest management while rarely used in forest hydrology. These parameters

quantitatively represent the spatial structure of the forest but little research has been carried out to study their effects on rainfall partitioning.

The effect of stand structure on rainfall partitioning deserves further study as it is of considerable importance for forest hydrology. In this paper, the effect of stand structure on throughfall, stemflow and rainfall interception are analyzed. The main objectives are to: (a) analyze the non-spatial and spatial structure of nine stands using diameter, height, LAI (leaf area index), neighbourhood comparison, mingling index, and uniform angle index; (b) quantify the partitioning of rainfall into throughfall, stemflow, and interception loss by nine typical forests; and, (c) determine the relationships between stand structure and rainfall partitioning.

Materials and Methods

The study area was located in the Jinyun Mountain National Nature Reserve (106° 20' 18" to 106° 24' 42" N, 29° 48' 25" to 29° 51' 53" E), Chongqing, China. It is a national nature reserve spanning a wide gradient of species diversity and complexity. The total area is 76 km² with altitudes from 350.0 to 951.5 m.a.s.l. and a humid subtropical monsoon climate with average yearly temperatures of 14.8 °C and 1360 mm precipitation mainly between April and October, accounting for 70%–80% of the total annual precipitation. Evergreen broadleaved species, conifers, and moso bamboo (*Phyllostachys pubescens* Pradelle) are the main forests in this region.

Stand structure measurements

Nine subtropical stands were selected (Table 1), each square and with an area of 3600 m². Diameters breast height (DBH) and heights of trees with DBH > 3 cm were measured; other trees were too small to affect rainfall interception. The coordinate origin was recorded at the northwest corner of each plot, and vertical and horizontal coordinates of each tree measured within areas at least 5-m from the plot limits to avoid edge effects. Six parameters, mean diameter, mean height, leaf area index (LAI), neighbourhood comparison, mingling index, and uniform angle index were used to analyze the stand structure. The representative diameter and height of the stand were estimated by mean diameters and heights of all trees.

LAI, defined as total leaf area divided by crown projection area, was measured by the LAI-2200 Plant Canopy Analyzer (LICOR Inc., Lincoln, NE, USA). Measurements were made monthly with two LAI-2200 sensors under blue sky conditions (ignoring the sun). A 45° field of view cap was used. Above-canopy readings ("A" readings) were made automatically in a nearby clearing space where the LAI-2200 sensor was centrally located and at a distance of 3.5 x the height of the trees. The other sensor collected below-canopy readings ("B" readings). A total of eight "B" readings along two perpendicular axes and four per axis were recorded in every plot. The "A" and "B" readings were taken into account by means of FV2200 software.

Neighbourhood comparison (U_i) is defined as "the proportion of the n nearest neighbour of a given reference tree which is bigger than the reference tree" (Gadow and Hui 2002) and expressed as:

Table 1. Basic information of the observation forest stand plots

Forest types	Abbr.	Exposition and Inclination (°)	Elevation (m)	Slope (°)	Main Tree species
mixed broadleaved/coniferous forest	C ₁	NW 32.2	780	23~28	<i>Pinus massoniana</i> , <i>Symplocos setchuensis</i> , <i>Gordonia acuminata</i> Chang, <i>Lindera kwang-tungensis</i> ;
mixed broadleaved/coniferous forest	C ₂	NW 20.9	830	17~23	<i>Cunning hamia lanceolata</i> , <i>Castanopsis fargesii</i> Franch, <i>Engelhardtia serrata</i> Blume, <i>Quercus fabri</i> ;
mixed broadleaved/coniferous forest	C ₃	NW 37.6	710	15~21	<i>Pinus massoniana</i> , <i>Cunning hamia lanceolata</i> , <i>Symplocos setchuensis</i> , <i>Gordonia acuminata</i> Chang, <i>Cinnamomum camphora</i> ;
evergreen broadleaved forest	B ₁	NW 31.2	830	21~25	<i>Gordonia acuminata</i> Chang, <i>Symplocos setchuensis</i> , <i>Adinandra bockian</i> ;
evergreen broadleaved forest	B ₂	NW 33.2	800 1	5~18	<i>Castanopsis fargesii</i> Franch, <i>Castanopsis carlesii</i> var. <i>spinulosa</i> , <i>Castanopsis carlesii</i> <i>sclerophylla</i> ;
mixed Moso bamboo/coniferous forest	M ₁	NW 35.0	860	13~19	<i>Phyllostachys pubescens</i> , <i>Pinus massoniana</i> , <i>Symplocos setchuensis</i> , <i>Cunning hamia lanceolata</i> , <i>Gordonia acuminata</i> Chang;
mixed Moso bamboo/broadleaved forest	M ₂	NW 36.2	810	16~22	<i>Phyllostachys pubescens</i> , <i>Cunning hamia lanceolata</i> , <i>Symplocos setchuensis</i> , <i>Castanopsis fargesii</i> Franch, <i>Gordonia acuminata</i> Chang;
mixed Moso bamboo/broadleaved/coniferous forest	M ₃	NW 38.9	770	13~20	<i>Phyllostachys pubescens</i> , <i>Gordonia acuminata</i> Chang, <i>Symplocos setchuensis</i> , <i>Lindera kwang-tungensis</i> , <i>Castanopsis fargesii</i> Franch;
Moso bamboo pure forests	M	NW 37.1	720	12~16	<i>Phyllostachys pubescens</i>

$$(1) \quad U_i = \frac{1}{4} \sum_{j=1}^4 k_j$$

If the neighbour j is smaller than the reference tree i , $k_j = 0$; otherwise, $k_j = 1$. With four neighbours, U_i can assume the five values in Fig. 1a.

The estimator for the neighbourhood comparison of a given forest is $\bar{U}$, the arithmetic mean of all U_i values is:

$$(2) \quad \bar{U} = \frac{1}{n} \sum_{i=1}^n U_i$$

Where U_i is the neighbourhood comparison of the i -th reference tree, n is the number of trees.

Mingling index (M_i) is defined as the proportion of the n nearest neighbours that do not belong to the same species (Gadow and Fuldner 1992), and is expressed as:

$$(3) \quad M_i = \frac{1}{4} \sum_{j=1}^4 v_j$$

If the neighbour j does not belong to the same species as the reference tree i , $v_j = 1$; otherwise, $v_j = 0$. With four neighbours, M_i can assume the five values in Fig. 1b.

The estimator for the mingling index of a given forest is $\bar{M}$, the arithmetic mean of all M_i values is:

$$\bar{M} = \frac{1}{n} \sum_{i=1}^n M_i$$

Where M_i is the mingling index of the i -th reference tree, n is the number of trees.

Uniform angle index (W_i) is defined as “the fraction of the angles a_j , which are smaller than the standard angle α_0 ” (Gadow and Hui 2002). In this study, the standard angle α_0 is 72° (Zhao *et al.* 2012). The formula is:

$$(5) \quad W_i = \frac{1}{4} \sum_{j=1}^4 z_j$$

If $a_j < \alpha_0$, $z_j = 1$; otherwise $z_j = 0$. With four neighbours, there are five possible values that W_i can assume (Fig. 1c).

Fig. 1 The meaning for the values of spatial structure parameters. **(a)** Different size of circles represent different tree sizes; **(b)** Different colors represent different tree species; **(c)** α is the angle between the reference tree and its neighbour tree, α_0 is the standard angle.

Most studies use the mean value $\bar{W}$ to reflect the overall distribution pattern of the stand which is expressed as:

$$(6) \quad \bar{W} = \frac{1}{n} \sum_{i=1}^n W_i$$

Where W_i is the mingling index of the i -th reference tree, n the number of trees. The $\bar{W}$ values fall in the interval 0.475–0.517, and the distribution pattern tends to be regular. If $\bar{W}$ values are > 0.517 , the distribution pattern tends to clump and $\bar{W}$ values < 0.475 tend to be random.

Total rainfall, throughfall and stemflow measurements

Total rainfall above the canopy from 27 March to 29 October 2013 was measured using a tipping bucket rain gauge 3 m above the ground and 200 m from the experimental plots. Measurements were recorded at 10-min intervals.

During the measurement period, 66 rainfall events with a total precipitation of 1085 mm were recorded (Table 2). The average amount of rain per event was 16.4 ± 21.2 mm, with a maximum of 81.6 mm and a minimum of 0.2 mm. The duration of rainfall events varied from 0.2 to 27.5 hr, with the average being 10.4 ± 8.1 h. The average rainfall intensity was 2.0 ± 2.0 mm hr^{-1} , with a maximum of 10.1 mm hr^{-1} and a minimum of 0.1 mm hr^{-1} .

Throughfall (TF) in each plot was continuously recorded by 25 rain gauges. Among them, 13 20-cm diameter and 100-cm high gauges automatically recorded the rainfall by 0.2 mm

per tip. The other 12 homemade rain gauges, 20-cm diameter and 40-cm high, verified the data of the automatic stations. These gauges were spaced evenly over a regular 10 m $\times$ 10 m grid in each plot (Fig. 2a) at fixed locations throughout the study period. The gauges were set up 1-m from tree trunks and 100 cm above the forest floor to avoid ground splash and understory effects. The tipping buckets provided automatic measurements of throughfall, and data loggers recorded at 10-min intervals. Data from homemade gauges were collected at three to seven days on days with no rain. The reliability of homemade gauges was examined in terms of independent experiments carried out in an open field, where one standard gauge and three homemade gauges were compared over the 66 rainfall events. A linear relationship with a R^2 of 0.974 was found between the results of standard and homemade gauges (Fig. 2b). Data measured by homemade gauges were corrected according to the linear relationship.

Five diameter classes were defined for each species and a representative tree with a diameter close to the mean value selected. Stemflow (SF) was collected from these trees using plastic tubes cut and surrounding the trunk two to three laps at 1.3 m. These tubes were attached with nails and grouted with glass cement and the ends put into plastic buckets. The water volume was measured at 3- to 7-day intervals on days with no rain, and translated into stemflow (mm) calculated as:

$$(7) \quad SF = \frac{1}{M} \sum_{i=1}^n \frac{SF_n}{K_n} M_n$$

Table 2. Rainfall characteristics

Event	Date	Amount (mm)	Duration (h)	Mean intensity (mm h ⁻¹)	Event	Date	Amount (mm)	Duration (h)	Mean intensity (mm h ⁻¹)
1	2013/3/27	1.0	12.50	0.08	34	2013/6/28	18.4	20.33	0.90
2	2013/4/7	0.6	3.17	0.19	35	2013/6/29	12.6	5.33	2.36
3	2013/4/9	0.4	0.33	1.20	36	2013/7/1	14.6	2.00	7.30
4	2013/4/10	1.8	3.67	0.49	37	2013/7/3	9.8	8.83	1.11
5	2013/4/12	11.4	15.00	0.76	38	2013/7/4	28.4	12.83	2.21
6	2013/4/16	0.2	0.17	1.20	39	2013/7/12	41.2	20.00	2.06
7	2013/4/17	3.4	5.50	0.62	40	2013/7/13	5.9	12.00	0.49
8	2013/4/18	0.6	2.83	0.21	41	2013/7/23	2.2	0.67	3.30
9	2013/4/20	16.2	8.83	1.83	42	2013/7/25	10.1	6.50	1.55
10	2013/4/24	0.2	0.17	1.20	43	2013/7/28	10.3	13.83	0.74
11	2013/4/25	5.4	2.17	2.49	44	2013/7/31	3.8	18.00	0.21
12	2013/4/28	15.0	5.17	2.90	45	2013/8/6	72.2	23.00	3.14
13	2013/4/29	7.6	12.00	0.63	46	2013/8/7	34.7	20.33	1.70
14	2013/4/30	7.0	0.83	8.40	47	2013/8/10	1.5	2.00	0.74
15	2013/5/1	5.0	7.00	0.71	48	2013/8/23	77.4	27.50	2.81
16	2013/5/6	13.8	2.33	5.91	49	2013/8/24	3.6	1.00	3.60
17	2013/5/8	25.2	16.33	1.54	50	2013/8/25	13.4	2.33	5.74
18	2013/5/10	40.2	13.67	2.94	51	2013/8/26	0.6	0.67	0.90
19	2013/5/12	16.0	20.00	0.80	52	2013/8/28	1.4	1.00	1.40
20	2013/5/14	12.0	6.17	1.95	53	2013/8/29	15.2	1.50	10.13
21	2013/5/21	75.8	18.67	4.06	54	2013/8/30	40.0	24.00	1.67
22	2013/5/22	29.4	20.50	1.43	55	2013/8/31	77.4	19.33	4.00
23	2013/5/23	4.8	13.33	0.36	56	2013/9/1	3.6	19.83	0.18
24	2013/5/24	25.0	20.67	1.21	57	2013/9/12	0.6	1.00	0.60
25	2013/5/25	14.0	17.67	0.79	58	2013/9/23	0.6	4.67	0.13
26	2013/5/28	5.0	12.00	0.42	59	2013/9/24	0.2	0.17	1.20
27	2013/5/29	55.6	10.00	5.56	60	2013/9/30	45.0	22.83	1.97
28	2013/6/1	12.0	3.67	3.27	61	2013/10/3	4.8	22.17	0.22
29	2013/6/7	2.4	0.67	3.60	62	2013/10/5	1.2	7.67	0.16
30	2013/6/14	3.0	18.00	0.17	63	2013/10/6	7.0	10.67	0.66
31	2013/6/24	81.6	23.00	3.55	64	2013/10/9	4.8	16.67	0.29
32	2013/6/25	13.2	6.50	2.03	65	2013/10/10	4.8	22.17	0.22
33	2013/6/27	10.6	13.83	0.77	66	2013/10/24	2.5	0.83	3.02

Fig.2 Spatial distribution of the throughfall gauges in each area and regression analyses of the rainfall between standard and homemade rain gauges.

Where SF is stemflow volume (mm), M is the number of trees per unit area (trees/m²), SF_n the stemflow of the sample tree in each diameter class, n the number of trees in the diameter class, K_n the average projection area of the sample tree (m²), and M_n the number of trees in the diameter class.

Statistical analysis

Throughfall data was analyzed using the accumulative percent TF which is the average of 25 rain gauges in each plot. The spatial variability of throughfall (Zimmermann *et al.* 2007) in each stand was measured by the coefficient of variation (CV):

$$(8) \quad CV = \sigma / \mu$$

Where σ is the standard deviation of TF gauge volumes, μ the mean value of TF gauge volumes.

Differences in the accumulative throughfall, stemflow and interception loss among the nine stands were analyzed with a one-way analysis of variance (ANOVA) and the Fisher LSD (Least Significant Difference) test.

The relationships between rainfall interception (dependent variable) and stand structure (independent variable) were investigated through linear regression. The accumulative interception loss was taken as the single dependent variable; total precipitation was classified into four groups to assess correlations between rainfall partitioning: Class I (drizzle, rainfall < 10.0 mm); Class II (moderate, rainfall 10.0–25.0 mm); Class III (heavy, rainfall 25.0–50.0 mm); and, Class IV (rainstorm, rainfall > 50.0 mm). A significance level of $p \leq 0.05$ was used for all analyses which were performed with the statistical SPSS 20.0 program (SPSS, Chicago, Illinois, USA) and Excel 2010.

Results

Stand structure characteristics

Table 3 shows the six structural parameters of the stands. Mean diameters were $7.2 (\pm 3.6)$ – $12.2 (\pm 4.1)$ cm; mean heights varied from 9.0 ± 2.4 m to 14.4 ± 3.3 m. Average LAIs were $1.7 (\pm 0.7)$ – $3.9 (\pm 1.4)$, indicating that the mixed broadleaved-coniferous forests have the highest LAI.

The neighbourhood comparisons of most stands were approximately 0.5, illustrating that they are in a co-dominant state. The M_1 stand is in a partial to a moderately suppressed

state (0.35) and the M_3 stand is almost in a dominant state (0.65). Pure moso bamboo forest illustrates zero mingling, and M_1 , M_2 , and M_3 stands each have the lowest mingling index of 0.5, suggesting that they tend to be moderate mingling. The mingling index of mixed forest C_2 and evergreen broadleaved forests B_1 and B_2 are between moderate and high mingling. Meanwhile, C_1 and C_3 with the highest mingling index (> 0.75) are between high and very high mingling. The uniform angles index of C_1 , C_3 , and B_2 fall in the interval [0.475–0.517], suggesting that the distribution pattern tends to be random. The uniform angle index of C_2 , B_1 , M_1 , M_2 , M_3 , and M is > 0.517 , indicating that the distribution pattern of these stands tend to be clumped.

Throughfall, stemflow and interception loss

During the measurement period, 66 rainfall events with a total precipitation of 1085.1 mm occurred. The average amount of rain per event was 16.4 ± 11.4 mm, with a maximum of 81.6 mm and a minimum of 0.2 mm. The total accumulative throughfall, stemflow and interception loss percentages in rainfall partitioning of the nine stands are presented in Fig. 3. Significant differences exist among most stands ($p < 0.05$). The total accumulative throughfall percentages are in the range of 72.8%–83.2%. The C_2 , B_2 and M_1 stands have significantly higher throughfall compared to the others; no significant differences exist among the three stands. Moreover, no significant differences were found between C_3 and M_3 , and among C_1 , B_1 , M_2 and M . The total stemflow ranges from 0.5% to 11.3%. The pure moso bamboo forest (M) has the highest stemflow compared to the other forest types, followed by mixed bamboo forests, and evergreen broad-leaved forest (M_1 , M_2 and M_3). There were no significant differences among the three stands. The average accumulative interception losses range from 13.3% to 26.2%, with a decreasing order of $C_1 > B_1 > C_3 > M_2 > B_2 > M_3 > C_2 > M_1 > M$. The C_1 and B_1 stands had significantly higher interception losses (26.2% and 24.9%, respectively) compared to the other stands, while M had the lowest at 13.3%. In addition, no significant differences exist between stands C_1 and B_1 , C_2 and M_1 , B_2 and M_2 , B_2 and M_3 , and M_1 and M .

Effect of stand structure on rainfall interception

Linear regressions between the average accumulated interception loss percentage and stand structure parameters are showed in Fig. 4. A significant negative correlation exists between interception loss and uniform angle index (Fig. 4f). Although no statistically significant relationships exist between the accumulated interception loss and the other parameters, interception loss increases with LAI and the mingling index (Fig. 4c and Fig. 4e).

Rainfall 0–10.0 mm and 10.0–25.0 mm accounted for 51.5% and 25.8% of the total number of rainfall

Table 3. Stand structure parameters in the study forest stands. LAI =leaf area index, U =neighbourhood comparison, M =mingling index, W =uniform angle index, SD =standard deviation

Forest types	DBH (cm)		Height (m)		LAI (m ² m ⁻²)		U	M	W
	Mean	SD	Mean	SD	Mean	SD			
C_1	11.2	4.1	12.6	3.0	3.9	1.4	0.52	0.82	0.485
C_2	10.2	2.8	9.0	2.4	3.2	0.9	0.43	0.65	0.519
C_3	11.1	5.3	9.7	3.8	2.8	1.3	0.42	0.79	0.499
B_1	10.5	4.0	10.8	3.1	2.4	1.2	0.47	0.6	0.523
B_2	12.2	4.1	10.4	3.1	2.2	1.6	0.45	0.73	0.517
M_1	10.6	3.7	9.4	2.2	1.7	0.7	0.35	0.57	0.526
M_2	11.4	3.1	9.2	2.4	2.7	0.9	0.47	0.48	0.533
M_3	7.2	3.6	11.8	2.8	3.4	1.3	0.65	0.57	0.529
M	10.0	1.5	14.4	3.3	2.1	1.8	0.52	0	0.548

Fig. 3 Percentage of the total accumulative throughfall, stemflow and interception loss in the nine stands. Bars with same letters are not significantly different according to the Fisher LSD at $p < 0.05$.

Fig. 4 Correlations between average total accumulative interception loss (%) and stand structure parameters.

events, respectively. Rain > 50.0 mm accounted for 9.1%, but the cumulative amount was the most (40.5%) (Table 4).

The uniform angle index was negatively correlated to interception loss which may be due to limited canopy water storage. Rainfall events were classified into four groups to further analyze possible correlations (Fig. 5). No significant relationships or tendencies existed between rainfall partitioning and average tree diameter and height. For all rainfall classes, there were no significant relationships between throughfall, stemflow and LAI (Fig. 5a-1 and Fig. 5a-2). Positive correlations exist between the interception loss and LAI for Class III rainfall (heavy; 25.0–50.0 mm) and Class IV rainfall (rain-storm; >50.0 mm) (Fig. 5a-3).

Although there were no strong relationships between neighbourhood comparisons and rainfall partitioning, throughfall decreased while interception loss increased with neighbourhood comparison for Class II rainfall (moderate; 10.0–25.0 mm) (Fig. 5b-1 and Fig. 5b-3). The mingling index was significantly related to throughfall and interception loss for Class I rainfall (drizzle; <10.0 mm). As the mingling index increased, throughfall decreased while interception loss increased. The mingling index was negatively correlated to stemflow for all rainfall classes, with $R^2 > 0.9$ (Fig. 5c-2). This indicates that the more complex the forest stand, the less rain reaches the ground and stemflow accumulates. Additionally, no significant relationship was found between throughfall and uniform angle index for all rainfall groups (Fig. 5d-1, Fig. 5d-2). For interception loss, significant relationships exist only for Class I (drizzle) and Class IV (rainstorm) (Fig. 5d-3).

Discussion

Forest canopies usually present considerable heterogeneity, resulting in a highly variable spatial distribution of throughfall (Rodrigo and Àvila 2001). Studies have determined that errors of 5.0% or 10.0% can be acceptable (Rodrigo and Àvila 2001; Carlyle-Moses *et al.* 2004). In our study, the 25 gauges were evenly spaced in a regular 10 × 10 m grid to reduce potential errors caused by spatial variability (Fig. 2a). The errors of the accumulative throughfall for 25 gauges in each stand are less than 10.0%, and a lower CV ranges from 0.05 to 0.07 (Fig. 6). This indicates that the array and number of rain gauges in this study are suitable for representing throughfall.

Comparison of the proportion of throughfall and stemflow to total precipitation

Throughfall accounts for 72.8%–83.2% of the total precipitation for the nine stands. The proportions are in the ranges reported in the literature, e.g., 60.0%–95.0% (Crockford and Richardson 2000; Staelens *et al.* 2006; Zimmermann *et al.* 2007). The proportion of throughfall in evergreen broadleaved forests (73.6% to 81.5%) is slightly higher than that observed in an evergreen forest in New Zealand where throughfall was approximately 63.0%–76.0% (Rowe 1983), while throughfall proportions of mixed forests are similar to those reported by Loustau *et al.* (1992) and Dolman (1987). The throughfall proportions measured in pure moso bamboo forests is approximately 10% lower than those documented by Shinohara *et al.* (2013) and Inoue *et al.* (2017).

Compared to throughfall, stemflow is a small component of the total precipitation. In this study, stemflow varied from 0.5% to 11.3%. Proportions measured in mixed broadleaved-

Table 4. Number and frequency of storms by rainfall classes during the study period

Class	Rainfall amount (mm)	Number of storms	Frequency (%)	Cumulative amount (mm)	Accounting for total (%)
I	0.00–10.00	34	51.52	107.3	9.89
II	10.00–25.00	17	25.76	228.8	21.09
III	25.00–50.00	9	13.64	309	28.48
IV	>50.00	6	9.09	440	40.55

Notes: I, II, III, IV represents drizzle rainfall, moderate rainfall, heavy rainfall, rain-storm, respectively.

coniferous and evergreen broadleaved forests are between 0.5% and 1.5%, while *mixed* moso bamboo forests have higher stemflow values of 2.8%–5.1%. These proportions agree with the findings of Levia and Frost (2003) who suggested that stemflow generally represents less than 10% of the total precipitation. *Pure* moso bamboo forests have the highest values of 11.3%. This is similar to the study by Shinohara *et al.* (2013) who estimated the stemflow at 15.2% in a pure bamboo forest of similar stem density. Our value is higher than that observed in a pure bamboo forest in Kumamoto, Japan where stemflow was 5.0% of the total precipitation (Inoue *et al.* 2017), which may be due to lower stem density.

Effect of stand structure on rainfall interception

There was no evidence of a statistically significant correlation between rainfall partitioning and average tree diameter and height in all rainfall classes. This suggests that the spatially averaged structure characteristics are insufficient for characterizing rainfall partitioning variations. Although no significant relationships were found for throughfall and stemflow with LAI in all rainfall classes, a positive correlation existed between interception loss and LAI for heavy rainfalls and storms > 25.0 mm. This could be attributed to limited canopy storage capacity for a specific forest stand. The majority of rain was intercepted by the canopy when the amount was less than the storage capacity, resulting in smaller differences in interception loss among stands. The percent interception loss with total rainfall forms a power law equation. In Fig. 7, our data indicates the threshold value was about 25.0 mm for the nine stands. The canopy storage capacity is largely dependent on leaf area index (LAI) which may explain why LAI plays a significant role on interception loss for rainfall > 25.0 mm.

Neighbourhood comparisons had no significant correlation with rainfall partitioning regardless of the size of the rainfall event. As the average neighbourhood comparisons of most forest stands was 0.5, there were no significant differences (Table 3). Nevertheless, throughfall decreased while interception loss increased with neighbourhood comparisons for moderate rainfall (10.0–25.0 mm). Higher neighbourhood comparisons resulted in greater dimension and superposition of leaves and branches which intercepted more rain and reduced the throughfall amount.

The mingling index played a significantly negative role on stemflow for all rainfall classes. Higher indices resulted in lower stemflow because stands with greater heterogeneity and a greater superposition of branches intercept a large proportion of stemflow and obstruct stemflow paths. This can lead

Fig. 5 Correlations between rainfall partitioning (%) and stand structure parameters under different rainfall classes. *Significant level $p < 0.05$ ** Significant level $p < 0.01$.

Fig. 6 Variation of accumulative TF (%) based on 66 rainfall events in the nine stands.

to a decrease in the stemflow mingling index. The close relationship between throughfall, interception loss and the mingling index for Class I rainfall (drizzle) could be because free throughfall is dominant in small rainfall events, while released throughfall is dominant in an intensive rainfall. As the mingling index does not represent the amount or area of leaves and branches, its potential to explain variations in throughfall is limited.

The uniform angle index is positively related to stemflow for all rainfall classes. Larger uniform angle indices result in larger gaps, providing greater direct access for rainwater flowing to the trunk (Crockford and Richardson 2000). In this study, no significant statistical relationships were found between throughfall and uniform angle index, whereas an increasing trend was found. As throughfall increases, significant relationships exist between uniform angle index and

Fig. 7 The relationship between interception loss (%) and rainfall amount.

interception loss for drizzle rainfall (Class I) and rainstorm (Class IV). In addition to the maximum rainfall frequency of drizzle rainfall (51.5%) and the maximum cumulative amount of rain in the rainstorm event (40.5%) (Table 4), the uniform angle index was closely correlated to the total accumulative interception loss (Fig. 4). This implies that an evenly distribution pattern is associated with a uniform canopy which generates less throughfall and stemflow, and results in an increase in interception loss.

Conclusions

Quantifying the effect of forest stand structure on rainfall partitioning is of considerable importance for forest hydrology. A focus is the impact of stand structure on rainfall partitioning, considering rainfall conditions. In this paper, the effects of non-spatial and spatial structure parameters of nine forest stands on rainfall partitioning were analyzed by 66 rainfall events. The results indicate that the effects of stand structure on throughfall, stemflow and interception loss vary greatly under different rainfall conditions. Leaf area index (LAI) is associated with interception loss for heavy rainstorms. The mingling index affects throughfall and interception loss for light rainfall, and a uniform angle index can affect interception loss for both light and heavy rainfalls. Stand structure, in combination with rainfall patterns, influences rainfall partitioning.

This research may enhance understanding of relationships between spatial structure of forest stands and rainfall partitioning. For all rainfall classes, the mingling index was negatively related to stemflow, while the uniform angle index was positively related. In addition to leaf and branch characteris-

tics, the mingling patterns of different tree species and the spatial distribution of tree positions related to spatial structure should be included in future studies to better simulate interception and calculate water budgets.

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