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# Spatial variability of throughfall and stemflow in an exotic pine plantation of subtropical coastal Australia

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## Abstract:

Large-scale exotic pine plantations have been developed for timber production in subtropical Australia. Few studies investigate the spatial variability of both throughfall and stemflow in such managed pine plantations despite their acknowledged effects on the heterogeneity of hydrological and biochemical processes of forested ecosystems. To examine the spatial variability of rainfall under a 12-year-old pine plantation in a subtropical coastal area of Australia, we observed gross rainfall, throughfall and stemflow over a 1-year period. Our results show that the spatial variability of gross rainfall within a 50 m× 50 m plot is minimal. Throughfall is significantly different among three tree zones (midway between rows, west and east side of trunks), particularly for rainfall <50 mm, with the highest throughfall on the east side of the tree trunks (sum = 85% of gross rainfall) and the lowest in the midway between tree rows (sum = 68% of gross rainfall). These spatial patterns persist among 84% of recorded rainfall events. Spatial variability and time stability of throughfall are better explained by canopy interception of the inclined rainfall resulting from the prevailing easterly wind direction throughout the experiment. The annual stemflow is different among individual sample trees, which is mainly ascribed to the difference in tree size (e.g. projected canopy area and stem diameter). The outcomes of this study would help future investigators better design appropriate sampling strategies in these pine plantations under similar climate conditions. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS gross rainfall; interception loss; canopy storage capacity; rainfall inclination angle; wind-driven rainfall

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## INTRODUCTION

Partitioning of gross rainfall (*P*) into throughfall (*TF*), stemflow (*SF*) and interception loss (*I*) by forest canopies exerts a significant role in the water budget of forest ecosystems (Llorens and Domingo, 2007). The presence of trees affects the volume and also the spatial distribution of net rainfall reaching the forest floor via throughfall and stemflow. The variable throughfall and stemflow fluxes and related solute inputs are of great importance, because they can produce ‘hot spots’ and ‘hot moments’ of hydrological and biogeochemical processes within soils (McClain *et al.*, 2003), e.g. water availability for plants (Ford and Deans, 1978; Bouillet *et al.*, 2002; O’Grady *et al.*, 2005), nutrient concentration and cycling (Whelan *et al.*, 1998; Laclau *et al.*, 2003; Zimmermann *et al.*, 2007) and localized groundwater recharge (Taniguchi *et al.*, 1996; Liang *et al.*, 2009; Guswa and Spence, 2012). Additionally, the spatial patterns of throughfall and stemflow will determine the accuracy of estimates on stand-scale interception losses (Loustau *et al.*, 1992; Shinohara *et al.*, 2010). Consequently, the spatial variability of throughfall and stemflow is potentially a significant control on forest hydrology and biogeochemistry (Hopp and McDonnell, 2011; Levia *et al.*, 2011; Coenders-Gerrits *et al.*, 2013).

Field investigations have exhibited considerable variability in throughfall over diverse forest types globally (e.g. Llorens and Domingo, 2007; Krämer and Hölscher, 2009; Wullaert *et al.*, 2009; Mululo Sato *et al.*, 2011). Stemflow has demonstrated even higher variability than throughfall (e.g. Lloyd and Marques, 1988; Loustau *et al.*, 1992; Levia *et al.*, 2010). The variability of throughfall and stemflow is influenced by a number of factors, including canopy structure and architecture (e.g. Crockford and Richardson, 2000, Loescher *et al.*, 2002; Deguchi *et al.*, 2006; Ziegler *et al.*, 2009), rainfall intensity and duration (e.g. Huber and Iroumé, 2001; Carlyle-Moses *et al.*, 2004; Zhan *et al.*, 2007), wind

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direction and speed (e.g. Herwitz and Slye, 1995; Šraj *et al.*, 2008; Van Stan *et al.*, 2011).

Apart from throughfall and stemflow, open-field gross rainfall is also characterized by high spatial variability from sub-kilometre scale to large catchment scale (Syed *et al.*, 2003; Ciach and Krajewski, 2006; Villarini *et al.*, 2008; Fiener and Auerswald, 2009). For example, McConkey *et al.* (1990) studied the spatial variability of gross rainfall using ten tipping-bucket rain gauges spaced between 800 and 4000 m apart and suggested that gross rainfall must be observed within a few hundred metres of the study site to obtain reliable gross rainfall. Krajewski *et al.* (2003) analysed the small-scale (<5 $km^2$) gross rainfall variability in different climatic regimes and identified large variability at the small distances. However, the spatial patterns of gross rainfall at finer scales (sub-hundred-metre scale) at which most throughfall experiments were performed have seldom been examined.

In subtropical Australia, as in many other regions and countries, exotic pine plantations have been largely developed for timber production in recent decades (Kanowski *et al.*, 2005). To optimize the management of these plantations in terms of soil water and nutrition availability, a better understanding of the spatial distribution of rainfall within forests and its controls is required. Although researchers have investigated the throughfall and stemflow in areas of pines (e.g. Valente *et al.*, 1997; Shachnovich *et al.*, 2008; Molina and Del Campo, 2012), few studies have focused on the spatial variability in both throughfall and stemflow, as well as their drivers in managed pine plantations. Particularly, the spatial variability of throughfall and stemflow in pine forests planted under subtropical coastal conditions characterized by hot humid summers with frequent intense thunderstorms and mild dry winters have hitherto not been reported.

Here, we examine the heterogeneity of gross rainfall, throughfall and stemflow, as well as the resulting interception loss in a typical pine plantation of subtropical Australia. Specific objectives of this study are to (1) identify the patterns and magnitudes of variability in gross rainfall, throughfall and stemflow, (2) explore the main driving factors for spatial variability of throughfall and stemflow and (3) determine the proportions of throughfall, stemflow and interception loss in this plantation.

## MATERIALS AND METHODS

### *Site description*

The present study was conducted on Bribie Island at an elevation of 9.0 m above sea level (26°59′04″S, 153°08′18″E), located in southeast Queensland, Australia. This area has a humid subtropical climate (Köppen climate classification *Cfa*) with a hot wet summer and a mild dry winter. According to the rainfall data from the Australian Bureau of Meteorology, the average annual rainfall over the last 30 years is 1405 mm, with 1082 mm (77.0% of annual rainfall) occurring during the wet season (November–April). The coldest and warmest months are July and January, with average monthly temperatures of 16.2 and 26.7 °C, respectively. A representative study plot (50 m× 50 m) was established in a pine stand surrounded by similar stands, extending 0.8, 1.2, 2.1 and 4.3 km to the west, east, north and south, respectively. The plot was established at least 15 m (15–20 m) away from the tracks to the south and the west to minimize the edge effect (Figure 1 (a)). The 12-year-old pine hybrid of *Pinus elliottii* Engelm. × *Pinus caribaea* Morelet var. *hondurensis* (second rotation) was planted in rows (roughly 5.0 m between tree rows and 2.5 m between the trees in a row). The pine trees reached an average height of 13.3 m, and the tree

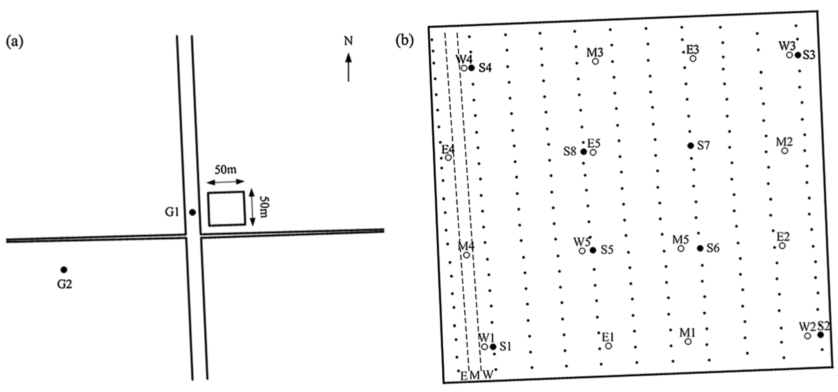


Figure 1. (a) Locations of two gross rainfall gauges (G1 and G2) on the track and in the nearby clearing. The 50 m× 50 m study plot used for throughfall measurements was represented by the square. (b) Locations of the 15 throughfall gauges deployed at three tree zones (E, W and M): tree trunk to east edge of projected crown area (E1–E5), tree trunk to west edge of projected crown area (W1–W5) and pathway in between edges of projected crown area (M1–M5) and eight stemflow gauges (S1–S8). The dots represent locations of pine trees

crowns were slightly overlapping above the rows (5–10%), leaving a gap area of ~1.5 m width between rows. The stem density was 840 trees $ha^{-1}$ and stand basal area was 23.6 $m^2$ $ha^{-1}$. The soils in the study area are classified as fine to medium sands based on US Department of Agriculture (USDA) soil classification system.

*Measurement of stand characteristics*

The forest canopy height was measured from the ground to the top of the tree canopy using a clinometer and a tape measure. The crown radius was determined as the horizontal distance from the tree trunk to the projected edge of the crown along four main compass directions (N, S, W and E). The stem diameter at breast height (DBH) (1.3 m above ground surface) was obtained using a diameter calipre. The number of trees and stem diameter were surveyed within the experimental plot to obtain stem density and stand basal area. The canopy gap fraction ($p$) and leaf area index (LAI) were seasonally measured 1.0 m above each rain gauge in the late evening using a LAI-2000 plant canopy analyser (LI-COR, Lincoln, USA). The $p$ and LAI above each throughfall gauge was determined for the circle with a radius of ~1.3 m at the canopy height, equivalent to a zenith angle of 7°. The $p$ was calculated as the ratio of below-canopy and above-canopy readings, and the canopy cover ($c$) was then determined as 1-$p$. The LAI-2000 plant canopy analyser tends to underestimate LAI for conifers because of the clumping effects (Gower and Norman, 1991). The estimated LAI values were thus corrected by a factor of 1.11, on the basis of the measurements in a pine stand of same species in southeast Queensland by Baynes and Dunn (1997). The canopy storage capacity ($S$) above each throughfall gauge was estimated by the method of Leyton *et al.* (1967), as the negative intercept of linear regression between gross rainfall and throughfall for rainfall events that were sufficient to saturate the canopy.

*Meteorological variables*

An automatic weather station was set up in the centre of the study plot to measure temperature and relative humidity (HMP155 sensor, Vaisala, Finland), wind speed and direction (Model 03002 wind sentry set, RM Young, USA), solar radiation (CNR4 net radiometer, Kipp & Zonen, the Netherlands) and soil heat flux (HFP01 soil heat flux plates, Hukseflux, the Netherlands). The weather station was mounted on a 15-m-high mast, which was ~1.5 m above the tree canopy. These meteorological variables were continuously measured at 5-min intervals and automatically recorded to a datalogger (CR3000, Campbell Scientific, USA) at 15-min intervals. Gross rainfall was measured using two HOBO tipping-bucket rain gauges with a 177 $cm^2$ orifice (RG3-M, Onset Computer Corp., USA), one in the middle of a ~30 m wide track next to the study plot, and the other in the centre of a nearby clearing at a distance of ~400 m (Figure 1(a)). The bucket tipping time (0.5 s resolution) and numbers were automatically recorded by a self-constructed datalogger.

*Experimental design*

To investigate the spatial variability of gross rainfall and quantify potential instrumental errors in rain gauge records, 16 tipping-bucket rain gauges were deployed within a 50 m × 50 m plot in the nearby clearing from 5 December 2011 to 14 March 2012 before the throughfall and stemflow measurements. These rain gauges were set up in a lattice-like arrangement at 16 m × 16 m spacing. All the tipping-bucket rain gauges used in this study were placed 50 cm above the ground to avoid droplet splash effects, and the screen covers on rain gauges were cleaned and maintained every one or two months to prevent from clogging by leaves and other debris. These rain gauges were calibrated to 0.2 mm per tip in the lab, and dynamically recalibrated in the field seasonally to ensure the accuracy of the rain gauges (Calder and Kidd, 1978).

Throughfall and stemflow were simultaneously measured from 20 March 2012 to 23 March 2013. Throughfall was sampled using 15 rain gauges identical to those used for gross rainfall measurements. To quantify the impact of tree rows on the spatial variability of throughfall, rain gauges were distributed over three tree zones (Figure 1(b)). Within each zone, five rain gauges were placed at a fixed position throughout the experiment period to evaluate the effects of rainfall characteristics on spatial variability of throughfall. Ten rain gauges were positioned ~0.75 m from the tree trunk on east and west sides of the trunks, and the other five rain gauges were located in the midway between tree rows.

Stemflow was collected on eight trees using spiral-type stemflow collectors made of wired rubber hose with 2.5 cm in diameter (Toba and Ohta, 2005). Each collector channel was wrapped at least one and a half loops around the tree stem, and the collected stemflow was diverted to a HOBO tipping-bucket rain gauge. The upscaled equivalent stand-scale stemflow depth was obtained following Hanchi and Rapp (1997):

$$SF = \sum_{i=1}^{n} \frac{S_i \cdot m_i}{A \cdot 10^4} \qquad (1)$$

where $SF$ is the stand-scale stemflow depth (mm) for the study area of $A$ ($m^2$), $n$ is the number of DBH classes and $S_i$ and $m_i$ are the average stemflow volume (ml) and the number of trees in the DBH class, respectively.

 

*Determination of rainfall inclination angle*

The rainfall inclination angle ($\alpha$, in degree from the vertical) was computed following a series of empirical equations (Herwitz and Slye, 1995):

$$D = 2.23(0.03937i)^{0.102} \quad (2)$$

$$u_r = 3.378 \ln D + 4.213 \quad (3)$$

$$\tan\alpha = u/u_r \quad (4)$$

where $D$ is the median raindrop diameter (mm); $i$ is the rainfall intensity (mm h$^{-1}$); $u_r$ is the terminal fall velocity of raindrops (m s$^{-1}$) and $u$ is the wind velocity (m s$^{-1}$). The rainfall inclination angle was calculated at 15-min intervals, and the average inclination angle for each rainfall event was computed as the mean of all 15-min values.

*Time stability of spatial variability of throughfall*

To evaluate the time stability of throughfall patterns, throughfall collected by each throughfall gauge during all rainfall events was normalized using Equation (5) (Keim *et al.*, 2005):

$$\widetilde{T} = \frac{T_i - \overline{T}}{SD} \quad (5)$$

where $\widetilde{T}$ is the normalized throughfall, $T_i$ is the throughfall at a sampling point, $\overline{T}$ is the mean throughfall for all sampling points and $SD$ is the standard deviation of throughfall for all sampling points.

*Data analysis*

Data analyses were carried out using statistical software SPSS (version 16.0, SPSS Inc., USA). The Kolmogorov–Smirnov statistic was used to test the normality of mean throughfall distribution (Molina and Del Campo, 2012). Differences in total throughfall among three tree zones were tested by nonparametric tests (Kruskal–Wallis test) because the (transformed) throughfall data were deviated significantly ($p < 0.05$) from normal distribution. The spatial variability of gross rainfall, throughfall and stemflow was indicated by the coefficient of variation (*CV*). The relationships between throughfall, stemflow, canopy structure and climate variables were studied by correlation analysis.

## RESULTS

*Rainfall characteristics*

A rainfall event was defined as a rainfall period from preceding and succeeding rainfall being separated by at least 6 h to entirely dry the wet canopy (Murakami, 2006). A total of 107 rainfall events were thus identified and analysed. The annual gross rainfall amounted to 1579 mm, which was higher than the long-term mean annual rainfall of 1405 mm. Specifically, the observed wet-season rainfall of 1250 mm was 171 mm greater than usual, whereas the dry-season rainfall of 321 mm remained similar to the usual mean of 326 mm. On the basis of the rainfall amounts, the gross rainfall was divided into five classes: <5, 5–10, 10–20, 20–50 and >50 mm (Table I). Most rainfall events were less than 20 mm (80.6% of total events). Small rainfall events (<5 mm) occurred frequently (46.9% of total events), but their contribution to the annual rainfall was less than 8.0%. Although only seven heavy storms (>50 mm) were recorded, they accounted for 41.4% of the annual rainfall. The average rainfall intensity during each rainfall event varied from 1.6 to 11.4 mm h$^{-1}$, with the maximum intensity of 58 mm h$^{-1}$. Eighty-six percent of rainfall events were accompanied by easterly winds (38% NE and 48% SE) and the rest by NW and SW winds (Figure 2). The average wind speed observed during rainfall mainly ranged from 1.5 to 4.0 m s$^{-1}$, with minimum and maximum wind speeds reaching 0.5 and 11.8 m s$^{-1}$, respectively. The rainfall inclination angle varied from 5° to 47° but was dominantly between 10° and 30°, accounting for 78.6% of all sampled events (Figure 3).

Table I. Throughfall measured at three tree zones for different rainfall classes (mean ± standard error). Within each rainfall class, values followed by the same letter are not significantly different ($p < 0.05$)

| Rainfall classes (mm) | Frequency (%) | Gross rainfall (mm) | Throughfall (mm) | | |
|---|---|---|---|---|---|
| | | | West side of trunk | East side of trunk | Midway between tree rows |
| <5 | 46.9 | 118.0 | 67.6 ± 1.6 a | 75.6 ± 1.8 b | 50.2 ± 2.2 c |
| 5–10 | 20.4 | 165.8 | 117.6 ± 1.2 a | 129.2 ± 4.5 b | 94.8 ± 2.8 c |
| 10–20 | 13.3 | 202.2 | 158.1 ± 5.7 a | 168.0 ± 1.8 b | 130.2 ± 6.5 c |
| 20–50 | 13.3 | 440.6 | 363.5 ± 2.6 a | 397.4 ± 5.7 b | 314.1 ± 9.4 c |
| >50 | 6.2 | 652.8 | 560.7 ± 9.5 a | 576.2 ± 16.2 a | 483.9 ± 18.4 b |
| All | 100.0 | 1579.4 | 1267.5 ± 14.9 a | 1346.4 ± 24.3 b | 1073.3 ± 37.6 c |

 

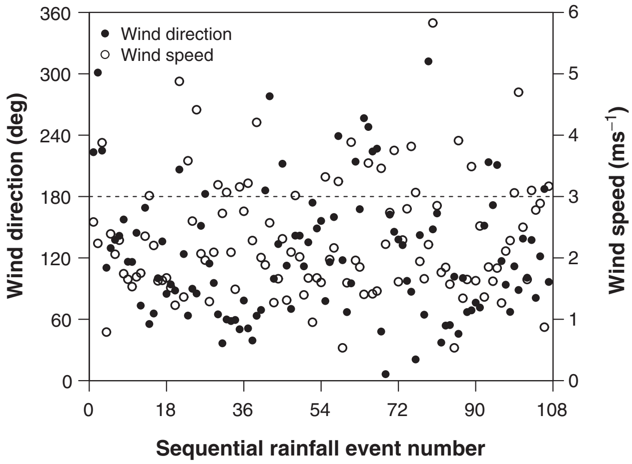


Figure 2. Mean wind direction and speed during individual rainfall event

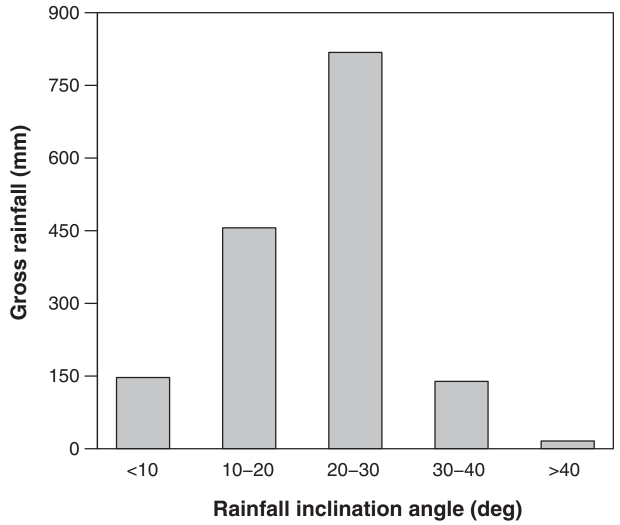


Figure 3. Total gross rainfall for different classes of rainfall inclination angle over the study period

## *Small-scale variability of gross rainfall*

The collected gross rainfall by 16 rain gauges showed a small variability from each other especially for rainfall events >5 mm, and the $CV_g$ remained almost constant at 3.5% for these rainfall events (Figure 4). The average standard error of mean gross rainfall was estimated at 2.1%, ranging from 3.7% to 1.2% in case of 1 and 170 mm rainfall events, respectively. It was thus assumed that gross rainfall was uniformly distributed over the small-scale plot (50 m× 50 m), but the resulting $CV_g$ was incorporated into the analysis of spatial variability of throughfall afterwards.

## *Variability of throughfall*

A strong and positive linear correlation was revealed between throughfall and gross rainfall ($TF = 0.802P$-1.023,

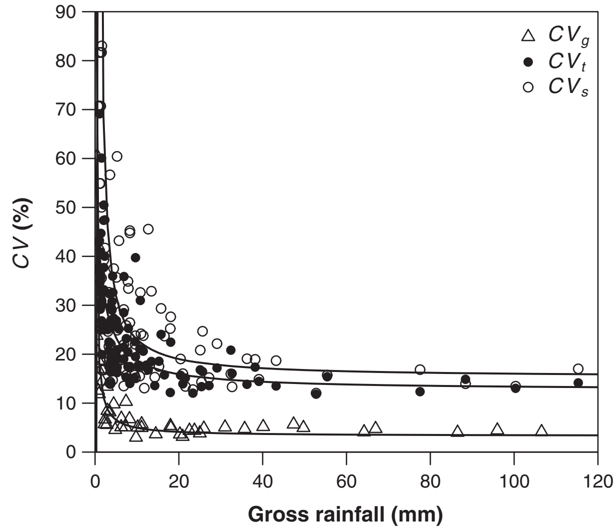


Figure 4. Coefficient of variation of gross rainfall ($CV_g$), throughfall ($CV_t$) and stemflow ($CV_s$) against gross rainfall

$R^2 = 0.996$, $n = 107$, Figure 5(a)). Annual throughfall was 1231 mm, representing 77.9% of the annual gross rainfall of 1579 mm. The relative throughfall ($TF_r$, expressed as percentage of gross rainfall) ranged from 21% to 85%, averaged 64% and tended to quasi-constant 81% as gross rainfall increased (Figure 5(b)). The coefficient of variation of throughfall ($CV_t$) coupled with $CV_g$ was greatly affected by the rainfall amount when gross rainfall was below 10 mm, and it was larger among these small rainfall events (mean = 40%, range = 13−66%). However, the $CV_t$ decreased down to 20% for gross rainfall of 20 mm and remained at ~16.5% for greater rainfall events.

On the basis of the nonparametric tests, significant differences in throughfall among different tree zones were revealed for 93 of 107 rainfall events ($p < 0.05$). The throughfall in the midway between tree rows was the lowest and throughfall on east side of tree trunks was the highest, but this difference was not statistically significant for heavy rainfall events (>50 mm), especially for throughfall gauges close to tree trunks (Table I). The confidence intervals of estimated throughfall varied from ±6% to ±17% of the mean throughfall, with 89 out of 107 being less than 10% of the estimates, and the confidence interval of the estimated annual throughfall was ±7% of mean annual throughfall.

Throughfall patterns indicated that the distribution of throughfall was heterogeneous, but the spatial patterns appeared to be stable among rainfall events (Table I), which was further confirmed by the time stability of the spatial variability of throughfall (Figure 6). Persistence of higher and lower throughfall was detected close to tree trunks and in the midway between tree rows, respectively. More rainfall was collected on east side of tree trunks than on west side. However, rain gauges in the midway

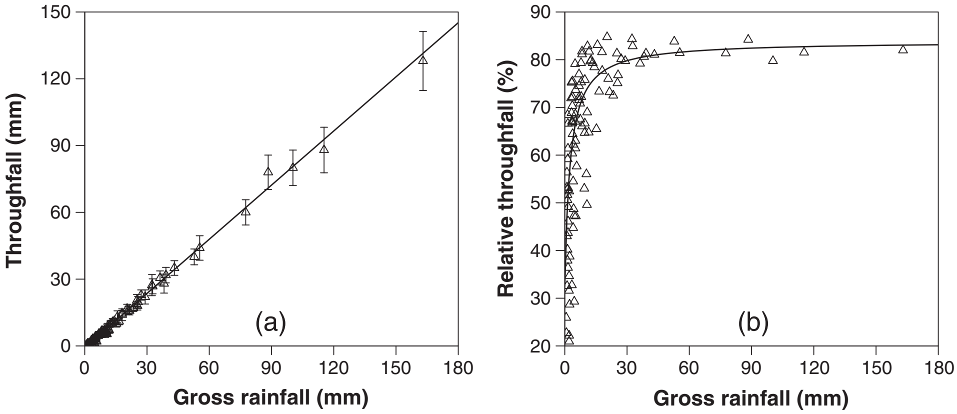


Figure 5. (a) Spatially averaged throughfall (mean ± standard deviation) and (b) relative throughfall (expressed as percentage of gross rainfall) as a function of gross rainfall

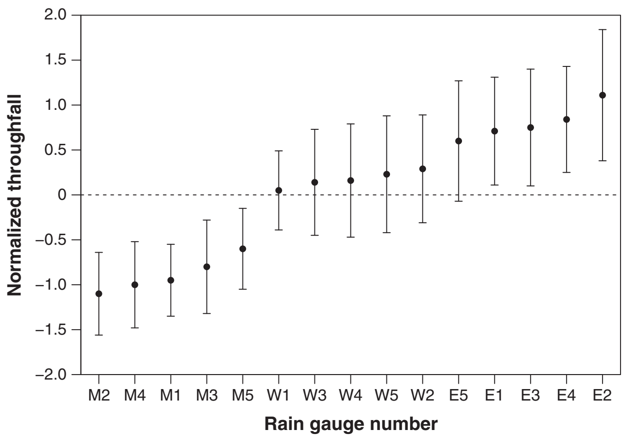


Figure 6. Time stability plot of normalized throughfall. The gauges were plotted along the horizontal axis and ranked by mean normalized throughfall, and error bars are plus and minus one standard deviation

showed slightly lower variability of normalized throughfall than gauges close to tree trunks, indicated by error bars.

The estimated canopy storage capacity above the 15 throughfall gauges based on the relationship between throughfall and gross rainfall, ranged between 0.61 mm and 1.67 mm during the study period, with a mean of 1.12 mm. The measured canopy cover within a zenith angle of 7° above the 15 throughfall gauges was on average 57%, ranging from 23% to 91%. The corresponding LAI ranged from 1.22 $m^2 m^{-2}$ to 2.56 $m^2 m^{-2}$, with a plot-average of 1.97 $m^2 m^{-2}$. A negative exponential correlation was revealed between relative throughfall and canopy storage capacity ($TF_r = 115.313e^{-0.283S}$, $R^2 = 0.761$, $n = 15$, Figure 7(a)). However, positive power correlations were found between relative throughfall and LAI ($TF_r = 68.596\text{LAI}^{0.332}$, $R^2 = 0.679$, $n = 15$, Figure 7(b)) and canopy cover ($TF_r = 94.234c^{0.178}$, $R^2 = 0.801$, $n = 107$, Figure 7(c)).

The wind direction was found to significantly influence the distribution of throughfall within different tree zones (Figure 8). The highest throughfall occurred on the windward side of tree trunks. However, throughfall gauges in between tree rows received lowest throughfall under both easterly and westerly wind conditions. No correlation was found for maximum rainfall intensity, but a negative relationship was revealed between the variability of throughfall and the average rainfall intensity (Figure 9). Generally, the coefficient of variation of throughfall tended to decline with the increase in rainfall intensity.

*Variability of stemflow*

Average annual stand-scale stemflow was 15 mm, accounting for only 1.0% of the annual gross rainfall. Stemflow was well correlated to gross rainfall and increased with increasing gross rainfall (Figure 10(a)). The stemflow was small for rainfall less than 30 mm. For rainfall larger than 50 mm, the stemflow varied from 1.0% to 1.3% of gross rainfall (Figure 10(b)). The coefficient of variation of stemflow ($CV_s$) among trees greatly depended upon the gross rainfall (Figure 4). The average $CV_s$ was 0.46 for rainfall below 5 mm. As observed for throughfall, the $CV_s$ tended to decline asymptotically to 18% as gross rainfall increased, but the $CV_s$ was higher than $CV_t$. The higher variability of stemflow caused much larger confidence intervals of estimated stemflow than throughfall (12−49% of mean stemflow).

The total stemflow volumes (TSV) differed among individual sample trees (Table II). The TSV received by the largest sample tree (tree 6) was 2.5 times larger than that sampled by the smallest sample tree (tree 1). Generally, positive relationships were obtained between stemflow volume per millimetre of rain (SVR) and projected crown area (PCA) (SVR = 0.0202 PCA-0.0003, $R^2 = 0.77$, $n = 8$) and DBH (SVR = 0.0194 DBH-0.2137, $R^2 = 0.67$, $n = 8$).

 

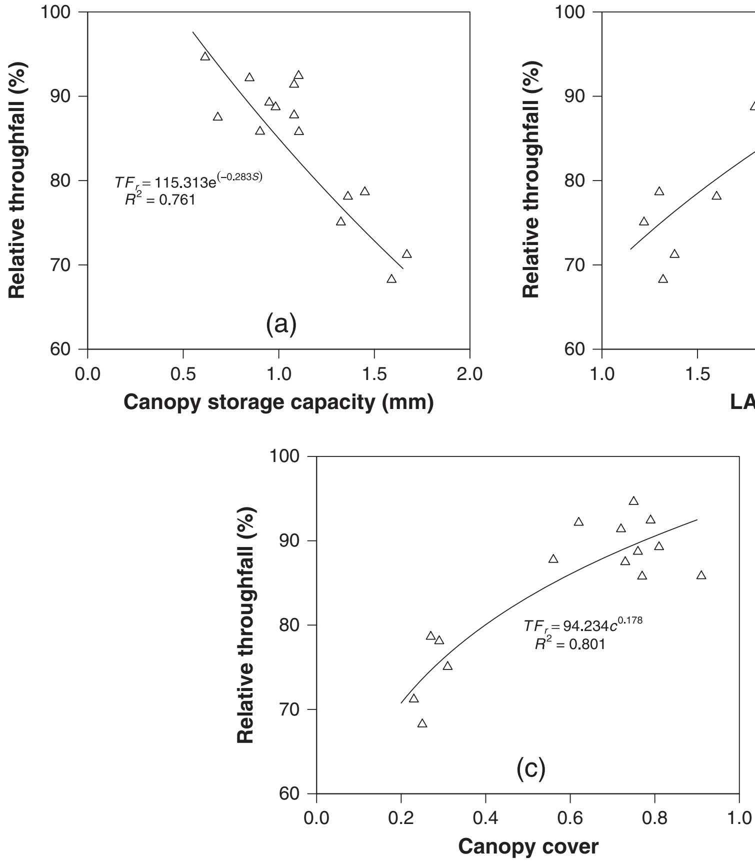


Figure 7. Relationships between relative throughfall ($TF_r$, as percentage of gross rainfall) and (a) canopy storage capacity ($S$), (b) leaf area index (LAI) and (c) canopy cover ($c$)

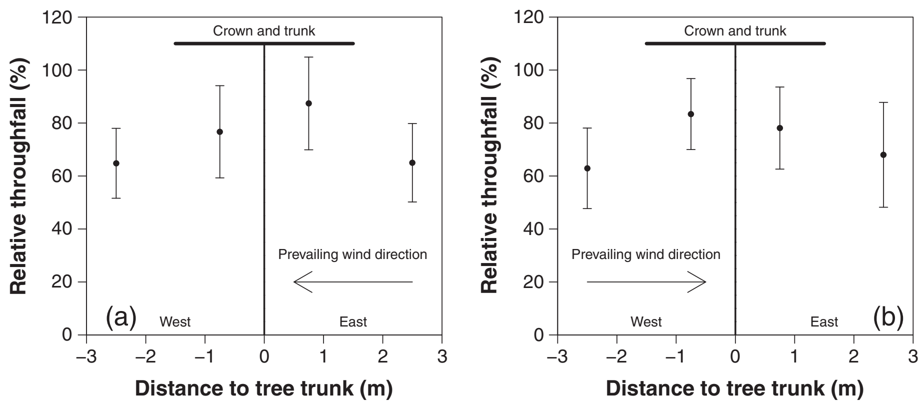


Figure 8. Distribution of mean relative throughfall (± standard deviation) within three tree zones: (a) during easterly wind-driven rainfall events ($n = 89$) and (b) during westerly rainfall events ($n = 18$)

*Derived rainfall interception loss*

Interception loss was estimated by the difference between the measured gross rainfall and net rainfall (throughfall plus stand-scale stemflow). The derived annual interception loss was 333 mm, representing 21.1% of gross rainfall. The interception loss increased as gross rainfall increased, but relative interception loss declined with increasing gross rainfall. Relative interception loss was large (average = 64%, range = 23−81%) for rainfall below 5 mm, around 30% for rainfall of 10 mm and was nearly stable (~20%) for heavier rain events (>30 mm). The total interception loss for rainfall below 5 mm only occupied 13% of the annual interception

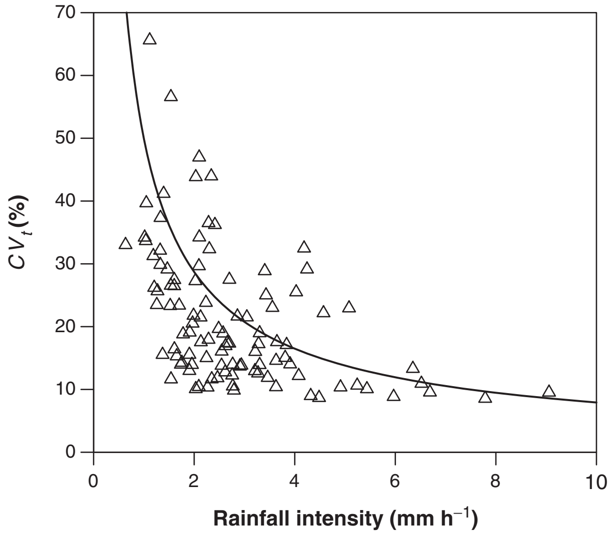


Figure 9. Coefficient of variation of throughfall ($CV_t$) against mean rainfall intensity

Table II. Tree size characteristics, total stemflow volume (TSV) and stemflow volume per mm of rain (SVR). PCA and DBH represent projected crown area and stem diameter at breast height, respectively

| Tree number | Canopy height (m) | PCA ($m^2$) | DBH (cm) | TSV (l) | SVR (l mm$^{-1}$) |
|---|---|---|---|---|---|
| 1 | 11.5 | 5.7 | 15.3 | 173 | 0.11 |
| 2 | 12.1 | 4.5 | 17.4 | 186 | 0.12 |
| 3 | 12.7 | 9.6 | 21.4 | 234 | 0.15 |
| 4 | 13.5 | 8.6 | 21.2 | 276 | 0.17 |
| 5 | 12.4 | 5.7 | 16.5 | 135 | 0.09 |
| 6 | 14.1 | 11.3 | 22.3 | 431 | 0.27 |
| 7 | 13.4 | 10.8 | 20.3 | 334 | 0.21 |
| 8 | 13.8 | 7.1 | 19.6 | 258 | 0.16 |

loss, whereas that for rainfall >30 mm accounted for 34% of the annual interception. The confidence intervals of interception loss were averaged at ±31% of the mean interception loss.

## DISCUSSION

### *Spatial variability of gross rainfall*

The assumption of uniform distribution of gross rainfall within the experimental plot is usually applied when investigating the spatial variability of throughfall. The low coefficient of variation (3.5%) and average standard error (2.1%) of gross rainfall in the present study indicated that this assumption could be valid over a small study plot (50 m× 50 m) in subtropical coastal areas. Particularly, the variability of gross rainfall measured at this small scale can be most likely subject to the stochastic errors from tipping-bucket rain gauges (Krajewski *et al.*, 2003). Therefore, the variability of variation resulted from these instrumental errors needs to be considered when analysing the spatial variability of throughfall.

### *Spatial variability of throughfall*

The minimum number of throughfall gauges ($N_{min}$) required to estimate throughfall within a preset percentage of mean ($E$) at 95% confidence interval can be estimated from $CV_t$ following Kimmins (1973):

$$N_{\min} = \frac{{z_c}^2 \times {CV_t}^2}{E^2} \quad (6)$$

where $z_c$ is the critical value of the 95% confidence level (approximately 2.0).

To estimate the throughfall within 10% of mean at the 95% confidence interval on the basis of $CV_t$, the required number of throughfall gauges would be on average 17 (range = 4−66) for gross rainfall events >3 mm. For gross rainfall events <3 mm, much more throughfall gauges would be required (average = 67, range = 15−173). The 15 throughfall gauges used in the present study were sufficient to estimate the mean throughfall within the acceptable error limit of 10% for gross rainfall events

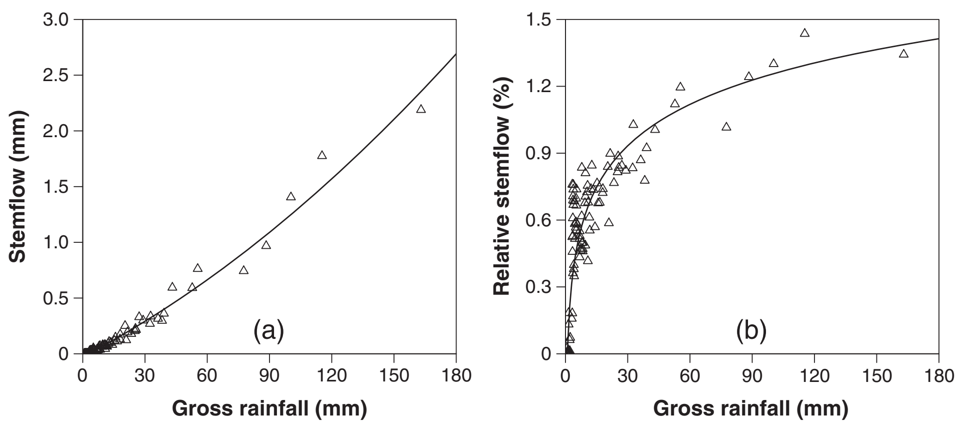


Figure 10. (a) Stand-scale stemflow and (b) relative stemflow (expressed as percentage of gross rainfall) as a function of gross rainfall

>3 mm (mean = ±9%) and for the total throughfall over the study period (±7%).

Stationary collectors were found to typically produce higher $CV_t$ than roving collectors (Holwerda *et al.*, 2006; Levia and Frost, 2006). More collectors are thus required to obtain reliable estimates on plot-average throughfall. To minimize the number of gauges for throughfall estimates with high confidence level and low error, periodically relocating the collectors has been adopted (Ritter and Regalado, 2012). In difficult-to-access areas, collecting troughs with larger sampling area are recommended (Ziegler *et al.*, 2009; Mair and Fares, 2010). However, fixed gauges have to be used, as we did in this study, when focusing on the spatial distribution of throughfall and determining their drivers. Although the layout of throughfall gauges appeared to produce acceptable throughfall estimate in our study, the uncertainty in estimation of stand-scale throughfall resulted from the specific placement of gauges has to be acknowledged. The throughfall gauges were fixed in the centre of each tree zone throughout the experiments, which could leave the other locations poorly sampled and thus cause sampling errors on stand-scale throughfall estimation.

The quasi-constant $CV_t$ of ~16.5% appeared lower than generally reported values in non-subtropical pine forests. Gash and Stewart (1977) reported that the variability of throughfall in a Scots pine plantation was around 22% based on 24 roving gauges. Using 40 rain gauges, Zhan *et al.* (2007) found $CV_t$ remained at 18% in a Chinese pine plantation. Similarly, Loustau *et al.* (1992) found the $CV_t$ to be around 19% in a maritime pine stand using 52 fixed gauges. However, the present result was higher than the findings by Llorens *et al.* (1997) in a Mediterranean mountainous *Pinus sylvestris* forest, where a lower steady $CV_t$ of 6% was revealed. In the aforementioned studies, number and type of rain gauges, forest and rainfall characteristics were different from this study. The lower canopy cover and higher canopy openness in this studied young pine plantation may reduce potential drip points and hence produced less spatial variability in throughfall (Carlyle-Moses *et al.*, 2004). Besides, the lower variability of throughfall may be ascribed to relative high rainfall intensity from summer storms in the humid subtropical areas where the canopy was saturated in a short time (Zhan *et al.*, 2007). Finally, the lower variability of throughfall could be caused by the limited sampling points of throughfall, as discussed earlier.

Time stability analyses confirmed the persistence of higher relative throughfall close to the pine trees and lower relative throughfall in the midway between tree rows among rainfall events. In contrast, Whelan *et al.* (1998) found less throughfall close to the spruce trunks, whereas Loustau *et al.* (1992) found that the throughfall in between pine trees was the highest for light rainfall but the lowest for heavy rainfall events. Keim *et al.* (2005) reported higher throughfall close to tree trunks in young coniferous forests, but lower throughfall occurred close to trunks in old stands of conifers, which was attributed to the difference in tree structure.

The average $S$ of 1.12 mm determined with the regression method compared favourably with observed values in coniferous forests, ranging from 0.3 mm to 3.0 mm (Llorens and Gallart, 2007). However, the negative relationship between $S$ and LAI indicates that estimated $S$ values for the canopy above the individual throughfall collectors were modified by the winds. In general, relative throughfall decreases with the increase in LAI and canopy cover (Molina and Del Campo, 2012). However, our results revealed the opposite tendency, which indicates that the meteorological variables had a greater effect on the spatial viability of throughfall than did the canopy structure.

Intense and wind-driven rainfall events occur frequently in subtropical coastal areas. As reported by earlier studies, the variability of throughfall decreases with increasing rainfall intensity. As we found in this study, the windward canopy intercepted more rainfall than the leeward canopy and throughfall in between trees was the lowest at all times (Figure 8), which can be largely explained by the rain shadow effects. This further supports our conclusion that spatial distribution of throughfall is mainly controlled by meteorological conditions. Wind-driven rainfall is always inclined from a vertical pathway (Ford and Deans, 1978; Herwitz and Slye, 1995). The tree crowns probably create lateral rain shadowing effects on the leeward side and midway areas between tree rows. Only part of the inclined rainfall passes directly through small gaps in the canopy and falls in the shadowed midway areas as free throughfall, but the intercepted rainfall will drip down under canopy as released throughfall or evaporate to the atmosphere as interception loss. The dominant wind during the study period blew from east to west (86%), which caused slightly higher throughfall on the east side of tree canopy.

*Spatial variability of stemflow*

Stand-scale stemflow accounted for only a small percentage (1.0%) of gross rainfall, which was similar to the quantified values by other authors, e.g. 1.3% by Llorens *et al.* (1997), 1.4% by Shachnovich *et al.* (2008) and 0.88% by Shi *et al.* (2010). The low stemflow fraction was expected because of the low stem density and rough bark in our pine forests. Compared with throughfall, the stand-scale stemflow was considerably small, which would underestimate the actual stemflow input per unit area because stemflow only concentrates within a small area around tree trunks instead of the stand area (Levia and Frost, 2003). The concentrated stemflow are important inputs of water and nutrients to the soils. Liang *et al.* (2007, 2009), for example, have presented a coupled mechanism termed 'double-funneling', which led to a stemflow-induced preferential infiltration process along root pathways. Silva and Rodríguez (2010) have reported that stemflow concentrations were enriched with leaching nutrients of $C_u$, Fe, $M_n$ and $Z_n$ compared with gross rainfall concentrations in a pine forest (*Pinus pseudostrobus* Lindl.). Apparently, the effects of stemflow serving as highly localized inputs of rainfall on the spatial distributions of soil water and solutes in forested ecosystems cannot be ignored.

Total stemflow volumes among individual trees were different from each other. Variability of stemflow within the same tree species is commonly resulted from the differences in canopy size and tree architecture (Levia and Frost, 2003). The positive relationship between SVR and PCA and DBH showed that stemflow generation generally increased with the increase in crown and stem sizes, which indicates the variability of stemflow among trees was mainly attributed to differences in tree size. However, the small sample size (eight trees) and relatively low coefficient of determination suggests that this conclusion has to be treated with a degree of caution. That's because the difference in stemflow yields can be also due to architectural variables not measured in our study, e.g. branch angles and flow path obstructions (Ford and Deans, 1978). However, this study supported the findings by Llorens *et al.* (1997) that indicate tree size does affect stemflow yields. More trees should be studied in the future to confirm the conclusion and investigate the effect of tree architecture on stemflow production.

### *Interception loss estimation*

Interception loss by the pine plantation as measured in the present study (21.1% of gross rainfall) was in the low range of observed values in other coniferous forests, mainly ranging from 20% to 40% (Carlyle-Moses, 2004; Komatsu *et al*., 2010), which was possibly due to the low canopy coverage and LAI in the young pine plantation. The relative error for the interception loss estimate was high due to the sampling errors on throughfall and stemflow. Because stemflow was relatively small, the major errors were considered from the throughfall measurements (Llorens *et al*., 1997). To reduce the confidence interval on the interception estimate to below 10%, it would require an increase in sample size of between threefold and fourfold of throughfall rain gauges, especially for small rainfall events. Instead of employing a large number of rain gauges to integrate the variability of throughfall and minimize the sample errors, rovers or troughs are two feasible options to apply as suggested before. Compared with broadleaf forests, conifers generally produce higher rainfall interception losses mainly due to their higher canopy storage capacity (Carlyle-Moses, 2004), which indicate that the conversions from native forests to commercial pine plantations may result in a reduction in the soil water availability of these forested ecosystems.

## CONCLUSIONS

As presented in this work, annual gross rainfall in the subtropical pine plantation was partitioned as follows: 77.9% throughfall, 1.0% stemflow and 21.1% interception loss. The spatial variability of gross rainfall over a small plot (50 m × 50 m) in subtropical coastal areas was found minimal. Throughfall proved to be spatially heterogeneous, but the spatial patterns persisted among most individual rainfall events. Interception of inclined rainfall by tree crowns appeared to be the main driver of the spatial patterns of throughfall and nearly single prevailing wind direction caused stability of these patterns. The total stemflow volumes per tree were variable. The variability of stemflow was more related to the tree size (canopy area and stem diameter) than meteorological variables. This research suggests that the spatial variability of throughfall and stemflow in the subtropical pine plantation is sensitive to meteorological variables and canopy structure, respectively.

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## REFERENCES

Baynes J, Dunn GM. 1997. Estimating foliage surface area index in 8-year-old stands of *Pinus elliottii* var. *elliottii Pinus caribaea* var. *hondurensis* of variable quality. *Canadian Journal of Forest Research* **27**: 1367–1375. DOI: 10.1139/x97-085.

Bouillet JP, Laclau JP, Arnaud M, M'Bou AT, Saint-André L, Jourdan C. 2002. Changes with age in the spatial distribution of roots of *Eucalyptus* clone in Congo. *Forest Ecology and Management* **171**: 43–57. DOI: 10.1016/S0378-1127(02)00460-7.

Calder IR, Kidd CHR. 1978. A note on the dynamic calibration of tipping-bucket gauges. *Journal of Hydrology* **39**: 383–386. DOI: 10.1016/0022-1694(78)90013-6.

Carlyle-Moses DE. 2004. Throughfall, stemflow, and canopy interception loss fluxes in a semi-arid Sierra Madre Oriental matorral community. *Journal of Arid Environments* **58**: 181–202. DOI: 10.1016/S0140-1963(03)00125-3.

Carlyle-Moses DE, Laureano JSF, Price A. 2004. Throughfall and throughfall spatial variability in Madrean oak forest communities of northeastern Mexico. *Journal of Hydrology* **297**: 124–135. DOI: 10.1016/j.jhydrol.2004.04.007.

Ciach GJ, Krajewski WF. 2006. Analysis and modeling of spatial correlation structure in small-scale rainfall in Central Oklahoma. *Advances in Water Resources* **29**: 1450–1463. DOI: 10.1016/j.advwatres.2005.11.003.

Coenders-Gerrits AMJ, Hopp L, Savenije HHG, Pfister L. 2013. The effect of spatial throughfall patterns on soil moisture patterns at the hillslope scale. *Hydrology and Earth System Sciences* **17**: 1749–1763. DOI: 10.5194/hess-17-1749-2013.

Crockford RH, Richardson DP. 2000. Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. *Hydrological Processes* **14**: 2903–2920. DOI: 10.1002/1099-1085(200011/12)14:16/17<2903::AID-HYP126>3.0.CO;2-6.

Deguchi A, Hattori S, Park HT. 2006. The influence of seasonal changes in canopy structure on interception loss: application of the revised Gash model. *Journal of Hydrology* **318**: 80–102. DOI: 10.1016/j.jhydrol.2005.06.005.

Fiener P, Auerswald K. 2009. Spatial variability of rainfall on a sub-kilometre scale. *Earth Surface Processes and Landforms* **34**: 848–859. DOI: 10.1002/esp.1779.

Ford ED, Deans JD. 1978. The effects of canopy structure on stemflow, throughfall and interception loss in a young Sitka spruce plantation. *Journal of Applied Ecology* **15**: 905–917. DOI: 10.2307/2402786.

Gash JHC, Stewart JB. 1977. The evaporation from Thetford Forest during 1975. *Journal of Hydrology* **35**: 385–396. DOI: 10.1016/0022-1694(77)90014-2.

Gower ST, Norman JM. 1991. Rapid estimation of leaf area index in conifer and broad-leaf plantations. *Ecology* **72**: 1896–1900.

Guswa AJ, Spence CM. 2012. Effect of throughfall variability on recharge: application to hemlock and deciduous forests in western Massachusetts. *Ecohydrology* **5**: 563–574. DOI: 10.1002/eco.281.

Hanchi A, Rapp M. 1997. Stemflow determination in forest stands. *Forest Ecology and Management* **97**: 231–235. DOI: 10.1016/S0378-1127(97)00066-2.

Herwitz SR, Slye RE. 1995. Three-dimensional modeling of canopy tree interception of wind-driven rainfall. *Journal of Hydrology* **168**: 205–226. DOI: 10.1016/0022-1694(94)02643-P.

Holwerda F, Scatena FN, Bruijnzeel LA. 2006. Throughfall in a Puerto Rican lower montane rain forest: a comparison of sampling strategies. *Journal of Hydrology* **327**: 592–602. DOI: 10.1016/j.jhydrol.2005.12.014.

Hopp L, McDonnell JJ. 2011. Examining the role of throughfall patterns on subsurface stormflow generation. *Journal of Hydrology* **409**: 460–471. DOI: 10.1016/j.jhydrol.2011.08.044.

Huber A, Iroumé A. 2001. Variability of annual rainfall partitioning for different sites and forest covers in Chile. *Journal of Hydrology* **248**: 78–92. DOI: 10.1016/S0022-1694(01)00394-8.

Kanowski J, Catterall CP, Wardell-Johnson GW. 2005. Consequences of broadscale timber plantations for biodiversity in cleared rainforest landscapes of tropical and subtropical Australia. *Forest Ecology and Management* **208**: 359–372. DOI: 10.1016/j.foreco.2005.01.018.

Keim RF, Skaugset AE, Weiler M. 2005. Temporal persistence of spatial patterns in throughfall. *Journal of Hydrology* **314**: 263–274. DOI: 10.1016/j.jhydrol.2005.03.021.

Kimmins JP. 1973. Some statistical aspects of sampling throughfall precipitation in nutrient cycling studies in British Columbian coastal forests. *Ecology* **54**: 1008–1019. DOI: 10.2307/1935567.

Komatsu H, Onozawa Y, Kume T, Tsuruta K, Kumagai T, Shinohara Y, Otsuki K. 2010. Stand-scale transpiration estimates in a Moso bamboo forest: II. Comparison with coniferous forests. *Forest Ecology and Management* **260**: 1295–1302. DOI: 10.1016/j.foreco.2010.06.040.

Krajewski WF, Ciach GJ, Habib E. 2003. An analysis of small-scale rainfall variability in different climatic regimes. *Hydrological sciences journal* **48**: 151–162. DOI: 10.1623/hysj.48.2.151.44694.

Krämer I, Hölscher D. 2009. Rainfall partitioning along a tree diversity gradient in a deciduous old-growth forest in Central Germany. *Ecohydrology* **2**: 102–114. DOI: 10.1002/eco.44.

Laclau JP, Ranger J, Bouillet JP, De Dieu Nzila J, Deleporte P. 2003. Nutrient cycling in a clonal stand of *Eucalyptus* and an adjacent savanna ecosystem in Congo: 1. Chemical composition of rainfall, throughfall and stemflow solutions. *Forest Ecology and Management* **176**: 105–119. DOI: 10.1016/S0378-1127(02)00280-3.

Levia DF, Frost EE. 2003. A review and evaluation of stemflow literature in the hydrologic and biogeochemical cycles of forested and agricultural ecosystems. *Journal of Hydrology* **274**: 1–29. DOI: 10.1016/S0022-1694(02)00399-2.

Levia DF, Frost EE. 2006. Variability of throughfall volume and solute inputs in wooded ecosystems. *Progress in Physical Geography* **30**: 605–632. DOI: 10.1177/0309133306071145.

Levia DF, Van Stan JT, Mage SM, Kelley-Hauske PW. 2010. Temporal variability of stemflow volume in a beech-yellow poplar forest in relation to tree species and size. *Journal of Hydrology* **380**: 112–120. DOI: 10.1016/j.jhydrol.2009.10.028.

Levia DF, Van Stan JT, Siegert CM, Inamdar SP, Mitchell MJ, Magee SM, McHale PJ. 2011. Atmospheric deposition and corresponding variability of stemflow chemistry across temporal scales in a mid-Atlantic broadleaved deciduous forest. *Atmospheric Environment* **45**: 3046–3054. DOI: 10.1016/j.atmosenv.2011.03.022.

Leyton L, Reynolds ERC, Thompson FB. 1967. Rainfall interception in forests and moorland. In *Int. Symp. Forest Hydrology*. Pergamon Press: Oxford; 163–178.

Liang WL, Kosugi K, Mizuyama T. 2007. Heterogeneous soil water dynamics around a tree growing on a steep hillslope. *Vadose Zone Journal* **6**: 879–889. DOI: 10.2136/vzj2007.0029.

Liang WL, Kosugi K, Mizuyama T. 2009. A three-dimensional model of the effect of stemflow on soil water dynamics around a tree on a hillslope. *Journal of Hydrology* **366**: 62–75. DOI: 10.1016/j.jhydrol.2008.12.009.

Llorens P, Domingo F. 2007. Rainfall partitioning by vegetation under Mediterranean conditions. A review of studies in Europe. *Journal of Hydrology* **335**: 37–54. DOI: 10.1016/j.jhydrol.2006.10.032.

Llorens P, Gallart F. 2007. A simplified method for forest water storage capacity measurement. *Journal of Hydrology* **240**: 131–144. DOI: 10.1016/S0022-1694(00)00339-5.

Llorens P, Poch R, Latron J, Gallart F. 1997. Rainfall interception by a Pinus sylvestris forest patch overgrown in a Mediterranean mountainous abandoned area I. Monitoring design and results down to the event scale. *Journal of Hydrology* **199**: 331–345. DOI: 10.1016/S0022-1694(96)03334-3.

Lloyd C, Marques ADO. 1988. Spatial variability of throughfall and stemflow measurements in Amazonian rainforest. *Agricultural and Forest Meteorology* **42**: 63–73. DOI: 10.1016/0168-1923(88)90067-6.

Loescher HW, Powers JS, Oberbauer SF. 2002. Spatial variation of throughfall volume in an old-growth tropical wet forest, Costa Rica. *Journal of Tropical Ecology* **18**: 397–407. DOI: 10.1017/S0266467402002274.

Loustau D, Berbigier P, Granier A, Moussa FEH. 1992. Interception loss, throughfall and stemflow in a maritime pine stand. I. Variability of throughfall and stemflow beneath the pine canopy. *Journal of Hydrology* **138**: 449–467. DOI: 10.1016/0022-1694(92)90130-N.

Mair A, Fares A. 2010. Throughfall characteristics in three non-native Hawaiian forest stands. *Agricultural and Forest Meteorology* **150**: 1453–1466. DOI: 10.1016/j.agrformet.2010.07.007.

McClain ME, Boyer EW, Dent CL, Gergel SE, Grimm NB, Groffman PM, Hart SC, Harvey JW, Johnston CA, Mayorga E, McDowell WH, Pinay G. 2003. Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. *Ecosystems* **6**: 301–312. DOI: 10.1007/s10021-003-0161-9.

McConkey B, Nicholaichuk W, Cutforth H. 1990. Small area variability of warm-season precipitation in a semiarid climate. *Agricultural and Forest Meteorology* **49**: 225–242. DOI: 10.1016/0168-1923(90)90034-4.

Molina AJ, Del Campo AD. 2012. The effects of experimental thinning on throughfall and stemflow: a contribution towards hydrology-oriented silviculture in Aleppo pine plantations. *Forest Ecology and Management* **269**: 206–213. DOI: 10.1016/j.foreco.2011.12.037.

Mululo Sato A, de Souza Avelar A, Coelho Netto AL. 2011. Spatial variability and temporal stability of throughfall in a eucalyptus plantation in the hilly lowlands of southeastern Brazil. *Hydrological Processes* **25**: 1910–1923. DOI: 10.1002/hyp.7947.

Murakami S. 2006. A proposal for a new forest canopy interception mechanism: splash droplet evaporation. *Journal of Hydrology* **319**: 72–82. DOI: 10.1016/j.jhydrol.2005.07.002.

 

O'Grady AP, Worledge D, Battaglia M. 2005. Temporal and spatial changes in fine root distributions in a young Eucalyptus globulus stand in southern Tasmania. *Forest Ecology and Management* **214**: 373–383. DOI: 10.1016/j.foreco.2005.04.021.

Ritter A, Regalado CM. 2012. Roving revisited, towards an optimum throughfall sampling design. *Hydrological Processes* **319**: 72–82. DOI: 10.1016/j.jhydrol.2005.07.002.

Shachnovich Y, Berliner PR, Bar P. 2008. Rainfall interception and spatial distribution of throughfall in a pine forest planted in an arid zone. *Journal of Hydrology* **28**: 123–133. DOI: 10.1002/hyp.9561.

Shi Z, Wang Y, Xu L, Xiong W, Yu P, Gao J, Zhang L. 2010. Fraction of incident rainfall within the canopy of a pure stand of *Pinus armandii* with revised Gash model in the Liupan Mountains of China. *Journal of Hydrology* **385**: 44–50. DOI: 10.1016/j.jhydrol.2010.02.003.

Shinohara Y, Onozawa Y, Chiwa M, Kume T, Komatsu H, Otsuki K. 2010. Spatial variations in throughfall in a Moso bamboo forest: sampling design for the estimates of stand-scale throughfall. *Hydrological Processes* **24**: 253–259. DOI: 10.1002/hyp.7473.

Silva IC, Rodríguez HG. 2010. Interception loss, throughfall and stemflow chemistry in pine and oak forests in northeastern Mexico. *Tree Physiology* **21**: 1009–1013. DOI: 10.1093/treephys/21.12-13.1009.

Šraj M, Brilly M, Mikoš M. 2008. Rainfall interception by two deciduous Mediterranean forests of contrasting stature in Slovenia. *Agricultural and Forest Meteorology* **148**: 121–134. DOI: 10.1016/j.agrformet.2007.09.007.

Syed KH, Goodrich DC, Myers DE, Sorooshian S. 2003. Spatial characteristics of thunderstorm rainfall fields and their relation to runoff. *Journal of Hydrology* **271**: 1–21. DOI: 10.1016/S0022-1694(02)00311-6.

Taniguchi M, Tsujimura M, Tanaka T. 1996. Significance of stemflow in groundwater recharge. 1: evaluation of the stemflow contribution to recharge using a mass balance approach. *Hydrological Processes* **10**: 71–80. DOI: 10.1002/(SICI)1099-1085(199601)10:1<71::AID-HYP301>3.0.CO;2-Q.

Toba T, Ohta T. 2005. An observational study of the factors that influence interception loss in boreal and temperate forests. *Journal of Hydrology* **313**: 208–220. DOI: 10.1016/j.jhydrol.2005.03.003.

Valente F, David JS, Gash JHC. 1997. Modelling interception loss for two sparse eucalypt and pine forests in central Portugal using reformulated Rutter and Gash analytical models. *Journal of hydrology* **190**: 141–162. DOI: 10.1016/S0022-1694(96)03066-1.

Van Stan JT, Siegert CM, Levia DF, Scheick CE. 2011. Effects of wind-driven rainfall on stemflow generation between codominant tree species with differing crown characteristics. *Agricultural and Forest Meteorology* **151**: 1277–1286. DOI: 10.1016/j.agrformet.2011.05.008.

Villarini G, Mandapaka PV, Krajewski WF, Moore RJ. 2008. Rainfall and sampling uncertainties: a rain gauge perspective. *Journal of Geophysical Research-Atmospheres* **113**: Article Number: D11102. DOI: 10.1029/2007JD009214.

Whelan M, Sanger L, Baker M, Anderson J. 1998. Spatial patterns of throughfall and mineral ion deposition in a lowland Norway spruce (*Picea abies*) plantation at the plot scale. *Atmospheric Environment* **32**: 3493–3501. DOI: 10.1016/S1352-2310(98)00054-5.

Wullaert H, Pohlert T, Boy J, Valarezo C, Wilcke W. 2009. Spatial throughfall heterogeneity in a montane rain forest in Ecuador: extent, temporal stability and drivers. *Journal of Hydrology* **377**: 71–79. DOI: 10.1016/j.jhydrol.2009.08.001.

Zhan W, Zhang Z, Wu J, Xiao J. 2007. Spatial variability of throughfall in a Chinese pine (Pinus tabulaeformis) plantation in northern China. *Frontiers of Forestry in China* **2**: 169–173. DOI: 10.1007/s11461-007-0027-y.

Ziegler A, Giambelluca T, Nullet M, Sutherland R, Tantasarin C, Vogler J, Negishi J. 2009. Throughfall in an evergreen-dominated forest stand in northern Thailand: comparison of mobile and stationary methods. *Agricultural and Forest Meteorology* **149**: 373–384. DOI: 10.1016/j.agrformet.2008.09.002.

Zimmermann A, Wilcke W, Elsenbeer H. 2007. Spatial and temporal patterns of throughfall quantity and quality in a tropical montane forest in Ecuador. *Journal of Hydrology* **343**: 80–96. DOI: 10.1016/j.jhydrol.2007.06.012.