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Throughfall in an evergreen-dominated forest stand in northern Thailand: Comparison of mobile and stationary methods

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ABSTRACT

Throughfall determined by stationary and mobile methods in a disturbed evergreen-dominated forest stand in northern Thailand was 82% of rainfall (1134 mm) during a 4-month study period in the monsoon rain season of 2002. Associated coefficients of variation and standard errors were ≤10% and 2%, respectively, for both methods. Agreement between four stationary trough collectors and 20 mobile standard gauge collectors was achieved only after 35 sampling occasions, having a total rainfall depth >700 mm, and included one storm event >100 mm. Several canopy trees contributed to points with throughfall > rainfall by channeling stemflow to common drip points on the trunk and large limbs. However, no significant correlation was observed between throughfall point measurements and corresponding canopy cover. Although 180-point measurements of throughfall provided a realistic representation of the spatial variability within the 500-m^2 forest stand, it is questionable that they duplicated the basin-scale variability, which would be affected both by tree gaps and variable topographically related rain shadow effects.

1. Introduction

Interception loss is the portion of the rain captured by leaves, stems, and branches of a vegetative cover that is subsequently evaporated (Hewlett, 1982; Dingman, 1994). Throughfall is the portion falling directly through and/or dripping to the ground from the canopy. Stemflow is the portion that reaches the ground by flowing down the trunks. Throughfall and stemflow are commonly measured as a means of estimating interception loss (Bruijnzeel, 2000; Dunkerley, 2000). Of the two, throughfall is typically given more attention because the stemflow component is generally small: <5–10% of rainfall (Bruijnzeel, 1990, 2000; Levia and Frost, 2003). Throughfall quantification is important for other types of investigations, including the study of solute inputs to forest ecosystems, runoff generation, soil erosion below canopies, and distribution of soil moisture on forest floors (e.g., Bouten et al., 1992; Robson et al., 1994; Calder,

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2001; Schroth et al., 2001; Raat et al., 2002; Hölscher et al., 2003; Schume et al., 2003).

Field experiments have demonstrated substantial spatial and temporal variability in throughfall at sites around the world (Levia and Frost, 2006). Variability is affected by season (e.g., Stout and McMahon, 1961; Peterson and Rolfe, 1979; Staelens et al., 2006; Cuartas et al., 2007), rainfall characteristics (e.g., Huber and Iroumé, 2001; Raat et al., 2002; Hall, 2003; Carlyle-Moses et al., 2004), and forest stand characteristics, including canopy structure, density, type, and level of disturbance (e.g., Helvey and Patric, 1965; Stogsdill et al., 1989; Asdak et al., 1998; Hall and Roberts, 1990; Aboal et al., 2000; Crockford and Richardson, 2000; Chappell et al., 2001; Loescher et al., 2002; Germer et al., 2006; Levia and Frost, 2006). Confounding the comparison of throughfall among sites is the uncertainty associated with a particular type of measurement method employed and the number of gauges involved in the estimate (e.g., Helvey and Patric, 1965; Czarnowski and Olszewski, 1970; Calder and Rosier, 1976; Bruijnzeel and Wiersum, 1987; Lloyd and Marques, 1988; Kostelnik et al., 1989; Forti and Neal, 1992; Rodrigo and Avila, 2001; Holwerda et al., 2006).

This study quantified throughfall in an evergreen-dominated forest stand in tropical northern Thailand using both a stationary and a mobile collection method. Objectives were: (1) calculate throughfall percentage for the stand; (2) determine whether stationary and mobile measurement techniques produce similar throughfall estimates; and (3) identify the spatial throughfall distribution.

2. Study site

Research was conducted in the Pang Khum Experimental Watershed (PKEW) in northern Thailand (19°03′N, 98°39′E). Pang Khum is located on the boundary of Samoeng and Mae Taeng Districts in Chiang Mai Province, approximately 60 km NNW of Chiang Mai (Ziegler et al., 2004). The 93.7-ha PKEW (Fig. 1a) is a headwater drainage of the Ping River, a major tributary to the Chao Phraya River. Elevation ranges from 1100 to 1600 m. The area has a monsoon rainy season extending from mid-May to October, which accounts for 80–90% of the annual rainfall total (1200–2000 mm).

3. Methods

3.1. *Experimental setup*

The study was conducted from 21 June to 7 October 2002 in a 500 m^2 study plot situated within a disturbed evergreen-dominated montane forest stand (Fig. 1; Tables 1 and 2). The plot was divided into 20 5 m × 5 m quadrants (Fig. 1e). Throughfall was recorded using four stationary gauges and 20 standard-type, mobile throughfall gauges (rovers) that were relocated to unique locations during each of 11 periods (Table 1; Fig. 1). Periods contained 2–6 sampling occasions, for a total of 49 during the study (Table 1). A sampling occasion refers to the interval over which throughfall was collected; each occasion included at least one distinct rainfall event.

Rainfall was measured at meteorological tower #401, located approximately 70 m from the study plot (Fig. 1a). Rainfall data were recorded at 1-min intervals at a height of 22 m – approximately 1 m above the canopy – with a 0.153-m diameter Texas Instruments tipping-bucket rain gauge and Campbell Scientific 21x data logger. Wind speed was monitored with a Met-One anemometer at the same height on the 401 tower.

3.2. *Throughfall measurements*

Stationary measurement gauges consisted of fabricated galvanized steel tipping-bucket gauges that received throughfall water captured in troughs that extended under the forest canopy (Fig. 2a). The tipping mechanism is a larger version of a commercial tipping-bucket rain gauge with a solid state reed switch that is monitored by a Campbell CR10x data logger (Fig. 2b). The initial volume of throughfall required to produce one tip was 150 cm^3 (0.2 mm). A dynamic calibration correction was then applied to account for differences in tip volume over the range of observed tipping rates (Calder and Kidd, 1978; Marsalek, 1981; Humphrey et al., 1997). Each collection trough was 43 mm wide, and had a triangular-shaped channel (120° angle) and 25 mm vertical risers to reduce rain splash loss (Fig. 2b). Four stationary gauges were installed to sample a variety of dense and sparse portions of the canopy (Fig. 1d). Each of three troughs was 6 m long; therefore, the sampling area for each gauge was approximately 0.77 m^2 (after correcting for trough angle). A total of 3.1 m^2 was sampled by the four stationary gauges. Troughs were positioned 0.5–1.0 m above the ground to limit interference by understory vegetation.

The rovers were galvanized funnels (angle = 60°; radius = 0.130 m; area = 0.054 m^2) that drained into 5-L collection bottles (Fig. 2c). Unlike the 401 rainfall gauge, the funnels did not have vertical sidewalls or screens to prevent splash loss. During each of the 11 measurement periods, 5–20 rovers were positioned systematically at unique locations such that throughfall was measured at 12–13 locations in each of the 20 quadrants (Table 1, Fig. 1f). Total area sampled at 180 unique measurement locations was 9.7 m^2. Minimum rover separation distance was 2 m, while the maximum separation distance was 33 m. Throughfall volumes were measured daily, but exceptions were made if researchers were away for 2–3 days. Evaporation losses from the collection bottles were assumed to be negligible.

Splash loss errors were corrected by establishing regression equations with depths measured by the tipping-bucket rain gauge during several storms prior to experimentation. Throughfall was calculated by three methods: (1) mean of throughfall estimates determined for 49 sampling occasions (stationary method); (2) mean of 20 rover throughfall estimates determined for 49 sampling occasions (rover method); and (3) mean of 180 unique rover-based throughfall values, determined for two to six sampling occasions (point method). Methods 1 and 2 were used for estimating stand throughfall and comparing stationary and mobile methods (objectives 1 and 2). The point method allowed investigation of the spatial distribution of throughfall (objective 3).

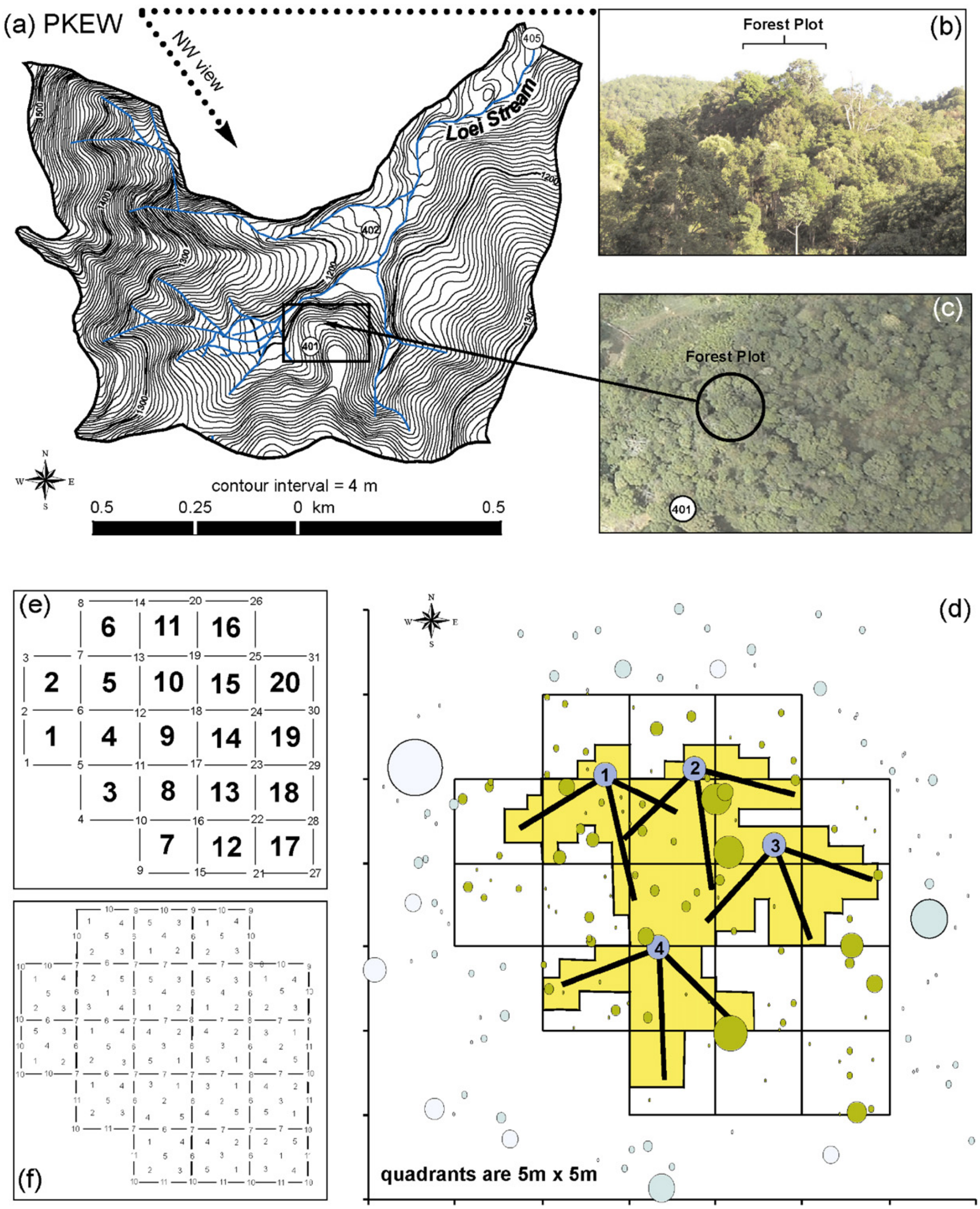

Fig. 1 – (a) Location of experimental forest plot, station 401 (rainfall and wind), and station 402 (above canopy PAR) in the Pang Khum Experimental Watershed (PKEW) in northern Thailand. (b) The experimental forest stand viewed from the northwest; the approximate location of the forest study plot is indicated. (c) Forest stand from light aircraft (500 m altitude). (d) Arrangement of four stationary throughfall collectors (numbered with three collection troughs) and location of 102 trees within the 500 m^2 experimental plot. Circles are tree trunks exaggerated in scale by 200%. Only trees within about 5 m outside the plot are also shown. The length of the stationary gauge collection troughs are to scale. Shading represents the subplot corresponding to the area roughly sampled by the stationary gauges (200 m^2). (e) Twenty 5 m × 5 m quadrants comprising the experimental forest study plot (large numbers). The small numbers represent locations where LAI values were measured in addition to the center of each of 20 quadrants (51 total locations). (f) Locations of 180 throughfall point measurements made with the mobile rovers. The numbers refer to one of 11 periods during which measurements were conducted (Table 1).

Table 1 – Setup of rovers and stationary gauges for 11 measurement periods in 2002.

Period	Start day	Stop day	Period duration (days)	Sampling occasions in period	Number of rovers deployed	Total rainfall (mm)	Method 1 stationary TF (%)[a]	Method 2 rover TF (%)[a]
1	21 June	28 June	7	6	20	76	66	86
2	28 June	8 July	10	4	20	74	70	71
3	8 July	21 July	13	6	20	76	65	65
4	21 July	4 Aug	14	5	20	93	72	72
5	4 Aug	12 Aug	8	5	20	59	76	75
6	12 Aug	23 Aug	11	4	20	101	81	79
7	23 Aug	28 Aug	5	5	20	112	85	95
8	28 Aug	9 Sept	12	4	6	154	97	88
9	9 Sept	12 Sept	3	4	5	48	84	86
10	12 Sept	24 Sept	12	4	20	177	89	90
11	24 Sept	7 Oct	13	2	9	164	86	86
Total			108	49	180[b]	1134	82[c]	82[c]

[a] Throughfall (percent of rainfall depth) values are means of four stationary or 5–20 mobile (rover) gauges for each sample period.
[b] A total of 835 rover measurements were taken at 180 unique locations over the course of 11 periods (seven measurements during period 1 were discarded because of experimental error). Four stationary gauges were deployed in the same location throughout the study (see Fig. 1).
[c] Total values are means of either 20 rovers or four stationary gauges, calculated for total throughfall (i.e., not column means).

3.3. *Statistical handling*

To assess statistical differences among the rover and stationary methods, we used parametric approaches that allowed paired testing: e.g., paired *t*-test and ANCOVA (with rainfall as the interaction term). The minimum number of gauges (N_{min}) required to estimate throughfall based on the spatial coefficient of variation (CV = mean/std dev × 100%) for a desired error (ε) and confidence level was estimated as follows (cf. Kimmins, 1973):

$$N_{min} = \frac{z_c{}^2 \times CV^2}{\varepsilon^2} \quad (1)$$

where z_c is the critical value at the stated confidence interval. Herein, we use $\varepsilon = 10\%$ and $z_c = 1.96$ for the 95% confidence interval (cf. Carlyle-Moses et al., 2004; Holwerda et al., 2006).

Variograms were used to examine spatial dependence between throughfall point measurements (Davis, 2002). Semivariance (γ_h) was calculated as follows:

$$\gamma_h = \frac{\sum (x_i - x_{i+h})^2}{2n} \quad (2)$$

where x_i is throughfall at any point measurement location, x_{i+h} is throughfall at another location that is distance *h* away (lag); and *n* is the number of data pairs that are distance *h* apart.

Prior to all statistical testing, skewness (*g*) was quantified to assess normality (Zar, 1999). When values of *g* exceeded critical values for two-tailed testing at $\alpha = 0.05$, a square-root transformation was applied (cf. Lloyd and Marques, 1988; Holwerda et al., 2006).

Table 2 – Name, type (evergreen or deciduous), and number of tree species (102 total) in the 500 m² forest patch.

Name	Type	No.
Wendlandia tinctoria (Roxb.) DC. (Rubiaceae)	E	27
Stryax benzoides Craib (Styracaceae)	E	15
Castanopsis tribuloides (Sm.) A. DC. (Fagaceae)[a]	E	12
Lithocarpus elegans (Bl.) Hatus. *ex* Soep. (Fagaceae)[a]	E	7
Castonopsis diversifolia (Kurz) King *ex* Hk. f. (Fagaceae)[a]	E	6
Helicia nilagirica Bedd. (Proteaceae)[a]	E	5
Heliciopsis terminalis (Kurz) Sleum. (Proteaeceae)[a]	E	5
Machilus bombycina King *ex* Hk. f. (Lauraceae)[a]	E	3
Aporusa villosa (Lindl.) Baill. (Euphorbiaceae)	D	2
Camellia pleurocarpa (Gagnep.) Sealy (Theaceae)[a]	E	2
Engelhardia serrata Bl. var. *serrata* (Juglandaceae)[a]	D	2
Falconeria insignis Roy. (Euphorbiaceae)[a]	D	2
Antidesma bunius (L.) Spreng. (Euphorbiaceae)[a]	E	1
Artocarpus lanceolata Trec. (Moraceae)[a]	E	1
Cinnamomum iners Rienw. *ex* Bl. (Lauraceae)[a]	E	1
Dillenia parviflora Griff.var. *kerrii* (Craib) Hoogl. (Dilleniaceae)	D	1
Eugenia albiflora Duth. *ex* Kurz (Myrtaceae)[a]	E	1
Euonymus cochinchinensis Pierre (Celastraceae)[a]	E	1
Garcinia cowa Roxb. (Guttiferae)[a]	E	1
Kydia calycina Roxb. (Malvaceae)	D	1
Litsea salicifolia Nees *ex* Roxb. (Lauraceae)[a]	E	1
Olea rosea Craib (Oleaceae)[a]	E	1
Rhus chinensis Mill. (Anacardiaceae)	D	1
Saurauia roxburghii Wall. (Saurauiaceae)[a]	E	1
Symplocos cochinchinensis (Lour.) S. Moore ssp. *laurina* (Retz.) Noot. (Symplocaceae)[a]	E	1
Ternstroemia gymnanthera (Wight & Arn.) Bedd. (Theaceae)[a]	E	1

[a] Primary growth species.

3.4. *Leaf area index (LAI) and canopy density*

Below-canopy photosynthetically active radiation (PAR) measurements were taken in the center of each of the 20 quadrants and at the 31 quadrant intersection/boundary points (Fig. 1f). PAR was measured with a Decagon AccuPAR LAI/PAR Ceptometer. LAI was calculated using the Decagon inversion model (Decagon Services, 2004), which takes into account above- and below-canopy PAR, canopy structure, and solar elevation angle (based on time, day, and latitude). Above-canopy PAR was measured simultaneously with a separate PAR sensor at station 402 (Fig. 1a).

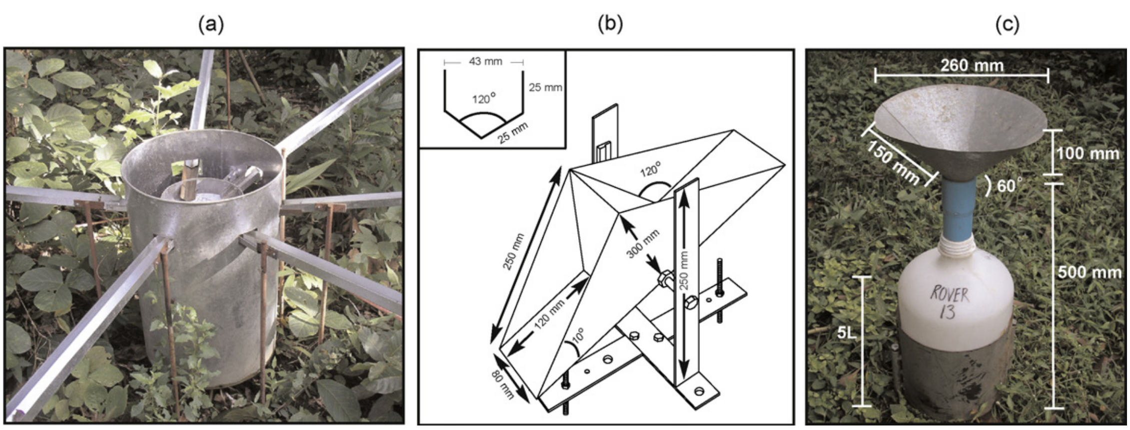

Fig. 2 – (a) Stationary collector with six collection troughs (only three troughs were used in this study because site was on non-level terrain). (b) Schematic of stationary gauge tipping-bucket mechanism; the inset shows the dimensions for the collection troughs. (c) Dimensions of the mobile rover throughfall collector; the collection bottle rests in a steel ring that was anchored to the ground to level/secure the funnel.

At 180 throughfall measurement locations (including all 51 LAI measurements points, Fig. 1e), a canopy density index (CDI) was determined as the product of canopy cover and canopy depth. Cover was quantified by comparing the overhead canopy cover with values on pattern cards (±10% estimated accuracy). Depth was determined both with a measuring tape and extension rod (for heights <4 m) and via trigonometric methods (heights >4 m). The CDI has the same units as LAI ($m^2\ m^{-2}$).

4. Results

4.1. *LAI*

Leaf area index estimated at 51 locations ranged from 0.2 to 4.1 $m^2\ m^{-2}$. CDI values determined at the same 51 locations ranged from 0.6 to 7.6 $m^2\ m^{-2}$. The following logarithmic regression was established between these two variables ($r^2_{adj} = 0.65$; *p*-value < 0.0001; Fig. 3a):

$$LAI = 1.062 + 1.304 \ln CDI \quad (3)$$

Eq. (3) was then used to estimate LAI for the remaining 129 throughfall point measurement locations. LAI was interpolated throughout the plot using an inverse distance weighting function (Fig. 4a). Most high LAI values were associated with a few large canopy trees, whereas many low LAI values were grouped in the SW corner, where tree density immediately outside the forest plot was low.

4.2. *Rainfall*

During the 108-day experiment, 1134 mm of rainfall was recorded (Table 1). The smallest rainfall depth during any 1 of the 11 measurement periods was 48 mm; the largest was 177 mm (Table 1). The smallest depth measured during any of the 49 sampling occasions was 0.88 mm; the maximum was 159 mm; and the median was 12.6 mm. During three sampling

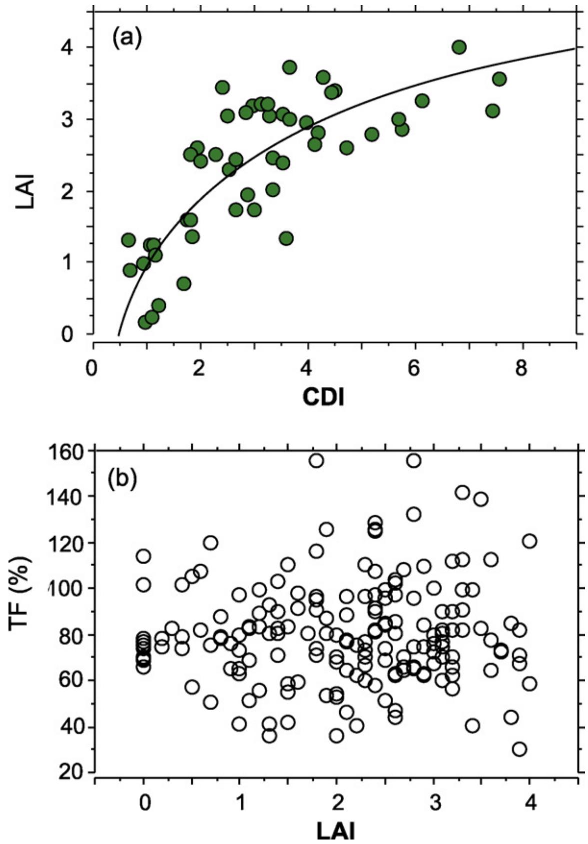

Fig. 3 – (a) Relationship between canopy density index (CDI) and leaf area index (LAI). The logarithmic regression is significant ($r^2_{adj} = 0.65$; *p*-value < 0.0001) for the 51 data pairs taken at the locations identified in Fig. 1e. (b) The plot of point throughfall (from method 3) versus LAI, both determined at the 180 measurement locations shown in Fig. 1f, reveals no relationship between the two variables. Units for LAI and CDI are $m^2\ m^{-2}$.

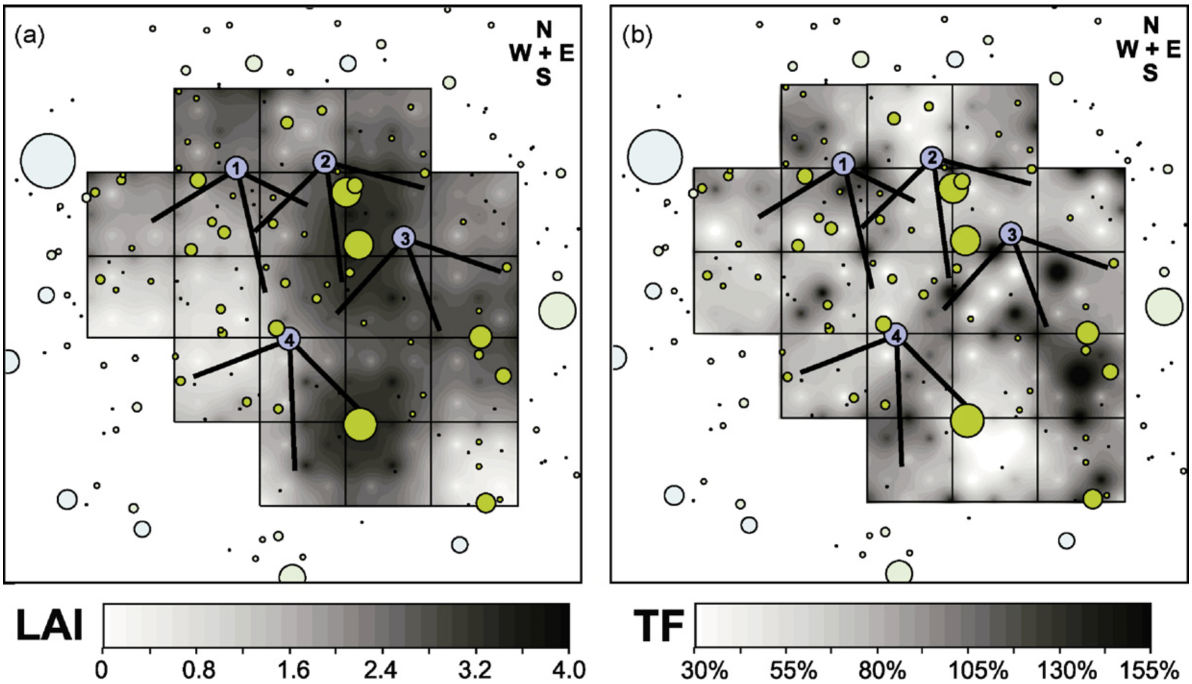

Fig. 4 – (a) LAI ($m^2\ m^{-2}$) distribution within the 500 m^2 forest plot. (b) The distribution of the throughfall (TF) percentage of rainfall (determined via method 3). LAI and throughfall were interpolated as moving averages using an inverse distance weighting function (weight = 1; arbitrary limiting distance = 5 m).

occasions, rainfall depth exceeded 139 mm. Of the periods with recorded rainfall, approximately 17% had 1-min intensities >35 mm h^{-1}, which together accounted for 36% of the total rainfall depth. The maximum 1-min intensity was 133 mm h^{-1} (9 tips min^{-1}).

4.3. *Throughfall*

Mean throughfall was 82% for both the stationary and rover methods (Table 3). Standard errors for both methods were equally low (2%); and the coefficients of variation were ≤10%

Table 3 – Throughfall statistics for three measurement methods.

Variable[a]	Units	Method 1 Stationary gauges	Method 2 Rovers	Method 3-point measurements		
				Entire plot	Inside stationary subplot[a]	Outside stationary subplot[a]
Mean	%	82	82	81	82	80
Std. dev.	%	4	8	22	25	20
CV	%	5	10	28	31	25
Std. error	%	2	2	2	3	2
Min.	%	77	66	30	37	30
Max.	%	86	95	157	157	157
Skewness (*g*)	–	na[b]	−0.25	0.63	0.74	0.46
Median	%	82	83	79	78	79
MAD[c]	%	3	3	13	15	12
N[d]	–	4	20	180	73	106
$Area_{guage}$[e]	m^2	3.08	9.66	9.66	3.94	5.72
Area[f]	m^2	200	500	500	200	300

Rainfall for methods 1–2 was 1134 mm; rainfall varied by sampling occasion for the point measurements (48–177 mm).
[a] Subplot areas shown in Fig. 1d.
[b] Not applicable because measurement number was 4.
[c] Median absolute deviation of the median.
[d] Number of gauges or locations for which the throughfall statistics are calculated.
[e] Total collection area of *N* gauges.
[f] Corresponding forest area sampled by the method.

(Table 3). No significant difference existed between the two methods (tied p-value = 0.47, n = 49 sampling occasions).

Despite the similarity in throughfall, the range of values was quite different: throughfall for the 20 rovers ranged from 66% to 95%; the four stationary gauges, 77–86% (Table 3). Minimum and maximum rover values during any of the 49 sampling occasions were 3% and 230%, compared with 23% and 168% for the stationary gauges (not shown). The range difference results because stationary collectors integrate measurements over an area roughly equivalent to 14 rovers: 0.77 m^2 versus 0.054 m^2 (cf. Cuartas et al., 2007).

Approximately 18% of the 835 individual rover throughfall measurements were ≥100% (Fig. 5a). In comparison, only 7% of the 196 values recorded by the stationary gauges were ≥100%. Stationary gauges 1–4 recorded throughfall >100% during 1, 2, 2, and 8 sampling occasions, respectively. Throughfall percentage was highly variable for rainfall depths less than about 30 mm, but both rover- and stationary-based estimates increased asymptotically towards 100% for sampling occasions with large rainfall depths (Fig. 5b). Throughfall for individual stationary gauges was 81%, 83%, 77%, and 86%. No statistical difference was found between estimates made by the rovers and any group of three stationary gauges; this was not true for groups of two stationary gauges. The sampling area of three stationary gauges (2.3 m^2) was <25% the total area sampled by the rovers.

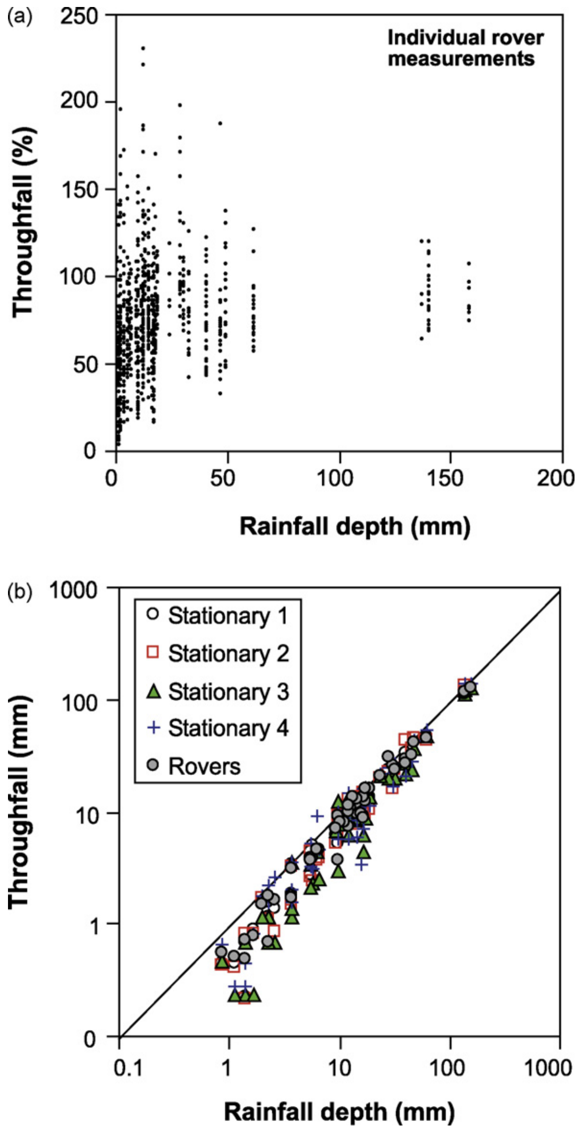

Fig. 5 – (a) Throughfall values, determined for 835 individual rover samples, demonstrate a general decrease in throughfall variability with increasing rainfall. (b) Rover- and stationary-gauge-estimated throughfall for each of the 49 sampling occasions, plotted versus associated rainfall depth.

4.4. *Point measurements of throughfall*

Mean throughfall of the 180-point measurements was 81% (Table 3). Individual values determined from 2 to 6 sampling occasions ranged from 30% to 157% of rainfall (Table 3). Compared with the rover data of method 2, these point-based (method 3) data were significantly skewed (g = 0.63 versus g-critical = ±0.357 at α = 0.05) and the coefficient of variation was higher (28% versus 10%). No statistical difference was found between point throughfall measured inside versus outside the area sampled by the four stationary gauges (unpaired t-test, tied p-value = 0.80; area shown in Fig. 1d). Mean throughfall values for these 200 and 300 m^2 subplots were 82 and 80%, respectively (Table 3). Neither estimate was different from the value determined for the entire 500 m^2 plot (ANCOVA, α = 0.05).

About 15% of the 180-point throughfall values were ≥100% (Fig. 4b). These canopy drip points were observed somewhere in the plot during 44 of 49 sampling occasions; however, no significant correlation existed with depth of rainfall. Furthermore, no predictive relationship existed between LAI and throughfall (Fig. 3b). Thus, the spatial structure of throughfall in the forest stand was not simply a function of the immediate overhead canopy cover. Furthermore, a sill was not reached during variogram analysis, indicating that all throughfall measurement locations in the 500 m^2 plot were correlated to some degree.

5. Discussion

5.1. *Comparison with other SE Asian studies*

The throughfall estimate obtained in this study is within the range of those reported for several forest types of various disturbance conditions in the SE Asia region (Table 4). Importantly, it is lower than the 86–91% range reported by Tanaka et al. (2001, 2005) for a montane evergreen forest at the Kog Ma research station located <50 km from PKEW. That study measured throughfall with 30 randomly located, non-roving collectors for 4 years. Vegetation characteristics were somewhat different at the two sites: e.g., *Lithocaropus* spp. and *Quercus* spp. were among the most abundant trees at Kog Ma (cf. Table 2); and most canopy trees at Kog Ma were 25–40 m in height. The main difference between the two forests was that fog precipitation totalling as much as 5–10% of rainfall augmented throughfall at Kog Ma (Tanaka, pers. commun.). Fog was not a significant precipitation component at PKEW. If fog is taken into consideration, the PKEW estimated falls within the range of values reported at Kog Ma.

Table 4 – Throughfall estimates for various forests in SE Asia.

Location	Throughfall (%)	Forest type
Brunei[a]	81	Mature mixed dipterocarp rainforest
Kalimantan, Indonesia[b]	87	Lowland unlogged tropical rainforest
Peninsular Malaysia[c]	70	Lowland tropical rainforest
Peninsular Malaysia[d]	81	Primary lowland mixed dipterocarp
Peninsular Malaysia[e]	84	Tropical evergreen (*kelat kendondong*)
Sabah, Malaysia[f,g]	81–83	Lowland dipterocarp rainforest
Sabah, Malaysia[h,i]	91	Lowland dipterocarp
Sarawak, Malaysia[j]	82–88	Lowland evergreen tropical
Sulawasi, Indonesia[k]	70	Lower montane rainforest
Taiwan[l]	92	Moist subtropical mixed evergreen
Thailand (Kog Ma)[m]	86–91	Montane evergreen
Thailand (PKEW)[n]	82	Montane evergreen-dominated

[a] Dykes (1997).
[b] Asdak et al. (1998).
[c] Saberi and Rosnani (2004).
[d] Konishi et al. (2006).
[e] Zulkifli et al. (2001).
[f] Sinun et al. (1992).
[g] Burghouts et al. (1998).
[h] Chappell et al. (2001).
[i] Bidin and Chappell (2004).
[j] Manfroi et al. (2006).
[k] Dietz et al. (2006).
[l] Lin et al. (2000).
[m] Tanaka et al. (2001, 2005).
[n] This study.

5.2. *Sufficient experimentation*

The study was conducted for just 4 months, during which about 70% of a yearly total of 1600 mm of rainfall fell. By the 36th sampling occasion, when approximately 730 of the total 1134 mm rain had fallen, throughfall estimated by the stationary gauges and rovers was indistinguishable (Fig. 6a and b). At this time, standard errors for all three-estimate methods were ≤2%—and no substantial change in mean throughfall took place afterwards (Fig. 6). Prior works have indicated that reliable throughfall estimates should have standard errors ≤5–10% (e.g., Kimmins, 1973; Rodrigo and Avila, 2001, Holwerda et al., 2006), indicating a sufficient number of sampling occasions had been included to obtain reliable estimates in this study. One drawback to method 3 was that throughfall at each of the 180 points was based on rainfall depths (48–177 mm, Table 1) that were much smaller than those after which the throughfall variation determined by the 20 rovers of method 1 stabilized (600–700 mm; Fig. 6a and b). A better approach may have been to sample until the variation at each point had stabilized.

Fixed-gauge methods typically produce higher CVs than roving methods; and therefore, more collectors are required to estimate throughfall at the same level of confidence and error (Holwerda et al., 2006). This was observed in our study, as the CV of the point method was 28% versus 10% for rover method 2 (Fig. 6c; Table 3). Based on these values, only about 31-point measurements versus four rovers would be needed to estimate throughfall at the 95% confidence interval for a 10% error (Eq. (1)). Both of these minimum sample sizes are smaller than the total measurement points or roving gauges employed in this study.

Of interest, however, was that the rover CVs were higher than those of the stationary gauges (10% versus 5%, Table 3). Again, this results because each stationary gauge integrates throughfall over a larger area. Importantly, reliable throughfall estimates with these gauges were facilitated by dynamic calibration of the tipping-bucket mechanism. Had we assumed a constant depth-per-tip relationship, individual stationary gauge throughfall estimates would have been underestimated by 20%; total rainfall depth would have been underestimated by about 15%.

5.3. *Spatial structure*

Some drip points occurred near crown perimeters and the trunks of large canopy trees (Fig. 7). Throughfall in the vicinity

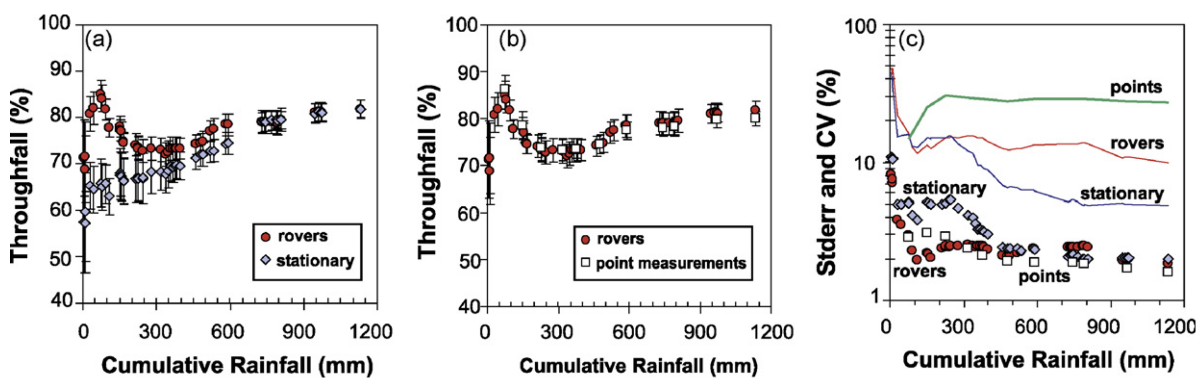

Fig. 6 – (a) Stabilization of the throughfall estimate, determined by the stationary (method 1) and rover (method 2) gauges. (b) Stabilization of the throughfall estimates, determined by rover methods 2 and 3 (point measurements). The values in panels (a) and (b) are mean ± standard errors. (c) For all three methods, the change in standard errors (symbols) and coefficients of variation (curves) are plotted for accumulating rainfall.

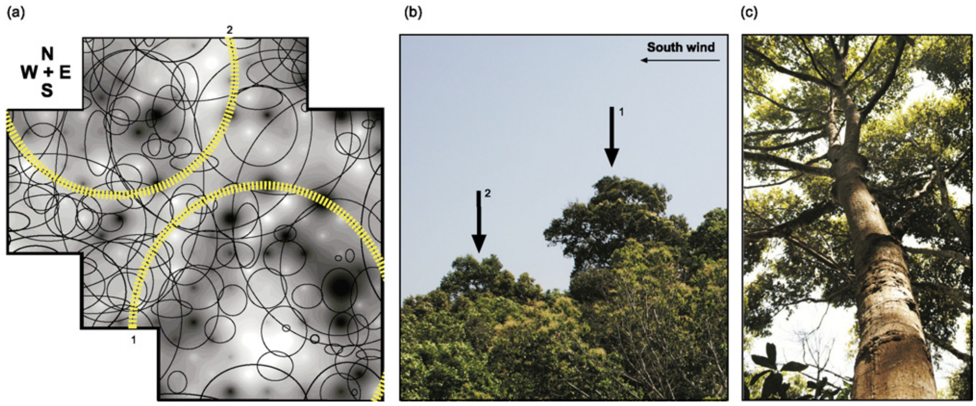

Fig. 7 – (a) Idealized representation of the crown perimeters for all trees affecting throughfall in the study plot. Interpolated throughfall is shown in the background (cf. Fig. 4b). The crown perimeters of the two trees shown in panel (b) are hashed. (b) Number 1 indicates the location of the 35-m tall *Eugenia albiflora* tree on the SE corner of the plot that potentially prevents rainfall from entering the plot during periods of strong south winds that produce non-vertical rain-driven wind. Number 2 marks the location of an upper-story *Castanopsis tribuloides* tree that creates a canopy drip point (panel c). (c) Canopy and trunk of a *C. tribuloides* (#2, panel b) for which stemflow water traveling down the trunk frequently exists as throughfall at many of the knots shown.

of a handful of upper-story *Castanopsis tribuloides* trees was often substantial because stemflow originating high in the sparse canopy flowed in a concentrated stream to common exit points at knots on the tree trunk or large branches (Fig. 7c). Our sampling strategy, however, did not reveal an obvious spatial structure in throughfall, as has been found by others (e.g., Whelan and Anderson, 1996; Llorens and Gallart, 2000). Similarly, Loescher et al. (2002) reported only a weak relationship between canopy cover and throughfall volume (cf., Bellot and Escarre, 1991); and Carlyle-Moses et al. (2004) determined that throughfall was only related to various upper- and understory canopy variables during relatively small rainfall events. The inability to ensure that estimated LAI values represented the actual canopy area affecting throughfall at any given point may have hampered our ability to identify such a relationship (Levia and Frost, 2006).

Konishi et al. (2006) found cyclic patterns in the spatial distribution of throughfall for distances greater than about 11 m in their study plot in Peninsular Malaysia. Others have noted that throughfall gauges should be separated by anywhere from half a crown diameter to >40 m to be spatially independent (Brouwer, 1996; Loescher et al., 2002; Keim et al., 2005). Given the lack of independence among throughfall measurement locations, it is important to be cautious when using these small-plot results to 'scale up' to the watershed level (cf. Scatena, 1990; Chappell et al., 2001; Manfroi et al., 2006).

Spatial structure in throughfall in PKEW might have been affected by the interaction of topography, variable tree height, and wind-driven rain (Herwitz and Slye, 1992, 1995). For example, low throughfall observed during the first six periods of the study coincided with comparatively strong southerly winds (Table 1, Fig. 8). Strong winds can produce substantially non-vertical rainfall in PKEW. In the case of southerly winds, the canopy of a 35-m tall *Eugenia albiflora* tree located on the SE corner of the plot would likely block non-vertical rainfall from entering the forest plot (Fig. 7a and b). An alternative explanation is an increase in canopy cover over the course of the study. However, the few deciduous trees within the stand were fully leafed by the beginning of the experiment; and no noticeable change in canopy vegetation density occurred thereafter.

5.4. *Practicality of stationary gauges*

Reduction of the number of gauges required for estimating throughfall with high statistical confidence and low error is desirable for minimizing cost and effort (Helvey and Patric, 1965; Rodrigo and Avila, 2001; Holwerda et al., 2006). The stationary gauges, which produced a throughfall estimate indistinguishable from the rovers, are advantageous because they integrate a sampling area equivalent to several rovers, do not require daily visits because they record data automatically, and do not have to be periodically repositioned. The stationary gauges also allow detailed examination of the rainfall interception process over the course of individual storms (Link et al., 2004; Cuartas et al., 2007). Furthermore, in remote and difficult terrain, reliable automatic recording gauges may be the only practical option for obtaining realistic throughfall estimates when determining the spatial distribution is not a goal.

Drawbacks include disruption of the understory in the immediate area around the troughs and routine site visits to clear the troughs of debris and repair them if damaged by limb-fall. The stationary gauge method is also substantially more expensive that the rover setup, because of the cost of fabrication, and the necessity of using a data logger and portable computer for downloading. Furthermore, the large volumetric capacity of the tipping mechanism allows for substantial error for small throughfall depths; and dynamic calibration of the tipping-bucket mechanism can be tedious in the field.

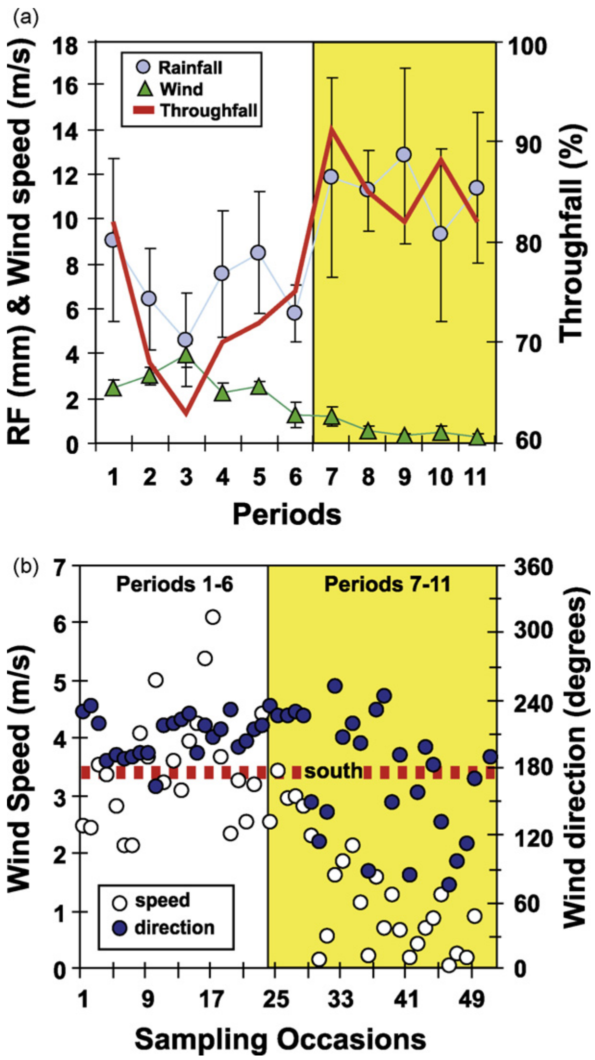

Fig. 8 – (a) Mean wind speed, rainfall, and throughfall for each of the 11 periods during the investigation. Error bars are standard errors. (b) Mean wind speed and direction during the 49 sampling occasions. Compared with the latter periods, sampling occasions during the initial periods were characterized by stronger south-dominated winds and lower throughfall.

6. Conclusions

Identical throughfall estimates (82%) in the 500-m^2 disturbed evergreen-dominated montane forest plot in northern Thailand were determined with mobile and stationary trough methods—but only after sampling more than about 700 mm, collected during 36 sampling occasions. The range of throughfall depths recorded during 49 sampling occasions varied between methods because the stationary gauges integrated throughfall over a much larger collection area than individual rovers. Two important keys for obtaining reasonable throughfall estimates were correcting for splash loss errors among the throughfall and rainfall collection gauges and performing dynamic calibration on all tipping-bucket mechanisms.

Standard errors (2%) and coefficients of variation (≤10%) for both mobile and stationary methods were low, in part, because of the absence of tree gaps. While we found no correlation between leaf area index and throughfall at corresponding understory locations, some canopy drip points (i.e., areas with throughfall greater than 100%) were located near crown perimeters of canopy trees and near the base of certain upper-story trees that generated substantial stemflow which dripped to the ground from the trunks and large branches. However, all throughfall measurement locations in the small patch were correlated to some degree, possibly because of the interaction of wind-driven rainfall and one dominant canopy tree. Although the throughfall estimates were similar to those observed at a nearby forest in northern Thailand, they might not be an accurate predictor of throughfall at the watershed scale in the study area, because of the lack of canopy gaps in the experimental plot and the variable topography in the basin.

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