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Rainwater Interception Pattern of a Regenerated Secondary Tropical Forest and Oil Palm (*Elaeis guineensis* Jacq.) Canopies in Bintulu, Sarawak

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ABSTRACT

Regenerated secondary tropical forest that resulted from logging activity and transforming of forest into oil palm (*Elaeis guineesis* Jacq.) estate are expected to influence the magnitude of rainfall water fraction under these plant canopies. In depth information and knowledge regarding interception pattern of rainwater are still very much lacking, especially under these canopies in tropical region. Thus, the objective of this study was to evaluate the amount of rainwater passing the regenerated secondary tropical forest and oil palm canopies, which currently cover 14.7% of the total land area in Malaysia. Three sampling sites were established, which consisted of a regenerated secondary tropical forest (RSTF), productive oil palm plantation (POP) and non-productive oil palm area (NPOP). The computed throughfall (Tf_d) for RSTF, POP and NPOP were 77.2%, 91.1% and 87.4%, respectively. The stemflow (Sf_d) was worked out as 0.5% (RSTF), 0.7% (POP) and 0.4% (NPOP) of gross rainfall during the study period. The findings revealed that 22.3%, 8.2% and 12.2% were intercepted by RSTF, POP and NPOP canopies, respectively and evaporated back to the atmosphere. The measured Tf_d, Sf_d and evaporation (E_i) were different among the three study sites even within the local environment and thus, suggesting the findings to be influenced by 1) canopy structures and trunk morphology; 2) installation of sampling material; 3) species and age of tree or trunk; and 4) local meteorological condition. The study recommends extra caution should be considered during the installation of sampling material, especially for Sf_d measurement to avoid leakage and improve the accuracy of E_i values. This is important because the portion of rainwater intercepted by these canopies is a significant component, which is vital for managing forest resources, oil palm estate, as well as catchment area for sustainable clean water resources.

Keywords: Interception loss, oil palm, rainfall, regenerated secondary tropical forest, Sarawak

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INTRODUCTION

The inter-relating effects on plant ecology and the environment is essential to increase the awareness for better management of agricultural land uses. One of the important alterations in hydrological fluxes resulting from forest conversion is the amount of water intercepted by and re-evaporated from vegetation surfaces. This interception loss of rainfall is believed to play an important role in the water balance of catchments and plant ecosystems. Furthermore, to improve catchment and water resources management, understanding on hydrological processes such as rainfall interception, throughfall and stemflow were very important especially under oil palm canopy (Geoffery, 2013). As tropical rainforest receives great variability in stemflow and throughfall (Lloyd & Marques, 1988; Marin *et al.*, 2000), factors attributed to climatic conditions, species composition, monitoring methodology (Germer *et al.*, 2010), structure of tree canopy and multiple data collections (Junior *et al.*, 2015) are necessary for investigating the rainfall interception of forest canopy. There were some queries remain concerning the relative importance of various mechanisms for interception loss process especially from old oil palm stands and regenerated secondary tropical forest. Generally, interception loss rates vary among tree species, forest density, canopy structure, vegetation physiology and different climatic conditions (Zhang *et al.*, 2006). A number of studies on interception loss had been conducted but a detailed relationship with vegetation has yet to be documented (Dietz *et al.*, 2006; Slamet *et al.*, 2015).

Information on the rates of interception loss are of importance in determining the water yield of forested areas (Gash & Stewart, 1977; Scatena, 1990; Loustau *et al*., 1992). Other researchers pointed out that forest conversion to other vegetation cover and reduction of forest canopy cover are the main determinants of the difference in water balance, which resulted in an increment in the catchment water yield (Sahin & Hall, 1996). It has been suggested that the rainfall interception loss measurements and models are prerequisites for any quantitative predictions of the effects of forest management on local hydrology (Asdak *et al*., 1998).

Malaysia is blessed with abundant natural resources and a conducive climate for commercial cultivation of crops such as oil palm. In a relatively short period of time, Malaysia has become a major palm oil producer and exporter. In 2016, Malaysia accounted for 39% of the world palm oil production and 44% of world exports. Being one of the biggest producers and exporters of palm oil and palm oil products, Malaysia has an important role to play in fulfilling the growing global need for cooking oil and fats sustainably. From about 400 hectares planted in 1920, the area had increased to 54,000 hectares in 1960. Since then, many more areas were opened up for oil palm cultivation, either from virgin jungles or from conversion of plantations that originally supported rubber or other crops (Abdullah & Nakagoshi, 2007). In 2004, the area covered by oil palm stood at a staggering 3.87 million ha representing 70-fold increase since 1960's (Md Noor & Harun, 2004). This represents about 60% of the total 6.08 million ha designated for agriculture under the National Agriculture Plan (NAP3) 1998-2010 (Yusof & Chan, 2004). Thus, about 14.7% of Malaysia's total land mass is currently covered by oil palm plantations.

Conversely, literature on rainwater interception loss from oil palm tree has received low priority for scientific study and so far, no scientific finding on regenerated secondary tropical forest is available. In this context, this study aimed to assess rainwater interception losses and storage rates under varied canopies structures namely regenerated secondary tropical forest (RSTF), productivity oil palm (POP) and non-productivity oil palm (NPOP) canopies.

MATERIALS AND METHODS

Study Area

The research activity was carried out in three locations under different canopies cover, namely regenerated secondary tropical forest (RSTF), productive oil palm plantation (POP) and non-productive oil palm plantation (NPOP) (Figure 1). These experimental sites are situated within Universiti Putra Malaysia (UPM) Bintulu Sarawak Campus, Bintulu, Sarawak, Malaysia. The RSTF is situated within a Forest Park (3°12'30.73" N, 113°05'53.02" E) that was 46 meters above the sea level. The POP and NPOP study sites are located approximately at 3°12'19.11" N, 113°03'57.74" E and 3°12'24.01" N, 113°03'53.01" E, respectively. The oil palm area is undulating with the altitude ranging from 43 to 62 m above the sea level. Slopes are moderate for all study sites with the maximum slopes of 21°.

The 30 hectares of RSTF was covered with mixed lowland dipterocarp and non-dipterocarp species. The mean basal area of trees was about 38 m^2 ha^{-1} with an average diameter at breast height (DBH) > 31 cm. The geology of the study site is mainly Nyalau formation of Oligocene-Miocene period (Geoffery & Yusop, 2005). The total area of POP is only about 5 hectares and NPOP is about 65 hectares. Both areas were planted with *Elaeis guineensis* Jacq. (clone PAMOL/FELDA). Genus *Elaeis* belongs to family Palmae and indigenous to West Africa (Hartley, 1988). The mean trunk heights were about 2.43 m and 5.1 m for POP and NPOP, respectively. The average trunk diameter was 64.6 cm for POP and 48.3 cm for NPOP. The average top height of POP and NPOP were 7.0 m and 15.0 m, respectively. The canopy cover was quite uniform, between 80 and 88% of the ground area. The leaf area index (LAI) normally increases with the palm age and reaches a maximum after about 10 years (Corley & Gray, 1976). The LAI values for oil palm trees on a highly fertile site, with planting density of 148 palm ha^{-1} range from 5.9 to 7.1 (Md Noor & Harun, 2004). The total basal area for POP was about 50 m^2 ha^{-1} with the average diameter at DBH of greater than 63 cm. However, the total basal area for NPOP is lower, which was about 42 m^2 ha^{-1} and the average DBH < 45 cm. The climate of the study areas is typical to the humid tropics, with a small variation of the mean daily

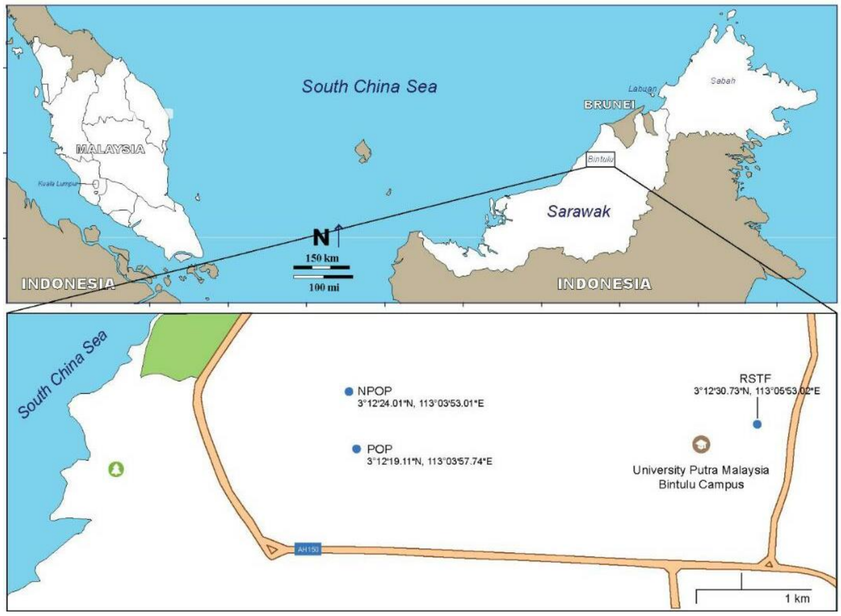

Figure 1. Location of research areas at regenerated secondary tropical forest (RSTF), productive oil palm (POP) and non-productive oil palm (NPOP) in Bintulu, Sarawak (Source: Google Maps).

temperature (25-26°C) in any month. The relative humidity was typically 100% at night but occasionally falls below 80% in the middle of the day.

Field Measurements

Rainfall

A 0.2 mm tipping-bucket rain gauge model HOBO ONSET RGM-2(US) was used to monitor the rainfall event. To determine for an event, rainfall data must be recorded within half an hour at a depth of approximately 0.5 mm (Germer *et al*., 2010). In addition, rainfall events were considered as separate event if the time between events exceeded 5 hours (Deguchi *et al*., 2006). The HOBO rain gauge was recorded when momentary contact-closure events happened, storing the date and time of each event in the logger and retrieving on a weekly basis using BoxCar Pro software that was designed to work with Onset Data Loggers. For the analysis, the rainfall was compared with long-term rainfall data from adjacent rainfall monitoring station.

Throughfall

Throughfall (*TF*) was collected by using 1.5 L polyethylene bottles with a funnel of 84 mm diameter. Each sampling bottle was covered with a nylon screen (0.5 mm mesh), which was placed in the funnel hole to prevent the entry of insects and litterfall. All bottles and funnels were washed by distilled water to make sure they are cleaned. Thirty units of throughfall manual collectors were installed with a minimum 1-m interval in a straight line under canopy at each site to gain more representative data (Geoffery, 2013). Each collector was hanged about 1 m above ground attached on bamboo stick to avoid splash of rain water at the ground enter the container.

Stemflow

Stemflow (*SF*) were collected using spiral-type gauges comprising of a plastic hose (2.0 cm internal diameter) attached to the tree and oil palm trunks and routed into 65 litres collecting tank. The sample trees from RSTF areas were selected during a pre-site survey to resolve the uneven distribution of tree diameter sizes. The sample trees were selected based on tree diameter at DBH, irrespective of tree species or bark texture. Eleven trees were selected for *SF* measurement under the RSTF areas, of which the trees consisted of four species, namely *Litsea castanea*, *Artocarpus anisophyllus*, *Palaquium clarkeanum* and *Shorea xanthophylla*. However, five oil palm trunks for each of POP and NPOP study areas were selected based on the physical condition of the palm oil tree. The physical characteristics of these selected sample trees and oil palm tree trunks are summarised in Table 1.

Installation of plastic hose to oil palm trunk was initially done by shaving the frond bases surrounding the trunk circumference to provide a clean and smooth surface. The plastic hose needs

Table 1. Physical characteristics of the measured trees and oil palm trunks.

Plant Types	Mean diameter DBH (cm)	Mean canopy diameter (m)	Dominant tree canopies at plot site	Canopy Projection Area (m^2)	Stem condition	Stem bark condition
RSTF	11.6	5.08	*Shorea xanthophylla*	20.25	Straight	Rather rough
RSTF	17.8	5.15	*Litsea castanea*	22.82	Straight	Smooth
RSTF	24.8	4.52	*Artocarpus anisophyllus*	25.32	Straight	Smooth
RSTF	39.6	7.08	*Palaquium clarkeanum*	29.71	Straight	Flaky
POP	69.0	10.23	*Elaeis guineensis* Jacq.	35.47	Straight	Rough
NPOP	44.0	9.89	*Elaeis guineensis* Jacq.	31.15	Straight	Rough

Notes: RSTF=regenerated secondary tropical forest; POP=productive oil palm plantation; NPOP=non-productive oil palm area.

to be inspected and maintained on a regular basis as the sampling device was not always entirely satisfactory due to the risk of leakage or blockage. Thus, a silicon sealant was used to seal the hose to the tree bark and oil palm trunk in order to make sure the rainwater did not leak through the tubing. Similarly, *SF* tanks were emptied on an event basis. The rainwater collected in the tank must be measured by using 1 L measuring cylinder for accurate measurement.

Samples were measured strictly six hours after the rainfall event ceased in order to prevent the mixing of rainwater samples with rainfall from other events.

Data Analysis

Rainfall and RSTF measurement were recorded from January to December 2016 which accounted for about 138 events. POP measurement samples were taken from January until April 2016 and collected in 15 events. NPOP measurement was collected in 55 events from August to December 2016.

Throughfall and stemflow parameters were used to determine the interception loss ratio of the individual plants or group of species. This study used the following terms for the analyses:

A = Canopy area projection (m^2)

B = Basal area (mm^2)

C_A = Open surface area of manual collector (mm^2)

E_i = Interception loss

I_R = Interception loss ratio

R_d = Rainfall depth (mm)

Sf_y = Stemflow yield (L), of which stemflow volume dropped in a manual collector and converted into unit (m^3)

Tf_y = Throughfall yield (mL), of which throughfall volume dropped in a manual collector and converted into unit (mm^3).

I. *Throughfall depth,* Tf_d was defined as throughfall per area of manual collector (mm^2). The throughfall depth was defined by (Germer *et al.*, 2010):

$$Tf_d = Tf_y / C_A \quad \text{(Equation 1)}$$

II. *Stemflow depth,* Sf_d was defined as stemflow per area of canopy diameter (m^2). The stemflow depth was defined by (Germer *et al.*, 2010):

$$Sf_d = Sf_y / A \quad \text{(Equation 2)}$$

III. *Interception loss,* $E_i = (R_d - Tf_d - Sf_d)$ (Equation 3)

IV. *Interception loss ratio,* $I_R = [(R_d - Tf_d - Sf_d) / R_d] \times 100\%$ (Equation 4)

V. *Stemflow funneling ratio* (S_{FR}): $Sf_y / (R_d \times B)$ and unitless (Herwitz, 1986) (Equation 5)

RESULTS AND DISCUSSION

Rainfall Characteristics

Throughout the measurement period, the study site encountered continual rainfall recorded without any outward separation in between the individual events. The individual rainfall event recorded from preceding and succeeding rainfall was separated from each other at least six hours in order to dry the wet canopy (Murakami, 2006). The gross total rainfall during one-year study period amounted to 2466.9 mm (Figure 2), which was lower than the 3-years of long-term mean annual rainfall of 3423.9 mm. During southwest monsoon (May-September), the observed rainfall was 894.6 mm, which was 1197.6 mm lower than usual, whereas northeast monsoon (October-March) rainfall was found to be 1326.2 mm and this was 1880.2 mm lower than usual. A total of

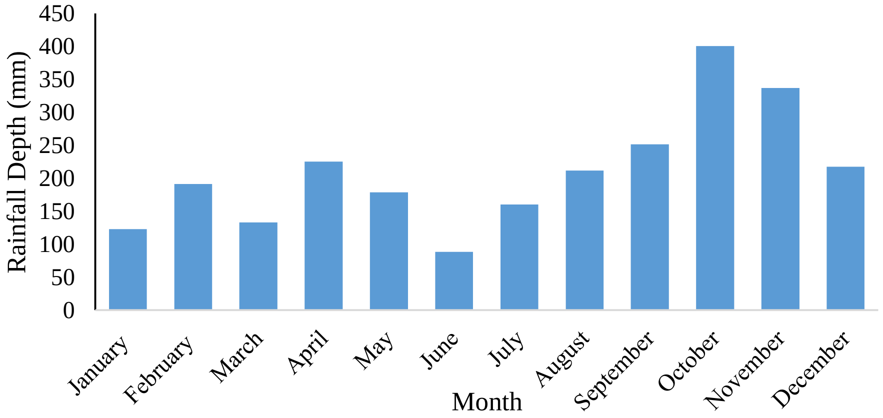

Figure 2. Annual rainfall events of year 2016 at Universiti Putra Malaysia, Bintulu campus.

210 individual rainfall events were recorded, which showed the numbers of rainy day during the study period were similar to the usual rainy day of 211 days. Although the numbers of rainy days almost similar, the quantity of rainfall within the study areas was 27% lower compared to the normal annual rainfall.

These rainfall events were then divided into five classes: < 5 mm, 6-10 mm, 11-20 mm, 21-50 mm and above 51 mm (Table 2). Most of the rainfall events were under the category of < 5 mm, contributing 174 mm of total annual rainfall. Small rainfall event (< 5 mm) occurred frequently compared to other rainfall classes. However, this small rainfall event only contributed 6.91% of the total rainfall. Although only eight heavy storms (> 50 mm) were recorded, they accounted for 19.22% of the annual rainfall. These recorded heavy storms mostly occurred during northeast monsoon (October-March) where the wind blew from the South China Sea. As such, the rainfall pattern during the study period could be described as moderate to slightly heavy.

Throughfall Depth

Throughfall depth (Tf_d) measurement were based on the selected rainfall events throughout the study period. The selected rainfall events were based on two criteria: 1) rainfall should be above 1 mm/hr to avoid less accuracy when dealing with very small rainfall depth (< 1 mm). According to Department of Irrigation and Drainage Malaysia (DIDM), gross rainfall below 1 mm/hr is considered as 'no rain'; 2) a continuous and long-hour rainfall event, which is considered unusual will be excluded to evade error. Therefore, 138, 15 and 55 rainfall events were carefully selected to compute interception loss under RSTF, POP and NPOP. The total Tf_d depth calculated from these different canopies amounted to about 77.3%, 91.1% and 87.4%, respectively of total selected rainfall from each study areas (Table 3). Based on the regression analysis, all *TF* measurements from each study

Table 2. The frequency and total rainfall based on five different rainfall classes.

Rainfall Classes (mm)	Events Frequency (%)	Gross Rainfall (mm)	Volume contribution to annual rainfall (%)
Below 5	49.05	174	6.91
6 – 10	13.81	228.6	9.07
11 – 20	15.24	445.4	17.68
21 – 50	18.10	1187.4	47.13
Above 51	3.81	484.2	19.22
Overall total	100	2519.6	100

Table 3. The percentage of rainwater passing through RSTF, POP and NPOP.

Study Area	R_d event (mm)	Total Tf_d (mm)	Percentage (%)
RSTF	2466.9	1906.0	77.3
POP	385.8	351.5	91.1
NPOP	1144.0	999.7	87.4

Notes: RSTF=regenerated secondary tropical forest; POP=productive oil palm plantation; NPOP=non-productive oil palm area.

site was highly correlated with the amount of rainfall (Figure 3). The empirical relationships for each regression analysis are given by Equation 6a, 6b and 6c. The results suggested that these equations can be used to estimate Tf_d under RSTF and oil palm canopies with similarity of physiographic conditions and plants characteristics.

Tf_d (RSTF) = $0.826R_d - 1.243$; $R^2 = 0.988$ (Equation 6a);

Tf_d (POP) = $0.979R_d - 1.749$; $R^2 = 0.985$ (Equation 6b);

Tf_d (NPOP) = $0.840R_d + 0.972$; $R^2 = 0.992$ (Equation 6c);

where; Tf_d = throughfall (mm); R_d = rainfall individual event (mm).

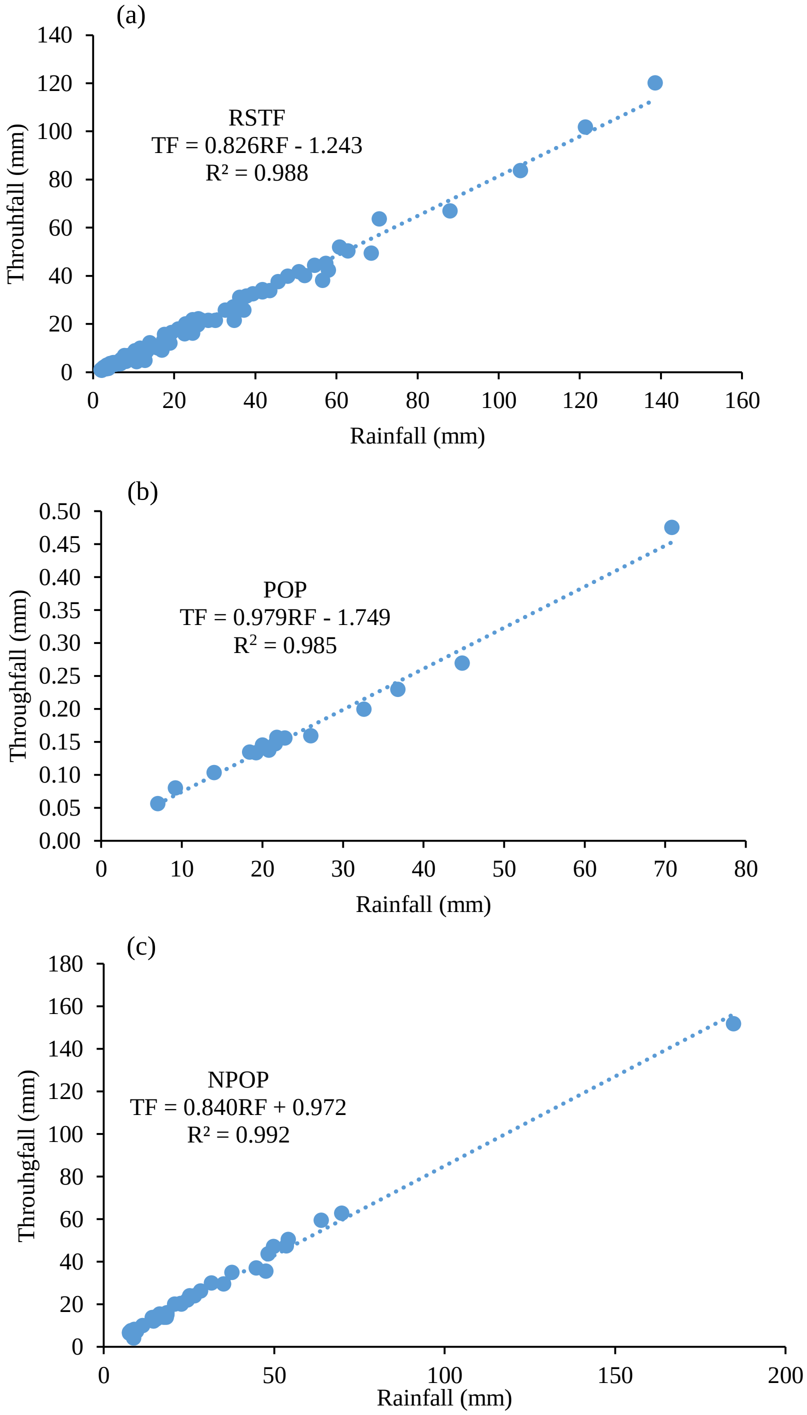

Figure 3. Regression of Tf_d against R_d for (a) regenerated secondary tropical forest (RSTF); (b) productive oil palm plantation (POP); and (c) non-productive oil palm area (NPOP).

The highest and lowest Tf_d recorded during the study period are summarised in Table 4. For an individual event, the ratio of Tf_d to rainfall ranged widely for RSTF (32.8 – 96.2%) and NPOP (47.2 – 96.6%). However, POP area showed less variation in term of Tf_d ratio to rainfall (70.6 – 98.6%). These variations of findings can be explained based on two mechanisms that affect the Tf_d rates after the canopies wet-up: 1) occurrence of evaporation of stored water on canopy during the storm (Crockford & Richardson, 1990) and 2) the variability of throughfall depth caused by the characteristics of foliage (Reid & Lewis, 2009).

In addition, both RSTF and NPOP have similar pattern of Tf_d ratio against R_d where the wide range might be due to the characteristics of the canopy structures. Figure 4 shows the relationship between throughfall depth and rainfall individual event. It is shown that the values were scattered and concentrated around the smaller rainfall sizes. This pattern can be associated with the recorded R_d (80.8%) that comprises of rain depth of less than 50 mm. Other studies within different forest types (mixed white oak forest – Silva & Okumura, 1996; deciduous broad-leaves forest – Deguichi *et al*., 2006) found almost a similar pattern in the relationship between rainfall size and *TF* (%).

The Tf_d value of 91.1% for POP obtained from this study was slightly higher compared to the finding by Banabas *et al*. (2008) in Papua New in which the Tf_d measured was 83% for productive oil palm canopy. Other studies by Geoffery (2013) in Johor, Malaysia, however revealed lower Tf_d values of 67% and 70%, respectively, under productive oil palm canopies. The variations of Tf_d values among these studies could be attributed to two factors as suggested by Geoffery (2013). Firstly, the orientation of the fronds above the Tf_d collectors at a particular time may vary due to wind effect during the rainfall event. Secondly, the overlapping canopies might probably become the shelter and therefore reduce the Tf_d dripping point. However, the Tf_d values measured under RSTF and NPOP were relatively difficult to compare as no study has yet to be conducted under these canopies in tropical regions.

Stemflow Depth

The estimated total stemflow depth (Sf_d) for RSFT, POP and NPOP study areas were 0.5%, 0.7% and 0.4%, respectively of total rainwater that reached the ground (Figure 5). The Sf_d pattern of three different sites obtained from the study were considered very low compared to other studies. For POP study area, the measured Sf_d of 0.7% of total rainfall appeared very low as compared to Kee *et al.* (2000), Banabas *et al.* (2008) and Geoffery (2013) that were 13%, 11% and 4.2%, respectively. Low volume of Sf_d measured during the study could be related to the sampling method and high absorbance of the oil palm trunks as suggested by Geoffery (2013). The variation of measured Sf_d is difficult to compare, mainly due to the differences of sample trunk and canopy characteristics. However, low Sf_d rate is favourable as high Sf_d yields may leach fertiliser from the soil at trunk base (Schroth *et al*., 1999). In addition, Levia and Frost (2003) also reported that Sf_d might have considerable effect on plant productivity and yield because of its capacity to leach fertilisers near plant stem.

The measured Sf_d at RSTF and NPOP are less correlated with individual rainfall, compared to POP which is highly correlated as illustrated in Figure 6 and Equation 7a, 7b and 7c. The variation of correlation among RSTF, NPOP and POP might be associated with their stemflow funneling ratio (S_{FR}) value introduced by Herwitz (1986) that quantifies the ratio of stemflow yield to gross rainfall and basal area. S_{FR} indicates more details of the plants or tree trunks that can capture gross rainfall and generating stemflow (Siegert & Levia, 2014). $S_{FR} > 1$, denotes that the Sf_d volume is yielded directly from the plants canopy and other components and it funnels the rainwater towards its stem. The other components of trees, include branches and

Table 4. The Tf_d pattern at RSTF, POP and NPOP.

Study Area	Tf_d highest (mm)	Tf_d lowest (mm)	Range of ratio Tf_d vs. R_d (%)
RSTF	120.0	0.7	32.8 – 96.2
POP	69.8	6.9	70.6 – 98.6
NPOP	151.7	4.1	47.2 – 96.6

Notes: RSTF=regenerated secondary tropical forest; POP=productive oil palm plantation; NPOP=non-productive oil palm area; Tf_d =throughfall depth.

epiphytic plants that grow on the tree stems or oil palm trunks. Based on the computed funneling ratio (Table 5) for the three study sites, POP revealed that 100% of FR values were > 1. Low correlation of Sf_d in RSTF was due to different height of canopies and the overlapping of other plants that were adjacent to the sample tree.

Sf_d (RSTF) = $0.0033R_d + 0.0301$; $R^2 = 0.476$ (Equation 7a);

Sf_d (POP) = $0.0062R_d + 0.0121$; $R^2 = 0.986$ (Equation 7b);

Sf_d (NPOP) = $0.0013R_d + 0.0286$; $R^2 = 0.208$ (Equation 7c);

where; Sf_d = stemflow (mm); R_d = rainfall individual event (mm).

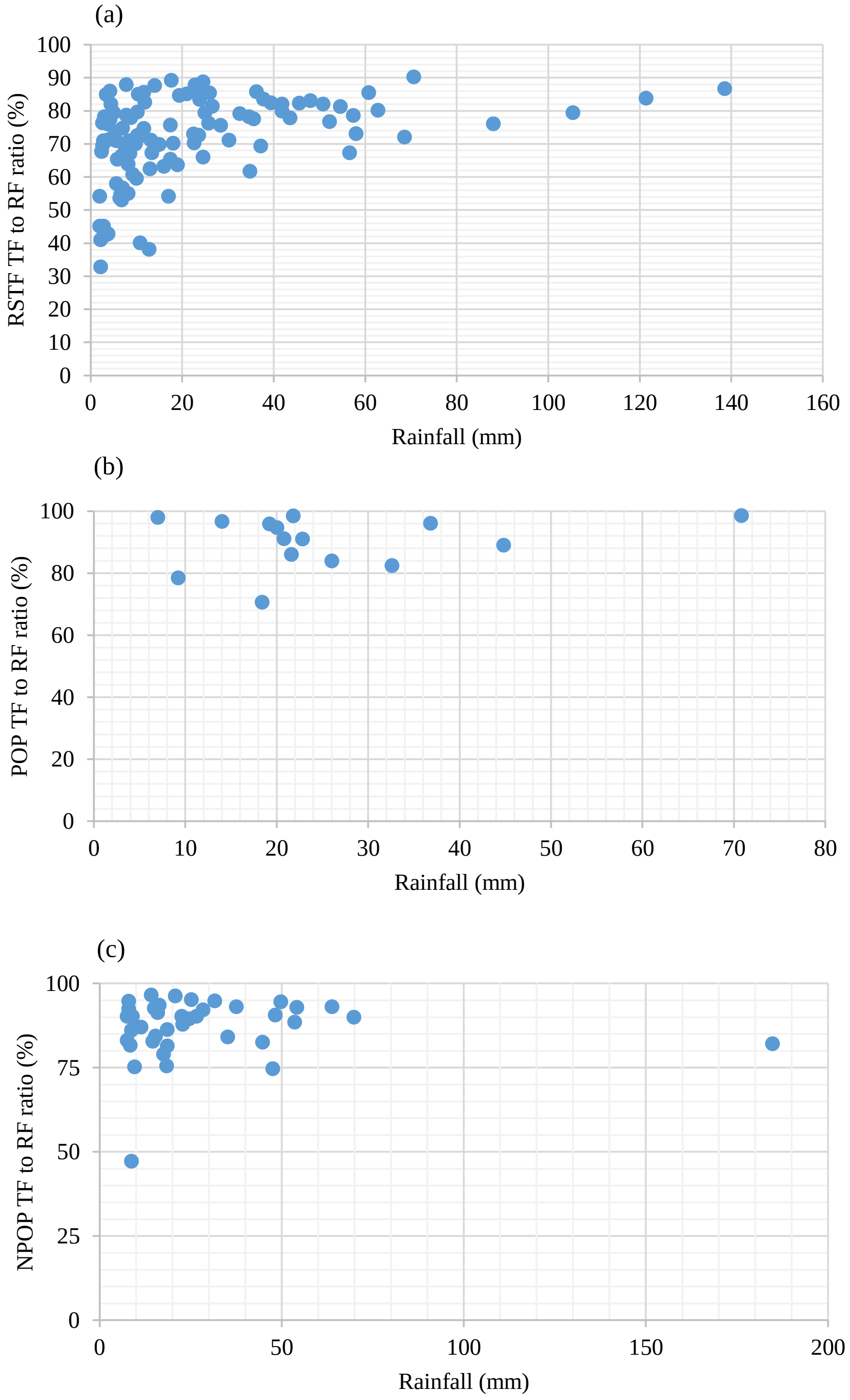

Figure 4. The relationship between Tf_d (%) and R_d (mm) for (a) regenerated secondary tropical forest (RSTF); (b) productive oil palm plantation (POP); and (c) non-productive oil palm area (NPOP).

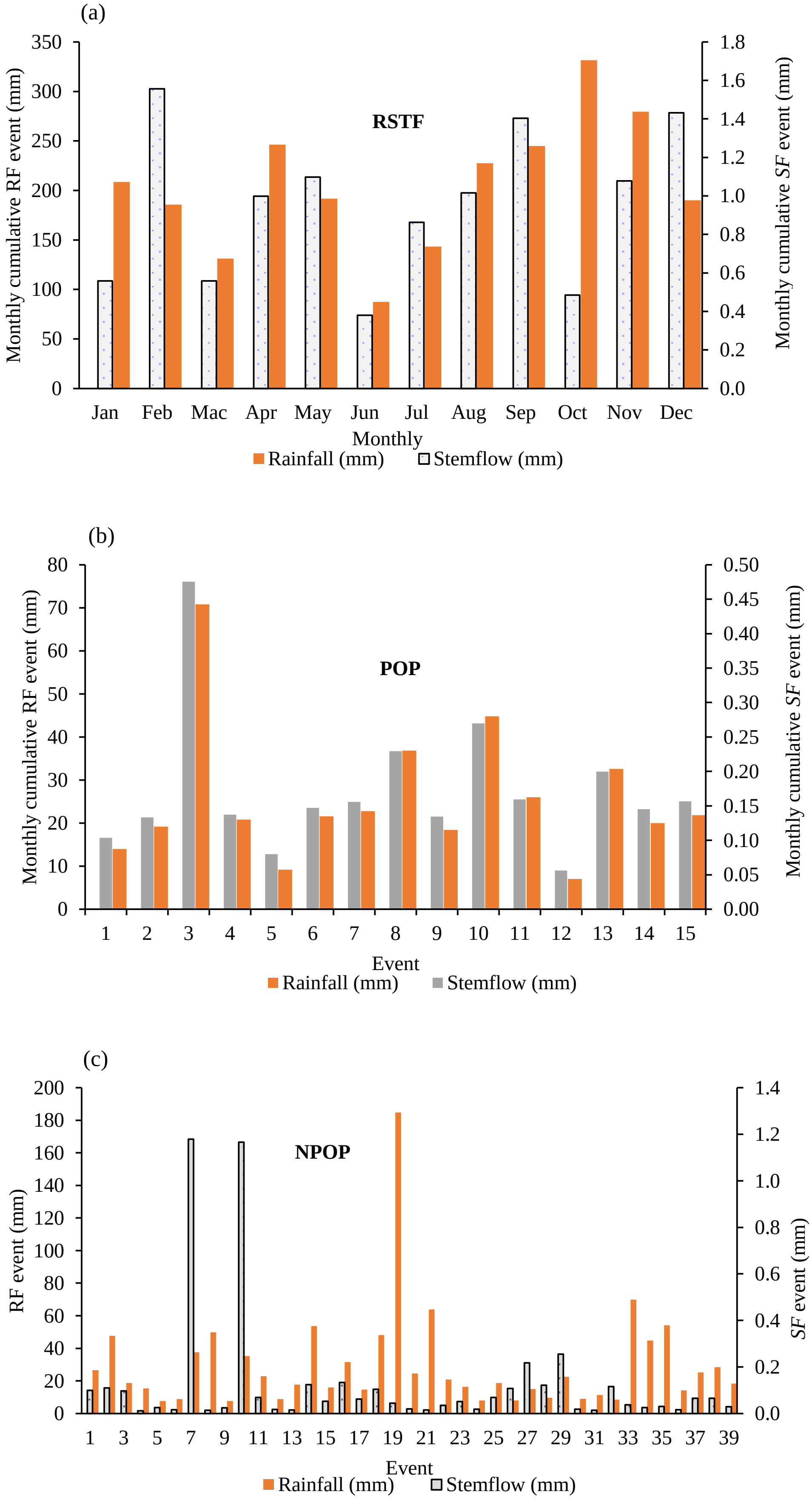

Figure 5. The *SF* pattern compared to *RF* event for (a) regenerated secondary tropical forest (RSTF); (b) productive oil palm plantation (POP); and (c) non-productive oil palm area (NPOP).

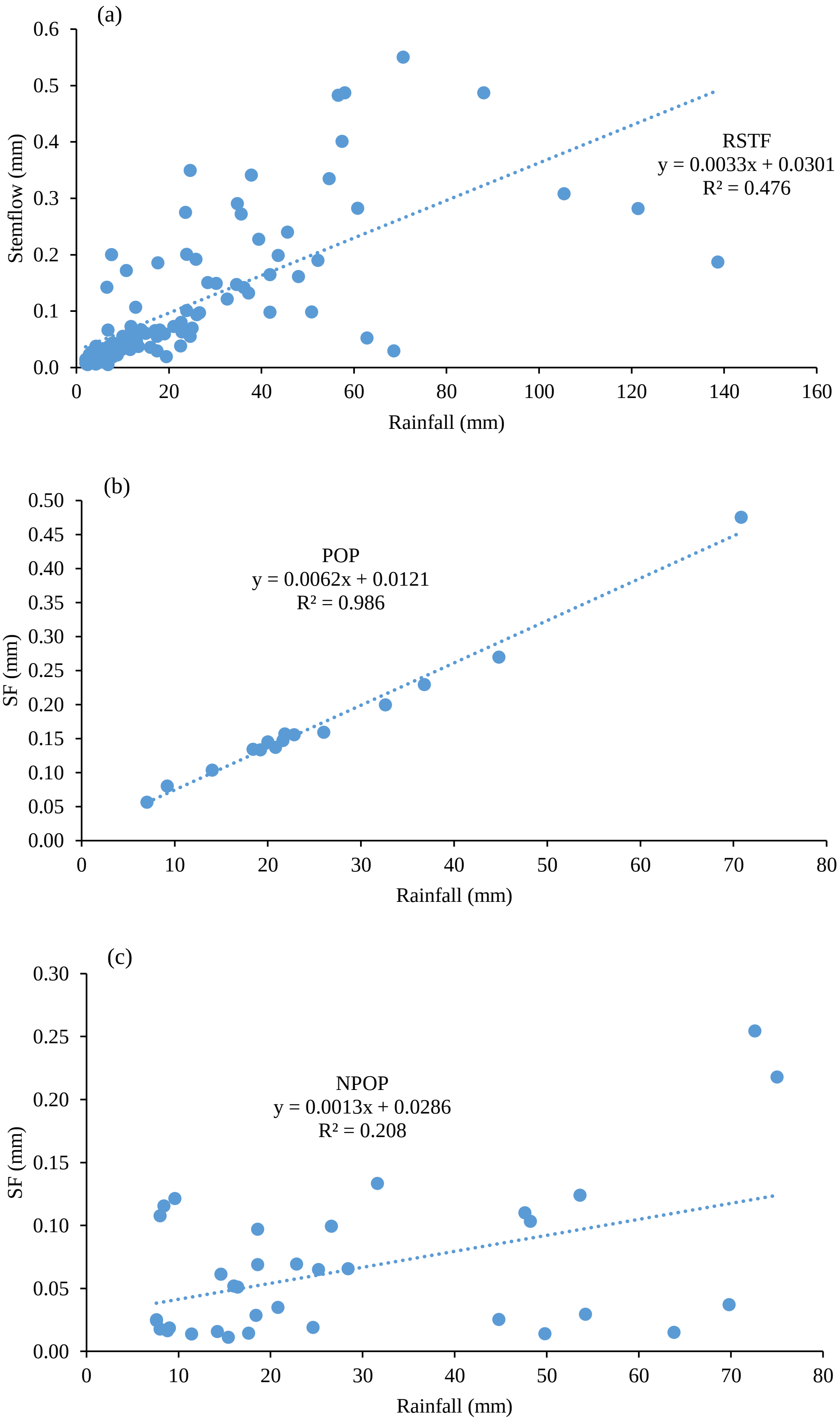

Figure 6. Regression of Sf_d against R_d for (a) regenerated secondary tropical forest (RSTF); (b) productive oil palm plantation (POP); and (c) non-productive oil palm area (NPOP).

Table 5. Funneling ratio (FR), Sf_d and interception loss values for RSTF, POP and NPOP.

	RSTF	POP	NPOP
Range of FR	0.44 - 4.73	1.4 - 4.4	0.8 – 6.9
FR average	1.9	2.6	2.4
SF (%)	0.46	0.67	0.41
Interception loss (%)	28.3	9.1	12.2

Notes: RSTF=regenerated secondary tropical forest; POP=productive oil palm plantation; NPOP=non-productive oil palm area.

The funneling ratios computed in this study ranged from 0.44 – 4.73, 1.4 – 4.4 and 0.8 – 6.9 for RSTF, POP and NPOP, respectively. Based on sampled trunk basal area of RSTF (15.8 m^2/ha), POP (18.6 m^2/ha) and NPOP (16.5 m^2/ha) and the computed funneling ratio of these trunks of RSTF (1.9), POP (2.6) and NPOP (2.4), indicating that 0.46% (RSTF), 0.67% (POP) and 0.41% (NPOP) of rainfall intercepted by the projected canopy area were diverted in Sf_d. These findings were lower compared to other studies elsewhere under different vegetation types. Such low observations of Sf_d might be linked to measurement method as suggested by Geoffery (2013) that indicates significant leakage may occur if the routed rubber collar installed at trunk is not properly fitted and sealed. Elsewhere, Germer *et al*. (2010) suggested that large stand might generate more Sf_d yield than medium-sized stand, but small stand was found to be of no different with the two larger sizes. Canopy density also plays important role to Sf_d generation, less density may generate higher Sf_d meanwhile high density of canopies may decrease the Sf_d (Siegert & Levia, 2014). Sf_d volume at POP generated large volume and thus, this finding need further attention for consideration of land management, especially for a productive oil palm plantation.

Interception Loss

The measured interception loss (E_i) computed at RSTF was 549.5 mm or 22.3% of the gross rainfall (Table 6). This is slightly higher than the 21.3% reported by Vernimem *et al*. (2007) in stunted heath forest, central of Kalimantan, Indonesia. Elsewhere, a study by Burghouts *et al*. (1998) in Sabah, Malaysia and Dykes (1997) in Brunei reported that 19% and 18% of rainfall, respectively, were accounted as E_i under lowland evergreen tropical forest canopy. Such a slightly higher E_i value obtained in this study might be attributed to the measured Sf_d which was significantly lower compared to those reported elsewhere. This might be due to leakage that occurred if the rubber collar is not properly fitted and sealed.

In other Southeast Asian region, a logged-over lowland forest E_i of 19% and 20% were reported in Sabah, Malaysia (Chappell *et al*., 2001) and Sarawak (Kumagai *et al*., 2005), respectively. In the central Sulawesi, the interception loss under logged forests and natural tropical rainforests were of 18-20% and 30%, respectively (Diezt *et al*., 2006). The E_i value under RSTF in this study showed almost similar findings with those areas with disturbed forest structures due to logging activities. Thus, it is suggested that E_i value might be controlled by vegetation structures and density.

In this study, RSTF was capable to entrain more incidental rainfall and generate higher E_i compared to POP and NPOP, which contributed about 8.2% and 12.2% of E_i, respectively. Lower E_i values obtained from these two oil palm canopies were due to a shorter study period for both sites. This happen due to unforeseen circumstances such as POP plantation area cleared for newly planting management plan. The data collected under NPOP was of shorter duration due to rain gauge faulty and inconsistency of results obtained from the automated logger. Thus, only four months of purely precise and stable results were used for further analysis. Other study on oil palm canopy in Peninsular Malaysia by Kee *et al*. (2000) reported that 17% of rainfall was estimated as E_i. Compared to Geoffery (2013), the E_i value under oil palm plantation was 28.9%. The high E_i value was associated with *La Nina* phenomenon during the two years of when the study was carried out.

In addition, some argued that rainfall interception loss in Southeast Asia may be at least two folds higher than those reported for Central Amazonia; this was possibly because of large-scale advection from the surrounding warm sea (Schellekens, 2000; Bruijnzeel, 2004). Furthermore, the partitioning of rainfall into throughfall, stemflow and interception loss were affected by three primary factors, i.e. rainfall characteristics, meteorological factors and vegetation structure (Crockford & Richardson, 2000; Staelen *et al*., 2007).

The E_i value of RSTF revealed better relationship with rainfall depth compared to POP and NPOP. The pattern of E_i against R_d in Figure 7 showed that whenever R_d is low, the E_i value increase, and *vice versa* if R_d increase, the E_i becomes low. This revealed an inverse relationship between E_i and R_d for RSTF, POP and NPOP. In addition, the relationship pattern among the three sites also demonstrated only a few storm events (> 50 mm) recorded during the study period.

This study suggests that oil palm trunk morphology and physical including amounts of fronds play an important role in influencing E_i values, especially different ages among the tree or trunk samples.

Comparison with Other Studies

This study revealed substantial correlation between E_i and R_d at all study sites. The E_i values were found to vary considerably among the three vegetative types. As for RSTF, POP and NPOP, about 77.7%, 91.8% and 87.8% of R_d, respectively, reaches the ground surface which is considered as interception storage (Table 6). This interception storage is important to be estimated and should not be neglected as it may have an impact on tree growth or oil palm fruits production. The average percentage of stemflow is normally low compared to throughfall and even negligible in some studies. However, Germer *et al*. (2010) reported that the variability of stemflow generation at tropical rainforest sites is still remarkable.

CONCLUSION

The results revealed that E_i characteristics of RSTF, POP and NPOP in Bintulu, Sarawak varied among the study sites due to duration of data collection and suggested to be site specific even under the same tropical condition. However, the E_i values under RSTF showed a similar pattern compared to logged mover tropical forest elsewhere. Thus, this study suggests that the disturbance of canopy and forest density may contribute to E_i value. The variabilities of Tf_d and Sf_d values obtained in this study suggest that these parameters were influenced by canopy structures and trunk morphology, local meteorological condition, installation of sampling material and age of sampling tree or trunk. Although the results of interception loss achieved at these study sites were considerably acceptable, future research is needed in order to establish a reliable interception component, which is vital for managing forest resources, oil palm plantation as well as catchment area for water resources.

Table 6. Rainfall separating at RSTF, POP and NPOP in Sarawak, Borneo and elsewhere within tropic regions.

Location	Forest type	R_d (mm)	Tf_d (%)	Sf_d (%)	E_i (%)	References
Central Kalimantan	LERF	2200^a	87.2	1.4	11.4	Asdak *et al.* (1998)
Central Kalimantan	LERF	2995	82.8	0.8	16.4	Vernimmen *et al.* (2007)
Sabah, Malaysia	LERF	3100	80.7	1.9	17.4	Sinun *et al.* (1992)
Sabah, Malaysia	LERF	2800	80.0	1.0	19.0	Burghouts *et al.* (1998)
Sabah, Malaysia	LERF	1400^b	92.0	1.1	6.9	Bidin & Chappel (2003)
Brunei	LERF	825^c	81.0	1.0	18.0	Dykes (1997)
Sarawak, Malaysia	LERF	2360	84.5	3.1	12.4	Manfroi *et al.* (2004)
Colombian Amazonia	LERF	3400	81.9 – 87.2	0.9 – 1.5	12.0 – 17.0	Marin *et al.* (2000)
Venezuela	LERF	3665	87.0	7.1	5.9	Sf_d from Jordan, 1978; Tf_d from Jordan and Heuveldop (1981)
Venezuela	THF	3500	90.5	1.5	8.0	Herrera (1979)
Central Kalimantan	THF	2995	89.1	1.3	9.6	Vernimmen *et al.* (2007)
Central Kalimantan	SHF	2995	76.7	2.0	21.3	Vernimmen *et al.* (2007)
Eastern Tibet, China	CF	2200	24.2	0.1	75.7	Liu *et al.* (2013)
Sedenak, Johore, Malaysia	POP	2830	66.9	4.2	28.9	Geoffery (2013)
Sarawak, Malaysia	RSTF	2466.9	77.2	0.5	22.3	This study
Sarawak, Malaysia	POP	385.8^d	91.1	0.7	8.2	This study
Sarawak, Malaysia	NPOP	1144^c	87.4	0.4	12.2	This study

Notes: Lowland Evergreen Rain Forest (LERF), Tall Heath Forest (THF), stunted Heath Forest (SHF), rainfall (R_d), throughfall (Tf_d), stemflow (Sf_d) and interception (E_i).

^{a} -6 month; ^{b} -Very dry period; ^{c} -4 months; ^{d} -3 months.

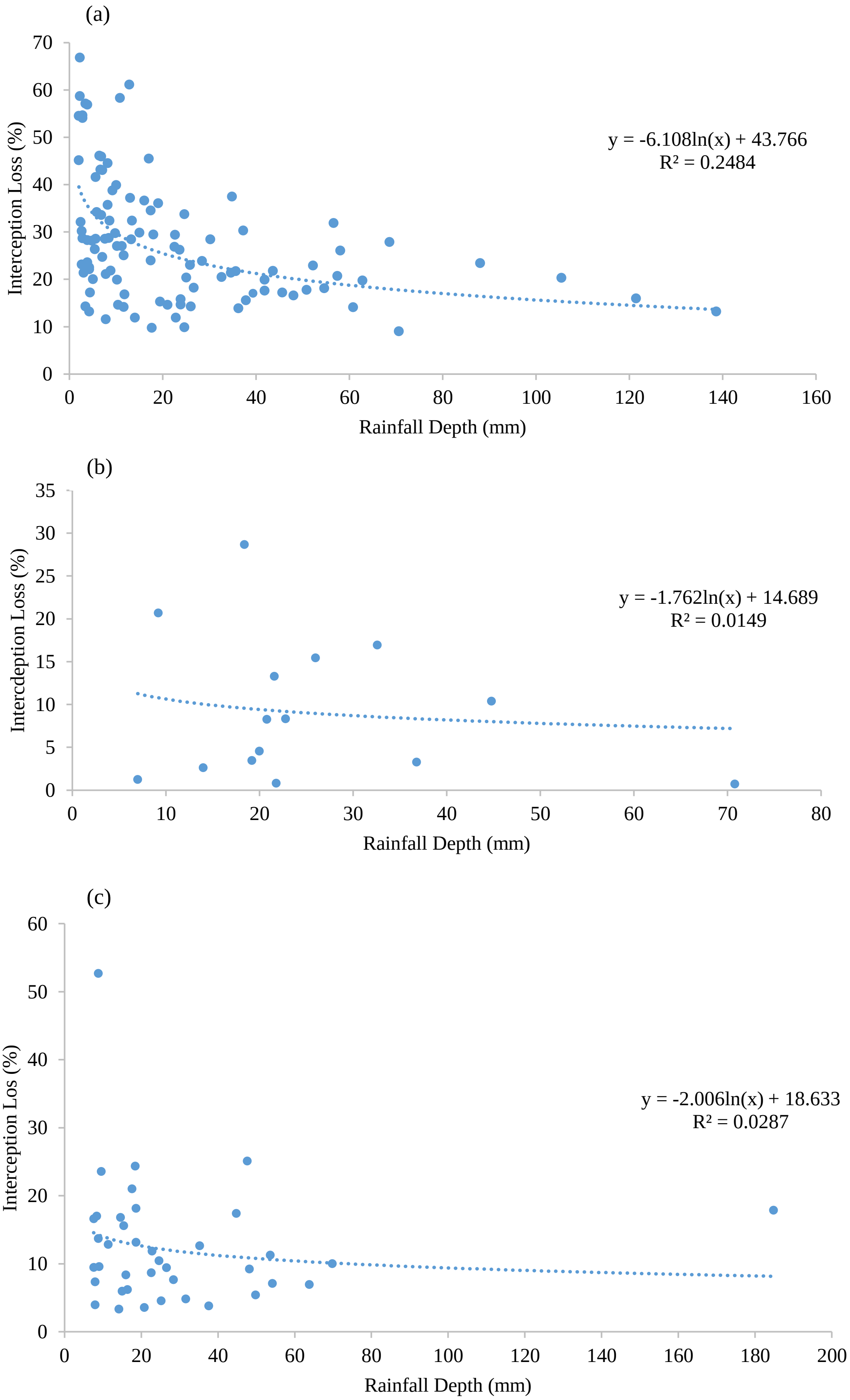

Figure 7. Inverse relationship between E_i and R_d at (a) regenerated secondary tropical forest (RSTF); (b) productive oil palm plantation (POP); and (c) non-productive oil palm area (NPOP).

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