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Throughfall quantity and carbon input beneath canopy gaps of varying size in degraded tropical peatland forest of West Kalimantan, Indonesia

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Abstract. *Astiani D, Curran Lm, Mujiman, Salim R. 2017. Throughfall quantity and carbon input beneath canopy gaps of varying size in degraded tropical peatland forest of West Kalimantan, Indonesia. Biodiversitas 18: 1258-1264.* Tropical peatland forest ecology, is mostly determined by peatland hydrological conditions. However, deforestation, forest degradation, or any other environmental disturbance can transform hydrological patterns and processes for peatland water movement, and thus alter carbon flow via water in this type of ecosystem. These changes arise from alteration in the quantity of throughfall (water that falls through plant canopies), in its interception, and in its evaporation to the atmosphere from vegetation surfaces. We have investigated the effects of a gradient of forest degradation levels, represented by canopy gaps (open, intermediate and closed), on throughfall quantity to the peatland forest floor. Nine plots, 50m x 50m in size, were stratified into the three forest canopy gap classes. Nine bucket collectors were used for throughfall, and tipping bucket rain gauges were set up for precipitation monitoring. Results show that annual precipitation in the area was 3,168.8 ± 111.3 mm, with a mean monthly rainfall of 264.0 ± 15.3 mm. Throughfall monitoring demonstrated that closed canopies transferred significantly more water as throughfall than intermediate or open canopies, due to differences in their effect on water movement through the canopies. The proportion of precipitation that passed through the canopies to the forest floor as throughfall was measured to be 76.5%, 77.3% and 89.4 %, or 202, 204 and 236 mm per month, respectively for open, intermediate, and closed canopies. It was found that higher levels of canopy cover resulted in significantly higher amounts of total organic carbon (TOC) content per unit of throughfall; specifically, 2.5 2.8 and 3.4 mg L^{-1} respectively for the open, intermediate, and closed canopies. When coupled with the higher quantity of throughfall in the closed canopy, the higher concentration of carbon results in a greater amount of carbon brought to the peatland forest floor by the throughfall pathway. This could also have impacts for other nutrients in the peatland soil.

Keywords: Canopy gaps, forest degradation, peatland, total organic carbon

INTRODUCTION

Water and nutrient inputs from precipitation have important roles in maintaining peatlands. Rydin and Jeglum (2006) consider hydrology to be probably the most important factor influencing peatland ecology, development, function, and processes. Peatland forests have critical ecosystem functions either by mitigating or intensifying flooding and/or by maintaining various hydrological functions including drainage and the filtering of inputs and outputs. Hydrology controls the chemical and biotic processes in peatlands (Haahpalehto et al. 2011; Mitsch and Gosselink 1993); influences landform development by regulating interactions among vegetation, nutrient dynamics and carbon fluxes (Waddington and Roulet 1997); and alters gas diffusion rates, nutrient availability and cycling, and soil redox status (Astiani et al. 2016; Holden 2005). Moreover, hydrological processes are vital for water resource management, flood prevention and stream water quality, and also affect carbon sequestration and release (Holden 2005).

Peatlands can accumulate large amount of water. Saturated peat holds approximately 90-98% water by mass. Even if peat is not saturated (above the water table), peat is able to store 90-95% water by volume (Holden 2005). However, deforestation or any other environmental disturbance or change can transform these hydrological patterns and processes for peatland water movement, and in turn alter both carbon storage (pool) and flux.

Tropical peatlands, as well as other forest types, are being converted to other land use types at a high rate. Indonesia, especially Sumatra and Kalimantan, have under gone rapid deforestation since 1990 (FAO 2001; Archard et al. 2002). Forest degradation, fire disturbance, and changes in land cover alter ecological functions especially within peat forest ecosystems. In tropical forests, the effects of forest conversion by fire or for agricultural uses have resulted in severe changes in the hydrological cycle, with alteration of soil water storage and the ability to abstract water from soil depth (Brown et al. 2013; Turetsky et al. 2015).

The most important changes in hydrological fluxes as a consequence of forest conversion is the alteration in the quantity of water intercepted and evaporated to the atmosphere from vegetation surfaces (Dietz et al. 2006). However, less information is available for the impacts of more gradual changes in vegetation structure such as arising from logging practices or alteration in landcover/forest conditions. Until recently, we have very little empirical studies in tropical peatland forests that especially focused on hydrological events dealing with carbon and nutrient flows as inputs and outputs of this ecosystem. Calculating the nutrient inputs and outputs through water in peatlands can be facilitated by constructing a water balance for the ecosystem (Carter, 1986). This water balance equation requires quantifying water movement into and out from peatlands, including throughfall, stemflow, and ground water exchanges during a specified period. Wikipedia mention that "Throughfall is the precipitation that passes directly through a canopy or is initially intercepted by above-ground vegetative surfaces and subsequently drips from the canopy, whereas stemflow is the precipitation that drains from outlying leaves and branches and is channeled to the bole (or stem) of plants".

The main objective of the study reported here was to estimate in one tropical forest peatland, the quantity and carbon content of that portion of the incident rainfall that is partitioned into throughfall, and to assess the impact on these parameters of variation in the forest cover arising from gaps in its canopy.

MATERIALS AND METHODS

Study site

The study was conducted on a rain-fed coastal peat swamp forest in Kubu Raya District, West Kalimantan, Indonesia ($0^0$13' S and109^{0}26' E, ca~ 4 m a.s.l.). Mean annual rainfall is 3,195 mm ± 156 (mean ± s.d. 2000-2014, Supadio Airport, <3km from the site). In 'normal' years, no months with ≤100 mm rainfall are recorded, but some variation in dry season severity occurs at the onset of the El Niño Southern Oscillation (ENSO); e.g. three consecutive dry months ≤100 mm in rainfall. Recent ENSO-associated droughts occurred in this region in 2004, 2006, and 2009. Figure 1 depicts the Kubu Raya study site and the surrounding land use context. These forests have been degraded by low-impact logging that likely occurred in 2002. However we have determined that the site represents the least disturbed contiguous block of peat swamp forest available and is representative of peat land being converted or lost to fire. Nine sample plots were marked out for the study, stratified according to three levels of canopy cover (<30%, 30-60%, and >60% canopy gaps).

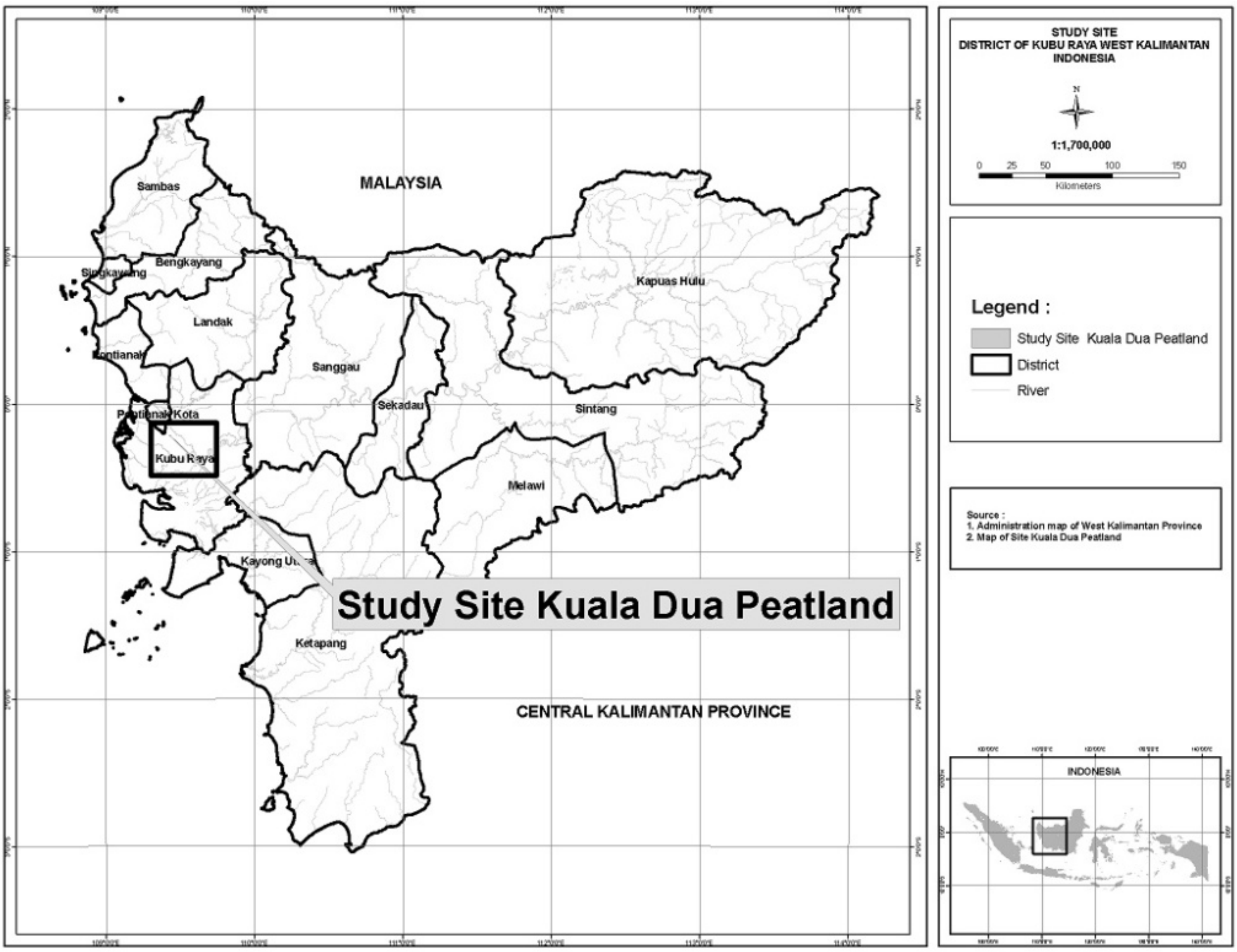


Figure 1. Study site at Kuala Dua Kubu Raya, West Kalimantan Indonesia

Figure 2. A. Throughfall collectors, B. Hobo set up under forest canopy

Bulk precipitation

Precipitation monitoring used tipping bucket rain gauges (Rain Wise Inc.). Two monitoring buckets were placed in bare land <300m from the forested peatland and connected to a data logger (Campbell Scientific, Inc). Adding to previous data from 2009-2011, at the beginning of January 2013, the data loggers were programmed to record measurements of rainwater inputs within 30 minutes intervals. In addition, daily rainfall data was obtained from Supadio Airport weather station (~3 km from research area) throughout 2015. These values were compared, and compiled as bulk precipitation data for the area.

Throughfall

Throughfall was measured in nine 50m x 50m plots that were stratified in three forest canopy gap classes, <30%, 30-60%, and >60%. The throughfall quantities were monitored using tipping bucket rain gauge (Rain wise Inc.). Each tipping bucket was connected to a data logger. Three tipping buckets were recorded at this site both from July 2009 to December 2011 and from January 2013 through to December 2015, in three canopy gaps classes determined by Spherical Crown Densiometer (Forestry Suppliers Inc.). These approximate canopy gaps measurements were refined using LAI-2000 (Licor Inc., in January 2013the LAI reading ranged between 0.32-5.06).

In addition to the tipping bucket monitoring (Figure 2.B), throughfall quantity was also collected in each plot using nine bucket collectors connected to plastic funnel by flexible plastic tube. The plastic funnels were placed upright with wood/PVC bar support at about 1 m above ground (Figure 2.A). To prevent unintentional litterfalls and water clogging the plastic funnels, we used polyurethane foam at the funnel necks. These collectors were distributed to the three canopy gap classes.

The contents of the collectors were measured 2-4 times a week depending on the frequency and intensity of rain. Throughfall was quantified monthly to bimonthly, depending on the frequency and quantity of rainfall events, to avoid over-flow in the collectors. Each month, we transferred water samples from each collector into 0.5 L amber glass vials, and kept them in a refrigerator at a temperature of approximately 3^0 C for carbon and chemical pollutant analysis. Eight analyses annually were carried out from monthly samples in 2009/2011, and four samples were analyzed between 2013 and 2015, distributed to represent both dry and wet months. These samples were analyzed for inorganic and organic C, mineral nitrogen and sulphur, with similar procedures as for precipitation.

Data analysis

For the measurement of throughfall and rainfall, data are expressed as the mean and standard error (SE), together with a 95 % confidence interval. To test throughfall under different canopy gap classes, one-way repeated measures ANOVA analysis and then pairwise comparisons were made between the canopy gaps classes. Similar analyses were carried out to compare gap classes for carbon and chemical constituents in the throughfall. Repeated measures ANOVA analyses were used to compare the canopy gap classes within and across times of sampling. T-tests were used to examine potential differences between dry and wet seasons in the quantity of throughfall and the concentrations of dissolved organic carbon (DOC) and particulate organic carbon (POC).

RESULTS AND DISCUSSION

Rainfall carbon and nutrient input

Monthly mean precipitation (2009-2015) was 257.3 with SE = 15.3 mm (n=72) (Figure 2). Annual precipitation averaged 3,138.9 ± 122.5 mm (n=6) over the six years. Based on the monthly and annual precipitation data, coupled with values for carbon content of rainfall, we estimate that the annual carbon input from precipitation was 0.07 ± 0.003 Mg C ha^{-1} or ≈ 0.25 ± 0.01 Mg CO_2 -e ha^{-1}. Similar methods, coupling N-NO_3 and S-SO_4 concentrations in 2 years (means of 1.65 mg/L and 3.94 mg/L, respectively) to annual precipitation , provided estimates of the mean annual inputs for N and S equivalent to 0.05 ± 0.002 Mg ha^{-1} and 0.12 ± 0.005 Mg ha^{-1}, respectively.

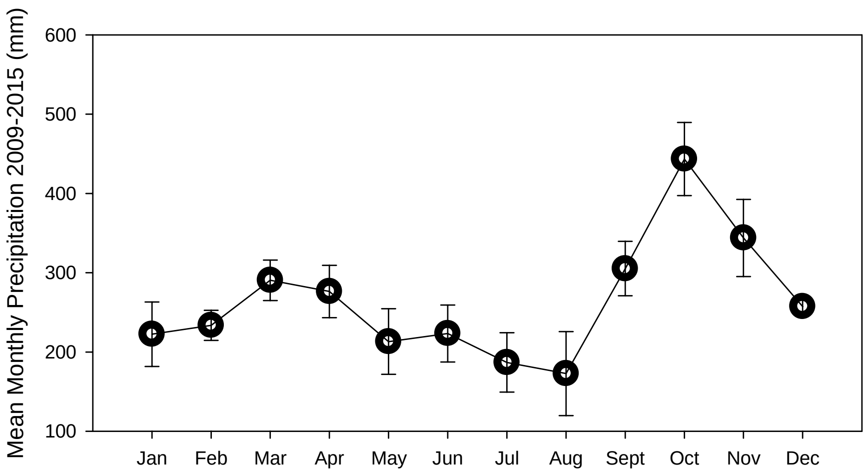


Figure 3. Mean monthly rainfall (mm) distribution (2009-2015) collected in peatland forests area of Kuala Dua, West Kalimantan, Indonesia

The water balance on the earth's surface can be disrupted because of forest degradation and conversion, especially in terms of the partitioning of bulk precipitation into evapotranspiration, surface runoff, and groundwater flow (Sahin and Hall 1996). Generally, surface runoff and stream outflow increase when forest is cleared or degraded (Sahin and Hall 1996; Piao et al. 2007).

The ability of peatland forests to sequester high carbon stores - especially in peat soil - indicates that these forests play a major role in moderating atmospheric CO_2 concentrations. However, forest degradation, fires, conversion to agricultural land, and altered drainage, combined with temperature and precipitation change, are converting peatlands into sources of carbon rather than stores/sinks of carbon (Fargione 2008). Because hydrological processes occupy such a significant role in tropical peatland dynamics, forest degradation and conversion may impart a profound effect on the water balance, as well as on the flow of carbon and nutrients in and through the peatlands.

Throughfall under peatland forests

Five years of throughfall monitoring, reveal fluctuations in its monthly distribution. The distribution is depicted in Figure 4. The monthly mean and SE was 190.9 ± 9.9 mm. The highest throughfall in one month was 442.8 ± 15.2 mm and the lowest was 138.7 ± 14.3 mm. The mean throughfall within the forest demonstrated that ~80% of monthly rainfall reached the forest floor as throughfall. Monthly throughfall was highly correlated with rainfall (Figure 4b, R = 0.86) across the year.

Several other studies on the effect of logging on rainfall partitioning have yielded results that are relevant to our study. In a lowland mixed Dipterocarp forest in Central Kalimantan, Indonesia, the rainfall interception was 11% of precipitation in an unlogged natural forest and 6% of precipitation in a logged forest (Asdak et al. 1998). In another lowland mixed Dipterocarp forest in northern Borneo, (Sabah, Malaysia), 91% of precipitation reached the ground as throughfall in an unlogged natural forest, whereas 80% and 84% throughfall were recorded in plots of moderately and highly damaged patches of forest respectively (Chappell et al. 2001), indicating that interception rates increased with disturbance intensity. These two studies from lowland mixed Dipterocarp forests, highlight the fact that logging through its effect on forest cover produces changes in rainfall partitioning.

When coupled with carbon content in throughfall, dissolved organic carbon (DOC) and particulate organic carbon (POC) contribution from throughfall is estimated at 0.023 ± 0.005 and 0.052 ± 0.0052 Mg C ha^{-1} y^{-1} respectively, i.e. total C input is 0.075 or ≈ 0.28 Mg CO_2 -*e* $ha^{-1}y^{-1}$. Precipitation is a significant tool for nutrient movement from the forest canopy to soils. Dissolved materials in precipitation are the principal inputs of plant nutrients to ombrothrophic peats (Moore and Bellamy 1973). In forested peatlands, some bulk precipitation falling on tree canopies is intercepted while the reminder reaches the forest floor as throughfall and stemflow, which carries in nutrients and pollutants. Leaching of the foliage, branches and stems also transfers dry deposited material from canopy to the soil surface. Dezzeo and Chacon (2006) have reported significant inputs of nutrients in throughfall and stemflow compare to the nutrient content of the incident rainfall - especially for K - with throughfall and stemflow amounts representing 71-77% and 2-8% of the annual incident rainfall, respectively.

There was large variability of throughfall among the plots, with values ranging between 30.8 to 531.5 mm per month (Figure 5). The large variability in throughfall was due to differences in forest structure and composition. Our previous study indicated that the amount of water through stemflow also varied in accordance with species composition of the study area (Astiani et al. 2017). In that study, the variability in tree density and canopy closure was large (Astiani 2016). Here, forest cover acted as mediator of the transfer of precipitation to soil. Water capture and distribution in a forest is influenced by tree and stand structure of the vegetation such as vertical and horizontal of leaf arrangement, leaf morphology, branching, tree age, and density (Levia and Frost 2006; Holder 2007); and as well as by landscape features e.g., topography, slope aspect landscape position and wind (Dietz et al. 2006; Weathers 2006). Variability in tree density and canopy closure has significant impacts on carbon sequestration and stocks (Astiani and Ripin 2016), and also on soil nutrients (Lawrence et al. 2007).

Stem density, tree height, and canopy properties (i.e. leaf area index, canopy cover, crown surface area and epiphytes) may alter throughfall (Levia & Frost 2006). Figure 5 shows the spatial variability in throughfall between our nine sample plots arising from the above factors.

Effects of canopy gaps on throughfall quantity

Further analysis using One-Way Repeated Measures Analysis indicated significant differences in throughfall between different canopy gap levels. Closed canopies delivered higher amount of water to the forest floor than open canopies (p= <0.05) (Figure 6a). The proportion of the incident precipitation that became throughfall was measured at 76.5, 77.3 and 89.4 % or 202, 204, and 236 mm per month, respectively, for open, intermediate and closed canopy. Other results have shown that differences between tree species have significant impacts on the quantity of rainfall partitioned through stemflow; smooth-barked tree species deliver more precipitation as stemflow to the forest floor than do rough-barked species (Astiani et al. 2017).

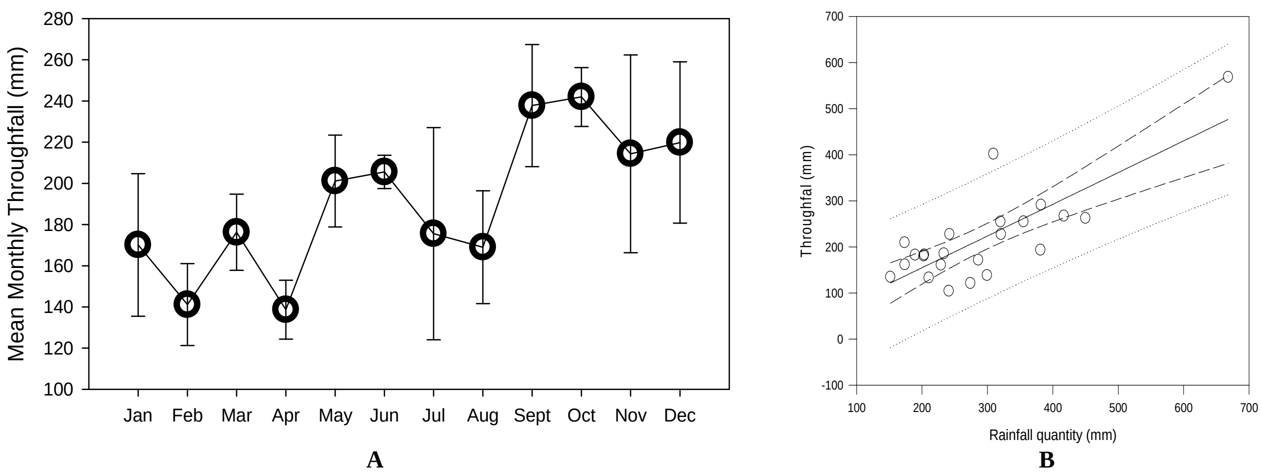


Figure 4. A. Mean monthly throughfall (mm) distribution for 2009 -2015; B. Pearson correlation between rainfall and throughfall. They were highly correlated (R=0.866)

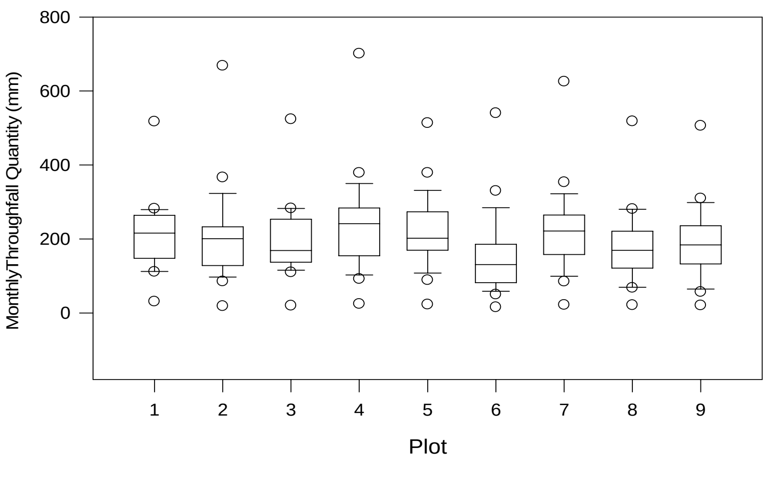


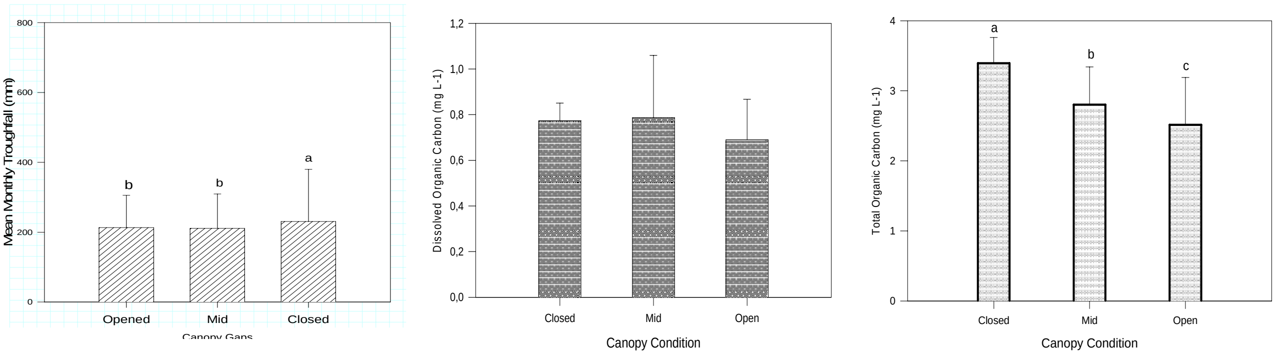
Figure 5. Spatial variability in throughfall between the nine plots measured in the peatland forest

The results imply that forest degradation and species losses could have significant influence on the hydrological system of tropical peatland forest and can be used to predict hydrological impact on the larger peatland landscape (Ahmad-Shah & Rieley, 1989; Nadkarni & Sumera, 2004). Among alterations in rainfall partitioning that arise from forest degradation, changes in the quantity of throughfall could have a significant influence on the amount of carbon reaching the soil, both from the rainfall and from forest canopy leaching

Figure 6b. shows that dissolved organic carbon in throughfall was not significantly different among the three forest canopy cover levels; however, greater tree density with higher canopy cover had a significant impact on the quantity of particulate organic carbon brought from the canopy onto the forest floor. Higher canopy cover resulted in significantly greater amounts of total organic carbon (TOC) content per unit volume of throughfall (3.4, 2.8, and 2.5mg L^{-1} respectively for closed, intermediate, and open canopies, Figure 6c). It is clear that the greater quantity of throughfall coupled with its higher concentration of particulate matter, results in minimally degraded forest with a closed canopy delivering more carbon and presumably other nutrients into the peatland soil than occurs under degraded canopies. These results are in general agreement with those of Ponnete-Gonzales et al. (2010) who report that forest landcover changes have a significant influence on the quantities of nutrients (N, S, and C) received by forest soils from precipitation.

Further analysis, comparing dry seasons and rainy seasons show significant differences both in the quantity and the total carbon content of the throughfall between the seasons. T-test comparison revealed that the carbon content (mg/L) of the throughfall in the dry months was ~18 times higher than in the wet months in 2013. When coupled with the throughfall quantities, the total carbon input was 4.3 times higher in dry months (Figure 7a and 7b). In the dry season, carbon concentration in precipitation water increased sharply due to higher levels of soil particles in the atmosphere. On the other hand, the water quantity from precipitation was higher in rainy season, therefore lowering the carbon concentration of the rainfall and the throughfall resulting from it.

The results of this study demonstrate the impact that forest degradation has in reducing the amount of water falling onto peatland forest floor through the throughfall mechanism. This, in turn, alters the dynamics of carbon-flow in and through the tropical peatland ecosystem.



A B C

Figure 6. A. Throughfall quantity; B. Dissolved Organic Carbon (DOC); and C. Total Organic Carbon (TOC), among canopy gaps (closed, intermediate and open) in tropical peatland forest of West Kalimantan, Indonesia

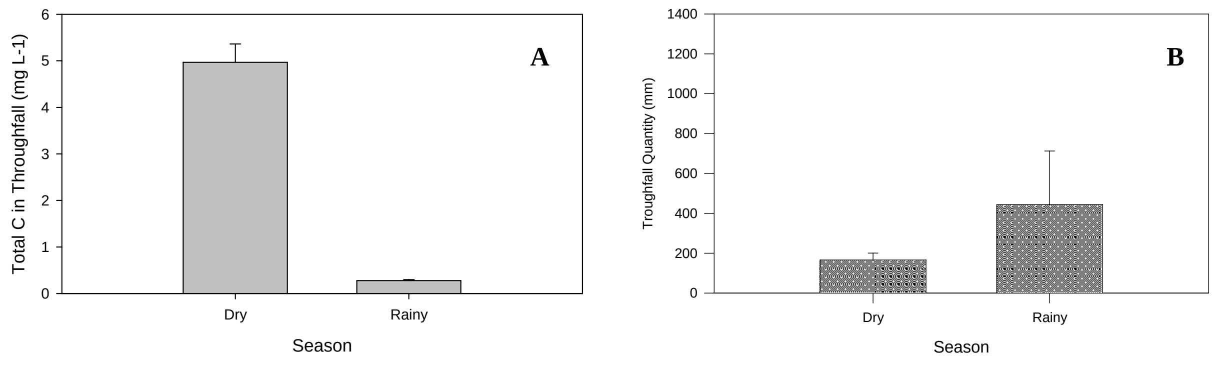


Figure 7. A. Dry and rainy seasons comparison on carbon content delivered to forest floor through the throughfall mechanism; B. Dry and wet season comparison of throughfall quantity

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