Net-rainfall and wet-canopy evaporation in a small selectively-logged rainforest catchment, Sabah, Malaysia.

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ABSTRACT: In order to understanding the impact of the selective removal of trees from a tropical rainforest on the rate of wet-canopy evaporation for an area of lowland dipterocarp forest, selectively-logged some eight years prior to the study, a network of 450 throughfall gauges, plus 22 gross rainfall and 40 stemflow gauges, was installed within the 44 hectare Baru Experimental Catchment (Sabah, Malaysian Borneo). Most of these gauges were located randomly within plots, themselves stratified according to the six canopy classes identified. The results showed that more rainfall reached the forest floor beneath the undisturbed remnants of rainforest (*i.e.*, the protected areas), than those patches of canopy subject to light or heavy impact. This may have been because the disturbed forest patches had a higher rate of wet-canopy evaporation (*i.e.*, 12 - 18 % of gross rainfall) in comparison to the undisturbed remnants (*i.e.*, 7 % of gross rainfall). Alternatively, the difference may, at least in part, have been caused by the lower disturbed patches of vegetation being sheltered by the undisturbed forest remnants, leading to the receipt of less rainfall on their canopy surfaces.

1 INTRODUCTION

Wet-canopy evaporation (E_{wc}) is the vapourisation of rainfall from wetted vegetation surfaces, and is an important component of the water budget of tropical catchments (Bruijnzeel, 1990; Black, 1996). Understanding the impact of the selective removal of trees from a tropical rainforest on the rate of wet-canopy evaporation and transpiration is critical to the assessment of the impact of so called 'sustainable forestry' on local climate, and the water resources potential of rivers. Accurate quantification of the changes in the wet-canopy evaporation component is, however, difficult given the extreme heterogeneity of the vegetation patchwork produced by commercial, selective logging. Despite this, there is a dearth of studies on the impact of selective commercial forestry on rates and patterns of wet-canopy evaporation from tropical forests (Asdak *et al.* 1998). This study, therefore, aims to quantify the rates of wet-canopy evaporation and the remaining component of rainfall that reaches the ground as throughfall and stemflow (also called 'sub-canopy rainfall') within a lowland diperterocarp rainforest recovering from selective forestry.

2 RESEARCH SITE

The study area is 44 ha Baru Experimental Catchment, situated near the Danum Valley Field Centre (DVFC) in the Malaysian state of Sabah, Northeast Borneo (Figure 1). The catchment has an undulating terrain with an altitudinal range of 70 m.

The area was selectively logged in early 1989 using bulldozers and high-lead yarding, leaving the complex structure of regenerating forest patches, areas of protection forest and areas of highly damaged forest. The 'forest mosaic' within the Baru Catchment has been classified into six categories depending on the level of forest disturbance and recovery rate.

The study period 1 May 1997 to 30 April 1998 coincided with the 1997/98 El Niño-Southern Oscillation (ENSO) drought. Not suprisingly the recorded 1520 mm of rainfall during this period was the smallest on record at the DVFC meteorological station from 1986-1999. The longer-term average annual rainfall for the area being 2638 mm.

3 SAMPLING / INSTRUMENTATION NETWORK

The sampling network for this study includes a distribution of raingauges within canopy openings (min diameter of openings was 40 m), and throughfall and stemflow gauges to measure the rainfall penetrating the forest canopy.

3.1 *Rainfall measurement*

The raingauges installed within the 44 ha Baru Experimental Catchment are a subset of the larger network of raingauges within the 4-km^2 Sapat Kalisun Experimental Catchment. There are 22 raingauges within openings in the Baru Catchment, comprising the 16 simple storage raingauges, and six tipping-bucket raingauges.

3.2 *Throughfall measurement*

Sub-canopy rainfall or net rainfall refers to the volume of rainfall that reaches the forest floor and comprises 'direct throughfall' (*i.e.*, rainfall that falls through canopy gaps), 'leaf drip throughfall' and 'stemflow'. In this study the direct throughfall and leaf drip throughfall was measured together using 450 simple storage raingauges.

Most of the throughfall gauges were located within plots beneath clearly defined 'canopy categories'. These are (i) undisturbed forest canopy (category 1), (ii) moderately impacted forest canopy (category 2), (iii) vine-covered forest canopy (category 3), (iv) *Macaranga* spp pioneer tree canopy (category 4), and (v) sprawler-covered canopy gap (category 5). Eighty to 85 gauges were installed in each of the canopy categories 1, 2, 3, and 4. Only 20 gauges were installed beneath the 'sprawlers' of canopy category 5. The locations of sites for throughfall measurement beneath all canopy categories were located close to the five existing recording rain gauges within the Baru Catchment (Figure 1). Two clusters (plots) of gauges (*i.e.*, 40 to 45 gauges in each plot, except in canopy category 5) were installed for each canopy category. Plots were selected randomly within each of the stratified canopy categories, with the plot sizes ranging from 100 m^2 to 200 m^2.

Additional throughfall measurements were made with 105 gauges installed within mixed canopy categories found along two transects (North-South and East-West) across the Baru Experimental Catchment (Figure 1). Collectors were located approximately every 20 m along the 650 m 'North-South transect' and every 10 metres approximately along the 720 m 'East-West transect'.

3.3 *Stemflow measurement*

Exactly 40 trees and lianas were measured for stemflow. The trees and lianas were selected randomly within each plot. Stemflow 'collars' were used to measure the stemflow. These collars were shaped out of aluminium plate, supported by 1-cm nails and sealed with a marine adhesive ('Mastik'). Silicon sealant was used to repair any leakage of the collars throughout the study period. Stemflows were then collected volumetrically

4 RESULT AND DISCUSSION

4.1 *Throughfall variability within each canopy classes*

Within each canopy category, the coefficient of variation (CV) in annual throughfall catch ranged from 16.2% for canopy category 1 to 30% in canopy category 5 (Table 1). The standard error in the catch was, however, small due to the large number of gauges used. The standard error can be seen to reduce exponentially as the number of randomly sampled gauges increases, comparable with that observed by Lloyd and Marques (1988). There were significant variations between the different canopy categories. For example, category 1, the undisturbed forest, only required 10 gauges to constrain the uncertainty (*i.e.*, standard error) to 5 %, compared with 20, 30, 16, and 35 gauges for canopy categories 2, 3, 4, and 5 respectively. The highly heterogeneous transects required 40 gauges for 5 % sampling uncertainty. The different number of gauges required to constrain uncertainty to 5 % for different canopy covers suggests that throughfall in logged-over forest was much more variable than in remnants of undisturbed forest. Canopy category 5 was the most variable, followed by categories 3, 2, and 4 respectively. The lowest uncertainty for the disturbed forest blocks was for canopy 4, due to the fact that almost 80 % of the trees within the plot were *Macaranga* spp. pioneer trees.

Over the year, the standard errors in throughfall catches were only 1.8 %, 2.6 %, 3.3 %, 2.0 %, 7.1 %, and 2.7 % for canopy categories 1, 2, 3, 4, 5, and the transects respectively (Table 1).

The percentage of throughfall catches that exceeded the gross rainfall were 28 %, 14 %, 20.6 %, 23 %, 20 %, and 35 % for canopy categories 1, 2, 3, 4, 5, and the transects, respectively (Table 1). This was consistent with the 29 % for undisturbed Amazon rainforest (Lloyd and Marques, 1988), but larger than the 13 % observed by Wong (1991) during the wet period 1989/90 at Danum Valley.

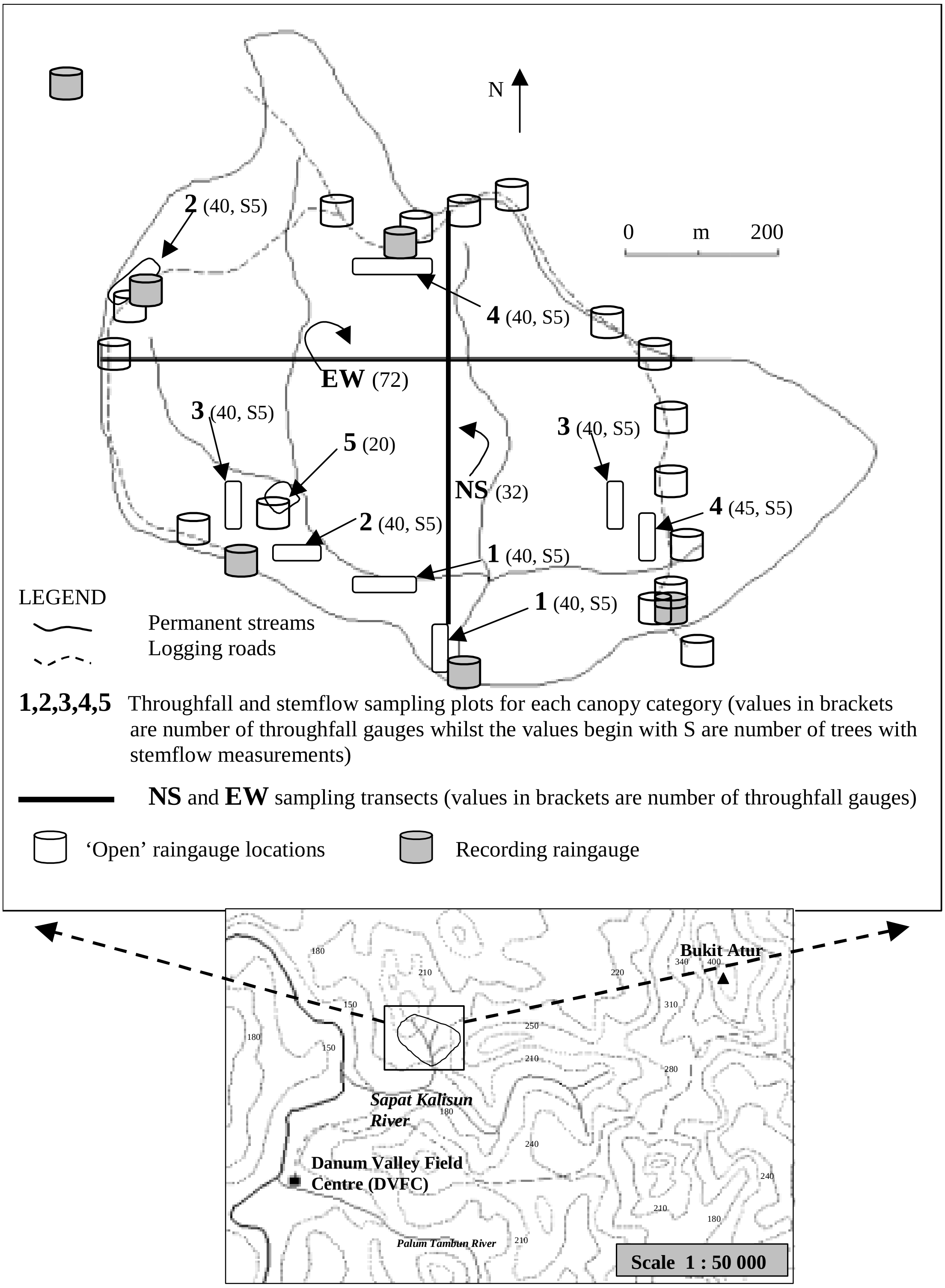

Figure 1. The 44 ha Baru Experimental Catchment (5° 01' N and 117° 48.75' E) showing the location of sub-canopy rainfall (throughfall and stemflow) sampling plots within canopy categories 1, 2, 3, 4, and 5. The cylinders represent the raingauges installed in the open canopy to measure gross rainfall (canopy category 6). See Section 2.3 for canopy classification.

Table 1. Sub-canopy and gross rainfall (Can. 6) of the five canopy categories and transects in Baru Catchment during 12-months period of monitoring 1 May 1997 to 30 April 1998. The non-parametric, Mann-Whitney U-test was used to estimate significance of mean difference.

	Canopy Category					**Transects**
	1	**2**	**3**	**4**	**5**	
Gross rainfall (Pg) – canopy 6						
N	3	3	6	8	2	22
Total (mm)	1398.0	1431.0	1417.7	1417.9	1453.3	1413.0
σ (mm)	138.6	22.7	58.4	94.5	19.2	100.1
CV%	9.9	1.6	4.1	6.7	1.3	7.1
σ_x (mm)	80.0	13.1	23.9	33.4	13.6	21.3
Diff. in mean[1]	-	ns	ns	ns	ns	ns
Net rainfall (Pnet)						
Throughfall						
N	80	80	80	85	20	105
Total (mm)	1285.9	1150.2	1157.1	1241.9	1205.6	1201.3
σ (mm)	208.0	262.5	340.0	234.2	383.3	335.0
CV%	16.2	22.8	29.4	18.9	30.0	27.9
σ_x (mm)	23.3	29.4	38.0	25.4	85.7	32.9
Diff. in mean[2]	P < 0.001					
Diff. in mean[3]	P < 0.001	ns				
Diff. in mean[4]	P < 0.1	P < 0.1	P<0.05			
Diff. in mean[5]	ns	ns	ns	ns		
Diff. in mean[6]	ns	ns	ns	ns	ns	
%Tfall (%)	92.0	80.4	81.6	87.6	83.0	85.0
Stemflow						
N	10	10	10	10	-	-
Total (mm)	15.0	27.0	14.0	5.9	14.0*	15.5**
σ_x (mm)	2.4	6.2	4.6	1.9	3.8*	3.8**
%Sflow (mm)	1.1	1.9	1.0	0.4	1.0	1.1
Pnet total (mm)	1300.9	1177.2	1171.1	1247.8	1219.6	1216.8
σ_x total (mm)	25.6	35.6	42.6	27.3	89.5	36.6
Comparison of gross and net rainfall						
Diff. mean (Pg vs Pnet)	P < 0.1	P<0.05	P<0.005	P<0.05	ns	P<0.05
Pg - Pnet (mm)	97.1	253.8	246.6	170.1	233.7	196.2
$\sigma_{compound}$ (mm)	249.9	263.5	344.9	252.5	383.8	349.6
Diff. Pg – Pnet[2]	P < 0.05					
Diff. Pg – Pnet[3]	P<0.001	ns				
Diff. Pg – Pnet[4]	ns	ns	P<0.05			
Diff. Pg – Pnet[5]	ns	ns	ns	ns		
Diff. Pg – Pnet[6]	ns	ns	ns	ns	ns	
%Pnet (%)	93.1±7.5	82.3±3.1	82.6±4.4	88.0±4.2	83.9±6.9	86.1±3.9
Tfallgauges > Pg (%)[7]	28.8	13.8	20.6	23.1	20	34.7

Notes:
[1] level of significance for difference with canopy category 1
[2] level of significance for difference with canopy category 2
[3] level of significance for difference with canopy category 3
[4] level of significance for difference with canopy category 4
[5] level of significance for difference with canopy category 5
[6] level of significance for difference with transect canopy
[7] throughfall gauges recorded rainfall totals more than gross rainfalls
[ns] not significant at P < 0.1
* estimated value – assumed as that of canopy category 3 (corresponding error mean of canopy 1 – 4)

** estimated value – assumed as an average of canopy category 1 to 4 (also corresponding error)

4.2 Difference in annual throughfall between the canopy types

No statistically significant differences were observed between plots of the same canopy category (Table 1). In contrast, the differences in mean catch of canopy category 1, the undisturbed forest, and both canopy 2 (moderately impacted forest) and canopy 3 (vine-covered, highly disturbed forest) were highly significant ($P < 0.001$). Canopy category 3 was also significantly different to canopy 4 (*Macaranga* spp trees) ($P < 0.05$). On average, canopy 1 allowed 1286 mm of rainfall to reach the forest floor compared with 1150 mm, 1157 mm, 1242 mm, 1206 mm, and 1201 mm for canopies 2, 3, 4, 5, and the transects, respectively. These figures suggest that disturbed canopies allowed less rainfall penetration than undisturbed canopies. There are several possible reasons why less rainfall reaches the forest beneath disturbed canopies of selectively logged lowland forest. These relate to possible differences in: (i) gross rainfall intercepted by the canopy, and (ii) canopy surface characteristics.

The higher canopies of virgin forest patches of forest within selectively logged forest may shelter the lower disturbed canopies, and hence lead to reduced rainfalls received in the lower disturbed forest patches (Hayes and Kittredge, 1949; Aldridge, 1975; Ford and Deans, 1978; Barry and Chorley, 1982 p300; Herwitz and Slye, 1992). Herwitz and Slye (1992) termed the process 'the differential interception of inclined rainfall' and produced a model to illustrate the process within their tropical rainforest in Queensland. Ford and Deans (1978) explained that when rain falls at an angle, the leading shoots at the top of a canopy tree present a greater intercepting area than its vertically projected crown area. Thus if patches of undisturbed forest canopy receive more gross rainfall, then greater throughfall volumes would be expected if wet-canopy evaporation rates with the same or smaller then those of the disturbed forest patches.

There are two aspects of canopy surface that may have attributed to lower throughfall in disturbed canopy. Firstly, qualitative field observation shows that there is an increased density of leaves on the outer surfaces of the disturbed upper canopy, as a result of the expansion of the woody climbers. This outer surface experiences the highest temperatures and rates of net radiation, thus may be subject to higher rates of potential E_{wc}. Additionally, some of the disturbed canopy appeared to contain more dead leaf and woody matter, turning parts of the canopy a darker colour and hence reducing the albedo. The increased leaf density and reduced albedo in this part of the canopy may, therefore, have had a disproportionate effect on the whole canopy E_{wc}. Secondly, selective removed of the upper canopy trees during the logging operations increases the roughness of the forest surface. This could increase the ‘atmospheric conductance’ and lead to a net increase in evaporation rate (Dingman, 1994). Indeed, Klaassen *et al.* (1996) found that windspeed tended to increase around forest gaps, generating more turbulence, thus promoting E_{wc}.

Amongst the canopies in disturbed forest, canopy category 4 (*Macaranga* spp trees) recorded significantly higher throughfall (*i.e.*, $P < 0.1$ and $P < 0.05$ relative to canopies 2 and 3, respectively). This is probably because the *Macaranga* spp trees at Danum have a very open canopy structure and low leaf area index (LAI, cf. Pitman, 1989) allowing much rainfall to penetrate. Additionally, the smooth bark of the *Macaranga* spp trees will not promote storage and subsequent evaporation from the tree trunk (cf. Herwitz, 1985).

4.3 Estimation of wet-canopy evaporation

Subtracting the combined throughfall and stemflow totals from local measurements of gross rainfall gave annual wet-canopy evaporation (E_{wc}) percentages of 7 %, 18 %, 17 %, 12 %, 16 %, and 14 % from the canopy categories 1, 2, 3, 4, 5, and the transects, respectively (Table 6.1).

An estimate of the catchment-average E_{wc} was calculated by weighting the canopy-specific rates by the estimated proportions of the catchment covered by that canopy type. This gave an average E_{wc} for the Baru Catchment of 13.6 %. Encouragingly, this rate is comparable with that from the mixed canopies along the two transects within the Baru catchment (Table 2).

4.4. Rate of wet-canopy evaporation within undisturbed lowland rainforest

The E_{wc} value of 7 % for undisturbed forest blocks in this study is amongst the lowest rates for tropical rainforests (Table 3) but within range of reliable values defined Bruijnzeel (1990). If one considers the errors with some other studies (Lloyd *et al*. 1988), then the rate is comparable to the 9 % for undisturbed Amazonian terra firma rainforest reported by Lloyd and Marques (1988) and the 11 % reported for Kalimantan rainforest by

Asdak *et al.* (1998b). These uncertainties include (a) the ±1 % reported standard errors, (b) admissions of gauge overflows during extreme events (cf. Asdak *et al.*, 1998b), and (c) the distance between throughfall collectors and the rainguages measuring gross rainfall (cf Lloyd, 1990). Given that this study was undertaken during an ENSO drought year, differences may have resulted from this longer-term temporal cyclicity (Chappell *et al.*, 2001). The smaller annual rainfall is probably associated with less rainfall being delivered as wind-driven, inclined rainfalls (Herwitz, 1985; Herwitz and Slye, 1992, 1995) giving reduced potential for wet-canopy evaporation. Tsukamoto and Ishigaki (1989) have also reported increased E_{wc} with increased gross rainfall. Indeed.

Table 2. Mixes of disturbed and undisturbed forest mosaics E_{wc} rates representing Baru Catchment measured by different combinations of throughfall gauges, showing no significant different in the values. However the upscaled value of E_{wc} is slightly lower, as this approach considered the area covered by roads and gaps, producing 0% E_{wc}.

Measurement of throughfall and calculation approach	**No. gauges**	**Annual**		
		Rainfall (mm)	**Sub-canopy rainfall (mm)**	**E_{wc} (%)**
1- Arithmetic mean of gauges in transects across catchment	105	1413	1217	13.9
2- Arithmetic mean of gauges in plots of different canopy categories regardless of the area covered by each canopy	345	1424	1225	14.0
3- E_{wc} values from plots of different canopy categories considering of proportional areas covered by each canopy	345	1424	1230	13.6
4- Arithmetic mean of gauges in 1 & 2 regardless of the area covered by each canopy	450	1422	1223	14.0

Table 3. Pertinent studies presenting annual rates of E_{wc} measured in undisturbed secondary rainforest.

Reference	**Location**	**No. gauges**	**…….annual………**	
			Rainfall (mm)	**E_{wc} (%)**
Calder *et al.*, 1986	West Java	2[b] (s)	2850	21
Walsh, 1987	Dominica	nk[d]	5204	27
Lloyd *et al.*, 1988	Amazon	36 (m)	2805	9
Kasran, 1989	West Malaysia (central)	4[a] (s)	3786	27
Sinun *et al.*, 1992	East Sabah	40 (m)	2824	17
Asdak *et al.*, 1998	Central Kalimantan	50 (m)	2199	11
Current study	East Sabah	80 (s)	1398	7[+]

Notes:

[a]0.7 m^2 trough, [b]-plastic sheet, [d]-not known, s-stationary, m-moved
+-undisturbed patches with logged-over forest

4.5 Effect of selective forestry on wet-canopy evaporation

Depending on the integration procedure, the catchment-average E_{wc} for the Baru catchment ranges from 13.6-14.0 % of the incident rainfall (Table 2). This rate is comparable with those observed by Asdak *et al.* (1998b) for the 'closed canopy' logged forest at their Kalimantan site, and for the disturbed lowland forest at Bukit Tarek in Peninsular Malaysia (Yusop, 1996). There is, however, considerable variability in the rates reported for disturbed tropical forests (Table 4).

Table 4. Pertinent studies presenting annual rates of E_{wc} measured in disturbed secondary rainforest.

Reference	Location	No. gauges	…….annual………	
			Rainfall (mm)	**E_{wc} (%)**
Nik *et al.*, 1979	West Malaysia (central)	11[a] (s)	nk[d]	27
Scatena, 1990	Puerto Rico	22 (m)	5745	39
Yusop, 1996	West Malaysia (central)	nk[d]	2723	13
Asdak *et al.*, 1998	Central Kalimantan	50 (m)	3563	15**
Current study	East Sabah	265 (s)	1427	13.6-14.0

Notes:
[a]-0.7 m^2 trough, [d]-not known, s-stationary, m-moved
** Arithmetic mean of 3 different disturbed canopy types (excluding open canopy) provided by the authors.

5 CONCLUSIONS

The 1997/8 water-year studied, turned out to be a severe ENSO drought. During this period, the remnants of undisturbed lowland dipterocarp forest studied allowed 93.1 ± 7.5 % of the rainfall through the canopy to the ground, giving wet-canopy evaporation rate of approximately 7 % of gross rainfall. This figure is towards the lower end of the range of wet-canopy evaporation rates observed for undisturbed tropical forests. The low rate may relate to the expected lack of storminess during the 1997/8 drought.

Selective harvesting of the forest generated patches of moderately-impacted forest (canopy category 2) and more heavily damaged areas, now with the remnant climax trees covered by vines (canopy category 3). Much smaller volumes of sub-canopy rainfall were observed below these forest patches (*i.e.*, 82.3 ± 3.1 % and 82.6 ± 4.4 % respectively). This result could be explained by (1) these (on average) lower forest canopies receiving less incoming rainfall due to sheltering by the undisturbed remnants, or (2) the changed canopy surface characteristics. The surfaces of the disturbed canopies often have a greater surface density of leaves, which may have a disproportionate effect on rates of wet-canopy evaporation. Further, the more uneven surface of the disturbed canopy patches may increase atmospheric turbulence and thus increase the rate of evaporation. These two phenomena may also account for the unexpectedly high estimates of wet-canopy evaporation from the areas of sprawlers and shrubs (canopy category 5).

Taking into account the area covered by the six canopy categories, the catchment-wide estimate for wet-canopy evaporation from the selectively-managed forest (following eight years of recovery) was 13.6 % of the gross rainfall. This figure was almost identical to the 14.0 % wet-canopy evaporation rate calculated from the two transects of mixed canopy types. The study, therefore, suggests that the rate of wet-canopy evaporation may significantly increase as a result of selective logging. It is then becomes important to know whether these extra losses are offset by reductions in the rate of transpiration, and also to know what is the resultant impact on the water yield of the river.

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