

CANOPY GAP DYNAMICS AND EFFECTS OF SELECTIVE LOGGING: A STUDY IN A PRIMARY HILL DIPTEROCARP FOREST IN MALAYSIA

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A systematic sampling was conducted in a primary hill dipterocarp forest of Peninsular Malaysia to evaluate the structure of the forest canopy before and after selective logging. The frequency distribution of gap area was strongly skewed. Before logging, the ridge had significantly higher gap area than hillside and ridgetop. However, after logging the canopy opening was much higher on the ridgetops due to high extraction of commercial trees. Unlike Brokaw's method of gap measurement, the photographic measurements of gap area showed reasonably stronger correlation. The results of selective logging showed reduction of overall canopy cover by an average of 21%. Significant linear relationship was observed between loss of canopy trees and canopy opening. Due to variations in logging layout, the canopy openness varied significantly in the two study compartments. The opening of canopy was responsible for increased habitat heterogeneity followed by invasion of pioneer species. The effect of logging on percentage canopy loss was compared with a range of other studies. To maintain the canopy structure from destructive logging, this study strongly suggests site-specific cutting limit and adoption of appropriate harvesting plan, as well as skill development of forest workers and logging operators.

Keywords: Tree fall, gap measurement, gap size-distribution, fish eye photography, canopy openness, pioneers, harvesting plan

INTRODUCTION

Tropical forests are extremely dynamic, subject to a variety of disturbances, such as small-scale windstorms and tree falls or large-scale drought and climatic change (Huston 1994). The causes and nature of tree falls and their intensity leads to various sizes of canopy gaps, resulting in increased light to many smaller plants in the under storey (Green 1996, Brown 1996). Responses of various tree species to gap environments have been discussed (Denslow 1987). Spatial and temporal heterogeneity of tropical tree fall gaps play an important role in maintaining species composition and structure of the forest (Whitmore 1984, Saiful and Latiff 2017).

Microclimate conditions in small and large gaps have been discussed by Whitmore (1990). Spatial variations of microclimates under different sizes of canopy gaps and effects of selective logging have been reported (Saiful et al. 2010). Microclimate of small gaps and adjacent

understorey is more or less similar, whereas in large gaps there is no difference of microclimate to that above the forest canopy (Whitmore 1990). This explains the differences in species composition for the two groups of tree species, climax and pioneers (Whitmore 1989).

The gap-size-frequency distribution can be a useful basis for comparing ecosystems (Denslow 1987). Green (1996) showed that 90% of canopy gaps were 120 m² or smaller in area and the median gap area was 40–60 m². The distribution of gap size was also strongly skewed. Few studies have examined the changes in canopy surface structure after logging (Uhl and Viera 1989, Crome et al. 1992). Harvested areas create a complex mosaic of undisturbed and disturbed forest comprising tree fall gaps, logging tracks and damaged canopy.

In planned logging, damage to forest canopy, trees and forest floor is insignificant (Johns et al. 1996, Pereira et al. 2002), but considerable

damage was reported to forest canopy when the harvesting plan was imperfect (Saiful 2002). In several studies, gap size and canopy cover have been discussed as two recognised parameters in logging impact assessments (Crome et al. 1992, Cannon et al. 1994, Saiful 2002).

In tropical rainforest, tree species of ≥ 20 cm dbh generally determine the main canopy layer (Saiful & Latiff 2017), and the dynamic features of the canopy after logging provide a good indicator for predicting the ecological soundness and sustainability of the operation (Clark et al. 1996). However, available studies show that there is lack of information on canopy gap dynamics of tropical hill dipterocarp rain forest before and after selective logging. The objectives of this study were to describe the structure and dynamics of rain forest canopy and examine the effects of selective logging in two adjacent compartments and discuss management implications.

MATERIALS AND METHODS

Study site

The study was carried out at Sungai Weng Catchment of Ulu Muda Forest Reserve, Kedah, Peninsular Malaysia ($5^{\circ} 50' N$, $100^{\circ} 55' E$). The study site is situated bordering Thailand at about

40 km northeast of Baling, Kedah and composed of two adjacent compartments i.e. C28 and C29 (Figure 1 and 2). The topography is characterised by a hilly and undulating terrain with moderately steep to very steep slope, up to 45° . The elevation of the study area ranges from 340 to 600 m above sea level (Saiful 2002). The climate is uniformly hot, averaging about $25^{\circ} C$ with mean annual precipitation averaging 2869 mm. The parent material is primarily made up of quartzite and sandstone (RRIM 1988). The soil is red-yellow podzolic, well drained with pH ranging from 3.2–4.5 (Saiful 2002).

The vegetation is primarily hill dipterocarp forest and classified within the lowland evergreen rain forest formation (Whitmore 1984). It is a primary forest as indicated by bio-physical characteristics of the study area (Saiful 2002, Saiful et al. 2010). In general, the forest consists of three tree-canopy layers, i.e. the under storey layer, main canopy layer and scattered emergent layer (Saiful & Latiff 2017).

Sampling design

A systematic sampling was adopted along the gradient directed transect in the 45 ha of study site for collection of data on canopy gap dynamics and other relevant information (Gillison and



Figure 1 Map of Peninsular Malaysia showing the study location (Saiful & Latiff 2014)

Brewer 1985). The study site was stratified into ridge, ridgetop and hillside in order to capture the topographic variation of canopy structure. A line transect of about 500–550m was laid out within each stand (i.e. hill) originating from stream bank, following the centre of the ridge and finally ended at the ridge crest (Figure 2). Lateral transects were established right angle to the main transect to sample hillside, and spaced systematically at 40-m distance (Figure 3). Study plots of 30 × 30 m or 20 × 45m were located at a 40-m distance on the transect line.

Data collection

All canopy trees ≥ 20 cm dbh were measured with a diameter tape at 1.3 m above ground or just above the buttress. Tree position including trees marked for felling was mapped. After six months to one year of the completion of logging, resurveying of the same plots was done. The presence or absence of a tree was recorded including the soundness or injury. Basal area of trees ≥ 20 cm dbh was estimated using regression equation developed by Kato et al. (1978). Taxonomic identification of tree species is available elsewhere (Saiful 2002).

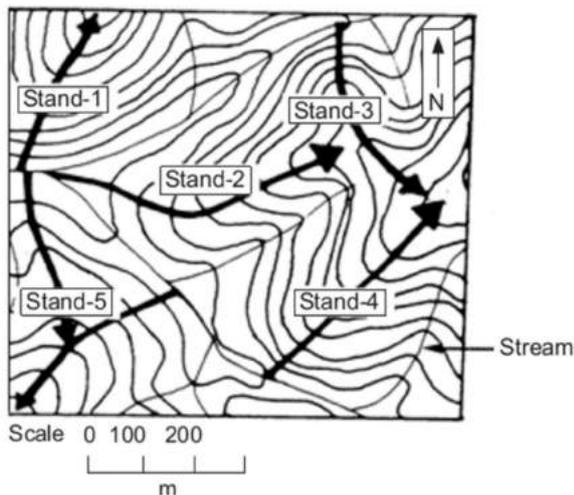


Figure 2 Topography of the study area showing direction of survey transects (indicated by arrow) along elevation gradient; lateral transects on hillside are not shown; stands 1 (Compartment 29), 2 and 3 (Compartment 28) are selectively logged covering 45 ha (Saiful & Latiff 2014)

Pre-logging gap measurements

Various information such as number of gaps with respect to tree fall, gap size and canopy cover were recorded for every sample plot. Only trees of ≥ 20-cm diameter were considered because these trees generally form the canopy layer. Tree fall gaps larger than 2 m² were considered. The most frequently used vertical projection method of measuring canopy gap on the ground has not been appreciated because the actual gap influence area is beyond that of the vertically projected area (Brokaw 1982, Green 1996, Popma et al. 1988). On average, the size of the colonised area was 3.4 times larger than the size of the projected canopy opening (Popma et al.1988). Moreover, reliable ground measurements are much more difficult to obtain (Avery and Burkhardt 1994, Saiful 2002). As such, canopy photographs using ground-level camera with 35-mm focal length lens at a distance of about

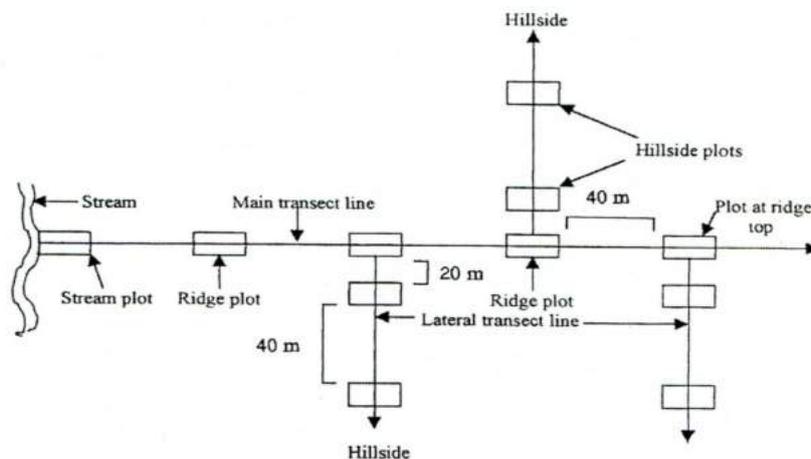


Figure 3 Diagram showing main and lateral transects and positioning of plots in a forest stand, lateral transects positioned alternately on either side of the main transect to sample hillside, study plots were regularly spaced on the transect line (Saiful & Latiff 2014)

1.6 m from the ground were used to measure the individual gap size before logging, and using fish eye lens photographic estimates of post-logging canopy openness were determined (Evans and Coombe 1959, Whitmore et al. 1993). Before logging, fish eye photography could not capture the adjacent canopy gaps due to obstruction created by uneven-aged trees. In such case, fish eye photography may produce an overestimate of closure (Crome et al. 1992, Saiful 2002).

For estimation of pre-logging gap size, photographic scale was calculated following the procedure laid down for vertical aerial photograph (Slama 1980, Avery and Burkhart 1994). Accordingly, the scale 'S' of a gap photograph was determined by comparing the distance between two points (a, b) on the photograph with the corresponding ground distance (AB). To adjust the difference in elevation between the points A and B on the ground, careful attention was paid for horizontal distance as near as possible. Similarly, tilting of camera from vertical position at the time of exposure was also avoided by holding camera as near vertical as possible. Without calculating the scale of every gap photograph, calculation of average photo scale of 25 randomly selected gaps covering all topographic locations was determined to increase the accuracy of subsequent photo measurements (Avery & Burkhart 1994).

After determining the average photo scale (i.e. 1: 119.85), a transparent dot grid was positioned over gap photograph (Figure 4) and the area of each dot on the ground (i.e. 1 dot = 0.144 m²) was then determined (see Appendix

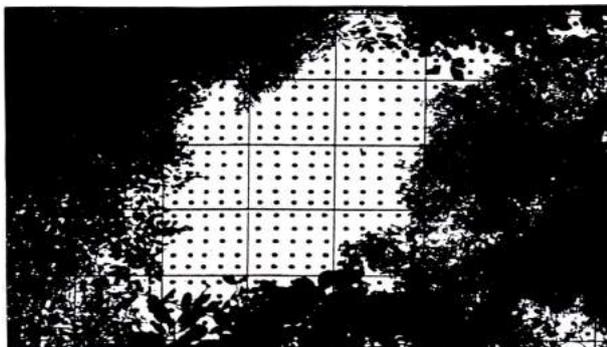


Figure 4 Transparent dot grid positioned over a canopy gap photograph for gap size determination; each dot represents a known area when used for a particular photographic scale

1). The total number of dots falling on the gap was counted (Figure 4). Multiplying the area of each dot with the total number of dots covered by each canopy gap determined the gap size.

Post-logging gap estimation

The percent canopy openness was calculated using fish eye photographs and measured as the ratio of canopy gaps and holes including any area of the open sky that is unobscured to the whole photograph area (Evans and Coombe 1959, Anderson 1964, Whitmore et al. 1993). By superimposing a dot grid to the fish eye photograph (Figure 5), the proportion of the total number of dots that falls on canopy gaps provided the estimates of canopy openness.

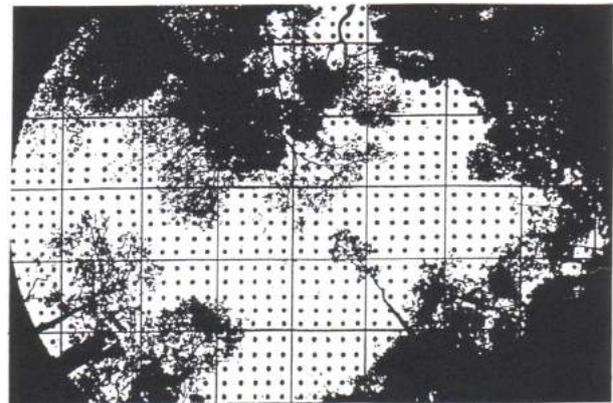


Figure 5 Transparent dot grid superimposed over a fish eye photograph to estimate per cent canopy openness; this photograph was taken from the centre of the study plot after six months of logging

Fish eye photographs were taken by fixing a fish eye lens onto a 35-mm camera. The camera was pointed vertically upward into the canopy at about 1.6-m from the ground, and captured canopy openness from the centre of the study plots. Hemispherical or fish eye photography has become an important tool in ecological studies (Evans and Coombe 1959, Whitmore et al. 1993) and can be adapted to provide detailed information on the density and distribution of foliage of different habitat types (Magurran 1988).

Methods of logging

Harvestable trees (55 cm dbh for non-dipterocarp and 65 cm dbh for dipterocarp species) were

marked using yellow plastic tags. Bulldozers were engaged for construction of logging tracks as well as to get timber out of the stump site. Felling was done by a power saw. The overall extraction level in 2.52 ha of sampled area was 27 trees ha⁻¹ with basal area and volume removal of 19.39 m² and 73.7 m³ ha⁻¹ respectively.

Assessment of ground damage

Damaged plot area by removal of top soil was positioned on a scaled graph sheet to assess the forest floor damage by logging tracks and log landing. Ground area disturbed by felling trees and skidding was also estimated. Transparent dot grid was used to determine the affected area.

Data analysis

One way Analysis of Variance (ANOVA) was applied to test for differences in mean values between different topographic positions. Where distributions were skewed, a non-parametric counterpart, Kruskal-Wallis test was performed. Mean comparison of the variables between two studied compartments were determined using one sample t-test. To determine the relationship between two sets of variables, a simple linear regression was also carried out. Statistical significance level was established at $p < 0.05$. Analysis was performed using the Minitab statistical package.

RESULTS AND DISCUSSION

Tree fall and canopy gaps before logging

Most of the canopy gaps were associated with single tree fall and most trees were found uprooted than snapping of the bole that conformed to Green (1996). The mean number of tree fall (≥ 20 -cm dbh) and canopy gaps per plot were 3.87 (SE = 0.33, $n = 32$) and 3.81 (SE = 0.26, $n = 32$), respectively. Both tree fall and canopy gaps significantly varied by topographic locations, and ridgetop had lower number of tree fall (ANOVA, $F = 3.34$, $df = 2$, $p < 0.05$) and canopy gaps (ANOVA, $F = 3.82$, $df = 2$, $p < 0.05$) than the ridge, but did not differ significantly from hillside.

The number of tree fall was fairly correlated with the number of canopy gaps ($r^2 = 50.5\%$,

$p < 0.001$, $n = 32$) as well as with the resulting gap size ($r^2 = 57.7\%$, $p < 0.001$, $n = 32$). Similar observation on the increase of gap size with the number of tree fall has been shown (Van der Meer and Bongers 1996). Unlike Brokaw's (1982) vertical projection method of gap measurement, the photographic measurement of gap area showed reasonable and stronger correlation with the number of tree fall (Brokaw's method $p < 0.05$ vs. this method $p < 0.001$). This could be due to the fact that photographic measurement takes full consideration of the actual gap perimeter (Figure 4).

Gap size-frequency distribution

Most gaps recorded were smaller in size in comparison with those reported elsewhere (Brokaw 1982, Green 1996), but similar to sizes reported by Thompson et al. (1992). The dissimilarity was perhaps due to the size range in those studies where gaps < 20 m² were not included. Chapman and Chapman (1997) also reported 74% of the canopy gaps were 1 m wide or less. The frequency distribution of the gap area of the study plots was strongly skewed and median gap area was 50.40 m². That is 5.6% of the plot area was covered by canopy gaps. However, out of 32 plots, twelve plots (37.5%) were < 30 m² gap area, ten (31.2%) were > 30 –70 m², eight (25%) were > 70 –130 m² and two plots (6.2%) were > 130 m² gap area. Like gap area estimates, the distribution of canopy cover of the study plots was also strongly skewed and median canopy cover was 94.4% ($n = 32$).

Gap size and species distribution

The variation of species composition and richness in the study site may partly be associated with the size of the canopy gaps and gap environment (Saiful 2002). Among the topographic locations, ridge and hillsides had significantly higher median plot area occupied by canopy gaps than ridgetops (Table 1, Figure 6). Stand profiles of the study site also showed that ridges and hillsides were mostly interrupted by tree fall gaps (Saiful & Latiff 2017). However, remarkable representation of pioneer species (e.g. *Macaranga* and *Mallotus*) was observed on the ridges and hillsides before logging (Saiful 2002), which was probably because of wider plot area occupied by

Table 1 Kruskal-Wallis tests on comparison of median values on gap area estimates within the study plots, Ulu Muda Forest Reserve, Kedah in different topographic locations before logging

Variable	Habitat	Sample size (n)	Median value	P-Value
Plot area (m ²) covered by canopy gaps	Hillside	11	38.70	0.013*
	Ridge	11	82.50	
	Ridgetop	10	19.30	

* = significance level at $p < 0.05$

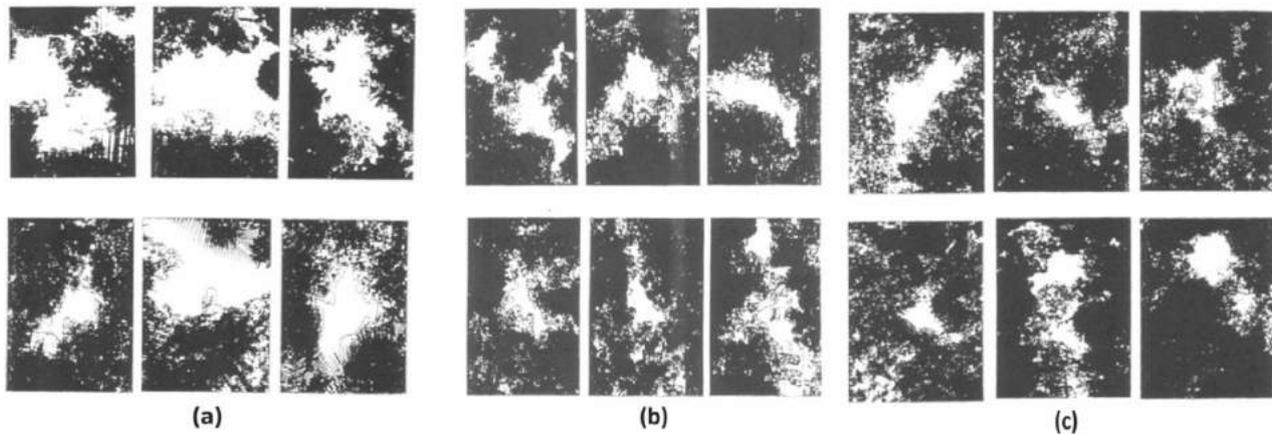


Figure 6 Vertical canopy photographs using 35-mm focal length lens showing size and shape of the canopy gaps in the study site before logging; gaps on the ridges (a) are bigger in size followed by hillside (b) and ridgetop (c)

the canopy gaps. Similarly, the overall dominant representation of climax (non-pioneer) species was also attributed to small sized gaps (Saiful 2002) and this finding was consistent with the study of Whitmore (1989). The presence of more shade-tolerant climax species of the study site is comparable with the forests of Barro Colorado Island (Brokaw and Scheiner 1989).

Canopy opening after logging

Based on the fish-eye photography, the distribution of plot data on percentage canopy openness was strongly skewed. Out of 28 study plots, twelve plots (43%) had < 25% canopy openness, ten plots (36%) had 25–50% and six plots (2%) were with > 50% canopy opening. The mean canopy openness (log transformed) was 29.2% (SE = 1.11, n = 28, range 12–80.6%) and corresponding median canopy cover was 73% (n = 28).

Harvesting damage and canopy openness

The occurrence of various types of harvesting damage (smashed, snapped bole, crown injury) to canopy trees was significantly higher on the ridgetops than hillside and ridges (ANOVA, $F = 4.68$, $df = 2$, $p < 0.05$) which may have played higher canopy opening on ridge crest (41.50%). In fact, ridgetop was heavily harvested (41% of total extracted trees) followed by 33.8% and 25% for ridge and hillside, respectively. However, across all habitat types, significant linear relationship was observed between the loss of overstorey canopy trees and increase in canopy openness ($r^2 = 76\%$, $p < 0.001$, $n = 28$) (Figure 7). Similar logical relationship was also exist between canopy openness with the amount of basal area decline for trees ≥ 20 cm dbh ($r^2 = 46\%$, $p < 0.000$, $n = 28$). From West Kalimantan, Indonesia, Cannon et al. (1994) reported linear relationship between basal area

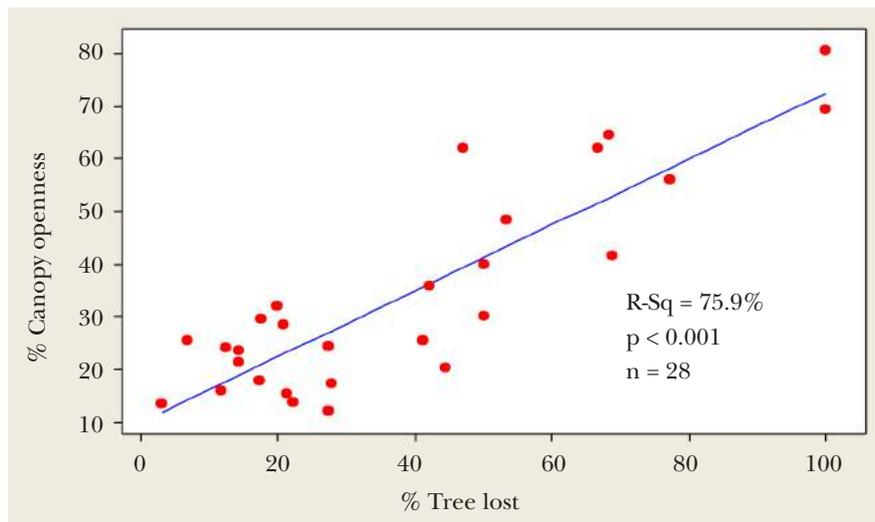


Figure 7 Relationship between loss of overstorey canopy trees (≥ 20 -cm diameter) and percent canopy openness in the study site; n = number of plot sampled

harvest ($\text{m}^2 \text{ha}^{-1}$) and canopy disturbance ($r^2 = 0.51$). In the Amazon, increased tree fall rates in logged forest were related to increased canopy opening (Schulze & Zweede 2006).

Effects of harvesting plans and canopy opening

The intensity of ground damage by logging tracks and skidding was primarily responsible for incidental damage to trees which ultimately had affected canopy structure. As such, significant linear relationship between intensity of ground damage and canopy openness ($r^2 = 63\%$, $p < 0.001$) was obtained (Figure 8). The effects of harvesting layout of the two study compartments were studied (Figure 9 and 10). Though basal area and volume removal of both compartments were not statistically significant ($t = 0.15$, $p = 0.88$, $df = 25$) (Saiful 2002), however, mean ground damaged area for all kinds of logging tracks and log decks combined was significantly higher in C29 than C28 ($t = 3.41$, $df = 17$, $p < 0.01$), and 56.6% of the total area affected was contributed by skid tracks alone followed by log landing (27.2%) and roads (16.3%).

The high percentage of ground damage in C29 could be mainly due to positioning of logging tracks along the centre of the ridge and ridge tops, where most merchantable trees were dominated. In contrast, the positioning of logging tracks away from the centre of the ridge as well as their low frequency was perhaps the key

factor in reducing damage in C28. As a result, extensive ground damage inside the study plots of C29 was significantly related with canopy opening ($r^2 = 73\%$, $p = 0.000$), and the low frequency of logging tracks and corresponding undisturbed area in C28 showed poor linear relationship ($r^2 = 26\%$, $p = 0.052$). However, due to variation in canopy openness ($t = 4.41$, $df = 15$, $p < 0.001$), the overall density and distribution of foliage in C28 was much higher than the C29 (Figure 11 and Figure 12).

Study of Pinage et al. (2016) showed that contribution of log decks and primary roads in the decrease of canopy cover were significant at a 95% confidence level, while the effect of secondary roads, tree fall gaps and skid trails were not. A gradient of increasing gap fraction that ranged from primary forests to log decks was also observed in selectively logged forests in Western Amazon (Pinagé et al. 2014). Log decks had the largest forest gap fractions at 0.5 yr post-harvest than roads and skid tracks. Selective logging in Myanmar reported highest canopy openness in log landing and showed favorable growth of teak seedlings due to increased light intensity (Ne Win et al. 2012).

Invasion of pioneer species

The variation of forest microclimates following logging has been elaborately discussed by Saiful et al. (2010). As such, the increase in air temperature had decreased the percentage

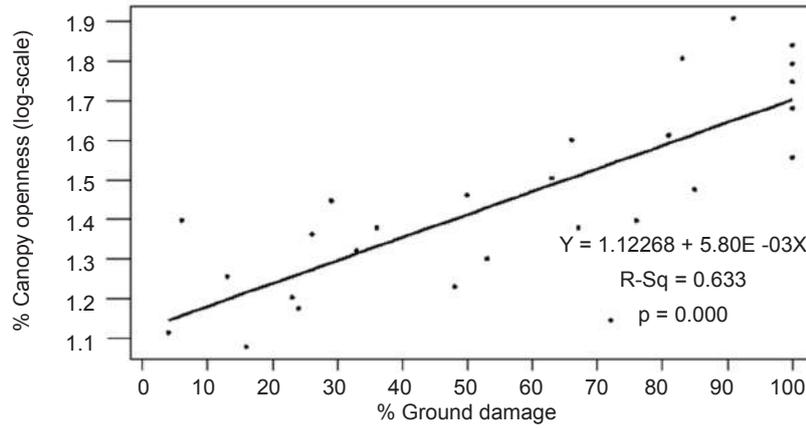


Figure 8 Relationship between intensity of ground damage and canopy openness in the study area, Ulu Muda Forest Reserve, Kedah

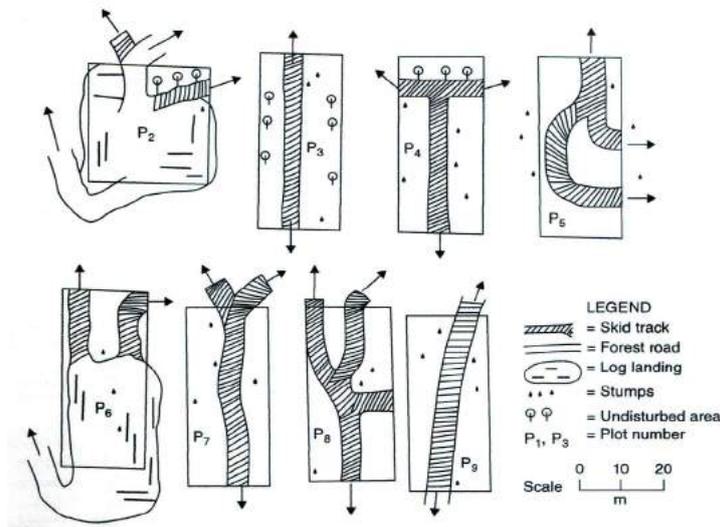


Figure 9 Harvesting layouts inside the study plots of compartment 29 showing positioning of logging tracks and their pattern, harvested tree stumps and undisturbed plot (Saiful 2002)

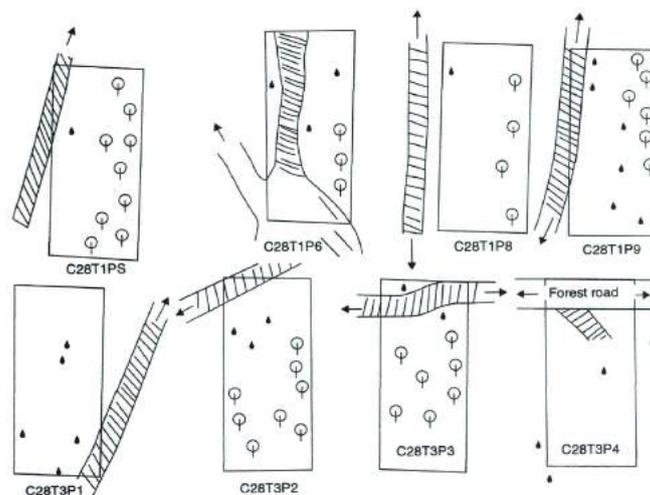


Figure 10 Harvesting layouts in compartment 28 showing position of logging tracks passing at a distance from the study plots, causing minimum damage to trees; see Figure 9 for legend (Saiful 2002)

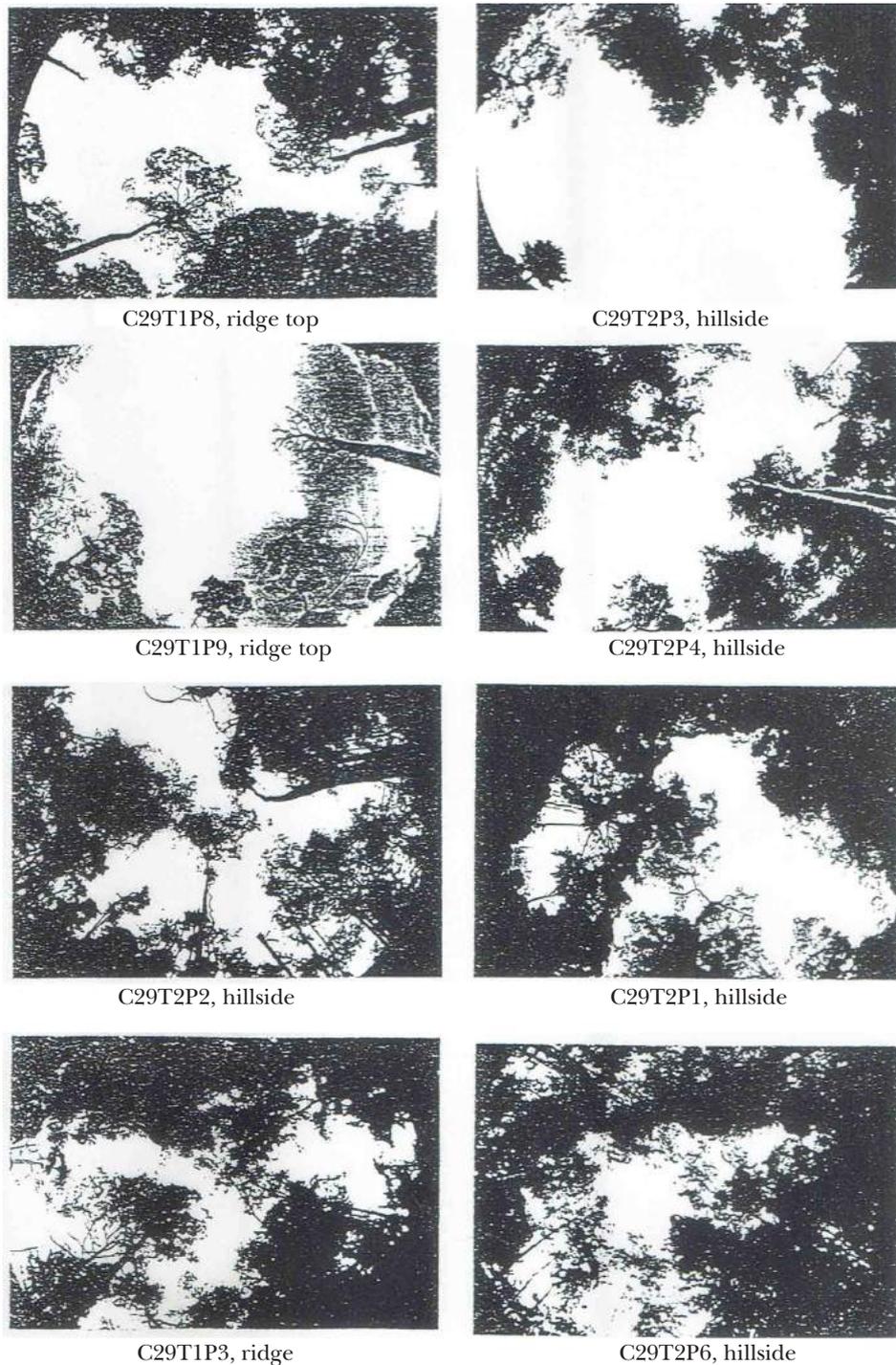


Figure 11 Fish eye photographs of study plots showing much lower density and distribution of foliage in compartment 29 due to high percentage of ground damage and loss of canopy trees

of relative humidity ($r^2 = 0.472$, $p < 0.001$) and increased soil temperature ($r^2 = 0.450$, $p < 0.001$). Fish eye photography of the logged-over forest depicted increased light intensity on the forest floor because of lesser stratification of canopy layers. Light availability to the forest understorey was significantly higher in the

regenerating forest of Pasoh Forest Reserve (Numata et al. 2006).

The overall changes in similarity of species composition by logging might be coupled with additional changes by invasion of pioneer species due to canopy opening (Saiful et al. 2010, Saiful and Latiff 2014). Interestingly, one particular

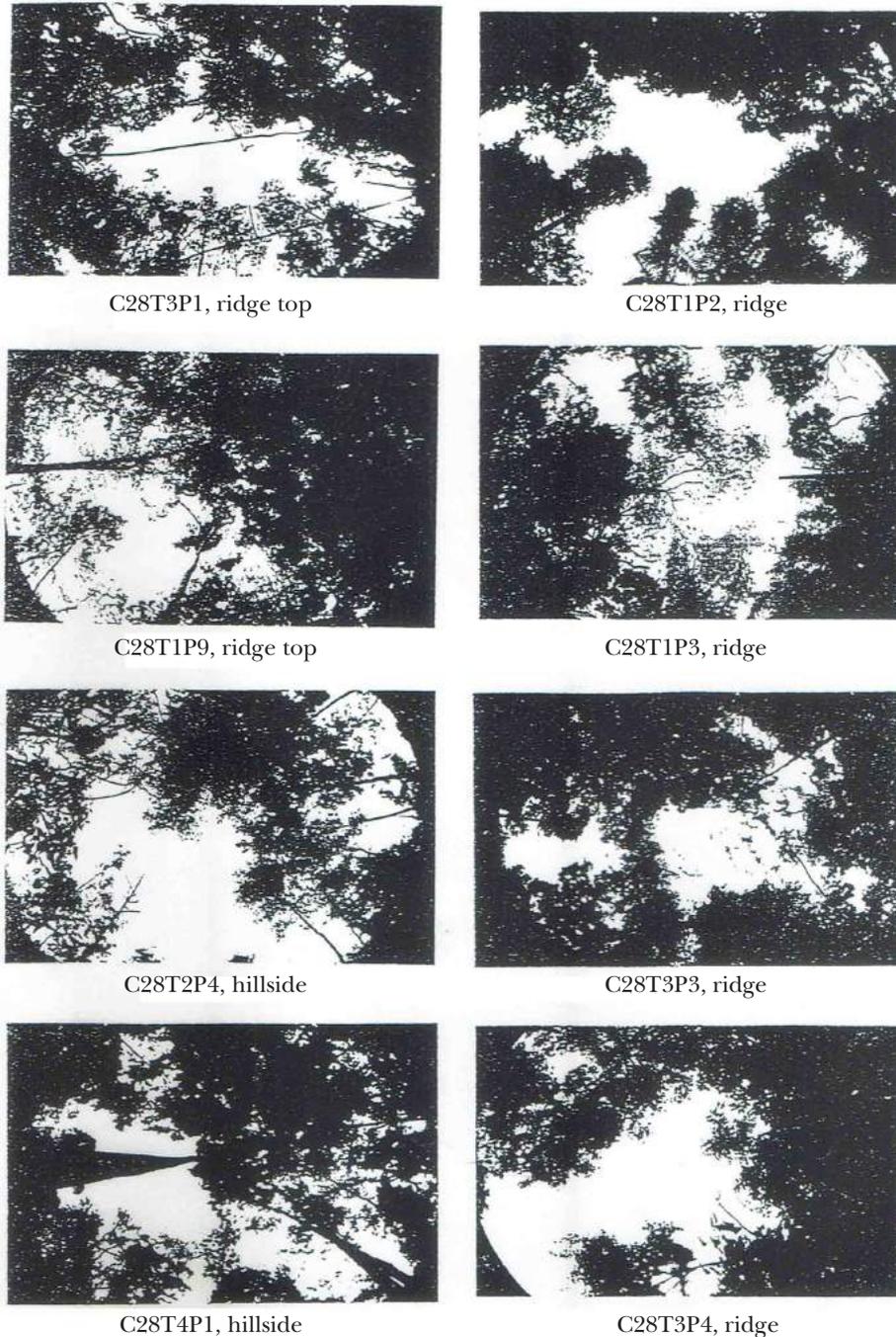


Figure 12 Fish eye photographs of study plots of compartment 28 showing much higher density and distribution of foliage due to low percentage of ground damage and higher retention of canopy trees

pioneer species (*Trema angustifolia*, Ulmaceae) was predominant in the heavily-damaged logged area (i.e. C29), which was not observed before logging, whereas in the lightly-damaged compartment (C28), members of the genus *Macaranga* were quite frequent. Seino et al. (2005) also observed a similar trend of species dominance of *Macaranga* in Tangkulap Forest Reserve in Sabah, Malaysia. In Southeast Asia, the

invasion of members of the family Euphorbiaceae (e.g. *Macaranga*, *Mallotus* spp.) in logged-over forest is well recognised (Johns 1988, Cannon et al. 1998).

Comparisons with other studies

Most of the study plots had 90–98% canopy cover before logging. The median canopy cover

Table 2 Comparison of canopy loss between different studies under conventional logging

Studies	% Canopy opening		% Canopy cover		% Canopy loss
	Before logging/ unlogged forest	After logging/ logged forest	Before logging/ unlogged forest	After logging/ logged forest	
Webb 1997	-	-	91.4	73.4	18 [^]
Uhl and Viera 1989			80.0	42.5	37.5
This study 2002	5.6	29.2	94.4	73.0	21.4 [@]
Verissimo et al. 1992	-	-	82	45	37
Crome et al. 1992	-	-	-	-	22.3 ^{^^}
Johns et al. 1996	-	-	-	-	19 [#]
Cannon et al. 1994	-	45	76	-	-
Periera et al. 2002	3.1	21.6	97	75.4	21.6

[^] = controlled selective logging, ^{^^} = measured by aerial photograph and ground survey, [#] = measured by holding viewfinder along transects, [@] = measured by ground-based vertical canopy photography using 35-mm focal length lens

for the study area (45 ha) was 94.4% (n = 32). Conventional logging published in different studies (Table 2) shows percentage removal of the original canopy cover. In the present study, logging decreased canopy cover by an average of 21% overall which is comparable to other studies except Uhl and Viera (1989) and Verissimo et al. (1992). Different studies adopted different methodologies for estimation of canopy loss but information for comparison was largely lacking. Webb's (1997) study on controlled selective logging showed lowest canopy loss (Table 2). Queensland study (Crome et al. 1992) showed less incidental damage to trees that resulted in 22.3% canopy loss. However, the lower value for the study site was mainly due to the contribution from C28 that was lightly logged in terms of frequency of logging tracks and damage to trees. With an exception of this study, other research compared unlogged forest with sites logged at different years prior to sampling (Table 2).

Implications for management

The residual stocking standards for the next cut in Malaysian Selective Management System (SMS) should have at least 32 sound commercial tree species per ha in the diameter class of 30–45 cm (Yuan et al. 1996). The SMS could not qualify this standard in the residual stock (Saiful 2002), and this resulted in even-aged appearance of the forest with significant canopy opening. Due to before-and-after logging study, the effects of logging on availability of required number of economically important trees for the next cut

had been precisely quantified (Saiful 2002). That is, the next felling operations would have different species list of rather poor commercial importance.

Moreover, the condition of residual stocking agrees that it would need more than one rotation to recover stand structure and canopy development. However, the recovery is largely dependent on the resilience of the residual species and their competition with pioneers. Post-logging growth of commercial tree species in the forest of Vietnam revealed that a duration of 30 years was insufficient to recover the status similar to unlogged forest (Do et al. 2016). There was limited evidence of canopy development after 8 years of selectively logged lowland rainforest (Cannon et al. 1994). It was also estimated that the gap pattern would be restored to a condition similar to undisturbed forest in about 53 years after logging (Priatna et al. 2004). Similar slower canopy recovery was reported on logging roads than on skid trails (Soemarno 2001).

This study proposes some improvements in harvesting operation. Harvesting plan should be drawn up in advance considering both exploitable trees and trees for retention. Trees for next cut (near to the exploitable trees) should be marked separately so that logging operators can avoid damages to these trees. A site-specific cutting rule would reduce the canopy opening and damage in areas dominated by commercial trees. Besides, enhancing the skills of forest workers and logging operators are important contributing factors in reducing damage to the residual trees and the forest canopy.

CONCLUSIONS

Gap dynamics is a biophysical variable related to micro-climate and regeneration, and is an important indicator of forest management quality. In this study, although there was no significant difference in harvesting intensities (basal area or volume felled) in the two studied compartments, imperfect logging layout showed significant logging damage to compartment 29, which was a significant research issue. In fact, it was assumed that both compartments could have been affected similarly due to similar extraction level. However, logging method was responsible for canopy disturbance, not harvesting intensity. The approach proposed in this study findings is useful for ensuring success of forest conservation and sustainable forest management. Trial and evaluation for low impact logging of highly rich *Shorea curtisii* stand along the ridgetops needs research support. Monitoring studies at different ages of logging on the changes of recovery of the canopy structure would facilitate the management to prepare an improved management plan.

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Appendix 1 Calculation of Photo Scale and Gap Area Measurements

For example, the distance between two points a and b of a canopy gap photograph was measured as 12.7 cm with their corresponding ground distance AB as 13 m (1300 cm). Based on this data, calculation would be as follows:

Step 1: Calculation of Photo Scale

$$\text{Scale 'S'} = \frac{ab}{AB} = \frac{\text{Photo Distance}}{\text{Ground Distance in Centimeter}} = \frac{12.7}{1300} = \frac{1}{102.36} = 1:102.36$$

At a given distance, on the ground is 102.36 times greater than the photograph.

Step 2: Gap area measurements

From the above photo scale, 1 cm² on the photograph = (102.36 cm)² = 10477.57 cm² on the ground.
Size of the canopy photograph (3R size print) = 8.9 × 12.6 cm = 112.14 cm² = 1120 dot.

Thus, 1 cm² (on the photograph) = $\frac{1120}{112.14} = 10$ dots = 10477.57 cm² on the ground

Thus, 1 dot = 10477.57/10 = 1047.76 cm² = 0.105 m²

Total number of dots counted for this gap = 429.

So, gap size = 429 × 0.105 = 45.0 m²