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EFFECTS OF FELLING GAP PROXIMITY ON RESIDUAL TREE MORTALITY AND GROWTH IN A DIPTEROCARP FOREST IN EAST KALIMANTAN, INDONESIA

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RUSLANDI, HALPERIN J & PUTZ FE. 2012. Effects of felling gap proximity on residual tree mortality and growth in a dipterocarp forest in East Kalimantan, Indonesia. The effects of proximity to felling gaps on residual trees in a selectively logged forest were monitored for eight years after nine 4-ha plots (n = 3 per treatment) were subjected to one of two intensities of reduced-impact logging (RIL), i.e. either 50 or 60 cm diameter cutting limits, or conventional logging of 60 cm diameter cutting limit with three additional plots reserved as unlogged controls. Each residual tree > 10 cm diameter at breast height (dbh) was classified as either being near (< 20 m from a gap centre) or far (> 20 m) from the nearest felling gap, defined as 20 m radii areas around the stumps of felled trees. Tree mortality rates did not vary with gap proximity, but were higher in logged than unlogged plots for the first two years after logging. In all logged plots combined, trees < 50 cm dbh of all species and dipterocarps < 30 cm dbh grew faster if they were near a gap. The observed increased growth rates of trees in the more intensively logged plots, regardless of the logging method used, was due to both higher proportions of trees near gaps and faster growth of trees in all locations.

Keywords: Borneo, reduced-impact logging, conventional logging, tropical silviculture

RUSLANDI, HALPERIN J & PUTZ FE. 2012. Kesan kehampiran ruang tebangan terhadap kematian serta pertumbuhan pokok sisa di hutan dipterokarpa di Kalimantan Timur, Indonesia. Kesan kehampiran ruang tebangan terhadap pokok sisa di hutan yang dibalak secara berpilih dipantau selama lapan tahun selepas sembilan plot bersaiz 4 ha (n = 3 setiap ujian) dikenakan dua intensiti penebangan berbeza iaitu penebangan impak rendah (RIL, yakni had penebangan sama ada 50 cm atau 60 cm) atau pembalakan konvensional (had pembalakan 60 cm). Tiga plot yang tidak dibalak dijadikan plot kawalan. Setiap pokok sisa dengan diameter aras dada (dbh) > 10 cm dikelaskan sebagai sama ada dekat (< 20 m dari tengah-tengah ruang) atau jauh (> 20 m) dari ruang tebangan yang terhampir, yang didefinisikan sebagai jejari 20 m mengelilingi tunggul pokok. Bagi dua tahun pertama selepas pembalakan, kadar kematian pokok tidak berbeza mengikut kehampiran ruang tetapi nilainya lebih tinggi di plot yang dibalak berbanding plot yang tidak dibalak. Jika semua plot yang dibalak digabungkan, didapati semua spesies < 50 cm dbh dan dipterokarpa < 30 cm tumbuh lebih cepat jika pokok-pokok tersebut berada hampir dengan ruang. Kadar pertumbuhan lebih tinggi di plot yang dibalak secara lebih intensif, tanpa mengambil kira kaedah pembalakan yang diguna, kerana terdapat lebih banyak pokok berhampiran ruang serta pertumbuhan pokok yang lebih cepat di semua lokasi.

INTRODUCTION

Industries based on timber from South-East Asian dipterocarp forests contribute substantially to the economies of the region. The extent to which these forests will contribute in the future depends on the rates at which commercial timber volumes recover after logging. Timber recovery rates vary with post-logging rates of recruitment, growth and mortality, all of which are known to increase after harvesting presumably in response to harvest-induced canopy openings (e.g. Silva et al. 1995, Tuomela et al. 1996, Clearwater et al. 1999, Ruslim et al. 2000, Sist & Nguyen-Thé 2002, Bischoff et al. 2005, Priyadi et al. 2006). To clarify this response, we studied the spatial dynamics of growth and mortality of residual trees for eight years after selective logging of a dipterocarp forest in Borneo. Specifically, we evaluated whether the number of trees close to canopy gaps opened by felling varied with logging intensity and how this proximity affected their mortality and growth rates.

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MATERIALS AND METHODS

Study site

This study was carried out in lowland (13–437 m elevation) dipterocarp forest in the PT Inhutani 1 Labanan Concession, District of Berau, East Kalimantan, Indonesia (Figure 1). Annual rainfall in Berau ranges from 1800 to 3000 mm with the wettest months being January–March and the driest, August. The topography of the area is gently undulating to hilly (BFMP 1998) and the soils are predominantly acidic and nutrient-poor Udults (Sumaryono 1998).

Plot establishment, logging methods and measurements

As part of a long-term study on the regeneration of logged-over forests (the STREK Project, Tyrie 1999), 12 permanent sample plots (4 ha each, 200 × 200 m) were established in 1989/1990 in a previously unlogged forest. Nine randomly selected plots were selectively logged in 1991–1992 and remeasured three months after harvesting with subsequent remeasurements at two-year intervals. Three different logging treatments were applied with three replicates of each, with three additional plots reserved as unlogged controls. The logging treatments were: (1) reduced-impact logging (RIL) with a minimum cutting diameter of 50 cm (diameter at breast height, dbh), (2) RIL with a minimum cutting diameter of 60 cm and (3) conventional logging with a minimum cutting diameter of 60 cm. All harvested trees were dipterocarps. Details of the logging operations and species harvested are described in Bertault and Sist (1997) and Sist and Nguyen-Thé (2002). For all trees > 10 cm dbh in each plot, species were identified, locations were mapped and dbh, height, crown form and crown positions were recorded. For this study we used data from the first eight years after logging (1992–2000). Since logging intensity was a much better predictor of collateral damage to the residual stand than whether reduced-impact or conventional logging techniques were used (Sist et al. 1998, 2003), we focused solely on logging intensity. In light of the finding that logging damage increased markedly if more than eight trees per hectare were harvested (Sist et al. 1998, 2003), we used that number to separate four high-intensity logging (HIL) from five low-intensity logging (LIL) plots (Table 1).

Tree felling gap proximity classification

Although all tree positions were mapped, felling gaps were not, so the classification of trees

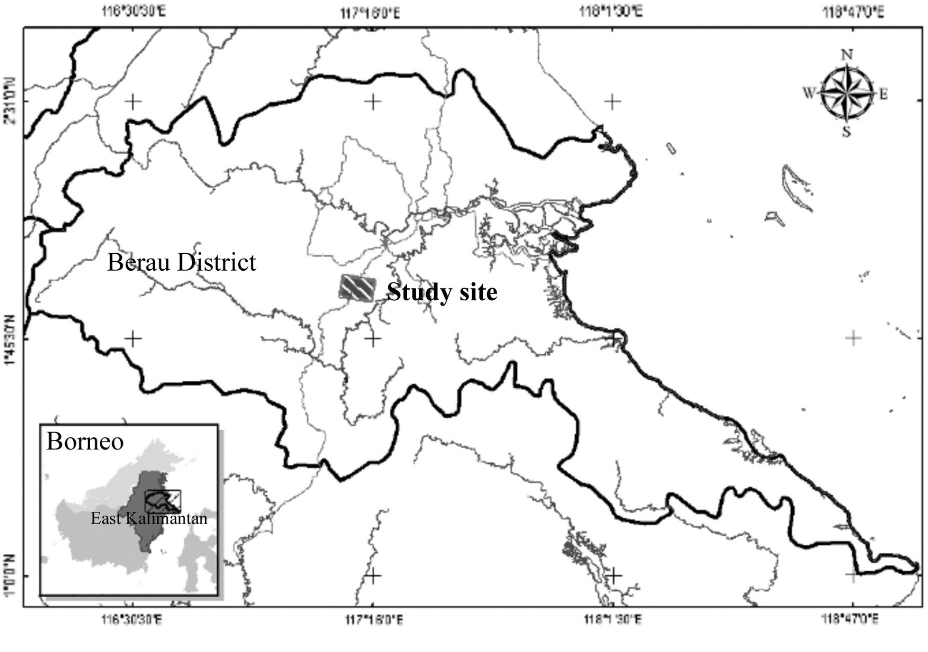


Figure 1 The STREK plot area (striped box) in Berau District, East Kalimantan Province on the island of Borneo, Indonesia

Table 1 Logging treatments applied to 4-ha plots in lowland dipterocarp forest in East Kalimantan, Indonesia

Treatment	Volume (m^3 ha^{-1})	No. of trees harvested (trees ha^{-1})	Pre-logging tree density (trees ha^{-1})	Plot number
Low-intensity logging (LIL)	57.3 ± 10.9	7.6 ± 1.7	569.4 ± 71.9	2, 3, 5, 6, 7
High-intensity logging (HIL)	123.9 ± 37.2	11.3 ± 2.7	486.7 ± 28.0	8, 9, 11, 12

as being near (< 20 m) or far (> 20 m) from the closest gap required two assumptions. We assumed that the stump of the felled tree was at the centre of the gap and that gaps were 20 m in radius. The first of these assumptions was at least partially supported by the fact that 94% of the dipterocarp trees > 50 cm dbh in the study plots were recorded as having symmetrical crowns during the pre-harvest inventory using Dawkins' crown form classification (Dawkins 1958). The assumption of 20 m gap radii is based on the reported average radius of the crowns of canopy trees and the gaps they create upon falling in lowland dipterocarp forests (Yamakura et al. 1986, Köhler & Huth 1998). This support for our assumptions about gap sizes and locations notwithstanding, given that felled trees leave gaps both where they stood and where they fell, we undoubtedly misidentified the locations of some residual trees. A further limitation in our tree location classification method was that lack of data precluded inclusion of proximity to canopy openings associated with skid trails but because few large trees were killed during skid trail construction and use (Bertault & Sist 1997), this effect was presumably negligible. For the analyses, tree species were classified as dipterocarps, commercial non-dipterocarps, and all species combined based on Rombouts (1998) and Phillips and van Gardingen (1999).

Data analysis

Mortality rates were calculated as the proportion of trees dying relative to the number alive at the commencement of each two-year monitoring period. Data from trees with tall buttresses for which diameter was estimated and those for which the height of diameter measurement changed were excluded from the growth analyses. We also excluded growth data from the first measurement period because it included both pre- and post-logging conditions. General linear model analysis of variance (ANOVA) and Tukey post-hoc tests were performed to assess the effects of different logging intensities on stand-wide mortality and growth, while t-tests were performed to assess the effects of tree felling gap proximity on mortality and growth of residual trees. All percentage data were arcsine transformed before statistical analysis with SPSS 17.0 (2008).

RESULTS

Residual tree density relative to tree felling gaps after high- and low-intensity loggings

Pre-logging densities of trees > 10 cm dbh did not differ between LIL and HIL plots ($t = 4.6$, $p = 0.69$, df = 8). However, three months after logging there were more trees in the LIL plots (mean = 461 trees ha^{-1}, SD = ± 71.1, N = 5) than in the HIL plots (mean = 352 trees ha^{-1}, SD = ± 38.7, N = 4) ($t = 7.5$, $p < 0.05$, df = 8). Trees in LIL plots were equally common near and far from gaps ($t = 0.3$, $p = 0.60$, df = 9), whereas there were more trees in HIL plots near gaps ($t = 12.5$, $p < 0.05$, df = 7). In contrast, when densities of residual trees near gaps were compared on the basis of proportions, there was no difference between logging intensities ($t = 3.7$, $p = 0.10$, df = 8; Table 2). The density of trees near gaps showed only a weak positive relationship was with the number of trees felled (Figure 2).

Residual tree mortality in LIL, HIL and unlogged plots

For the first two years after logging (1992–1994), mortality rates of residual trees in HIL plots were higher than in LIL and unlogged control plots for each species group (Table 3). Mortality rates of trees in LIL and unlogged plots differed only for commercial non-dipterocarps and all

Table 2 Density of residual trees per ha (mean ± 1 SD) near (< 20 m) and far (> 20 m) from the nearest felling gap three months after low-intensity logging (LIL) and high-intensity logging (HIL)

Gap proximity	HIL	LIL	All logging
Near gap	223.9 ± 31.2 (64.2%)	237.4 ± 50.4 (51.5%)	231.4 ± 41.0 (57.2%)
Far from gap	127.9 ± 46.7 (35.8 %)	223.8 ± 51.2 (48.5%)	181.1 ± 68.4 (42.8%)

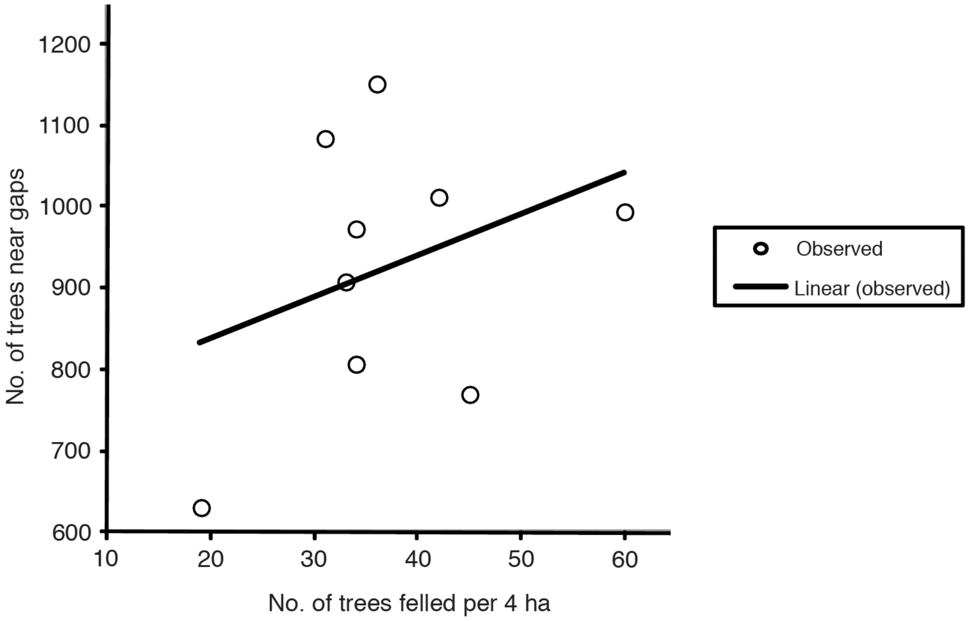


Figure 2 Number of trees < 20 m from the nearest felling gap in 4-ha plots as a function of the number of trees felled; no. of trees near gaps = 736.1 ± 5.1 (no. of trees felled per 4-ha); $p < 0.05$, $R^2 = 0.12$

species combined (Table 3). After 1994, there were no differences in residual tree mortality rates between HIL and LIL plots nor between logged and unlogged plots for any species group (Table 3).

Mortality rates of trees near and far from felling gaps

Over the first eight years after logging, there were no differences in mortality rates of residual trees for all species combined according to their proximity to the nearest felling gap (Table 4). In contrast, for the period of 1992–1994, the mortality rate of residual trees near gaps was higher in HIL than in LIL plots for all species groups (Table 5). For trees > 20 m from the nearest gap, mortality rates were higher in HIL plots only for dipterocarps.

Tree growth rates as a function of gap proximity

Stem diameter growth rates of residual trees for all species were 26% (0.09 cm $year^{-1}$) higher for trees near gaps (Table 6). Considering only the commercial species, growth rates were 22% higher near gaps. Overall, trees < 50 cm dbh grew faster if they were near logging gaps (Figure 3a), but when separated by species group, the effect of location was only significant for trees < 30 cm dbh (Figures 3b and c).

Growth of residual trees near and far from felling gaps after LIL and HIL

When not accounting for felling gap position, growth rates of residual trees in all species groups in HIL plots were higher than in LIL plots over

Table 3 Mortality rates of trees > 10 cm dbh in unlogged forest and over the same eight-year period after low- (LIL) and high-intensity loggings (HIL)

Species group	Annual mortality rate by period (% year^{-1})											
	1992–1994			1994–1996			1996–1998			1998–2000		
	Unlogged	LIL	HIL	Unlogged	LIL	HIL	Unlogged	LIL	HIL	Unlogged	LIL	HIL
Dipterocarp												
Mean ± SD	1.3 ± 0.3	2.7 ± 1.1	5.8 ± 1.9	2.1 ± 1.3	2.0 ± 0.8	1.3 ± 0.3	3.1 ± 0.6	2.9 ± 0.6	3.4 ± 0.3	1.3 ± 0.4	1.1 ± 0.1	1.5 ± 0.4
ANOVA	F = 14.6, p < 0.01			F = 0.8, p = 0.48			F = 1.1, p = 0.37			F = 2.1, p = 0.18		
Tukey test												
Unlogged LIL		ns			ns			ns			ns	
Unlogged HIL		**			ns			ns			ns	
LIL – HIL		*			ns			ns			ns	
Commercial non-dipterocarp												
Mean ± SD	0.8 ± 0.2	3.4 ± 1.5	5.9 ± 0.8	1.6 ± 0.6	1.6 ± 0.3	1.0 ± 0.4	1.9 ± 1.2	1.7 ± 0.6	1.9 ± 0.4	1.3 ± 0.5	1.4 ± 0.4	1.0 ± 0.4
ANOVA	F = 25.9, p < 0.001			F = 2.7, p = 0.121			F = 0.1, p = 0.92			F = 1.1, p = 0.37		
Tukey test												
Unlogged LIL		*			ns			ns			ns	
Unlogged HIL		**			ns			ns			ns	
LIL – HIL		*			ns			ns			ns	
All species												
Mean ± SD	1.4 ± 0.3	3.6 ± 1.1	5.7 ± 0.9	2.1 ± 0.8	2.0 ± 0.3	1.3 ± 0.3	2.5 ± 0.6	2.4 ± 0.4	3.0 ± 0.1	1.5 ± 0.3	1.5 ± 0.3	1.5 ± 0.2
ANOVA	F = 24.5, p < 0.001			F = 2.9, p = 0.10			F = 3.293, p = 0.08			F = 0.34, p = 0.97		
Tukey test												
Unlogged LIL		**			ns			ns			ns	
Unlogged HIL		***			ns			ns			ns	
LIL – HIL		*			ns			ns			ns	

***p < 0.001, **p < 0.01, *p < 0.05, ns = not significant

Table 4 Mortality rates of residual trees near (< 20 m) and far (> 20 m) from the nearest felling gap for eight years after logging

Species group	Annual mortality rate by period (% year^{-1})							
	1992–1994		1994–1996		1996–1998		1998–2000	
	Near	Far	Near	Far	Near	Far	Near	Far
Dipterocarp								
Mean ± SD	4.4 ± 2.5	3.6 ± 1.5	1.5 ± 0.9	1.9 ± 0.8	3.3 ± 1.1	2.9 ± 0.9	1.1 ± 0.3	1.4 ± 0.6
t-test	t = 0.56, p = 0.46		t = 0.92, p = 0.35		t = 0.64, p = 0.43		t = 2.0, p = 0.18	
Comercial non-dipterocarp								
Mean ± SD	4.7 ± 1.7	4.4 ± 1.9	1.3 ± 0.7	1.6 ± 0.5	2.0 ± 0.8	2.0 ± 103	1.2 ± 0.5	1.2 ± 0.9
t-test	t = 0.18, p = 0.67		t = 1.18, p = 0.29		t = 0.01, p = 0.94		t = 0.51, p = 0.48	
All species								
Mean ± SD	5.0 ± 1.4	4.2 ± 1.5	1.7 ± 0.6	1.7 ± 0.5	2.5 ± 0.6	2.5 ± 0.4	1.3 ± 0.3	1.4 ± 0.4
t-test	t = 1.21, p = 0.29		t = 0.10, p = 0.75		t = 0.02, p = 0.89		t = 0.62, p = 0.44	

Table 5 Mortality of residual trees during the first two years after low- (LIL) and high-intensity loggings (HIL) of trees that were near and far from logging gaps (< and > 20 m respectively)

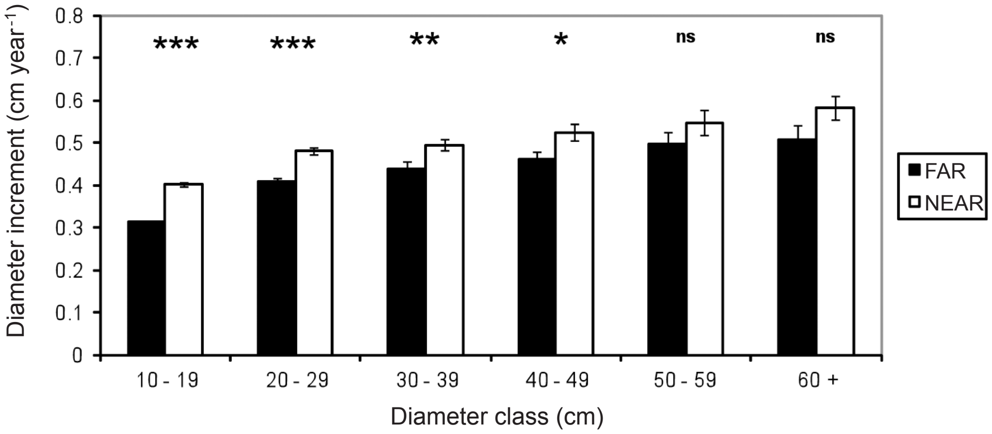
Species group	Mortality rate by gap category, 1992–1994 (% year^{-1})			
	Near		Far	
	LIL	HIL	LIL	HIL
Dipterocarp				
Mean ± SD	3.0 ± 1.1	6.0 ± 2.8	2.5 ± 1.0	4.9 ± 0.4
t-test	t = 5.67, p < 0.05		t = 15.11, p < 0.01	
Commercial non-dipterocarp				
Mean ± SD	3.5 ± 1.3	6.2 ± 0.6	3.4 ± 1.7	5.7 ± 1.6
t-test	t = 13.27, p < 0.01		t = 4.29, p = 0.08	
All species				
Mean ± SD	4.0 ± 1.0	6.2 ± 0.9	3.4 ± 1.3	5.2 ± 1.3
t-test	t = 10.56, p < 0.05		t = 4.75, p = 0.07	

Table 6 Mean annual stem diameter increment (cm year^{-1} ± 1 SD) of residual trees near (< 20 m) and far (> 20 m) from a harvest gap for all plots combined for the first eight years after logging

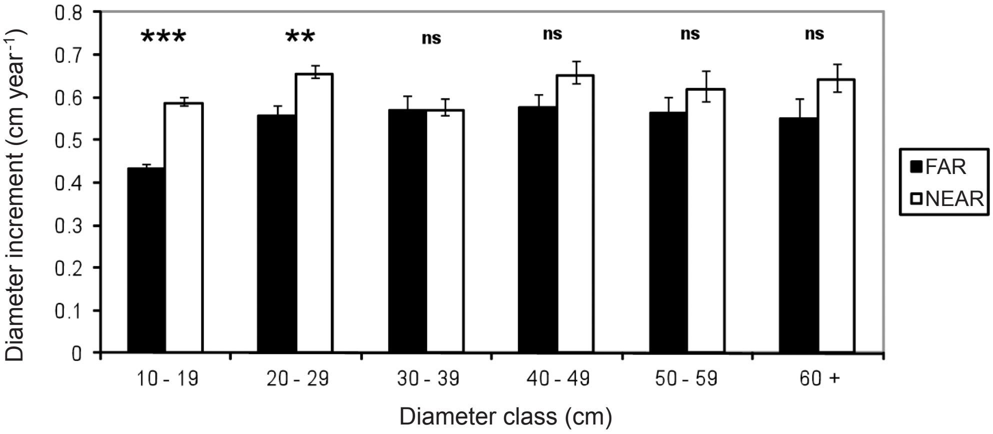
Species group	Near	Far	Statistical result
Dipterocarp	0.61 ± 0.36 (1439)	0.50 ± 0.34 (1136)	t = 60.3, p < 0.001
Commercial non-dipterocarp	0.39 ± 0.28 (1380)	0.32 ± 0.24 (1052)	t = 59.0, p < 0.001
All species	0.44 ± 0.31 (6776)	0.35 ± 0.28 (5524)	t = 232.1, p < 0.001

Values in parentheses are sample sizes

(a) All species combined



(b) Dipterocarps



(c) Commercial non-dipterocarps

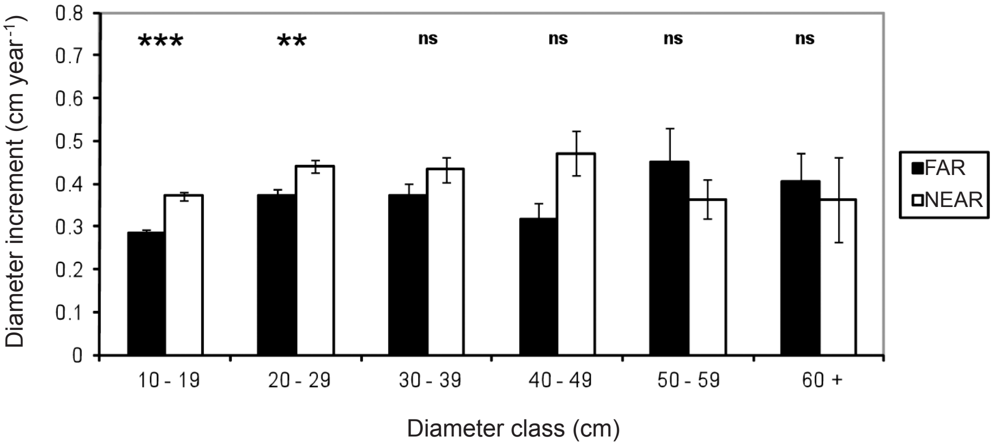


Figure 3 Mean diameter increments of residual tree groups far (> 20 m) and near (< 20 m) a felling gap by diameter class: (a) all species combined, (b) dipterocarps and (c) commercial non-dipterocarps; error bars indicate standard errors; ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, ns = not significant

the first eight years after logging (Table 7). Trees of all species grew about 30% faster in HIL than in LIL plots (Table 8); the same pattern was observed when trees near and far from gaps were considered separately. Apparently due to the combined benefits of higher logging intensity and gap proximity, near-gap trees in HIL plots grew 52% faster than trees far from gaps in LIL plots (Table 9). Considering all species combined, trees < 50 cm dbh grew faster in HIL plots if they were near a felling gap (Figure 4a). When the growth data were evaluated by species group, in contrast, only trees < 30 cm dbh that were near a gap grew faster in HIL plots. Commercial non-dipterocarp growth rates were highly variable in the > 40 cm dbh classes. Generally, dipterocarps were the most responsive to gap proximity.

Considering trees of all species that were far from felling gaps, HIL plot residual tree growth rates were faster for trees < 40 cm dbh (Figure 5). For trees > 40 cm dbh, there was no difference in residual tree growth between HIL and LIL in the far from felling gap category. Dipterocarps < 30 cm dbh grew faster after HIL (Figure 5b), whereas the commercial non-dipterocarps only grew faster in the 10–20 cm dbh class. Overall, dipterocarps responded more strongly than the commercial non-dipterocarps to both LIL and HIL.

Do trees grow faster in logged than in unlogged forest?

Regardless of their locations relative to felling gaps, residual trees of all species groups grew faster for the first eight years after logging in logged plots than in unlogged plots (Table 7). Considering their locations relative to felling gaps, trees near gaps in both HIL and LIL plots grew faster than trees in unlogged forest for all species groups (Table 9). The greatest stimulation of growth was observed in dipterocarps that were near gaps in HIL plots, with a mean growth rate benefit over control plot trees of 0.32 cm year^{-1}. Even trees of all species combined in the LIL plots that were far from gaps grew faster than trees in the control plots by 0.09 cm year^{-1}, a difference of 37%. This effect was significant for all species combined < 50 cm dbh, dipterocarps < 40 cm dbh and commercial non-dipterocarps < 30 cm dbh (Figure 6).

DISCUSSION

Proportions of trees near or far from felling gaps after LIL and HIL

High intensities of logging (> eight trees harvested ha^{-1}), regardless of logging technique, resulted in low post-logging tree densities (Ruslandi 2002, Sist & Nguyen-Thé 2002). In contrast, the proportions of trees near and far from felling gaps did not differ between plots subjected to low- or high-intensity logging. Although a higher proportion of near-gap trees might be expected after HIL, spatial clustering of harvested trees and thus overlapping felling gaps resulted in the creation of some very large gaps, which counterbalanced the expected trend. In view of this result, the locations of harvested trees should be taken into account in developing logging rules designed to avoid creation of large gaps.

Tree mortality rates after LIL and HIL

Mortality rates of residual trees in logged-over forests were proportional to logging intensities and much higher than in unlogged forest. This phenomenon was also observed in southern and northern East Kalimantan by Ruslim et al. (2000) and Priyadi et al. (2006) respectively. It is important to note that in our study forest, elevated post-logging mortality rates, regardless of logging intensity, persisted for only two years. This result is similar to that of Silva et al. (1995) for a forest in the Brazilian Amazon but shorter than that reported by Tang (1976) for a forest in Peninsular Malaysia.

Effects of felling gap proximity on residual tree mortality and growth rates

Post-logging tree mortality rates did not vary with tree location relative to logging gaps. This unexpected result differed from a study in Sarawak that reported higher mortality rates for tree seedlings and saplings growing near gaps (Primack et al. 1985). Given the elevated probability of felling damage to near-gap trees, post-logging liana infestations on gap edges, and the radical changes in light and temperature regimes experienced by gap edge trees, this result is difficult to explain. One possibility is

Table 7 Mean stem diameter increment (± 1 SD) for trees > 10 cm dbh in unlogged forest and over the same eight-year period after low- (LIL) and high-intensity loggings (HIL)

Species group	Growth rate by period (cm $year^{-1}$)											
	1992–1994			1994–1996			1996–1998			1998–2000		
	Unlogged	LIL	HIL	Unlogged	LIL	HIL	Unlogged	LIL	HIL	Unlogged	LIL	HIL
Dipterocarp												
Mean ± SD	3.5 ± 3.1	4.9 ± 3.6	6.3 ± 4.7	3.1 ± 2.9	5.0 ± 3.7	6.4 ± 4.8	3.3 ± 3.5	4.2 ± 3.2	5.4 ± 3.7	5.1 ± 4.0	7.2 ± 4.6	8.2 ± 5.3
ANOVA	F = 128.2, $p < 0.001$			F = 186.1, $p < 0.001$			F = 86.7, $p < 0.001$			F = 111.0, $p < 0.001$		
Tukey test												
Unlogged LIL	***			***			***			***		
Unlogged HIL	***			***			***			***		
LIL – HIL	***			***			***			***		
Commercial non-diptercarp												
Mean ± SD	1.9 ± 1.9	3.1 ± 2.8	4.5 ± 3.9	1.7 ± 1.8	3.2 ± 2.7	4.4 ± 3.8	1.7 ± 1.9	2.7 ± 2.5	3.5 ± 2.9	3.0 ± 2.5	4.4 ± 3.3	5.2 ± 3.7
ANOVA	F = 185.4, $p < 0.001$			F = 233.5, $p < 0.001$			F = 131.6, $p < 0.001$			F = 113.4, $p < 0.001$		
Tukey test												
Unlogged LIL	***			***			***			***		
Unlogged HIL	***			***			***			***		
LIL – HIL	***			***			***			***		
All species												
Mean ± SD	2.3 ± 2.5	3.4 ± 3.1	4.9 ± 4.0	2.0 ± 2.3	3.5 ± 3.0	4.8 ± 4.0	2.1 ± 2.5	3.0 ± 2.7	3.8 ± 3.2	3.5 ± 3.3	4.9 ± 3.9	5.7 ± 4.4
ANOVA	F = 830.7, $p < 0.001$			F = 983.0, $p < 0.001$			F = 451.8, $p < 0.001$			F = 415.9, $p < 0.001$		
Tukey test												
Unlogged – LIL	***			***			***			***		
Unlogged – HIL	***			***			***			***		
LIL – HIL	***			***			***			***		

***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, ns = not significant

Table 8 Mean annual stem diameter increment (cm year^{-1} ± 1 SD) of residual trees for a combined eight years after low- (LIL) and high-intensity loggings (HIL)

Species group	HIL	LIL	t-test	All logging
Dipterocarp	0.64 ± 0.39 (932)	0.52 ± 0.32 (1643)	t = 80.7, p < 0.001	0.56 ± 0.35 (2575)
Commercial non-dipterocarp	0.43 ± 0.30 (858)	0.32 ± 0.24 (1574)	t = 91.9, p < 0.001	0.36 ± 0.27 (2432)
All species	0.47 ± 0.33 (4487)	0.36 ± 0.27 (7813)	t = 406.9, p < 0.001	0.40 ± 0.30 (12300)

Values in parentheses are sample sizes

Table 9 Mean annual stem diameter increment (cm year^{-1} ± 1 SD) of residual trees near (< 20 m) and far (> 20 m) from the closest logging gap for the first eight years after low- (LIL) or high-intensity loggings (HIL) and in unlogged control plots

Species group	Near		Far		Control
	HIL	LIL	HIL	LIL	
Dipterocarp	0.68 ± 0.39	0.56 ± 0.32	0.57 ± 0.37	0.47 ± 0.32	0.36 ± 0.27
	t = 44.9, p < 0.001		t = 21.9, p < 0.001		t = 69.9, p < 0.001
Commercial non-dipterocarp	0.46 ± 0.31	0.35 ± 0.25	0.37 ± 0.26	0.29 ± 0.22	0.21 ± 0.16
	t = 53.4, p < 0.001		t = 26.1, p < 0.001		t = 90.6, p < 0.001
All species	0.50 ± 0.34	0.39 ± 0.28	0.42 ± 0.32	0.33 ± 0.26	0.24 ± 0.22
	t = 217.1, p < 0.001		t = 128.2, p < 0.001		t = 315.6, p < 0.001

that the deleterious impacts of gap proximity are suffered more by trees smaller than those we monitored. In a study of natural gaps in a temperate deciduous forest, Runkle (1991) also failed to find a gap proximity impact on tree mortality rates.

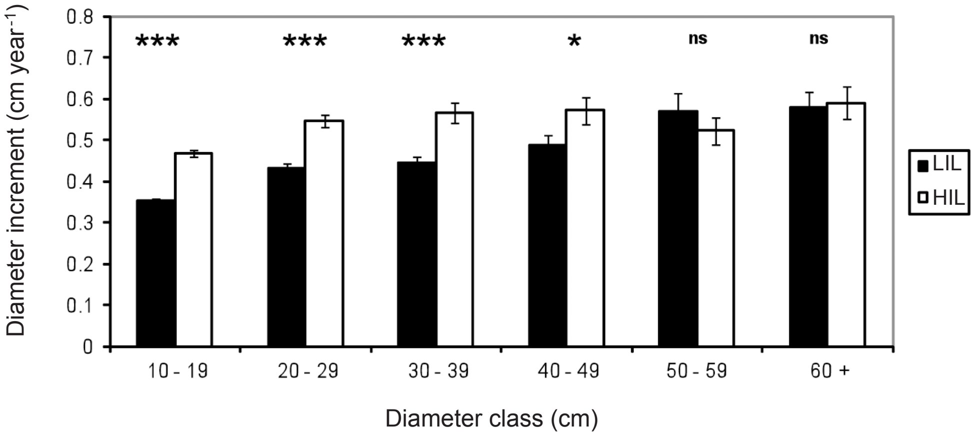
For the first eight years after logging, trees < 20 m from a felling gap grew substantially faster than those further away. This impact was very apparent for dipterocarps < 30 cm dbh, presumably because logging released them from competition from taller neighbours. Being released from belowground competition might also have played a role. The 'release' effect was formerly revealed by silvicultural studies conducted in the region on the impacts of canopy opening on the growth rates of commercial species (Appanah 1998). We concluded from these findings that logging and the silvicultural treatments that follow, as well as simulation models designed to capture post-logging forest dynamics should all take into account the locations of trees in residual stands relative to canopy gaps.

Residual tree growth rates after different intensities of selective logging

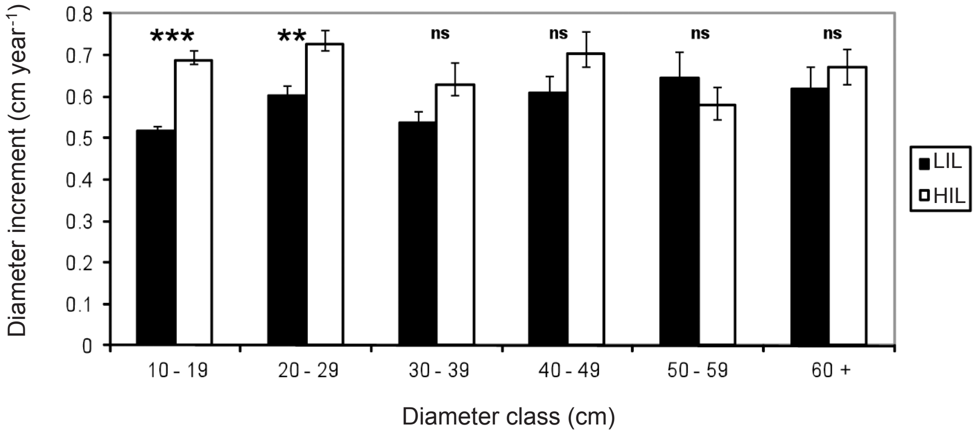
Logging stimulated stem diameter increments for eight years following the selective harvest. Although residual trees in intensively-logged areas had the highest growth rates, they seldom achieved 1 cm year^{-1} for dipterocarps and were much lower for all species combined. The eight-year period of growth stimulation observed was longer than the three-year response Silva et al. (1995) found in the Brazilian Amazon. An increased growth rate over a short period following logging was also reported by Primack et al. (1985) for a forest in Sarawak.

As previously reported (e.g. Ruslandi 2002, Sist & Nguyen-Thé 2002, Priyadi et al. 2006), trees in residual stands grew faster after HIL than after LIL. This effect was especially pronounced for dipterocarp trees < 30 cm dbh that were < 20 m from the nearest felling gap. A major contributor to this response was that HIL resulted in more large gaps near which light levels increased substantially while competition

(a) All species combined



(b) Dipterocarps



(c) Commercial non-dipterocarps

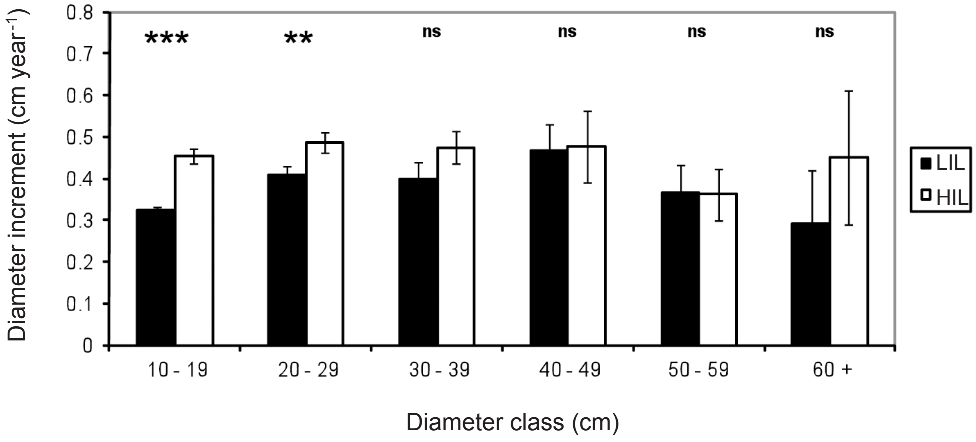
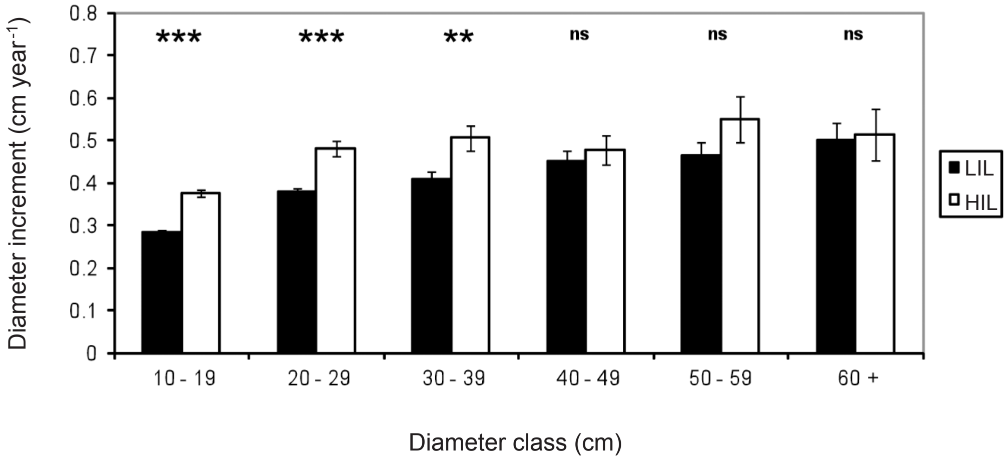
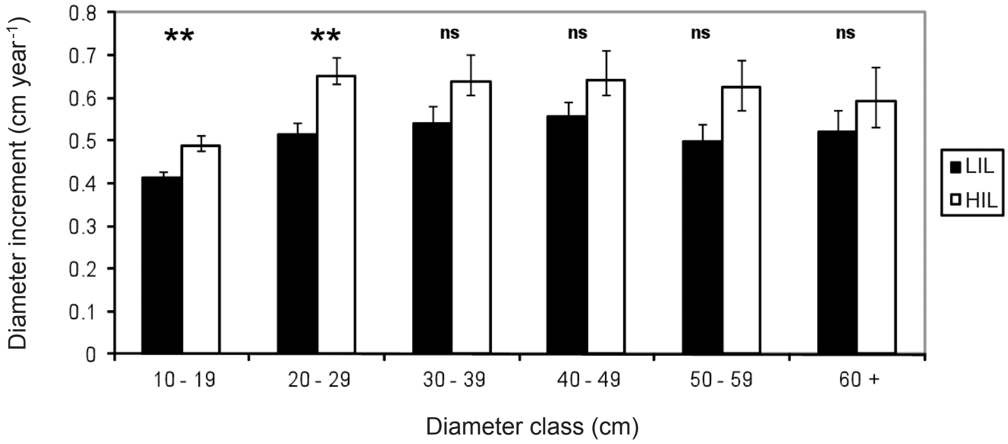


Figure 4 Mean annual diameter increments of trees near (< 20 m) a felling gap for the first eight years after low- and high-intensity selective loggings (LIL and HIL respectively) by diameter class: (a) all species combined, (b) dipterocarps and (c) commercial non-dipterocarps; error bars indicate standard errors, ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, ns = not significant

(a) All species combined



(b) Dipterocarps



(c) Commercial non-dipterocarps

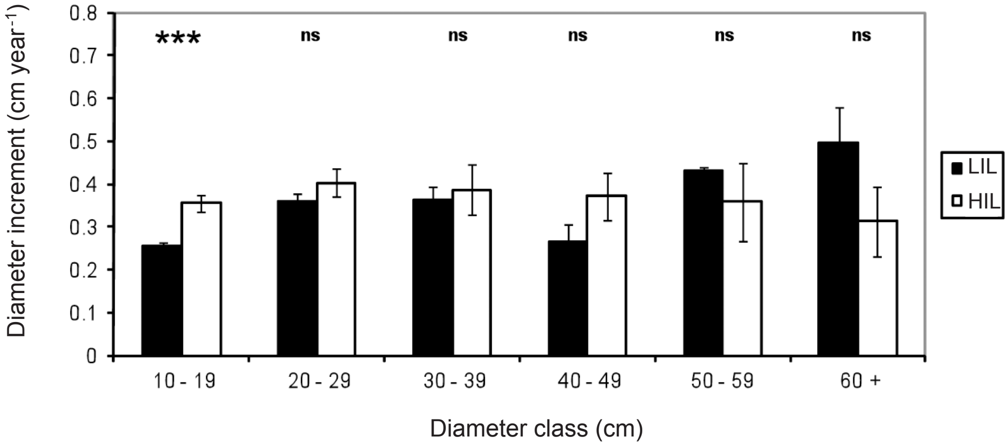
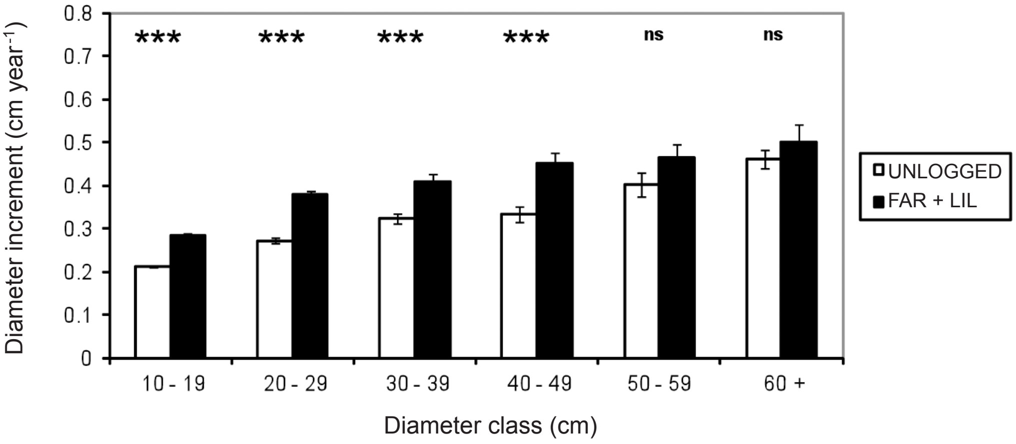
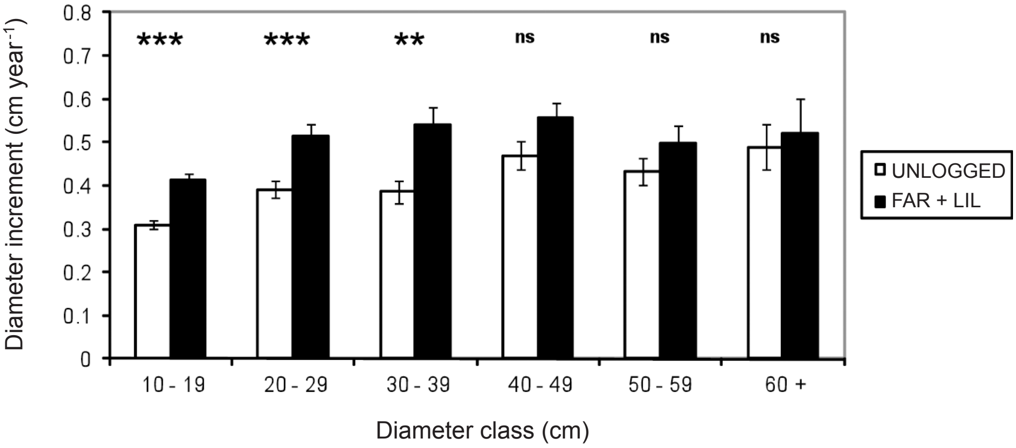


Figure 5 Mean diameter increment of residual trees located far from gaps after two different logging intensities (LIL = low-intersity logging and HIL = high-intersity logging) by diameter class: (a) all species combined, (b) dipterocarps and (c) commercial non-dipterocarps; error bars indicate standard errors, ***p < 0.001, **p < 0.01, *p < 0.05, ns = not significant

(a) All species combined



(b) Dipterocarps



(c) Commercial non-dipterocarps

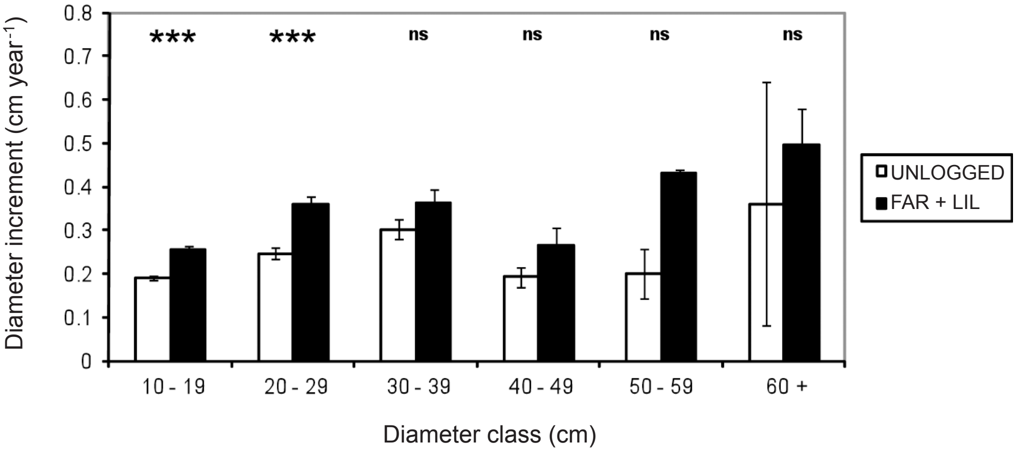


Figure 6 Mean diameter increments of trees in unlogged plots and far (> 20 m) from felling gaps after low-intensity logging (LIL) by diameter class. (a) all species combined, (b) dipterocarps and (c) commercial non-dipterocarps; error bars indicate standard errors, asterisks indicate statistical significance, ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, ns = not significant

for belowground resources declined. If this interpretation is correct, then dipterocarp trees > 10 cm dbh respond differently than the seedlings and saplings that reportedly are most favoured by small-and medium-sized gaps (Tuomela et al. 1996, Clearwater et al. 1999). It is important to recognise, however, that while post-logging growth rates of trees in residual stands after HIL are faster than after LIL, the excessive damage associated with the former results in poorly stocked stands that accumulate commercial timber volumes very slowly, even if the individual trees grow rapidly (Appanah 1998). Furthermore, stands subjected to HIL are very susceptible to infestations of lianas, pioneer trees and other light-demanding weeds (Pinard & Cropper 2000, Sist & Nguyen-Thé 2002).

Do trees far from felling gaps grow faster than trees in unlogged forest?

High-intensity selective logging of tropical forests leaves a matrix of heavily damaged and untouched areas but it is not clear whether the effects of logging extend far beyond the borders of felling gaps. Given that timber yields during the next planned harvest will be provided mostly by growth of trees that are present at the time of the first harvest and not by new recruits, the fate of these trees is of great consequence. We found that selective timber harvesting stimulated the growth of trees in residual stands especially, but not solely those that were near felling gaps in intensively harvested stands. This finding raises the question of whether it is better to cut less so as to retain higher stocking but lower growth rates of residual trees or to cut more, thereby reducing the residual stock but stimulating faster growth of residual trees. Given the increased likelihood and intensity of wildfires in severely disturbed forests, plus the susceptibility of these areas to weed infestations, we suggest that maintaining higher stocking by lowering harvesting intensities is the best approach. Our results also provide indirect support for the application of silvicultural treatments that serve to liberate future crop trees from competition.

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