DYNAMICS OF FOREST REGENERATION FOLLOWING LOGGING MANAGEMENT IN A BORNEAN LOWLAND DIPTEROCARP FOREST

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Stand dynamics were monitored for 10 years after conventional logging (CL), reduced-impact logging (RIL) and RIL followed by enrichment line planting (LP) and annual slashing (S) (RIL + LP/S) in three 1-ha plots in each of the three sites of a lowland dipterocarp forest in Central Kalimantan. All trees with diameter at breast height (DBH) >10 cm and planted *Shorea johorensis* were monitored for survival and growth. Natural recruitment poles of commercial *Shorea* sp. (DBH > 10 cm) were very low in CL site, intermediate in RIL and high (46 ± 29.5 trees ha^{-1}) in RIL + LP/S. Ten years after treatment, 78% of the planted seedlings were still alive. Although LP increased the stock of desirable *Shorea* sp. relative to RIL, the improvement of light conditions caused by strip cutting and slashing significantly promoted natural regeneration. For sustainable forest production, LP/S are appropriate treatments. From a financial perspective, LP is recommended when reintroducing desirable species. Selection of the appropriate silvicultural treatment will depend on the post-logging state of the forest and the relative cost of LP and S.

Keywords: *Shorea*, enrichment planting, line planting, selective logging, reduced impact logging

INTRODUCTION

Destructive logging of lowland dipterocarp forests in Southeast Asia has resulted in large degraded forests with low standing stock of commercial timber trees, in particular *Shorea*, light red meranti wood (Whitmore 1990, Sist et al. 1998, Slik et al. 2003, Ng et al. 2009). To avoid further environmental degradation, reduced-impact logging techniques (RIL) have been widely promoted (Pinard et al. 1996, Bertault & Sist 1997, Lagan et al. 2007, Medjibe & Putz 2012, Putz et al. 2008, Putz et al. 2012, Imai et al. 2012). To further enhance stocking, enrichment line planting (LP) with seedlings of commercial importance along cleared lines, is recommended (Weinland 1998, Schulze 2008, Edwards et al. 2009, Kettle 2010). It is promoted by the Indonesian Ministry of Forestry (MoF) as Tebang Pilih Tanam Jalur (TPTJ) or selective logging and line planting (Sève 1999, Chandrasekharan 2005).

The commercially important *Shorea* sp., traded as meranti timber (e.g., *S. leprosula* and *S. johorensis*), are often used in TPTJ where the seedlings are planted in open strips of selected logged forest due to their light-demanding characteristics (Tuomela et al. 1996, Clearwater et al. 1999, Phillips & Yasman 2002). Liberation thinning is sometimes used to improve the growth of commercial species (Ådjers et al. 1995, Kammesheidt et al. 2003, Romell et al. 2008). Less common than these canopy-focused treatments is the slashing of understory vegetation, other than regeneration of commercial timber trees (Ådjers et al. 1995, Schulze 2008, Sovu et al. 2010). However, success with enrichment planting in tropical forests is varied. Failures are attributed to the neglect of the rules outlined by Dawkins (1960), particularly in tending planted seedlings to prevent overtopping by lianas and other trees (Ådjers et al. 1995, Montagnini et al. 1997, Ashton et al. 2001, Matsune et al. 2006, Sovu et al. 2010). To adequately evaluate the impact of logging and subsequent silvicultural treatments such as line planting and understory slashing (LP/S), long-term monitoring of the growth and survival of planted trees and residual potential crop trees is necessary. In this study, the impacts of conventional logging (CL), RIL and RIL + LP/S on the stocking and growth of commercial timber trees were studied by analysing the dynamics of a lowland dipterocarp forest in Kalimantan, Indonesia for 10 post-logging years. The effectiveness of RIL in mitigating logging impacts and LP/S for regeneration of commercial timber species was assessed, after logging.

MATERIALS AND METHODS

Study area

The study was conducted in a 147,600 ha logging concession of Perseroan Tebatas (PT), Sari Bumi Kusuma (SBK) of a lowland dipterocarp forest in Central Kalimantan, Indonesia (00° 36'–01° 10' S, 111° 39'–112° 25' E) with an elevation of 400–600 m above sea level and a gentle undulating topography. Mean annual precipitation during 2001–2009 was 3240 mm in the concession area with an annual range of 2685–3902 mm. The monitoring plots were located in three management blocks where different treatments were applied (Figure 1). Indonesian forestry regulations are subject to frequent changes (Ruslandi et al. 2014). However, during the course of this study, SBK worked towards a 25-year harvest cycle with a focus on Dipterocarpaceae (e.g., *S. leprosula and S. johorensis*) and other commercial species including dipterocarps (*Shorea* sp., *Hopea* sp., *Dipterocarpus* sp. and *Vatica* sp.). Although some non-dipterocarp tree species [e.g., *Litsea firma* (Lauraceae), *Koompassia malaccensis* (Fabaceae) and *Cratoxylon sumatranum* (Guttiferae)] were also harvested, 50–60% of the timber volume was from light-demanding *Shorea* sp.

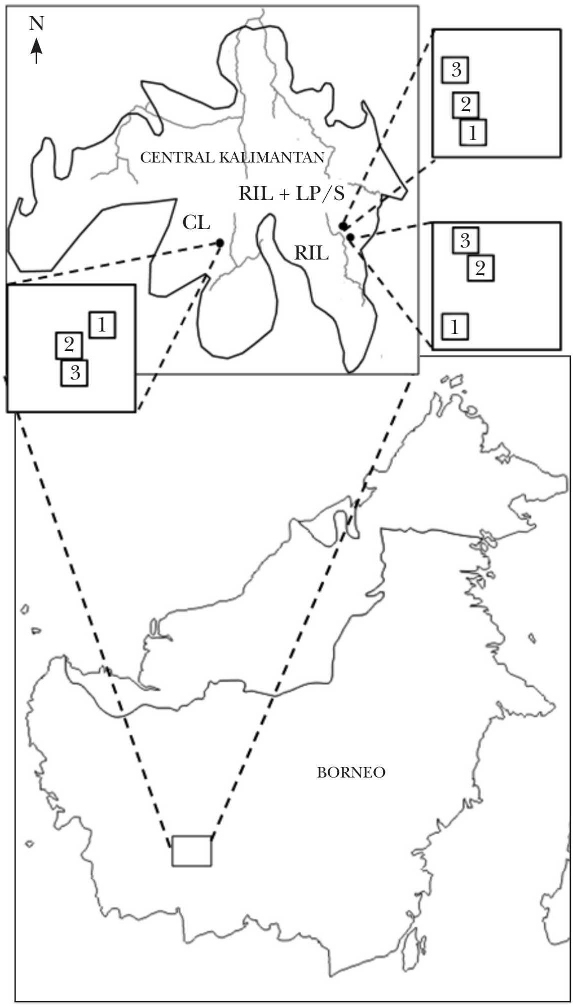

Figure 1 Map of concession area and sites where the study was conducted; in each site subjected to conventional logging (CL), reduced-impact logging (RIL) or RIL followed by line planting and understory slashing (RIL + LP/S), three 200 m × 200 m quadrats were established in which there was a 100 m × 100 m monitoring plot

Experimental treatment

Three 1-ha monitoring plots were established in each of the three logging sites, one subjected to CL and two others to RIL. At one of the RIL sites, nursery-grown *S. johorensis* seedlings were subjected to LP/S, where the seedlings were line planted and all lianas, shrubs, ferns, large herbaceous plants and pioneer tree seedlings were slashed annually. The 100-ha CL site was logged in 1994, with a mean logging intensity of 10.4 trees ha^{-1}, DBH > 50 cm, and a harvest volume of 45.6 m^3 ha^{-1}. The 72-ha RIL and 119-ha RIL + LP/S sites were logged in 2000 at mean logging intensities of 9.1 and 9.3 trees ha^{-1} (44.1 and 45.5 m^3 ha^{-1}), respectively, DBH > 40 cm. RIL was conducted by supervised workers using skid trails, planned after a preliminary inventory. Directional felling and pre-felling cutting of lianas were used to minimise stand damage.

In the RIL + LP/S site, enrichment line planting was conducted with *S. johorensis,* a meranti timber species. This treatment was intended to sustain productivity by promoting the regeneration of desired species. *Shorea johorensis* seedlings, grown in a shaded nursery for 8–10 months, were planted within 6 months of logging. Seedlings were placed at 5 m intervals along parallel 3 m wide clear cut strips oriented north to south at 25 m intervals. All plants rooted within the 3 m wide strips were cut, except for commercial timber species. Trees with crowns overtopping the planting lines, but rooted outside the 3 m strip were not cut. Five planting lines were cut in each of the three 100 m × 100 m monitoring plots at RIL + LP/S sites (Figure 2). Initially, 103, 98 and 105 seedlings were included in the three 1-ha monitoring plots. *Shorea johorensis* is a moderately light-demanding species considered appropriate for LP (Ådjers et al. 1995, Matsune et al. 2006, Phillips & Yasman 2002). The mean basal diameter of *S. johorensis* seedlings at the time of planting was 0.35 ± 0.1 cm. In addition to LP, the entire plots were subjected to an annual slashing

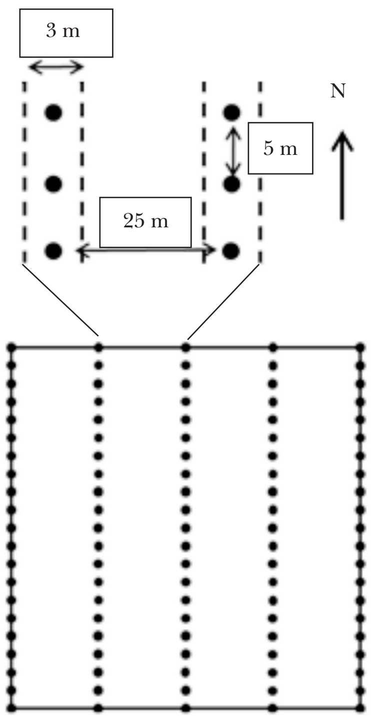

Figure 2 Schematic of line planting treatment and layout of the monitoring plots in reduced impact logging + line planting (RIL + LP/S) treatment site; strip-cutting of 3-m bands was performed along a north to south axis at 25 m spacing intervals; seedlings were planted in a line with 5 m spacing intervals in total, 105 seedlings were planted in this system; filled circles represent planted trees; all lianas pioneer seedlings and understory vegetation were slashed every years after logging

treatment throughout the 10-year monitoring period. In this treatment, pioneer tree seedlings and other understory vegetation were cut with machetes. The slashing treatment in RIL + LP/S plots was unusual, but was undertaken to test regeneration under intensive management. In the normal management of the concession, annual slashing occurs only in 3 m wide strips for three years after planting.

Monitoring of forest structure and pole recruitment

To compare the impact of logging and the subsequent management methods employed in the three experimental sites, post-logging dynamics of trees (DBH ≥ 10 cm) were monitored for 10 years. The first measurements were made 3–6 months after logging in CL plots (in 1994), and RIL and RIL + LP/S plots (in 2000). The second measurement was conducted 1-year later with subsequent measurements made at 2-year intervals (1996–2004 in CL plots and 2002–2010 in RIL and RIL + LP/S plots). During the monitoring period, the girths of all trees, DBH ≥ 10 cm, were measured at the position of a stripe painted at breast height 1.4 m or above the buttress, and newly recruited trees (i.e., trees reaching 10 cm DBH since the previous survey, hereafter termed 'pole recruitment') were marked and measured.

All planted meranti trees were monitored including smaller trees, DBH < 10 cm. Harvesting of these planted trees is expected to take place 25 yrs after planting, and the purpose of monitoring was to gauge their initial survival and growth.

Data analysis

For the analysis of residual trees and natural regeneration, trees were categorised into the following six classes based on commercial value and ecological function (Phillips & Yasman 2002). The dipterocarps were separated into three subgroups: commercially important light-demanding *Shorea* sp. (meranti), other commercial dipterocarps (not meranti) and non-commercial dipterocarps (other dips). In the monitoring plots, *S. leprosula* and *S. johorensis* were recorded as meranti, while less light-demanding *Shorea* sp. were included in the not meranti group. Planted meranti trees were always analysed separately from the meranti group, pioneer species were *Macaranga* sp. and *Anthocephalus chinensis*. Other tree species were separated into two subgroups: commercial (other commercial) and non-commercial (other), excluding dipterocarps and pioneers. Post-logging pole recruitment (DBH = 10 cm), stand growth based on tree density and cumulative basal area were recorded for all six groups.

Mortality rate of trees during the first census was calculated as:

$$m = 1 - (1 - (n_0 - n_1) / n_0) 1 / y$$

where m = annual mortality rate between two consecutive censuses, n = population of trees recorded, n_0 = first census, n_1 = second census and y = number of years between the two censuses (Sheil et al. 1995).

Relative growth rates (RGRs) were calculated according to Hunt (1990):

$$RGR = [\ln(d_0) - \ln(d_1)] / y$$

where RGR = annual relative growth rate, d_0 and d_1 = DBH measured during two consecutive censuses and y = number of years between the two measurements. To evaluate the impact of different treatments, mortality rate and RGR were calculated for trees with DBH ≥ 10 cm during the first census after logging (i.e., new recruits were not included). Although the three 1-ha plots in each treatment area were technically pseudo-replicate (Hurlbert 1984), mortality and growth rates we compared among the three treatments using a one-way ANOVA when the normality assumption was met, or the nonparametric Kruskal–Wallis test. Tukey's test or

Table 1 Stand parameters for trees with DBH ≥10 cm, 3–6 months after logging and 10 years later at sites subjected to conventional logging (CL), reduced-impact logging (RIL) or RIL followed by line planting and annual understory slashing (RIL + LP/S)

Treatment	Species group	Mean tree density (m^2 ha^{-1})		Mean basal area (m^2 ha^{-1})	
		Year of logging	10 years later	Year of logging	10 years later
CL	Meranti	17.0 ± 11.8	18.7 ± 6.4	2.9 ± 1.8	2.2 ± 1.6
	Not meranti	27.3 ± 24.8	30.3 ± 25.7	1.7 ± 1.0	2.1 ± 1.3
	Other dips	15.3 ± 3.5	16.0 ± 5.2	2.5 ± 0.8	2.8 ± 0.8
	Commercial	52.3 ± 3.8	61.7 ± 5.9	3.2 ± 0.4	3.8 ± 0.9
	Pioneer	2.7 ± 2.3	41.7 ± 14.0	0.0 ± 0.0	1.2 ± 0.4
	Other	215.0 ± 56.7	248.0 ± 29.8	14.7 ± 6.3	14.8 ± 3.5
	Total	329.7 ± 78.1	416.7 ± 74.0	25.1 ± 3.1	26.9 ± 2.8
RIL	Meranti	6.3 ± 2.1	12.7 ± 8.0	1.3 ± 0.7	1.3 ± 0.7
	Not meranti	39.3 ± 21.2	46.7 ± 25.4	4.5 ± 3.6	5.1 ± 3.2
	Other dips	11.7 ± 3.2	13.3 ± 6.7	0.7 ± 0.6	0.6 ± 0.2
	Commercial	65.3 ± 12.7	78.0 ± 10.5	2.8 ± 0.4	3.8 ± 0.2
	Pioneer	18.0 ± 20.3	16.0 ± 9.5	0.3 ± 0.3	0.8 ± 0.6
	Other	153.7 ± 16.6	187.7 ± 24.8	8.3 ± 2.6	11.2 ± 2.7
	Total	294.3 ± 16.3	354.3 ± 52.5	18.0 ± 0.1	22.8 ± 0.3
RIL + LP/S	Meranti	9.7 ± 8.1	54.7 ± 24.8	0.9 ± 0.8	1.9 ± 0.2
	Not meranti	54.7 ± 14.3	67.3 ± 8.1	5.7 ± 3.3	6.8 ± 2.8
	Other dips	5.3 ± 1.5	10.3 ± 5.7	0.5 ± 0.3	0.9 ± 0.4
	Commercial	71.7 ± 5.9	80.3 ± 6.0	3.2 ± 0.4	4.3 ± 0.5
	Pioneer	11.7 ± 12.4	10.3 ± 9.3	0.2 ± 0.2	0.6 ± 0.5
	Other	1.8 ± 7.9	137.7 ± 14.7	5.6 ± 0.2	7.6 ± 0.9
	Total	258.0 ± 1.0	360.7 ± 36.5	16.0 ± 3.0	22.0 ± 2.4
	Including planted trees		432.0 ± 35.0		23.5 ± 2.5

Values are means ± SD in 1 ha plots, n = 3 per treatment; RIL + LP/S did not include planted trees; meranti = commercailly important light demanding *Shorea leprosula* and *S. johorensis,* not meranti = commercial dipterocarps other than meranti species, other dips = other non-commercial dipterocaros, commercial = commercial species other than dipterocarps, pioneer = principally *Macaranga* spp. and *Anthocephalus chinensis,* other = all the non-commercial species other than dipterocarps and pioneers the nonparametric Steel–Dwass test were used for post-hoc multiple comparisons. A p-value < 0.05 was considered to be significant.

RESULTS

Changes in stand conditions and species composition

Tree density and the cumulative basal area of trees with DBH ≥ 10 cm increased in all three treatments (Table 1). Both tree density and basal area were lowest in RIL + LP/S plots and highest in CL plots, shortly after treatment. The mean post-logging cumulative basal area in CL plots was greater than in the other two treatments. After 10 years, stocks were marginally higher in RIL + LP/S plots, with no statistical difference among the three treatments. Although the planted trees contributed to the stock of desirable *Shorea* sp., stand stocks were still lower in all three treatments than the primary forest in the concession (536 trees ha^{-1} and 32.1 m^2 ha^{-1}).

Plots subjected to the three treatments differed in species composition 10 years after logging. At the CL site, pioneer species increased from 2.7 ± 2.3 trees ha^{-1} to 41.7 ± 14 trees ha^{-1}. At the end of the 10-year monitoring period, the density of pioneers at CL site was statistically higher than RIL + LP/S, but did not differ from RIL site. At RIL site, pioneer trees were most abundant in the year after logging (18 ± 20.3 trees ha^{-1}) but their abundance varied greatly (0, 14 and 40 per plot). Natural disturbance prior to logging explains the high initial pioneer density at RIL plot. Unlike CL site, pioneer tree density at RIL site decreased to 16 ± 9.5 trees ha^{-1} and meranti group trees increased from 6.3 ± 2.1 trees ha^{-1} to 12.7 ± 8 trees ha^{-1} within 10 years after logging. The greatest increase in natural (i.e., not planted) meranti tree density over 10 years was observed at the RIL + LP/S site, where density increased from 9.7 ± 8.1 to 54.7 ± 24.8 trees ha^{-1}, excluding planted trees. The density increase in not meranti and commercial groups did not differ among the three treatments.

Mortality of residual trees

Temporal patterns in the mortality rate differed among the three sites (Table 2). The impact of logging was most obvious at CL site, where mortality rate during the initial monitoring period (1994–1995) exceeded 3% and decreased steadily over the subsequent 9 years. In the RIL and RIL + LP/S plots, mortality was low for the first 4 years, increased 4-6 years after treatment, and then decreased again. Over the entire 10-year monitoring period, there was no difference in average mortality rates among the three treatments.

Pole recruitment

The mean cumulative pole recruitment of trees (i.e., the number of trees that reached 10 cm DBH before each survey) over 10 years in CL, RIL and RIL + LP/S plots were 178.3 ± 17.7, 117.7 ± 38.6 and 159.7 ± 33.1 trees ha^{-1}, respectively. The Steel-Dwass test indicated no difference among the three treatments (Table 3). Planted trees in the RIL + LP/S plot were excluded from analysis. Changes in species composition showed that the recruitment dynamics of meranti and pioneer groups differed among treatments. Greater pioneer recruitment was observed in CL plots (62 ± 18.4 trees ha^{-1}) than the other two treatments. Over the 10-year observation period, peaks in pioneer recruitment in CL plots were observed 2–4 and 6–8 years after logging. Pioneer recruitment in RIL and RIL + LP/S plots were quite low, 10.7 ± 4 and 2.7 ± 2.1 trees ha^{-1},

Table 2 Mean annual mortality rate (%) for all residual trees with DBH ≥10 cm during each post-logging monitoring period by treatment, conventional logging (CL), reduced-impact logging (RIL) or RIL followed by line planting and understory slashing (RIL + LP/S)

Treatment	Monitoring period (year)						
	0–1	1–2	2–4	4–6	6–8	8–10	Average
CL	3.7 ± 1.2	2.9 ± 3.5	2.6 ± 0.7	1.5 ± 0.9	1.3 ± 1.1	1.5 ± 0.8	2.1 ± 0.3
RIL	1.8 ± 0.9	2.1 ± 1.0	0.7 ± 0.3	3.4 ± 1.0	1.7 ± 0.7	1.2 ± 0.6	1.8 ± 0.1
RIL + LP/S	1.6 ± 0.0	2.9 ± 0.2	0.7 ± 0.5	4.4 ± 1.1	1.5 ± 1.0	1.5 ± 0.3	2.1 ± 0.0

Values are means ± SD in 1-ha plots, n = 3 per treatment

Table 3 Pole-recruitment (number of trees attaining 10 cm DBH) during each post-logging monitoring period at sites subjected to three treatments, conventional logging (CL), reduced-impact logging (RIL) or RIL followed by line planting and understory slashing (RIL + LP/S)

Treatment	Species group	Monitoring period (year)						Cumulative
		0–1	1–2	2–4	4–6	6–8	8–10	
CL	Meranti	0.7 ± 1.2	0.7 ± 1.2	0.3 ± 0.6	1.0 ± 1.7	0.7 ± 1.2	1.3 ± 1.2	4.7 ± 4.6
	Not meranti	1.7 ± 2.1	3.0 ± 3.5	0.3 ± 0.6	1.3 ± 1.2	0.7 ± 0.6	0.3 ± 0.6	7.3 ± 5.1
	Other dips	0	1.0 ± 1.0	0.3 ± 0.6	0	0.7 ± 0.6	0.3 ± 0.6	2.3 ± 1.5
	Commercial	2.0 ± 1.0	8.0 ± 5.3	2.7 ± 0.6	2.3 ± 1.2	2.0 ± 1.0	1.3 ± 1.5	18.3 ± 8.1
	Pioneer	0	19.7 ± 9.9	16.0 ± 6.6	0.7 ± 0.6	25.7 ± 14.4	0	62.0 ± 18.4
	Other	10.7 ± 8.6	34.3 ± 1.7	8.3 ± 2.1	3.3 ± 2.5	12.7 ± 6.0	14.3 ± 6.8	83.7 ± 27.2
	Total	15.0 ± 8.5	66.7 ± 10.3	28.0 ± 4.6	8.7 ± 0.6	42.3 ± 22.7	17.7 ± 9.0	178.3 ± 17.7
RIL	Meranti	0.3 ± 0.6	0	0.7 ± 1.2	1.0 ± 1.0	3.7 ± 1.2	1.7 ± 2.9	7.3 ± 5.1
	Not meranti	1.3 ± 1.5	1.7 ± 2.9	1.3 ± 0.6	3 ± 2.6	6.0 ± 6.6	1.0 ± 1.0	14.3 ± 12.7
	Other dips	1.0 ± 1.7	0	0.7 ± 0.6	0.3 ± 0.6	1.3 ± 1.5	1.0 ± 1.0	4.3 ± 3.8
	Commercial	3.7 ± 2.1	3.3 ± 0.6	4.7 ± 1.5	3.3 ± 2.0	7.0 ± 4.4	2.0 ± 1.0	24.0 ± 4.6
	Pioneer	1.3 ± 1.5	4.3 ± 3.1	4.3 ± 3.1	0	0.3 ± 0.6	0.3 ± 0.6	10.7 ± 4.0
	Other	11.0 ± 6.1	4.7 ± 1.5	4.3 ± 4.2	7.0 ± 1.0	25.7 ± 6.1	4.3 ± 1.5	57.0 ± 13.9
	Total	18.7 ± 8.1	14.0 ± 2.6	16.0 ± 9.2	14.7 ± 3.8	44.0 ± 16.4	10.3 ± 1.5	117.7 ± 38.6
RIL + LP/S	Meranti	0.7 ± 0.6	0.3 ± 0.6	0.7 ± 0.6	10.7 ± 5.5	24.3 ± 17.4	9.3 ± 7.6	46.0 ± 29.5
	Not meranti	1.7 ± 1.5	3.3 ± 1.5	4.7 ± 2.5	5.7 ± 102.0	12.3 ± 9.7	2.0 ± 1.0	29.7 ± 9.5
	Other dips	1.0 ± 1.7	0.3 ± 0.6	0.3 ± 0.6	0	2.7 ± 2.5	1.0 ± 1.7	5.3 ± 4.6
	Commercial	4.7 ± 2.3	2.4 ± 0.6	4.0 ± 1.0	3.7 ± 2.9	6.0 ± 3.6	1.3 ± 1.5	22.3 ± 6.0
	Pioneer	1.3 ± 0.6	0.7 ± 1.2	0.3 ± 0.6	0	0	0.3 ± 0.6	2.7 ± 2.1
	Other	12.3 ± 3.1	2.3 ± 1.5	4.7 ± 3.5	8.0 ± 4.0	23.0 ± 2.6	3.3 ± 2.1	53.7 ± 3.2
	Total	21.7 ± 1.5	9.7 ± 4.6	14.7 ± 5.5	28.0 ± 6.9	68.3 ± 27.2	17.3 ± 7.1	159.7 ± 33.1

Values are mean recruit densities ± SD in 1 ha plots, n = 3 per treatment; meranti = light demanding *Shorea leprosula* and *S. johorensis,* not meranti = commercial dipterocarps other than meranti species, other dips = other non- commercial dipterocaros, commercial = commercial species other than dipterocarps, pioneer = *Macaranga* genus species and *Anthocephalus chinensis*, other = other non-commercail species other than dipterocarps and pioneers

respectively. In contrast, meranti species recruited poorly in CL plots, i.e. only 4.7 ± 4.6 trees ha^{-1} with 10 cm DBH over 10 years. Meranti recruitment was also poor in RIL plots with only 7.3 ± 5.1 trees ha^{-1} over 10 years. The greatest natural recruitment of meranti was observed in RIL + LP/S plots. The cumulative recruitment of meranti trees was 46 ± 29.5 trees ha^{-1}. The best recruitment occurred 6–8 years after logging at RIL and RIL + LP/S plots (3.7 ± 1.2 and 24.3 ± 17.4 trees ha^{-1}, respectively) (Table 3). In the RIL + LP/S treatments, the density of natural recruitment into the 10 cm DBH class varied widely among the three plots. Cumulative recruitment of meranti trees over 10 years were 31, 27 and 80 trees ha^{-1}.

The impacts of logging on residual tree growth

The lowest mean RGR of residual trees over the 10 years was found in CL plots (Figure 3). Growth was better in RIL plots, and the difference was significant 1 year after logging. In the RIL + LP/S plots, RGRs were higher than RIL plots. Over 10 years, residual tree growth was generally lowest in CL plots and highest in RIL + LP/S plots. However, tree growth rates decreased 2–4 years after logging at all sites. Comparing size classes (Figure 4), logging effects on RGR were greater on smaller trees (DBH < 30 cm), which also had higher RGRs than larger trees.

Survival and growth of planted *Shorea johorensis*

In RIL + LP/S plots, the survival rate of planted trees over the first 10 years was 78.2 ± 6.7%. Average DBH values in the three plots were 15.7 ± 5.5, 14.8 ± 3.6 and 15.7 ± 4.6 cm, but individual tree sizes varied widely (DBH = 5.1–30.8 cm) among the 214 trees measured, 10 years after planting. Only two trees reached 30 cm DBH within 10 years.

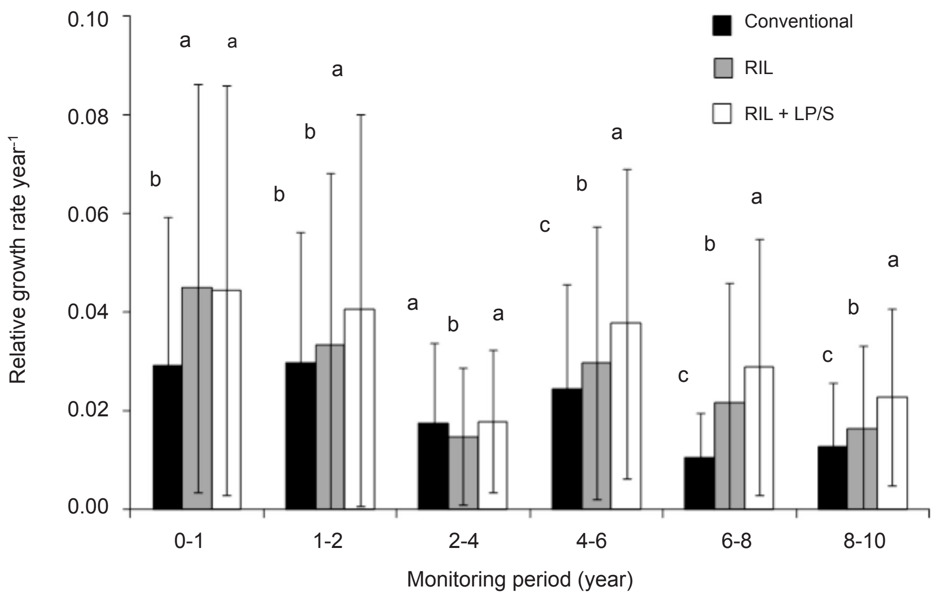

Figure 3 Relative growth rates (RGRs) for DBH of residual trees (DBH ≥ 10 cm) during each monitoring period at sites subjected to three different treatments; values are means ± SE; different lowercase letters above the bars indicate significant differences (one-way analysis of variance followed by a multiple comparisons test, $p < 0.05$); RIL = reduced-impact logging, RIL + LP/S = line planting + annual slashing after RIL

Size distribution of meranti trees

Ten years after logging, the density of harvestable commercial dipterocarps (i.e., trees with DBH > 40 cm) was indistinguishable among the three treatments, with 5 ± 4.6, 1.7 ± 1.2 and 2.3 ± 0.6 trees ha^{-1} in CL, RIL and RIL + LP/S sites, respectively (Table 4, Figure 5). These numbers were lower than the number of trees removed during the initial harvest (9–10 trees ha^{-1}). The abundance of potentially harvestable meranti trees (DBH = 10–40 cm) in the CL plots increased only from 11.3 ± 6.1 to 13.7 ± 2.5 trees ha^{-1}. In contrast, these potential crop trees increased from 4.7 ± 2.5 to 11 ± 7 trees ha^{-1} in the RIL plots. The highest number of potential crop trees was found in the RIL + LP/S plots where their density increased from 8 ± 6.1 to 52.3 ± 25 trees ha^{-1}. Planted *S. johorensis* in the RIL + LP/S plots further increased the density of meranti trees in the logged forest. In the RIL + LP/S plots, 75, 84 and 80 planted trees (66, 77 and 71 trees with DBH > 10 cm) survived. Including planted trees, the density of potential crop trees increased to 106.2 ± 25.9 trees ha^{-1}, 10 years after treatment. The abundance of natural recruits varied widely among the three plots (31, 27 and 80 trees ha^{-1}) within the RIL + LP/S site, but the among-plot variation was smaller for planted trees.

DISCUSSION

The effects of RIL on post-logging stand dynamics

Although the volumes harvested from the CL, RIL and RIL + LP/S plots were moderate (Sist and Nguyen-Thé 2002), the densities and basal areas of trees with DBH ≥ 10 cm were still low, 10 years after treatment (Table 1). Differences were noted in species composition and pole recruitment rates among the three treatments over 10 years. The differences were significant for meranti species and pioneer species, which are both light-demanding groups. In CL plots, pioneer tree densities increased dramatically 1–2 years after logging (Table 3). However, in the RIL plots pioneer recruitment was low, indicating that logging impacts were diminished as intended, as reported in previous studies (Pereira et al. 2002, Lagan et al. 2007, Imai et al. 2012). Pioneer recruitment was further suppressed by intensive annual slashing in the RIL + LP/S plots. Meranti tree recruitment into the DBH ≥10 cm class peaked 6–8 years after logging in RIL and RIL + LP/S plots. This recruitment peak was not observed in CL plots, presumably due to canopy closure by pioneer species (Slik & Eichhorn 2003, Romell et al. 2008).

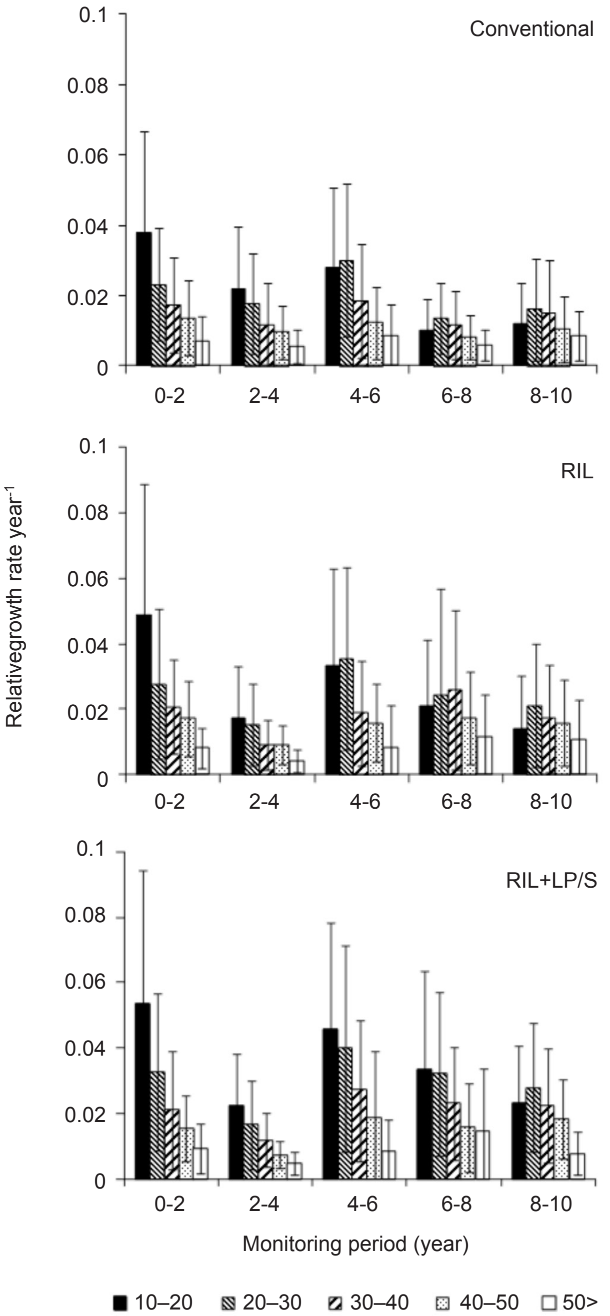

Figure 4 Relative growth rates (RGRs) for DBH of residual trees (each ≥10 cm DBH) by size class at each treatment site; bar shading indicates size classes, which are keyed beneath the lowermost horizontal axis; RIL = reduced-impact logging, RIL + LP/S = line planting + annual slashing after RIL

During the first year after logging, annual mortality rates exceeded 3% in CL plots but were lower in the RIL and RIL + LP/S plots, which indicated that RIL achieved its goal of reducing damage to residual trees. Surprisingly, mortality rate over the 10-year observation period did not differ among treatments.

Growth rate of residual trees were higher in RIL + LP/S plots than other treatments. The rate was lowest in CL site for most of the 10-year monitoring period. In RIL and RIL + LP/S plots, residual tree growth is promoted by the reduction of logging damage to trees (Fredericksen and Putz 2003). This effect was particularly notable in RIL + LP/S plots, subjected to strip cutting and slashing. Canopy opening and the removal of competitors apparently promoted crop tree growth, especially in small trees. The canopy of lowland dipterocarp forest has a multilayered structure (Romell & Karlsson 2009), with smaller trees located in the lower canopy. Harvesting of trees from the upper canopy changes the light conditions and stimulates growth of smaller trees (Peña-Claros et al. 2008).

In the RIL and RIL + LP/S plots, growth and mortality rates of residual trees during the period 2–4 years after logging were relatively low, and increased 4–6 years after logging. This change in growth rate could be explained by the shift in resource allocation away from branch extension to trunk diameter growth. Trees expand their branches initially to better intercept sunlight and to compete with neighboring trees for incoming radiation. This investment in branch expansion can affect trunk growth (Wadsworth & Zweede 2006), and promot high growth rates in superior competitors at the expense of weaker individuals, which dies 4–6 years after logging. Conventional unplanned logging killed and injured trees, whereas after RIL, mortality seemed more related to density effects and competition. This is supported by the observation that mortality rate did not change over the 10-year monitoring period. These findings emphasise the importance of long-term observation in RIL methods.

Regeneration of desirable *Shorea* sp. under intensive management

Inhibition of meranti regeneration by pioneer species was not apparent in RIL plots, but obvious in CL (Table 3). However, the density and pole recruitment of meranti trees were not higher at RIL site. In contrast, natural regeneration of trees with at least 10 cm DBH after logging was greatest in RIL + LP/S plots, where recruits of meranti trees (*S. leprosula* and *S. johorensis*) to pole size were particularly abundant. The light-demanding seedlings of *Shorea* sp. recruit best under a partially-open canopy (Tuomela et al.

Table 4 Number of naturally recruited (i.e., not planted) stems of meranti, commercial *Shorea* sp. (*S. leprosula* and *S. johorensis*) in three treatments immediately after logging operations (1994 in CL and 2000 in RIL and RIL + LP/S site) and 10 years later (2004 in CL and 2010 in RIL and RIL + LP/S site)

DBH class (cm)	Logging year			10 years after logging		
	CL	RIL	RIL + LP/S	CL	RIL	RIL + LP/S
10-20	6.3 ± 1.2	2.3 ± 1.5	5.0 ± 5.3	5.3 ± 3.2	7.3 ± 4.5	42 ± 22.5
20-30	2.0 ± 2.6	1.3 ± 1.5	2.7 ± 2.1	3.7 ± 1.2	1.3 ± 1.2	7.7 ± 3.5
30-40	3.0 ± 2.6	1.0 ± 1.7	0.3 ± 0.6	4.7 ± 2.5	2.3 ± 1.5	2.7 ± 0.6
40 >	5.7 ± 5.7	1.7 ± 0.6	1.7 ± 2.1	5.0 ± 4.6	1.7 ± 1.2	2.3 ± 0.6

Values are mean ± SD in 1 ha plots, n = 3 per treatment

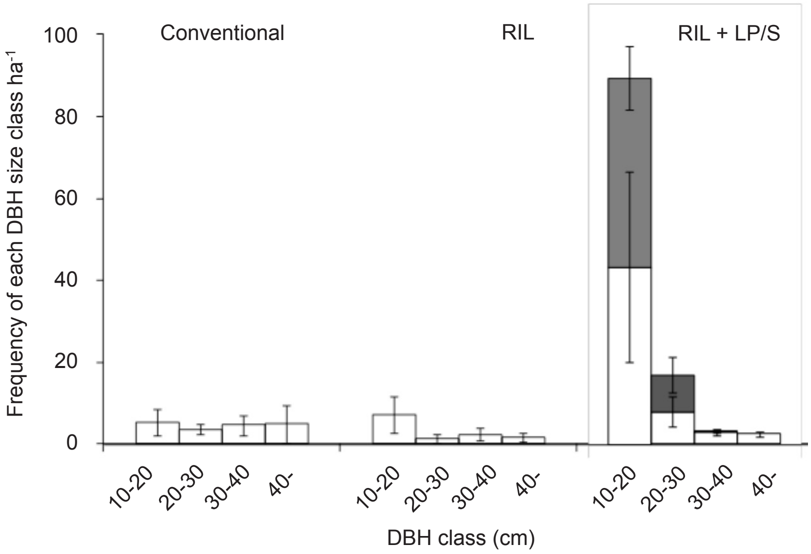

Figure 5 Frequency distributions of DBH for meranti trees in each of the three treatment sites 10 years after planting; RIL = reduced-impact logging; bar shading in the line planting + annual slashing after reduced-impact logging (RIL + LP/S) treatment site indicates the planted *Shorea johorensis;* values are means ± SD (n = 3)

1996, Tennakoon et al. 2005). The effect of RIL on the regeneration of light-demanding *Shorea* sp. is controversial (Fredericksen & Putz. 2003, Sist & Brown 2004). Substantial canopy opening is required for growth and it can be suppressed under RIL. Compared to the canopy opening created by logging, strip cutting provided a more linear opening. The cumulative sunfleck duration in the strip-cutting line was significantly shorter than in canopy gaps, created by logging and skidding with the same canopy openness (Inada et al. 2013). This may be a factor in the pole regeneration of meranti species in RIL + LP/S plots.

Mother tree density in the plots may also affect the natural regeneration of commercial *Shorea* sp. As the minimum size for cutting in RIL and RIL + LP/L plots was DBH = 40 cm, the residual commercial *Shorea* with 40 cm DBH or over was lowest in these two plots (Table 4). Thus, mother tree density was not a primary factor in controlling the natural regeneration of commercial *Shorea* sp. Pole recruitment of commercial *Shorea* seems to come from suppressed saplings that existed before logging, based on the growth of planted *Shorea* seedlings and the fact that pole recruitment in RIL + LP/S plots peaked 6 years after logging (Table 3). If so, sapling density will be the controlling factor for pole recruitment. Unfortunately, the sapling (DBH < 10 cm) density after logging is not available. The density of commercial *Shorea* trees with DBH 10–20 cm in the year of logging was highest in CL plots (Table 4), suggesting that sapling density was the main factor controlling the pole recruitment rate.

For planted *S. johorensis*, the enhancement of light conditions by liberation from neighboring trees and removal of competitors (e.g., shrubs and lianas) improved growth (Ådjers et al. 1995). The greater light availability created by RIL plus strip-cutting was likely a factor that promoted meranti recruitment. Removal of competitors by slashing was also likely to have enhanced natural recruitment and the growth of planted *S. johorensis* (Wadsworth & Zweede 2006, Schulze 2008, Keefe et al. 2009, Pamoengkas et al. 2014). Overall, many desirable *Shorea* seedlings were recruited under intensive management by strip-cutting and slashing. A large difference was noted in the number of recruits among the three RIL + LP/S plots, suggesting that regeneration of desirable species is dependent on the abundance of mother trees and the size of the seedling bank at the time of treatment (Sovu et al. 2010).

Effectiveness of line planting for sustainable management

Planted *Shorea* trees survived well and grew rapidly over the 10 years of observation in RIL + LP/S plots. Mortality rates were generally low among faster-growing individuals in favorable locations (Ong & Kleine 1995). Planted *S. johorensis* had markedly higher survival rates compared to those previously reported for wild *S. johorensis* seedlings transplanted post-logging, 55–72.5%, 2-years after planting (Ådjers et al. 1995) and 38–64.6% 3-years after planting (Matsune et al. 2006). Although the canopy openness varied gradually along the planting lines (Inada et al. 2013), the seedlings exhibited a wide adaptability to different light conditions (Brown 1996, Clearwater et al. 1999). Removing competitors by slashing contributed to the high survival rate within the10 years. Line-planted trees grew well and were likely to survive and contribute to the next harvest, 15 years after the last measurement. Thus, the LP treatment was effective in promoting commercial *Shorea* stocks and contributed towards increasing the sustainability of forest management. However, monitoring over the entire rotation period of 25 years is necessary to reach a definitive conclusion.

The total density and basal area of trees > 10 cm DBH (including planted and unplanted trees) in the RIL + LP/S plots reached 432 ± 35 ha^{-1} and 23.5 ± 2.5 m^2 ha^{-1}, respectively, after 10 years (Table 1). As the RIL + LP/S plots started with the lowest tree density and basal area among the three treatments, the recovery of forest in these plots was also the greatest. Thus, we can conclude that an intensive treatment, such as LP, is effective in promoting ecosystem recovery after logging.

Prospects for sustainable timber yield under the three management options

Compared to primary forests in the region (Manokaran and Kochummen 1987, Ong and Kleine 1995), the three sites in our study had higher RGRs but similar mortality rate, 8–10 years after logging. Residual trees recovered from logging damage, while forest dynamics due to large disturbances influenced seedling recruitment (Denslow 1987, Shugart 1984). Thus, monitoring pole recruitment dynamics for 10 years after logging produced information of great value to forest managers. Reduced-impact logging stimulated pole size (DBH > 10 cm) recruitment of meranti species, peaking 6–8 years after logging. The increased light effect that had stimulated recruitment in the immediate aftermath of logging, gradually diminished and disappeared.

The recruitment of commercially desirable *Shorea* sp. can be poor in primary forest (Manokaran & Kochummen 1987, Ong & Kleine 1995). Natural recruitment without augmentation, such as slashing and line planting in RIL + LP/S plots, would not permit the development of sustainable timber yields within the 25-year logging cycle planned. The results of the 10-year monitoring program suggested that a longer logging cycle is necessary, as recommended by previous studies (Huth and Ditzer 2001, Sist et al. 2003). In lowland dipterocarp stands, untended natural regeneration after logging, even RIL, will not be adequate for sustainable timber yields with cutting cycles less than 40–50 years. Based on the abundant natural regeneration of commercial species in RIL + LP/S plots, such a treatment will be sufficient to sustain timber yield. Enrichment line planting is an efficient method for reintroducing desirable species into logged forest, as suggested in previous studies (Ådjers et al. 1995, Montagnini et al. 1997, Ashton et al. 2001, Paquette et al. 2006, Sovu et al. 2010). However, the high cost of establishment and tending will reduce net income (Lamb 1969, Hartshorn 1995, Appanah & Weinland 1996, Putz 2004, Ruslandi et al. 2014), and financial incentives can lead to the forest being dominated by a few fast-growing desirable trees (Schulze 2008, Putz & Redford 2009). The natural regeneration of desirable species was insufficient without post-logging silvicultural treatment. Slashing and line planting treatments are practical means to increase post-logging stock. These two treatments differed in their dependence on the logged forest as a source of tree recruitment. The regeneration of desirable species is promoted by tending if there are abundant residual mother trees and a strong seedling bank, otherwise enrichment planting is recommended (Schwartz et al. 2013). For post-logging management, slashing is effective with a lower cost than line planting. The intrusive and expensive nature of LP makes it less practical, but preferable for high yields of *Shorea* sp. When RIL harvesting is used, a preliminary inventory of harvestable trees and potential crop trees is conducted. This inventory would be useful for deciding whether LP is advisable.

CONCLUSIONS

Poor growth, low recruitment of commercial timber species and pioneer invasion in CL plots led to considerable degradation of the forest ecosystem and low potential for sustainable timber yields. In contrast, RIL effectively reduced damage from logging. However, 10 years of subsequent monitoring revealed that this treatment alone is not sufficient to sustain timber yields, unless the harvest cycle is extended beyond 25 years. In contrast, RIL plus post-logging silvicultural treatments led to successful regeneration of commercial timber tree species. The improvement in light conditions caused by opening strips in the canopy and slashing non-commercial understory species and lianas, served to increase both the stock and growth of commercial species. Line planting of *S. johorensis* seedlings and subsequent tending further increased stocks to very high levels. However, from a cost perspective, promoting natural regeneration by slashing was preferred to LP.

Overall, the analysis of post-logging dynamics over10 years suggested that RIL combined with stand-tending operations, to promote natural regeneration, is a cost-effective way to sustain yields. Although enrichment LP was an effective way to reintroduce the meranti trees to a degraded forest, it should be used with caution due to the high cost and unnecessary loss of stand structure and diversity.

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