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Tropical Forests Stand Recovery 30-year After Selectively Logged in Peninsular Malaysia

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ABSTRACT

This article analysed the 25–30 years of growth of dipterocarps forests that were logged under the Selective Management System (SMS) at three sites in Peninsular Malaysia to understand how management regimes affected forest stem density and basal area. The management regimes were (1) unlogged, (2) moderately logged forests that logged all dipterocarps ≥ 65 cm diameter at breast height (dbh) and all non-dipterocarps ≥ 60 cm dbh, and (3) intensely logged forests that logged all dipterocarps ≥ 50 cm dbh and non-dipterocarps ≥ 45 cm dbh. The intensely logged regime is similar to the SMS practices in Peninsular Malaysia. This result showed that one-year post-logging, there was no difference in the total stem density and basal area between forests logged according to the two management regimes. Forest stem density decreased over time in all management regimes, significantly greater in unlogged forests (-15.1 stems/ha/yr, confidence interval (CI): -16.9 to -13.3). This decline in stem density reflected that mortality exceeded recruitment in all management regimes. Despite the consistent decline of forest stem density, the basal area increased over time, and the rate of increase in the intensely logged forest (0.22 m^2/ha/yr, CI: 0.19 to 0.25) was significantly greater than the other management regimes. Our study showed that 30 years post-logging, the effect of selective logging remained evident. Both logged forest stem density and the basal area did not recover to that of unlogged forests, indicating the importance of enrichment planting and extending the cutting cycles beyond 30 years for the sustainability of dipterocarps forests.

Keywords: Dipterocarps forests, management regime, natural recovery, selective logging

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INTRODUCTION

Removing large commercial trees is the main driver of forest degradation during logging (Sist et al., 2014). Selective logging, widely practised in southeast Asia, greatly impacts stand structure, species composition and regeneration dynamics of tropical forests (Hayward et al., 2021, Okuda et al., 2003; Yamada et al., 2013). However, these logged-over forests still possess significant elements of their original biodiversity and will recover over time, especially with silvicultural treatments such as enrichment planting using indigenous tree species (Berry et al., 2010; Philipson et al., 2020). Currently, 2.92 million ha or 59.1% of the total forest in Peninsular Malaysia are classified as production forests and will be selectively logged in the future (Forestry Department Peninsular Malaysia [FDPM], 2020).

The Selective Management System (SMS) is a selective logging system formulated in 1978 to manage Hill Dipterocarp Forests in Peninsular Malaysia (FDPM, 2003). The system prescribes a cutting cycle of 25-30 years, a cutting limit of 45 cm diameter at breast height for non-dipterocarps and 50 cm dbh for dipterocarp species and a minimum availability of 32 sound residual trees of 30–45 cm dbh/ha post-logging. This regime was defined on diameter growth of 0.77 cm/yr, annual recruitment of 0.60%, and mortality rate of 0.90%/yr for all trees above 30 cm observed over three years in 200 ha of permanent sample plots established in virgin and logged-over hill forests subjected to silvicultural treatments. It is expected that after 30 years, these logged forests will regenerate and be available for the next harvest (Thang, 1987).

Previous studies have shown that logged-over forests recovered more slowly in terms of the diameter growth above the threshold size for logging than was assumed by the SMS (Ismail et al., 2010; Rosli & Gang, 2013; Yong, 1996). However, these studies were limited by the small areas available for study (Rosli & Gang, 2013), the short duration of the census data (Yong, 1996), or possible biases associated with the timing of the study, such as when a census was carried out after extreme drought events that may have affected the growth and mortality of trees (Ismail et al., 2010). There is also limited information on the forest stand density and basal area recovery. The SMS is in the second cutting cycle since 2015 across most production forests in Peninsular Malaysia. Understanding the forest stand recovery of these logged forests will assist forest managers in planning for the third cutting cycle.

The Dipterocarpaceae is the dominant family in lowland and hill forests, compromising 30% of the total basal area or over 40% of the emergent, making them the main structure and support for other species (Saw & Sam, 1999). The Dipterocarpaceae dominates the canopy and sub-canopy forests in Southeast Asia (Ashton & Kettle, 2012). This dominance may be associated with their possession of root-inhabiting ectomycorrhizas that promote faster growth than other tree families, especially in a close canopy environment (Ashton, 1988; Banin et al., 2014; Brearley et al., 2016). This family is the main timber produced in

Peninsular Malaysia, and current practice in the SMS prescribes that the percentage of dipterocarps among the residual trees should not be less than in the pre-logging stand (Yong, 1996). The total timber production derived from dipterocarps amounted to 1.82 million m^3 or 46.6% for 2019 in Peninsular Malaysia (FDPM, 2020). The implication of the logged-over forest growth by removing mature Dipterocarpaceae and leaving small or intermediate-sized trees remains poorly understood (Ashton & Kettle, 2012).

The data presented the impact of the SMS on the stand structure and basal area of the logged-over forest through a time series of data collected over 25–30 years on permanent sample plots established in Peninsular Malaysia. This study aims to understand:

i. the impact of management regimes on the recruitment and mortality rate,
ii. the impact of management regimes and the recovery rate of forest stem density, and
iii. the impact of logging and the recovery rate of the total basal area, especially for Dipterocarpaceae tree species.

These insights provide a complete understanding of logged-over forest recovery status and the implication for sustainable forest management practices in Peninsular Malaysia.

METHODS

Study Area

The study was conducted in Lesong Forest Reserve, Sungai Lalang Forest Reserve, and Ulu Muda Forest Reserve, widely distributed across three different states in Peninsular Malaysia (Figure 1). The Forestry Department of Peninsular Malaysia established permanent sample plots in all three sites to evaluate the recovery of forests to logging in response to different management regimes and, in comparison, to an unlogged control. These sites were chosen to represent the lowland (Lesong) and hill (Sungai Lalang and Ulu Muda) Dipterocarp forests of Peninsular Malaysia. Over the past three decades (1990–2019) mean annual rainfall averaged across the three sites was 2,549.5 mm, and the mean annual temperature was 26.3°C. The climate of Peninsular Malaysia is characterised by two monsoon seasons: north-eastern winds bring rains from November to March during the boreal winter season,

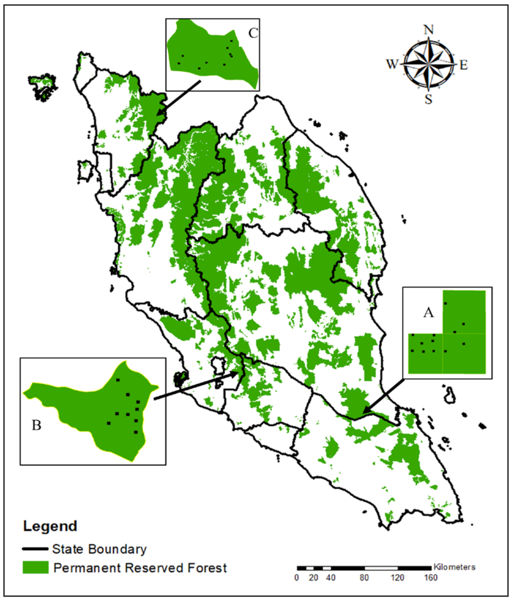


Figure 1. The study sites (black dots) in Peninsular Malaysia: (A) Lesong Forest Reserve, Pahang; (B) Sungai Lalang Forest Reserve, Selangor; and (C) Ulu Muda Forest Reserve, Kedah

and south-western winds bring strong winds from May to September during the boreal summer (Ministry of Environment and Water [MEWA], 2020). A detailed description of each site is shown in Table 1.

Thirty management blocks, each of 10.0 ha (316 m × 316 m), were established across the three sites: 12 in Lesong, 9 in Sungai Lalang, and 9 in Ulu Muda. Three management treatments were then implemented equally among management blocks within each site, as follows: (1) unlogged, (2) moderate logging, involving commercial extraction of all dipterocarp trees ≥ 65 cm dbh and all non-dipterocarp trees ≥ 60 cm dbh, and (3) intensive logging, involving commercial extraction of all dipterocarp trees ≥ 50 cm dbh and all non-dipterocarp trees ≥ 45 cm dbh. The intensive logging management regime replicated the SMS in terms of the diameter-cutting limits. The average volume logged was 131.8 m^3/ha

Table 1
Particular of each study site

Site	Lesong Forest Reserve	Sungai Lalang Forest Reserve	Ulu Muda Forest Reserve
Compartment no.	351, 371, and 372	50	10
Size of area (ha)	445.99	420	302.176
Forest type	Lowland dipterocarp forest	Hill dipterocarp forest	Hill dipterocarp forest
Altitude (meter above sea level)	100	400-800	300-400
Forest status	Virgin forest	Virgin forest	Virgin forest
Year logged	1989	1991	1993
Year of study plot established	1990	1992	1994
Year census	1990, 1991, 1992, 1993, 1994, 1996, 1998, 2000, 2002, 2009, 2014, 2019	1992, 1993, 1994, 1995, 1996, 1998, 2000, 2002, 2006, 2011, 2018	1994, 1995, 1996, 1997, 1998, 2000, 2002, 2004, 2006, 2008, 2013, 2018
Management regime	A, B, C	A, B, C	A, B, C
Size per plot (ha)	1.0	1.0	1.0
No. of a plot per regime	4	3	3
Total plot size (ha)	12	9	9
Plot number	A: 1, 2, 3, and 4 B: 5, 6, 7, and 8 C: 9, 10, 11, and 12	A: 13, 14, and 15 B: 16, 17, and 18 C: 19, 20, and 21	A: 22, 23, and 24 B: 25, 26, and 27 C: 28,29, and 30
Latitude Longitude	102^o 65’ 50” 2^o 40’ 54”	101^o 57’ 35” 3^o 7’ 35”	100^o 56’ 53” 5^o 51’ 15”
Mean annual temperature (^{o}C) (1990-2019)	26.4	25.9	26.7
Mean annual rainfall (1990-2019) (mm)	2,629.6	2,481.4	2,537.7

Note. Management regime:
A: Control/Unlogged
B: Moderately logged (all dipterocarps ≥ 65 cm and non-dipterocarps ≥ 60 cm dbh logged)
C: Intensely logged (all dipterocarps ≥ 50 cm and non-dipterocarps ≥ 45 cm dbh logged

for moderately logged, and intensely logged, was 157.0 m^3/ha. The logged areas were left to regenerate naturally without any post-logging silvicultural treatments.

A 1.0 ha permanent sample plot was established in the centre of each management block's one-year post-logging, yielding four replicates of each management treatment in Lesong and three replicates in the other two sites. All stems ≥ 5 cm dbh were numbered, tagged, measured, and identified to genus or family on all plots at the first census and on 10 (Sungai Lalang) or 11 (Lesong and Ulu Muda) subsequent censuses, which were conducted at intervals of one to seven years for 25 (Ulu Muda), 27 (Sungai Lalang), or 30 (Lesong) years. The mean census interval length was 2.5 years, and the mode of interval durations was one year. None of the sites was exposed to anthropogenic or natural disturbances, such as burning, encroachment and landslides, over the study period. Further details of the design and layout of the plots are presented in Figure 2 and Table 2.

Data Processing

The diameter growth data were screened for errors based on the methods adopted by Qie et al. (2017) and Talbot et al. (2014). These protocols were modified to accept growth rates up to 6 cm/yr for individuals of fast-growing *Macaranga* spp. and *Mallotus* spp. (Manokaran & Kochummen, 1987). The data set comprised 147,687 diameter measurements on 18,247 individual stems over 82 years of censuses. The total data corrected were 3,659 or 2.48% of the total data set.

For analysis, stems were partitioned into 2 diameter size classes labelled poles (5.0-29.9 cm dbh) and trees (30.0 and above dbh). Mortality, recruitment, and growth rates are important demographic variables

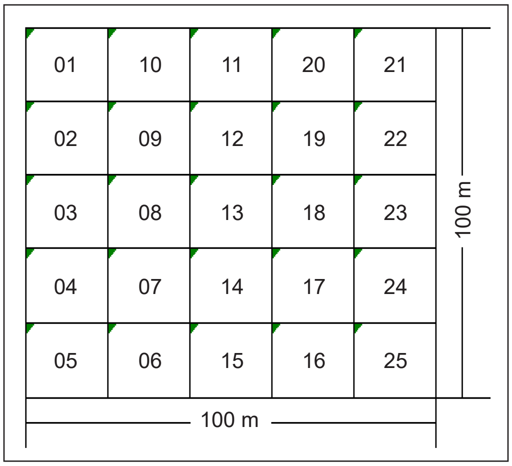


Figure 2. Layout design for the study plot. Each plot was divided into 25 subplots with a size of 0.04 ha (20 m × 20 m)

Table 2
Enumeration of stem for the study plot

Subplot sizes (m)	Subplot number	Tree dbh sizes (cm)	Stem class
20 × 20	1, 2, 3, 4, 5, 6, 10, 11, 15, 16, 20,21, 22, 23, 24, 25	15.0-29.9 30.0-44.9 > 45	Big pole, Small tree Big tree
20 × 20	7, 8, 9, 12, 13, 14, 17, 18, 19	5-14.9 15.0-29.9 30.0-44.9 > 45	Small pole, Big pole, Small tree Big tree

that may help managers make decisions to manage and conserve production forests (Dionisio et al., 2018). The rates of mean annual mortality (m) and recruitment (r) were calculated based on Sheil et al. (1995, 2000) as follows:

$$m = 1 - (nm / N_0)^{(1/t)}$$

$$r = 1 - [1 - (nr/N_1)^{(1/t)}]$$

where N_0 and N_1 are population sizes at the beginning and end of the census interval, nm is the number of dead stems, nr is the number of recruits, and t is the census interval length.

Mortality and recruitment rates were adjusted to account for the variation in census interval length (Lewis et al., 2004) as follows:

$$\lambda_{corr} = \lambda \times t^{0.08}$$

where λ_{corr} is the corrected mortality or recruitment rate in %/yr, λ is the mortality or recruitment rate, and t is the census interval.

Basal area is the cross-sectional area of all trees at diameter breast height (dbh) in a unit area. It is an informative measure of stand density used in prescribing silvicultural options in managed forest stands (Zhao et al., 2020). Basal area is used to compute the growth rate in reflecting the growth of trees over time. The basal area will provide information on the growth of trees in a unit area which will fluctuate over time due to mortality and recruitment of trees. The formula for basal area is as follows:

$$BA = \frac{\pi \times dbh^2}{4 \times 10{,}000}$$

where BA is the basal area in m^2/ha, and dbh is the diameter at breast height in cm.

The census enumerates stems of 5–14.9 cm in only 9 subplots. For estimation of stem density and basal area at the 1-ha plot scale, the mean values computed for stems of 5–14.9 cm dbh sampled on 9 subplots were multiplied by 25.

Statistical Analysis

Repeated measurements of sample trees determine forest growth over time. Separate values in the time series are not independent because they are based on the same sample of subject trees (Shek & Ma, 2011; Zuur et al., 2007). Analysing forest growth data with a linear mixed effects model addresses the issue of non-independence inherent to longitudinal time series data sets by specifying the plot as a random effect nested within spatial covariates as required by the sampling design (Qie et al., 2017). In this paper linear mixed effects model was fitted to values of mortality, recruitment, stem density, poles density, trees density, basal area, Dipterocarpaceae basal area, and non-Dipterocarpaceae basal area with fixed effects of management regime and time since logging. Plots and sites were fixed as random effects. The analysis was carried out using the *lmer* function in the R package *lme4* (Bates et al., 2015) using the syntax shown in Equation 1 below. Recruitment and mortality rates were calculated per year, and the equation applied to understand the changes is shown in Equation 2.

Response_variable ~ Year * regime + (1|Plot) + (1|Site)

(Equation 1)

$$\text{Response\_variable} \sim \text{regime} + (1|\text{Plot}) + (1|\text{Site}) \quad \text{(Equation 2)}$$

The linear mixed effect model assumed equal variances and a normal distribution of residuals, validated by examining the residual of fitted variance value against plots and sites (Philipson et al., 2020). The 95% confidence intervals (CI) of parameter estimates were obtained using restricted maximum likelihood estimation and bootstrapping. The *LmerTest* package was used to obtain the *p*-value (Kuznetsova et al., 2017). The model for recruitment rate was $\log_{10}$ transformed as the distribution of variances was not homogenous without transformation. The results were back-transformed before being presented in this paper.

RESULTS

Effect of Management Regime on Mortality and Recruitment Rate

There was a significant difference in mortality rate between unlogged forests with the other two management regimes (Figure 3). The unlogged forest has the lowest mortality rate at 1.8%/yr (CI: 1.0 to 2.5). There was no significant difference between moderately (4.0%/ yr, CI: 3.3 to 4.8) and intensely logged (3.9%/yr, CI: 3.40 to 4.50) forests. As for the annual recruitment rate (stems ≥ 5 cm dbh), the lowest was in unlogged forests at 0.5%/yr (CI: 0.40 to 0.70), which was significantly different from the other two management regimes (Figure 4). Moderately and intensely logged forests had the same recruitment rate at 2.1%/yr (CI: 1.4 to 2.9) and 2.1%/yr (CI: 1.6 to 2.6), respectively.

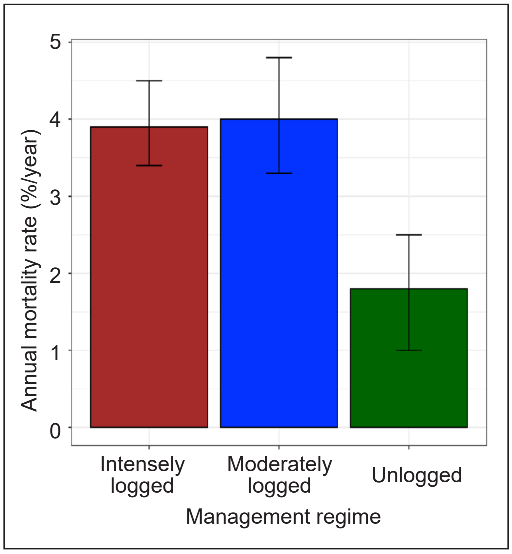


Figure 3. Annual mortality rate for all management regimes. The interval bar showed the confidence interval for each management regime

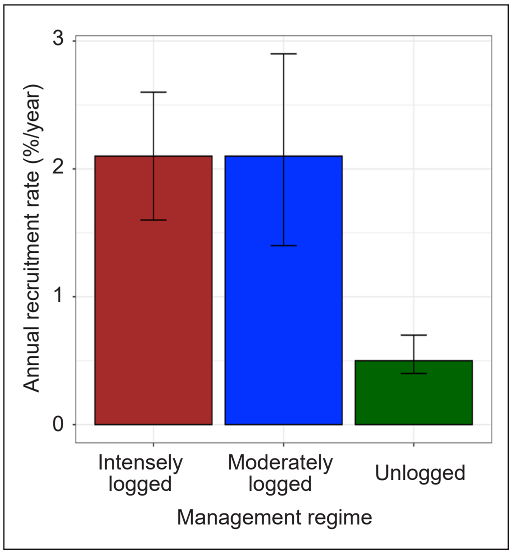


Figure 4. Annual recruitment rate for all management regimes. The interval bar showed the confidence interval for each management regime

Effect of Management Regime on Forest Stem Density

There was a significant difference in the forest stem density between unlogged and the two logging regimes one-year post logging for all diameter classes (Table 3, Figure 5). There were no differences in the stem density between intensely and moderately logged forests. The only diameter class that had a significant difference between all management regimes are the trees class (30 cm dbh and above). The stem density of trees was highest in the unlogged forest (108.0 stems/ha, 95% CI 95.2 to 120.3) and lowest in the intensely logged forests (37.1 stems/ha, 95% CI 24.4 to 49.1).

Stem Density Changes Over Time

The forest stand for all management regimes showed decreased stem density over time

Table 3
Diameter class, mean, and the confidence interval for all management regimes one-year post logging

Class diameter / Management regime	Stem/ha		
	Mean	2.5%	97.5%
Forest stem (5 cm and above)			
Unlogged*	1,192.2	1,111.6	1,269.6
Moderately logged	772.9	694.6	846.8
Intensely logged	665.2	588.9	750.4
Poles (5–29.9 cm dbh):			
Unlogged*	1083.1	1,003.5	1,162.8
Moderately logged	719.0	636.4	807.3
Intensely logged	627.0	537.7	715.2
Trees (30 cm and above dbh):			
Unlogged*	108.0	95.2	120.3
Moderately logged*	52.8	39.9	64.3
Intensely logged*	37.1	24.4	49.2

Note. * indicates management regime is significantly different

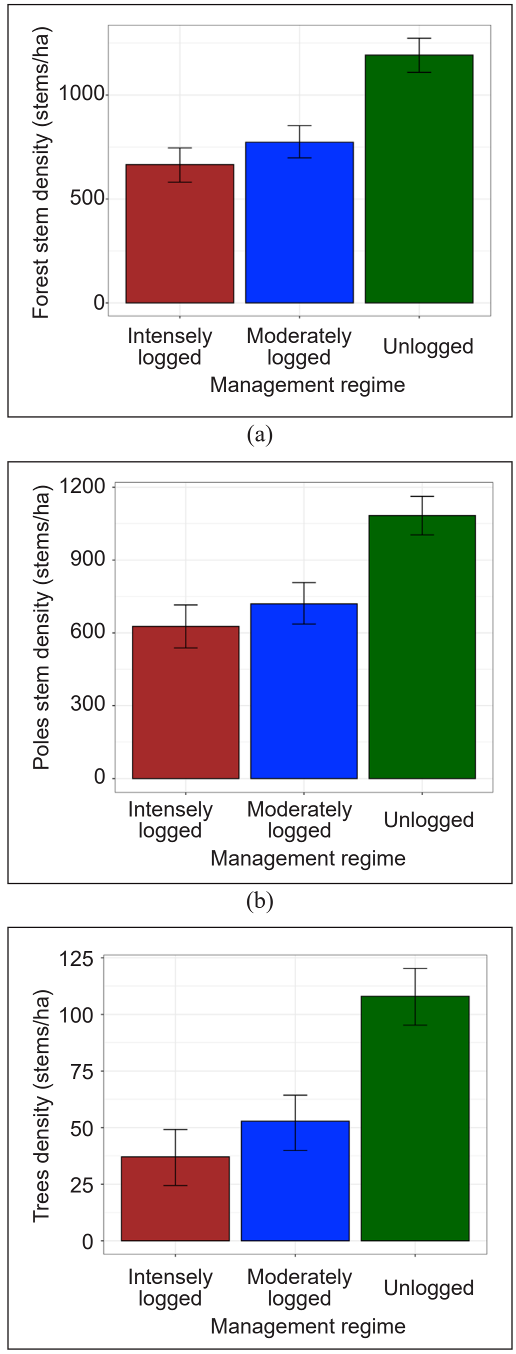


Figure 5. Total stem density one year post logging for all management regimes: (a) Forests (5 cm and above dbh); (b) Poles (5–29.9 cm dbh); and (c) Trees (30 cm and above dbh). The interval bar showed the confidence interval

(Figure 6a). The unlogged forest had the highest rate of decrease at -15.1 stems/ha/yr (CI: -16.9 to -13.3) and the second highest at -12.90 stems/ha/yr (CI: -14.7 to -11.1) was in moderately logged forest. The lowest rate of decrease was in the intensely logged forest at -9.50 stems/ha/yr (CI: -11.5 to -7.7). The only significant difference in the rate of stem density changes over time of forest stand was between unlogged forests and intensely logged forests. The unlogged forests had the highest decrease in stem density at 453 stems/ha in 30 years. The decrease in moderately and intensely logged forests was 387 stems/ha and 285 stems/ha, respectively, over the 30 years since logging. Although the unlogged forests had the highest decrease in stem number, the total stem density/ha was still the highest compared to the other two management regimes (Table 4).

The changes in pole stem density over time significantly differed between all management regimes (Figure 6b). The unlogged forests have a greater decrease (-15.3 stems/ha/yr, CI: -17.1 to -13.6) followed by moderately logged forests (-13.9 stems/ha/yr, CI: -15.5 to -12.1) and lowest in intensely logged forests (-11.0 stems/ha/yr, CI: -12.9 to -9.3). The highest decrease of poles was in the unlogged logged forest with 459 stems/ha and the lowest in the intensely logged forest at 330 stems/ha 30 years post-logging.

The trees class stem showed an increasing stem density between all management regimes compared to the poles class stem (Figure 6c). The changes over time in trees class stems were significant among all management regimes, with the highest rate in intensely logged forests (1.5 per ha per yr, CI: 1.4 to 1.6 stems). The second highest rate was in intensely logged forests (1.0 stems/ha/yr, CI: 0.9 to 1.1) and lowest in unlogged forests (0.2, CI: 0.1 to 0.3). The highest increase was in intensely logged forests at 45.0 stems/ha and the lowest in unlogged forests at 6.0 stems/ha 30 years post-logging. For the intensely and moderately logged forests to recover to the pre-logging tree stem density of unlogged forests, it will take 47 and 55 years, respectively.

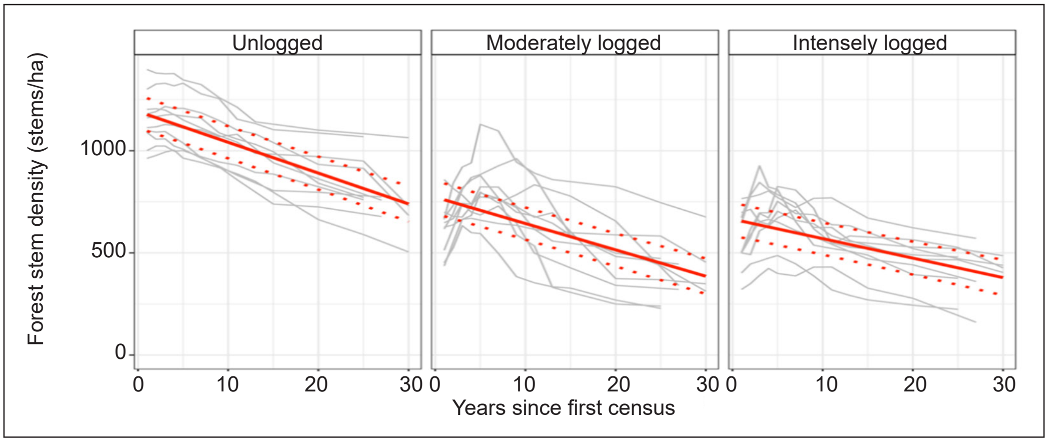
Effect of Management Regime on Basal Area

As expected, the total basal area was significantly greater one year after logging in the unlogged forest than the other two management regimes at 36.7 (CI: 33.2

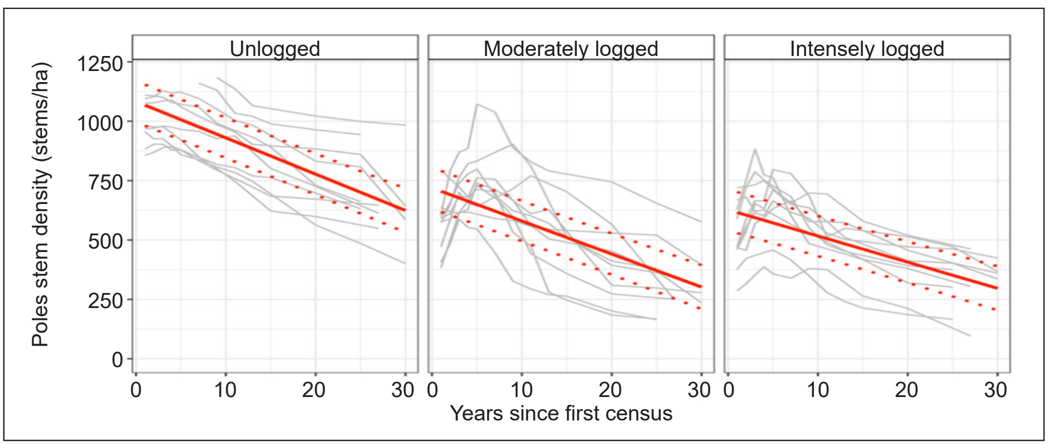
Table 4

Total stem density changes in 30 years for all management regimes

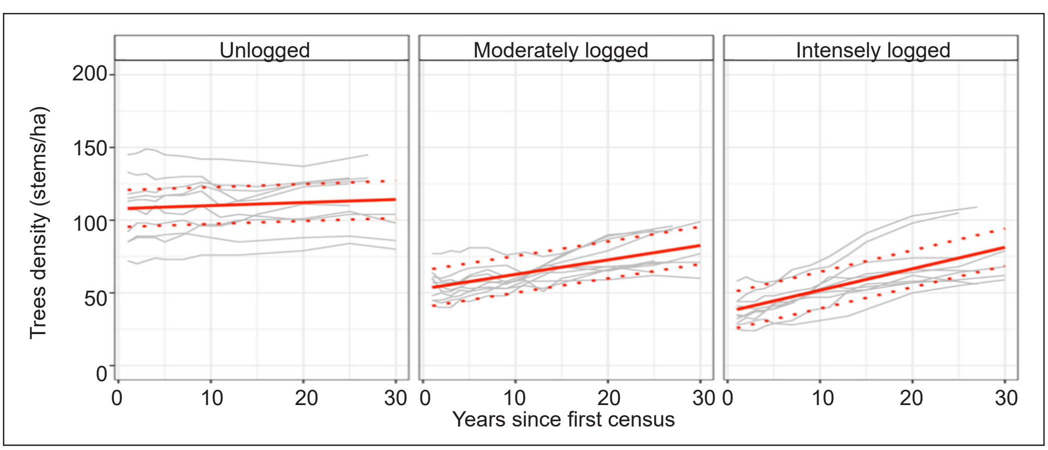
Management regime	Total stem density during the first census (stem/ha)	Total stem density changes in 30 years (stem/ha)	Total stem density in 30 years (stem/ha)
Unlogged	1,192.2	- 453	739.2
Moderately logged	772.9	- 387	385.9
Intensely logged	665.2	- 285	380.2



(a)



(b)



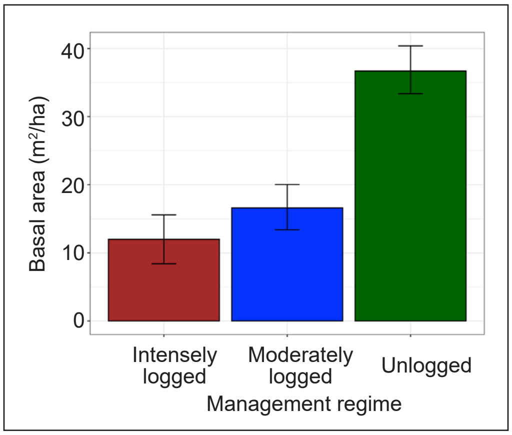
(c)

Figure 6. Total stem density as a function of time: (a) Forests stem; (b) Poles; and (c) Trees. The red solid line represents the mean timber volume growth, while the red dotted line represents the 95% confidence interval. The grey line represents each plot no. of stem growth in each census interval

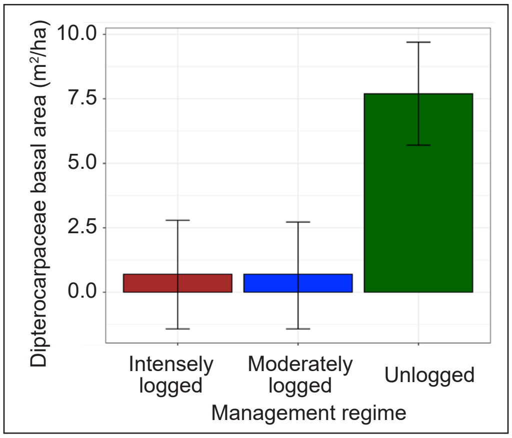
to 39.8) m^2/ha (Figure 7a). There was no difference in the total basal area between moderately logged (16.6 m^2/ha, CI 13.1 to 19.9) forests and intensely logged (12.0 m^2/ha, CI 8.4 to 15.5) forests at this stage.

The unlogged forests had the highest total basal area for Dipterocarpaceae at 7.7 m^2/ha (CI: 5.6 to 9.7), significantly different from moderately and intensely logged forests one year after logging (Figure 7b). The basal area of dipterocarps in moderately (0.7 m^2/ha, CI -1.3 to 2.7) and intensely logged (0.7 m^2/ha, CI -1.3 to 2.8) forests did not vary one year after logging. Moderately and intensely logged forests lost an average of 7.0 m^2/ha basal area compared to values of unlogged forests one-year post-logging.

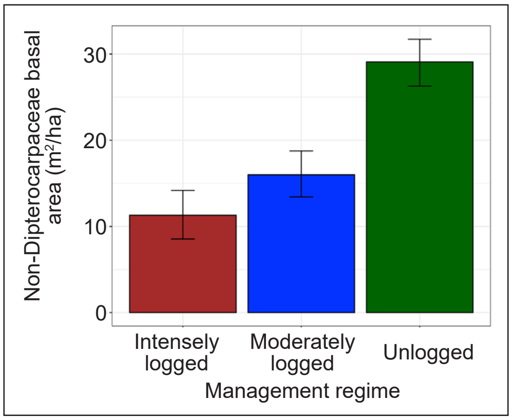
All management regimes significantly differed in the total basal area for non-Dipterocarpaceae one-year post-logging (Figure 7c). The unlogged forest had the highest total basal area for non-Dipterocarpaceae species at 29.1 m^2/ha (CI: 26.3 to 31.8 m^2/ha). The total basal area for non-Dipterocarpaceae in the moderately logged forest was 16.0 m^2/ha (CI: 13.3 to 18.7 m^2/ha), higher than the value of 11.3 m^2/ha (CI: 8.6 to 13.8) in intensely logged forest. Intensely logged forests lost the greatest amount of basal area of non-dipterocarps with an average of 17.8 m^2/ha compared to the value of 13.1 m^2/ha in moderately logged forests one-year post logging.



(a)



(b)



(c)

Figure 7. Total basal area one year post logging for all management regimes: (a) All species; (b) Dipterocarpaceae; and (c) Non-Dipterocarpaceae. The interval bar indicates the confidence interval

Basal Area Changes Over Time

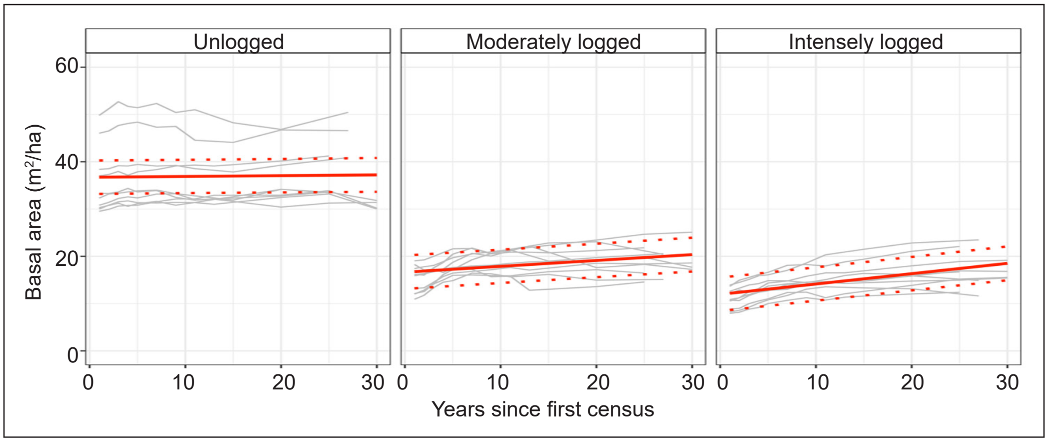
The rate of change in basal area over time was significantly different among the three management regimes but showed positive values in all cases (Figure 8). The rate of change in the intensely logged forest was highest at 0.22 m²/ha/yr (CI: 0.19 to 0.25), followed by 0.12 m²/ha/yr (CI: 0.10 to 0.15) in moderately logged forest. The unlogged forests had the lowest rate at 0.02 m²/ha/yr (CI: -0.01 to 0.05). Thirty years post-logging, intensely logged, and moderately logged forests had recovered 6.60 m²/ha and 3.6 m²/ha (Table 5). The recovery of the basal area to pre-logging status would require 112 years for intensely logged forests and 167 years for moderately logged forests. There were no changes in the basal area for unlogged regimes in the past thirty years, as the gain is just 0.6 m²/ha.

There was no significant difference between the three management regimes in the rate of change in basal area over time for Dipterocarpaceae basal area, which showed an increasing trend (Figure 8b). The highest changes over time rate occurred in the unlogged forests at 0.05 m²/ha/yr (CI: 0.03 to 0.06). The intensely logged forest rate of 0.04 m²/ha/yr (CI: 0.02 to 0.05) was higher than the value of 0.03 m²/ha/yr (CI: 0.01 to 0.04), which occurred in moderately logged forests. The biggest total change over time of Dipterocarpaceae basal area after 30 years since the first census was in the unlogged forests, which saw a 1.5 m²/ha growth. The second highest increase was in the intensely logged forest at 1.2 m²/ha, and the lowest at 0.9 m²/ha occurred in moderately logged forest. The recovery of the Dipterocarpaceae basal area to the pre-logging status would require 175 and 234 years in intensely and moderately logged forests, respectively.

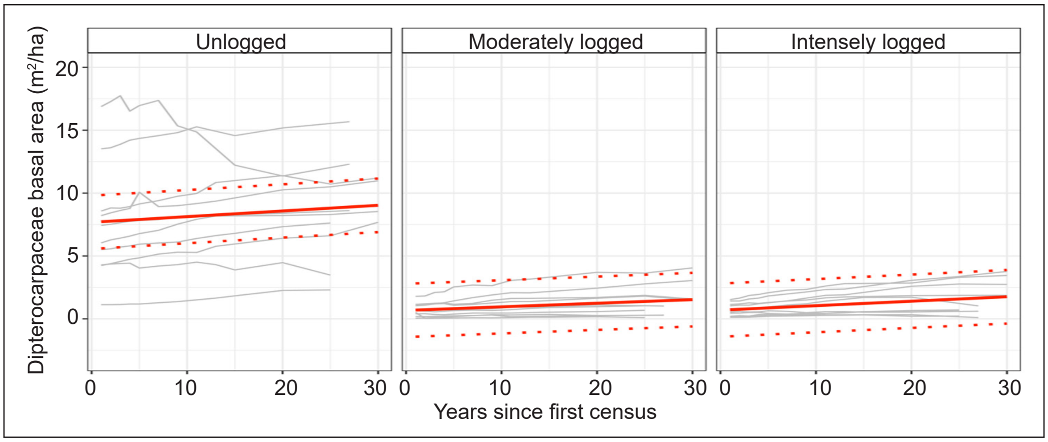
The basal area of non-Dipterocarpaceae increased through time in moderately and intensely logged forests but decreased in the unlogged forest (Figure 8c). The changes over time in the non-Dipterocarpaceae basal area were significantly greater in the intensely logged (0.18 m²/ha/yr, CI: 0.15 to 0.21) than in the moderately logged forest (0.10 m²/ha/yr, CI: 0.07 to 0.13). The unlogged forest displayed a decrease in non-Dipterocarpaceae basal area of -0.03 m²/ha/yr (CI: -0.06 to 0.00). The unlogged forests lost 0.9 m²/ha of non-Dipterocarpaceae basal area over the 30 years since the first census, but this forest retained a higher basal area than the two logged forest types, which gained 3.0 m²/ha (moderately logged forest) and 5.4 m²/ha (intensely logged forests), respectively. It is estimated that intensely logged forests would require 98.4 years to recover to the pre-logging basal area, while moderately logged forests would require 130.8 years.

Table 5
Total basal area changes in 30 years for all management regimes

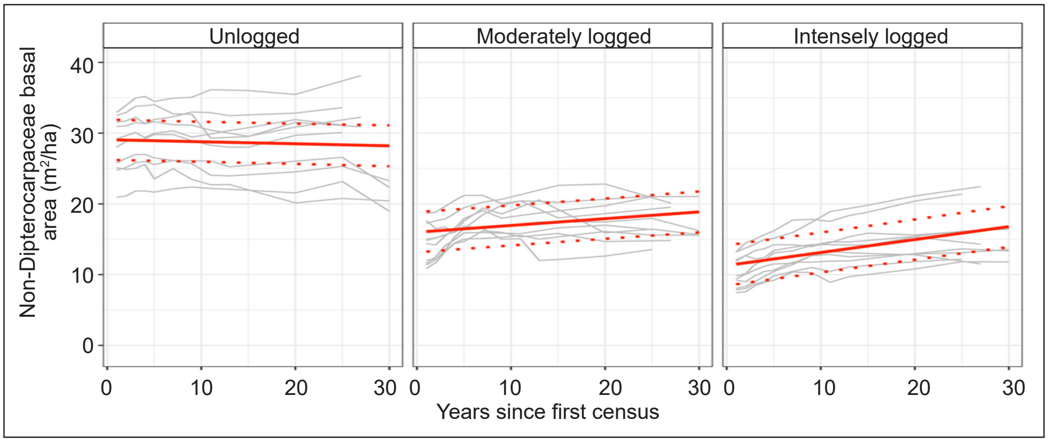
Management regime	Total basal area during the first census (m²/ha)	Total basal area changes in 30 years (m²/ha)	Total basal area in 30 years (m²/ha)
Unlogged	36.7	0.6	37.3
Moderately logged	16.6	3.6	20.2
Intensely logged	12.0	6.6	18.6



(a)



(b)



(c)

Figure 8. Total basal area growth as a function of time; (a) All Species; (b) Dipterocarpaceae; and (c) Non-Dipterocarpaceae. The red solid line represents the mean timber volume growth, while the red dotted line represents the 95% confidence interval. The grey line represents each plot's basal area growth in each census interval

DISCUSSION

Annual Mortality and Recruitment Rate

The mortality rate in unlogged forests did not vary from previous studies of below 2.0%/yr (Ismail et al., 2010; Yong, 1996). In the logged forest, the rate is higher than 0.9%/yr in the SMS for 30 cm and above trees (FDPM, 2003); 2%/yr in Ismail et al. (2010); and 2.50%/yr from Yong's (1996) result. The recruitment rate in the logged forest plots was higher than the value of 0.6%/yr reported in studies of the SMS (FDPM, 2003). It was lower compared to the study by Yong (1996) at 3.35% but did not vary from the value of 2.0%/yr reported by Ismail et al. (2010). Our mortality and recruitment rate results differed because SMS was based on a 30 cm and above dbh tree class. Yong's study (1996) was based on 5 cm and above dbh trees but from only one site and a shorter period of only 14 years, which may explain the greater recruitment rate.

The annual mortality in unlogged and logged forests was higher than the recruitment rate in previous studies, as shown (Ismail et al., 2010; Manokaran & Kochummen, 1987; Yong, 1996). It indicates that the tropical forests lost stem density over time as recruitments could not offset the high mortality rate. This trend is especially prevalent in logged forests, as the mortality is twice the recruitment rate. The mortality and recruitment rate also did not vary between logging intensity.

Effect of Logging on Forest Stem Density

The intensely logged regime lost more stem/ha compared to moderately logged regimes. One-year post-logging, the intensely logged forests lost 44% of the original stem density, while 35% in moderately logged forests. Poles stem density (5–29.9 cm dbh) was reduced by 34% in moderately logged and by 51% in the intensely logged forest compared to the unlogged forest. The percentage of stem loss will be higher for the trees class (30 cm and above dbh), which may go up to 51 and 65% for moderately and intensely logged regimes, respectively. The result showed no difference in the effect of logging intensity on the overall forests except for tree class stems. Even though the logging operation only involved the tree above 45 cm dbh class, the effect was also evident in smaller classes stem. The loss of stem density after logging operation can also be seen in other selective logged-over forests with different management regimes (Dionisio et al., 2018; Hayward et al., 2021; Okuda et al., 2003). The losses of stem density post-logging were not solely due to the removal of commercial tree species but also to mortality caused by logging activities (Shenkin et al., 2015). Mortality in logged-over forests is usually high immediately post-logging, and the effect may last up to three years (Ismail et al., 2010; Sist et al., 2014).

The unlogged forests' stem density of 5.0 cm and above of 1,192.2 stems/ha (CI: 1,111.6 to 1,269.6) was lower than the Amazon basin of 1,561 stems/ha (Myster, 2016) but higher than Africa at 425.6 stems/ha (95%, CI: +11.1) for 10 cm an above tree (Lewis et al., 2013). There was variation in stem density/ha between the three blocks of tropical forests, with the lowest in Africa and the highest in the Amazon. The unlogged forest stem density was also lower than Yong's (1996) 1,376.57 stems/ha results.

The increasing stem density trend of trees above 30 cm dbh showed that the logged-over forest is still recovering from logging operations. Selective logging eliminates the competition of big trees for growth resources and allows small trees to grow into the next diameter class. Bigger trees (30 cm in dbh and above) are not as greatly affected by this competition as smaller trees (below 30 cm in dbh), which resulted in an increasing trend over time (Rozendaal et al., 2020). The decreasing trend for unlogged forests, especially for poles, is contributed by the close canopy characteristic of mature forests that limits light availability to the understory. The limited availability of light will decrease the photosynthesis rate and halt growth, which eventually causes tree mortality due to carbon starvation (Gora & Esquivel-Muelbert, 2021). Changing climate conditions will also contribute to the decreasing trend of poles as for the past four decades, Malaysia has been experiencing an increased mean temperature of 0.13 to 0.24°C with Peninsular Malaysia having the highest changes (Fung et al., 2020; Ministry of Energy, Science, Technology, Environment and Climate Change [MESTECC], 2018). The first signal of response by trees to climate change is through changes in phenology (Deb et al., 2018). Southeast Asian tropical forest trees need a combination of drought and low temperatures during the day and night for general flowering to be triggered. The ideal flowering conditions, especially for Dipterocarpaceae, are a 54–90-day period of low temperature between 25.5–27.8°C and 93-186 mm precipitation per month (Chen et al., 2018; Yeoh et al., 2017). An increase in temperature or extreme drought events will disrupt the flowering of Dipterocarpaceae, decreasing the seed availability for forest natural regeneration.

The SMS emphasises that a minimum of 32 residual trees of 30–45 cm dbh should be retained post-logging as these trees are used to determine that the logged-over forest is fully stocked and are scheduled to become the next crop trees without the requirement of silvicultural treatments such as enrichment planting. However, the logged-over forests showed that the number of poles stem densities one \year post-logging will decrease by 35–45%. The low stem density with high turnover will affect the ability of small poles to grow into the next size class and eventually drive the recovery process of logged-over forests. Silvicultural treatment such as enrichment planting needs to be carried out to ensure that enough poles are present, even though the number of residual trees is sufficient.

Effect of Logging on Basal Area

The moderate and intense logging regimes greatly impacted the basal area as the losses were 54.8 and 67.3%, respectively, one year post-logging compared to the unlogged regime. The logged-over forests had a faster recovery rate of basal area, but even 30 years post-logging, these forests are still recovering. However, the recovery rates are lower than Yong's (1996) result of 0.25 m^2/ha/yr. The lower recovery rate for the logged-over forests is due to the higher number of big trees, especially Dipterocarpaceae, being logged and a higher proportion of the non-Dipterocarpaceae family in the residual stands (Ismail et al., 2010). Dipterocarpaceae has higher growth than non-Dipterocarpaceae trees (Banin et al., 2014).

The mean basal area of 36.7 m^2/ha (CI: 33.25 to 39.84) in unlogged forests does not vary from Borneo of 37.5 + 2.62 m^2/ha but is higher than Amazon of 31.5 and 30.3 + 0.77 m^2/ha of Africa (Lewis et al., 2013; Myster, 2016). The high basal area in unlogged forests indicates that the trees are bigger in Peninsular Malaysia compared to Amazon and Africa. The increase in basal area of 0.6 m^2/ha in unlogged forests over 30 years may indicate that these old-growth forests are not in equilibrium with changes to the total basal area over time. Thirty years after the first census, the basal area of the unlogged forest showed an increase in the proportion of Dipterocarpaceae and a decrease in non-Dipterocarpaceae. It suggests that species of the Dipterocarpaceae family are increasing in dominance over time.

The basal area for Dipterocarpaceae accounted for about 20.9% of the total basal area in the unlogged regime. This figure is lower than Pasoh Forest Reserve, which recorded 27.3% of the total basal area for trees > 1 cm (Okuda et al., 2003). One-year post logging, the basal area for Dipterocarpaceae was reduced to 4.2 and 5.8% in moderately and intensely logged regimes, respectively. The remaining small and intermediate-sized trees of Dipterocarpaceae stems contributed a small percentage of the total basal area. The logging of big Dipterocarpaceae trees also affected the basal area recovery rate, removing the family's competitive advantage and forest ecosystem dominance (Brearley et al., 2016). Our study highlighted the importance of maintaining big Dipterocarpaceae trees to improve the recovery rate of logged-over forests.

CONCLUSION

The effect of selective logging on the forest stand structure and the basal area remained evident even after decades post-logging. The high mortality and low recruitment rates showed that the natural regeneration of logged-over forests would be challenging. The stand density and total basal area, especially the Dipterocarpaceae composition of the logged-over forests, have not recovered to the pre-logging status of unlogged forests even 30 years post-logging. It shows that a logging regime that is only based on cutting limits without volume control will require a cutting cycle that is substantially longer than 30 years to deliver a sustainable yield. The SMS prescription of maintaining the Dipterocarpaceae stem percentage during pre- and post-logging may need to be reviewed as the recovery period of logged-over forests depends on the availability of big Dipterocarpaceae trees rather than small intermediate trees. Residual trees that will form the next crop trees need to combine small and big trees to improve the recovery rate of logged-over forests. Carrying out enrichment treatments with indigenous timber trees will increase the stem density of poles and assist in the regeneration of logged-over forests.

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