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EFFECTS OF SELECTIVE MANAGEMENT SYSTEM ON BIOMASS STRUCTURE AND FOREST SUSTAINABILITY: A CASE STUDY OF A TROPICAL RAINFOREST IN PENINSULAR MALAYSIA

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We analysed the effects of a selective management system (SMS) on the biomass structure (frequency distribution and spatial distribution of biomass) of a tropical rainforest in Peninsular Malaysia. The biomass structure of total biomass, i.e. the sum of the aboveground and belowground biomass of all individuals ≥ 5 cm diameter at breast height, was analysed in a forest logged under a SMS and compared with that of an unlogged natural forest. We also analysed new approaches to improve the logging system using unlogged natural forest census data. Mean total biomass value and its variance were lower in the logged forest (256 ± 52 Mg ha^{-1}) than in the unlogged natural forest (464 ± 120 Mg ha^{-1}). Logging operations also changed the spatial pattern of the total biomass, as spatially clustered and random distributions were observed in the logged forest and the reference forest respectively. To mitigate the impacts of logging on the original biomass structure, we recommend reducing the logging ratio by adopting a maximum cutting limit, as well as a uniform logging intensity throughout a stand. This will ensure a spatially random arrangement of remaining emergent trees and vital forest regeneration processes.

Keywords: Frequency distribution, maximum cutting limit, SMS, spatial distribution pattern, sustainable forest management, total biomass

INTRODUCTION

Tropical forests contain 46 and 11% of the global living terrestrial carbon pool and soil carbon pool respectively (Brown & Lugo 1982). Their importance in global carbon cycling, particular as it pertains to climate change, is widely understood. These forests are some of the most structurally complex and diverse ecosystems in the world. This complexity is related to the size–frequency distribution of trees, which varies spatially according to environmental factors such as edaphic conditions and topographic position (Laurance et al. 1999, Clark & Clark 2000).

Management of tropical forests change over time depending on the growing demand of human society. Traditionally, these forests were valued as important sources of timber, and forest harvesting practices were performed to the detriment of forest structure and biodiversity. However, in recent decades, many functions and processes of these ecosystems, such as climate regulation, have attracted increasing attention. These interests are evidenced by the implementation of several systems of payment for ecosystem services (Fearnside 2008, Wunder 2009). Therefore, forest management systems should address the twin objectives of timber production and conservation of ecosystem integrity (Edwards et al. 2014). Both of these goals could be achieved by maintaining the structural and compositional complexity of stands in selectively logged forests (Lindenmayer et al. 2006, Putz et al. 2012).

Peninsular Malaysia has been endowed with extensive areas of tropical rainforests—mainly dipterocarp forests. However, easily accessible lowland and hill dipterocarp forests have already been exploited under clear-cutting or selective logging operations (Thang 1987). A selective management system (SMS) that comprises a reduced-impact logging regimen was introduced in Peninsular Malaysia in 1978 to achieve sustainable polycyclic (cycles of 25–30 years) management of the remaining hill dipterocarp forests. This management regimen should be based on using pre-harvesting inventory data to optimise timber production and ensure sustainable forest development and its basic prescriptions are as follows (Okuda et al. 2003, Thang 1987):

(1) The cutting limits for Dipterocarpaceae and non-Dipterocarpaceae should be > 50 cm diameter at breast height (DBH) and 45 cm DBH respectively. *Neobalanocarpus heimii* is exception, for which it should be > 60 cm DBH.
(2) The proportion of Dipterocarpaceae trees number ≥ 30 cm DBH after logging should not be less than that in the original stands.
(3) More than 32 healthy commercial trees of 30–45 cm DBH ha^{-1} should remain after logging. In this case, trees > 45 cm DBH are assumed to be equivalent to two trees of 30–45 cm DBH, while three trees of 15–30 cm DBH are assumed to be equivalent to one tree of 30–45 cm DBH.

The effects of SMS on forests have been elucidated gradually. Contrary to expectations, recruitment process in dipterocarp forest can be too slow and long rotations are needed for the management of the forest (Appanah et al. 1990). The sustainability of SMS is questionable because middle sizes trees are not well represented in the dipterocarp forests and they may not respond rapidly to logging, and future regeneration may not be evenly distributed or adequate (Appanah & Weinland 1990). In 2.5 years after felling stand, *Shorea curtisii*, *Dryobalanops aromatica* and *Scaphium macropodum* had reduced basal area and tree density as well as high damage of poles caused by a single logging event (Wickneswari et al. 2004). These changes can persist in regenerated forests even after 50 years of logging. Increment rates of trees ≥ 30 cm DBH 14 years after logging were lower than the rates assumed under the SMS, and their mortality rates were higher (Yong 1996).

Past studies indicated insufficient recruitment and biomass recovery in forests under SMS. However, to propose ecologically sustainable forest management, more integrated evaluation of the effects of SMS is required, focusing on structural complexity of the stand. From the ecological point of view, approaches that promote rapid forest recovery and conservation of the structural characteristics, such as size–frequency distribution of trees, high biomass stock and its spatial variation, are preferred.

The aim of this study was to evaluate the effects of a SMS on the biomass structure (i.e. the frequency distribution and spatial distributions of biomass) of a tropical rainforest and propose new approaches to improve the ecological sustainability of this forest management system. Frequency and spatial distributions of total biomass, i.e. the sum of aboveground and belowground biomass of all individuals ≥ 5 cm DBH, were analysed in a forest managed under SMS and compared with those of an unlogged natural forest. Interferometric synthetic aperture radar (IFSAR) data and field measurement data were used for total biomass estimations in these forests. The use of different data sources could influence the results. Thus, analyses were conducted at different spatial scales to lessen the influence of each data source.

MATERIALS AND METHODS

Study sites

The study was conducted in forest subcompartment 47-B (hereafter, C47) (2° 58' N, 102° 19' E) of the Pasoh Forest Reserve, Negeri Sembilan, Peninsular Malaysia (Figure 1). Thirty-seven hectares of this compartment were selectively logged in 2005 under a SMS protocol, and forest roads and log landing sites had been established to extract the logs. The topography is more complex in the south-western part, where a hill is surrounded by a stream swamp (Figures 1b and c). There is also a small stream in the eastern part of C47. Apart from these swamp areas, the topography is flat, and the soil is generally dry over the alluvial plain.

The 50-ha permanent forest research plot (hereafter, P50) (2° 58' N, 102° 18' E) of the Pasoh Forest Reserve, which was established on unlogged forest by the Forest Research Institute

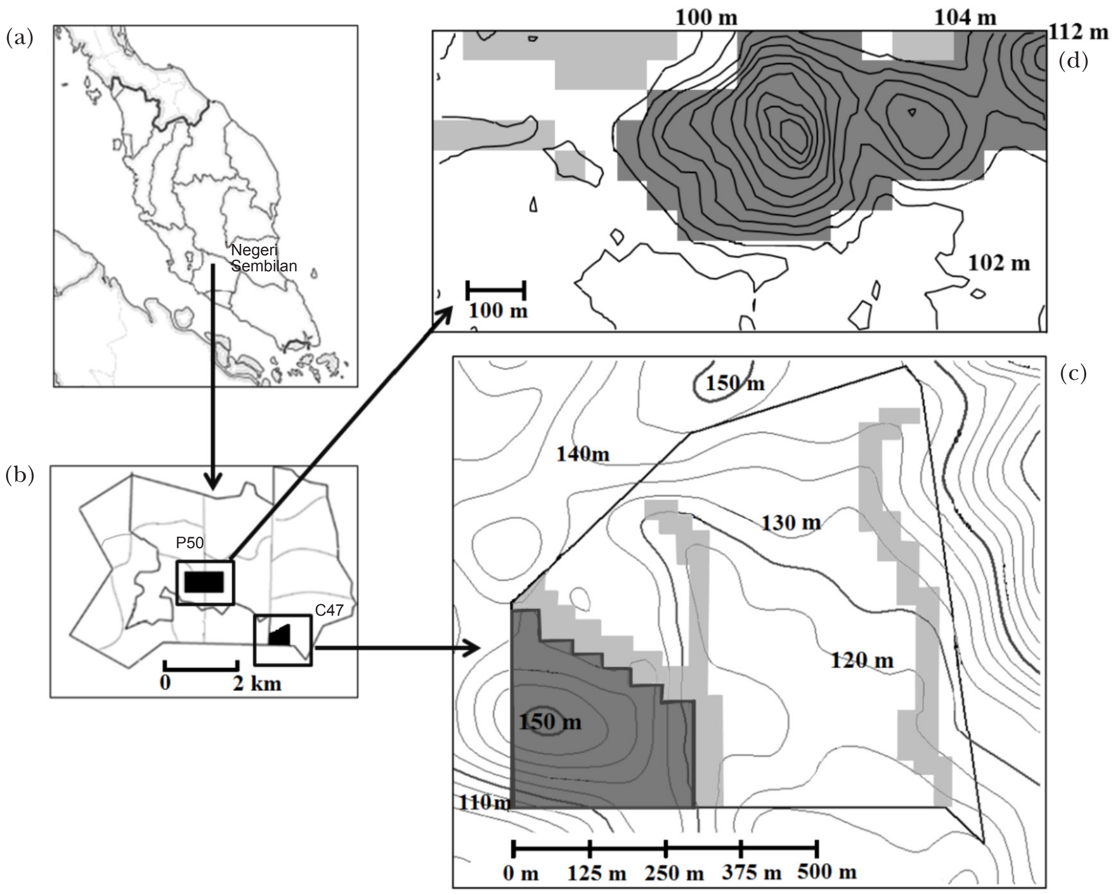

Figure 1 (a) Location of the Pasoh Forest Reserve in Peninsular Malaysia, (b) location of C47 and the P50 within the reserve, (c) outline of C47 with topographic contour lines at 5-m elevation intervals derived from IFSAR's digital terrain model, (d) outline of the P50 with topographic contour lines at 2-m elevation intervals; (c) and (d) dark grey, light grey and white areas indicate hill, stream swamp and alluvial plain respectively

Malaysia (FRIM) and the Smithsonian Institute in 1985, was used as a reference site (Figures 1b and d). The topography is flat, and the plot is interspersed with swamps and a series of low hills (Davies et al. 2003). C47 is located approximately 2 km from the P50 site. Floristic features of these two sites were similar to each other, and they were composed of high proportions of Dipterocarpaceae, Euphorbiaceae, Leguminosae and Annonaceae (Kochummen et al. 1990, Yoneda et al. 2010).

Data sources

Airborne X-band IFSAR data taken in 2008 were used to analyse the biomass structure of C47. X-band IFSAR data allow measurement of the canopy surface when they are incorporated into a digital surface model (DSM). A digital terrain model (DTM) was used to analyse underlying terrain information. Both DSM and DTM are three-dimensional models composed of coordinate and height data. Some commercially available X-band IFSAR output contains simultaneous analyses by DSM and DTM, making it possible to calculate canopy heights for large area of forested landscapes. The spatial resolution of the models was 5 m × 5 m.

Analyses in P50 were based on the re-census data conducted by Hamada in 2008 (Hamada T, personal communication). In this re-census, location and DBH were recorded for all individuals ≥ 30 cm DBH.

Biomass estimation

Rectangular prism method

In C47, we divided the site into subplots (10 m × 10 m to 50 m × 50 m) for convenience, and we estimated the total biomass (including under canopy vegetation ≥ 5 cm DBH) for each of them with a rectangular prism procedure using IFSAR-derived canopy height. We revised biomass density as the apparent density of the total aboveground biomass under a canopy tree (Kubota et al. 2015). The estimated total biomass was calibrated to that of 7 years after logging (2012) using reference field census data, and it was referred to as CTBi (calibrated total biomass estimated from IFSAR data).

Allometric relationships method

In the P50, tree heights of recorded individuals were estimated from DBH using allometric relationships obtained from measurements that were made previously in the primary forest of this reserve (Kato et al. 1978). Total mass of each recorded tree was calculated as the summation of its aboveground and belowground mass (Niiyama et al. 2010). We divided the site into subplots (ranging from 10 m × 10 m to 50 m × 50 m) for convenience. For each subplot, we summed the total mass of all individuals ≥ 30 cm DBH and then extrapolated this value to Mg ha^{-1} (TB_{30}).

Total biomass of all individuals ≥ 5 cm DBH (TB_5, Mg ha^{-1}) was estimated from TB_{30} using equation 1 that was parameterised with data obtained from the re-census (800 subplots of 25 m × 25 m each, $r^2 = 0.98$, $p < 0.05$) of P50, which was conducted by FRIM in 2000.

$$TB_5 = 0.99\ TB_{30} + 162 \qquad (1)$$

Data analysis

In C47, analyses of biomass structure were conducted in 29 ha of alluvium (Figure 1) where the suitability of IFSAR for the total biomass estimation was preliminarily examined (Kubota et al. 2015). Hill and stream swamp were excluded because of bias in the IFSAR data. In the P50, 29 ha of alluvium were also selected for the analyses.

To analyse the frequency distribution, mean CTBi was compared with mean TB_5 using the Wilcoxon rank-sum test. The variance of CTBi and that of TB_5 was also compared using Brown–Forsythe test. Moran's I test was used to analyse the spatial distribution of CTBi and TB_5. This test measures the standardised spatial autocorrelation, which corresponds to a correlation in the value among nearby locations in space. In this analysis, Moran's I values of -1, 0, and 1 represented dispersed, random and clumped arrangements respectively. Each subplot in these analyses had a neighbouring subplot. Therefore, spatial independence among the subplots could not be assumed. Consequently, a randomisation test was used to determine the p value for all statistical analyses.

In these analyses, effects of difference of data sources and biomass estimation procedure were expected because the TB_5 of subplots without individuals ≥ 30 cm DBH would be unified as 162 Mg ha^{-1} through equation 1. CTBi values at subplots without trees ≥ 30 cm DBH will vary because IFSAR detects some canopy height even in forest gaps (Kubota et al. 2015) and, consequently, derived biomass obtained via the rectangular prism method will be different. In order to reduce effects of these differences, comparisons between TB_5 and CTBi were conducted at different spatial scales: both sites were divided into 10 m × 10 m, 15 m × 15 m, 20 m × 20 m, 25 m × 25 m, 30 m × 30 m, 35 m × 35 m, 40 m × 40 m, 45 m × 45 m and 50 m × 50 m subplots.

Simulation under improved SMS protocol

To increase ecological sustainability, we analysed possible improvements of the management system; we call these approaches improved SMS (Table 1). The purpose of these approaches was to achieve a management system with low impact on the structural characteristics of the forest, keeping as much as possible the volume of wood extraction.

We modelled the improved SMS in 29 ha of the P50. For improved SMS-1 and improved SMS-2, we focused on increasing the number of remaining trees. Improved SMS-1 and improved SMS-2 differed from the SMS because more than 32 and 40 healthy trees of > 30 cm DBH should remain after logging respectively. In both cases, individuals > 45 cm DBH were not assumed to be equivalent to two trees of 30–45 cm DBH. For improved SMS-3, we changed the diameter category of remaining trees incorporating the concept of maximum cutting limit. In this approach, trees < 100 cm DBH should be kept.

The difference between effects of the SMS and improved SMSs were analysed by frequency and spatial distributions of the total biomass, numbers of after-logging remaining trees and logging trees, conducted in the 29 ha P50 using 50 m × 50 m subplots.

Table 1 Basic prescriptions of the selective management system (SMS), improved SMS-1, improved SMS-2 and improved SMS-3

Protocol	Cutting limit	Number of Dipterocarpaceae with DBH > 30 cm	Number of remaining trees[1]
SMS	Dipterocarpaceae > 50 cm DBH, non-Dipterocarpaceae > 45 cm DBH, *Neobalanocarpus heimii* > 60 cm DBH	Its proportion after logging should not be less than the original stands	More than 32 healthy trees of 30–45 cm DBH ha^{-1}. Trees > 45 cm DBH were assumed to be equivalent to two trees of 30–45 cm DBH[2]
Improved SMS-1	"	"	More than 32 healthy trees > 30 cm DBH ha^{-1}
Improved SMS-2	"	"	More than 40 healthy trees > 30 cm DBH ha^{-1}
Improved SMS-3	Dipterocarpaceae > 50 cm to < 100 cm DBH, non-Dipterocarpaceae > 45 cm to < 100 cm DBH , *N. heimii* > 60 cm to < 100 cm DBH	"	Same as SMS

[1]Commercial and non-commercial species were not distinguished, [2]trees of 15–30 cm DBH were ignored; DBH = diameter at breast height

RESULTS

Frequency distribution

Mean CTBi values in C47 were lower than the TB_5 values in P50 across spatial scales, and these differences were significant (Table 2, Figure 2, $p < 0.05$ for all scales). The total biomass in C47 was reduced by nearly half after logging. Mean CTBi in C47 corresponded to 58% of TB_5 in the P50 (Table 2). This showed that 7 years after logging, total biomass was 42% lower than that of the original intact forest, when the P50 was assumed to show the initial conditions of the logged stand.

The variances of CTBi in C47 were significantly lower than those of TB_5 in the P50 across space scales (Table 2, Figure 2, $p < 0.05$ for all scales). In C47 and P50, variance decreased as spatial scale increased. As shown in Figure 2a, no distinct difference of the frequency distribution pattern was observed between spatial scales in C47. In contrast, a distinguishably large frequency peak was observed at two smaller space scales, i.e. 10 m × 10 m and 15 m × 15 m in the P50, where the relative frequencies were 49 and 24% respectively. The distribution pattern did not differ significantly between other spatial scales (Figure 2b).

Spatial distribution

In C47, significant spatial autocorrelations of CTBi were detected across spatial scales (Table 3, Figure 3a, $p < 0.05$ for all). The arrangement of CTBi tended to be spatially clustered regardless of spatial scales. In P50, TB_5 was not significantly autocorrelated in any of the spatial scales (Table 3, Figure 3b, $p > 0.05$, for all), and there was no clear change of Moran's I across spatial scales. TB_5 tended to show a random distribution regardless of the spatial scale.

Frequency and spatial distributions under improved SMS

More trees will be conserved with improved SMS approaches (Table 4, Figure 4). Even though the numbers of remaining individuals were higher under improved SMS-1 and improved SMS-2, the impacts of logging operations on the frequency distribution of biomass were lower under improved SMS-3 (Table 2, Figure 4b). However, improved SMS-3 approach reduced the volume of harvested wood compared with SMS (Table 5). When P50 was under improved SMS-3, harvestable stand level aboveground for Dipterocarpaceae except *N. heimii*, non-Dipterocarpaceae and *N. heimii* trees would be 27, 4.4 and 60% less of that of SMS respectively. Although improved SMS-3 resulted in the harvest of 15 fewer trees (a 2.1% decrease),

Table 2 Mean calibrated total biomass estimated from IFSAR data (CTBi), mean TB_5 and their standard deviation (SD) at nine spatial scales in C47 and the P50 in the Pasoh Forest Reserve

Space scale	Mean and SD of CTBi and TB_5 (Mg ha^{-1})					
	C47		P50		p value	
	Mean	SD	Mean	SD	Mean[1]	SD[2]
10 m × 10 m	265	118	464	611	< 0.05	< 0.05
15 m × 15 m	267	105	465	405	< 0.05	< 0.05
20 m × 20 m	268	91	461	304	< 0.05	< 0.05
25 m × 25 m	268	78	464	246	< 0.05	< 0.05
30 m × 30 m	268	73	465	207	< 0.05	< 0.05
35 m × 35 m	269	66	465	170	< 0.05	< 0.05
40 m × 40 m	263	54	459	148	< 0.05	< 0.05
45 m × 45 m	265	52	457	141	< 0.05	< 0.05
50 m × 50 m	256	52	464	120	< 0.05	< 0.05
[3]50 m × 50 m	-	-	234	28	-	-
[4]50 m × 50 m	-	-	250	37	-	-
[5]50 m × 50 m	-	-	276	40	-	-
[6]50 m × 50 m	-	-	287	92	-	-

[1]Wilcoxon rank-sum test with randomisation, [2]Brown–Forsythe test with randomisation, [3]mean TB_5 and its SD if the selective management system (SMS) is applied at the 29-ha stand of the P50, [4]mean TB_5 and its SD if improved SMS-1 is applied at the 29-ha stand of the P50, [5]mean TB_5 and its SD if improved SMS-2 is applied at the 29-ha stand of the P50, [6]mean TB_5 and its SD if improved SMS-3 is applied at the 29-ha stand of the P50

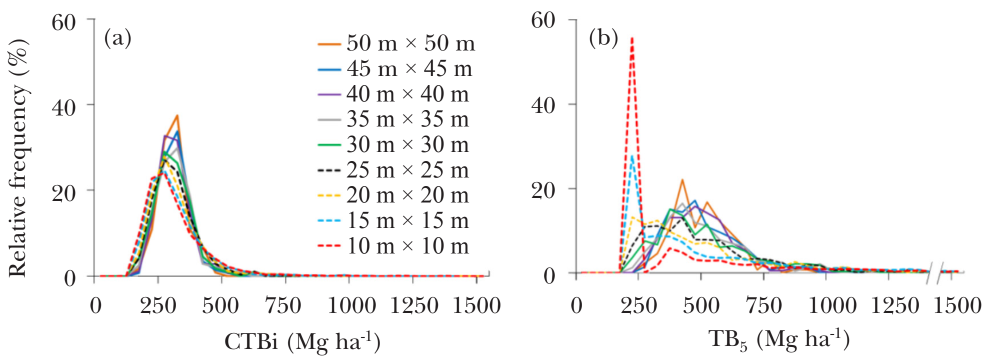

Figure 2 (a) Frequency distribution of calibrated total biomass estimated from IFSAR data (CTBi) in C47 at different spatial scales and (b) frequency distribution of TB_5 in the P50 at different spatial scales; the value of 50 Mg ha^{-1} was adopted for classifying biomass and to calculate relative frequency in (a) and (b)

the difference in aboveground was 1088 Mg $stand^{-1}$ (a 20% decrease).

DISCUSSION

Consideration of the methodologies

The effects of applying different data sources and total biomass estimation procedures were highlighted in the frequency distribution analysis (Figure 2). In P50, the frequency peaks observed at 10 m × 10 m and 15 m × 15 m spatial scales could be distinguished from the curves of other subplot dimensions, while in C47, the peaks at all spatial scales exhibited similar biomass value. Differences in data sources and methodologies were less distinguishable at greater spatial scales.

Despite these limitations, statistical results of the distribution analyses at each site were unchanged between spatial scales (Tables 2 and

Table 3 Spatial autocorrelation (Moran's I) at nine spatial scales in C47 and the P50 in the Pasoh Forest Reserve

Space scale	C47		P50	
	Moran's I	p value[1]	Moran's I	p value[1]
10 m × 10 m	0.46	< 0.05	-0.01	> 0.05
15 m × 15 m	0.30	< 0.05	0.00	> 0.05
20 m × 20 m	0.26	< 0.05	-0.01	> 0.05
25 m × 25 m	0.28	< 0.05	0.01	> 0.05
30 m × 30 m	0.23	< 0.05	-0.03	> 0.05
35 m × 35 m	0.26	< 0.05	-0.01	> 0.05
40 m × 40 m	0.27	< 0.05	0.01	> 0.05
45 m × 45 m	0.24	< 0.05	0.02	> 0.05
50 m × 50 m	0.42	< 0.05	0.05	> 0.05
[2]50 m × 50 m	-	-	0.10	> 0.05
[3]50 m × 50 m	-	-	-0.06	> 0.05
[4]50 m × 50 m	-	-	0.04	> 0.05
[5]50 m × 50 m	-	-	-0.01	> 0.05

[1]Moran's I test with randomisation, [2]spatial autocorrelation of TB_5 if the selective management system (SMS) is applied at the 29-ha stand of the P50, [3]spatial autocorrelation of TB_5 if improved SMS-1 is applied at the 29 h-a stand of the P50, [4]spatial autocorrelation of TB_5 if improved SMS-2 is applied at the 29 h-a stand of the P50, [5]spatial autocorrelation of TB_5 if improved SMS-3 is applied at the 29-ha stand of the P50

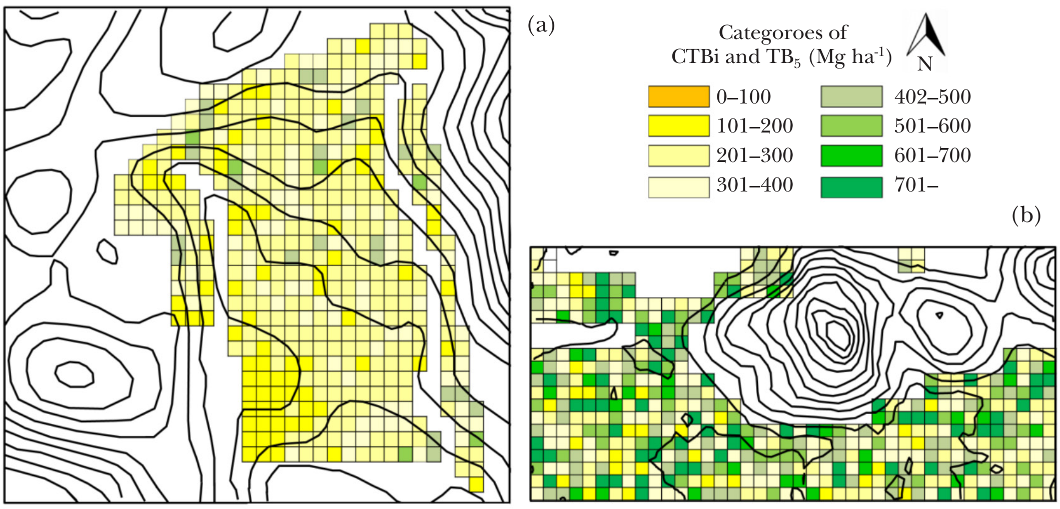

Figure 3 (a) Calibrated total biomass estimated from IFSAR data (CTBi) map of the alluvial plain of C47 with topographic contour lines at 5-m elevation intervals derived from the digital terrain model and (b) TB_5 map of the alluvial plain of the P50 with topographic contour lines at 2-m intervals

3). These results suggested the suitability of employing combined data sources and estimation procedures (i.e. rectangular prism and allometric relationship methods) for the comparison of biomass structure at both sites.

Effects of SMS in C47

The frequency distribution of total biomass differed between the two studied sites, indicating that the SMS practice affected the biomass structure of C47 (Table 2, Figure 2). If we applied the SMS approach (i.e. the system comprising the basic prescriptions that was presented in the Introduction) in 29 ha of the P50 without considering the installation of forest roads and log landings, we obtained slightly lower TB_5 and standard deviations than that of C47 (Table 2, Figure 4a). The total biomass in C47 should be lower than that of P50 because of the presence

Table 4 Estimated numbers of after-logging remaining trees > 30 cm DBH for each logging approach at the 29-ha stand of the P50 in the Pasoh Forest Reserve

Group of species	Original forest	SMS	Improved SMS-1	Improved SMS-2	Improved SMS-3
Dipterocarpaceae (except *Neobalanocarpus heimii*)	17.1	8.1 (10.6)	10.9	12.6	8.1 (10.6)
Non-Dipterocarpaceae	38.3	23.4	23.4	26.9	23.6 (23.7)
N. heimii	1.4	0.5 (0.7)	0.5	0.6	0.9 (1.5)
Total	56.8	32.0 (34.7)	34.8	40.0	32.6 (35.8)
% Dipterocarpaceae	32.6	26.9 (32.6)	32.8	33.0	27.6 (33.8)
% mass of remaining trees	100	24.1	29.4	29.5	38.5

SMS = selective management system; values in parentheses represent the number of remaining trees if we assume that trees > 45 cm DBH are equivalent to two trees of 30–45 cm DBH; the number of trees ha^{-1} is shown; proportion of remaining Dipterocarpaceae > 30 cm DBH and proportion of remaining trees > 30 cm DBH with respect to original forest are also shown SMS-2, we focused on increasing the number of remaining trees

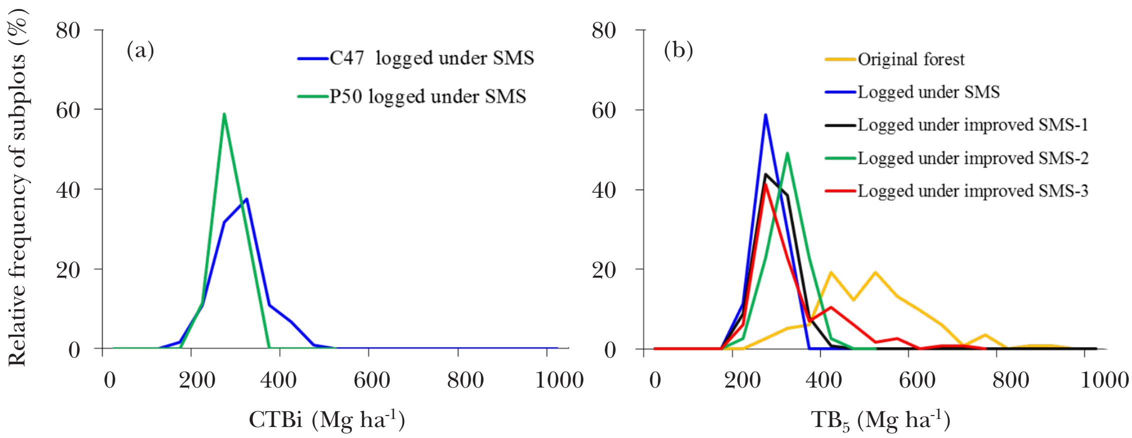

Figure 4 (a) Frequency distribution of calibrated total biomass estimated from IFSAR data (CTBi) of the 29-ha stand at 7 years post-logging in C47 and TB_5 of the 29-ha stand of the P50 if the SMS is applied; establishment of forest roads and log landings were not considered when modelling the SMS in the P50, (b) TB_5 in original forest, after logging under the SMS regimen, and after logging under improved SMS-1–3 in the 29-ha stand of the P50

Table 5 Estimated numbers and AGB (Mg ha^{-1}) of logging trees for SMS and improved SMS-3 approach at the 29-ha stand of the P50 in the Pasoh Forest Reserve

Group of species	Original forest	SMS		Improved SMS-3	
		No. of tree	AGB	No. of tree	AGB
Dipterocarpaceae (except *Neobalanocarpus heimii*)	17.1	9.0	91.9	9.0	67.3
Non-Dipterocarpaceae	38.3	14.9	79.9	14.7	76.4
N. heimii	1.4	0.9	15.6	0.5	6.2
Total	56.8	24.8	187.4	24.2	149.9

AGB = aboveground biomass, SMS = selective management system of roads and log landings. However, total biomass estimation for C47 was higher probably because of stand recovery 7 years after logging. This result suggested that the logging ratio applied in C47 probably fulfilled the SMS protocol.

Our results regarding biomass reduction agreed with other similar studies that were conducted in Peninsular Malaysia. In a forest in Negeri Sembilan, large trees (> 45 cm DBH) of three tree species (*S. curtisii*, *D. aromatica* and *S. macropodum*) were absent immediately after logging under SMS (Wickneswari et al. 2004). In a stand in Johore, there was a 48.1% reduction in the basal area (50.9% including areas cleared for logging roads, skid trails and log landing sites) after 3 months of logging under SMS, in which all trees > 45 cm DBH were felled (Seng et al. 2004). The authors also reported a 49.4% reduction in the basal area in a forest in Negeri Sembilan after 2.5 years of logging (51.8% including areas cleared for skid roads and log landings), in which trees > 45 cm DBH showed the largest reduction and all trees > 75 cm DBH were removed.

Based on these results, we suggest that the SMS protocol caused severe reduction in biomass and its variance inside a stand. The low number of reproductive trees contemplated in the protocol caused severe biomass reduction. A post-logging stand could be composed, for example, of 96 individuals of 15–30 cm DBH, 32 individuals of 30–45 cm DBH, or 16 individuals of > 46 cm DBH. The spatial distribution of the total biomass also differed between the two study sites, indicating that the SMS practice affected the biomass structure of C47 (Table 3, Figure 3). If we applied SMS in the P50, TB_5 exhibited a random distribution, unlike CTBi in C47, which adopted a spatially clustered distribution (Table 3, Moran's I = 0.10, $p > 0.05$, and Moran's I = 0.42, $p < 0.05$ respectively). These results suggested a spatially non-uniform logging intensity in C47. Total biomass lost could be more severe at more accessible places because of the ease of logging and extraction operations. The spatially clustered distribution of the total biomass suggested a similar distribution pattern of remaining emergent trees, including the commercial Dipterocarpaceae species. In this case, the clustered distribution of remaining trees could reduce the regeneration capability and economic value of the recovering forest.

The spatial variability of biomass seemed to be an original feature of old-growth tropical forest and it was reported also in Neotropical forest (Chave et al. 2001). The spatially non-uniform logging pattern allows unbalanced biomass extraction, which may affect the distribution of remaining commercial species. To attain sustainable polycyclic forest management, forest regeneration can be enhanced by ensuring that the remaining trees are distributed evenly.

New propositions for sustainable forest management

Improved SMS-3 seemed to be better than the other two improved SMSs. To mitigate the loss of the original biomass structure, diameter class of remaining trees might be more important than stem density. This is because of dependence of the stand biomass of tropical rainforests on scattered, emergent trees.

From an ecological point of view, felling large trees could have greater negative impacts on a forest stand, compared with felling smaller diameter trees. Similarly, compared with smaller trees, most large individuals are more likely to contain hollows in their stems, thereby reducing the usable volume (Monda et al. 2015). For this reason, hollow logs are sometimes abandoned in the forest. In contrast, conserving trees > 100 cm DBH is relevant because they are the home of several fauna and flora species.

We conclud that logging operations under the SMS had adversely affected the biomass structure of C47. The SMS simplified the stand-scale biomass structure by halving the total biomass, as well as changing its frequency and spatial distributions. To support the resilience of biomass structure and to attain ecologically sustainable forest management, we recommend reducing the logging ratio by adopting a maximum cutting limit. Additionally, the logging ratio should be uniform throughout a stand to retain spatial arrangement of the remaining emergent trees and support the forest regeneration process.

To obtain more concrete improvements of forest management systems, it is also important to: (1) analyse the intensity and condition of forest roads and log landings, (2) analyse the economic viability of improved SMS-3 by considering the current market cost of forest management and the market price of logs, and (3) examine the influence of mortality of remaining trees on the sustainability of forest management.

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