Original article

Sustainable cutting cycle and yields in a lowland mixed dipterocarp forest of Borneo

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Abstract – Based on a 6 year monitoring of the dynamics of a mixed dipterocarp forest in East Borneo (1990-1996), we built a matrix model to predict the sustainable cutting cycle in relation with the extraction and damage rates. Plots were ordered according to three main groups of damage and logging intensity. The first group G1 gathered slightly damaged plots with a remaining basal area $\geq 80\%$ of the original (mean logging intensity = 6 trees ha^{-1}). Plots belonging to G2, had a remaining basal area varying between 70 and 79% of the original one (mean logging intensity = 8 trees ha^{-1}). Finally, G3 gathers highly damaged plots with a remaining basal area < 70% of the original one and a high logging intensity (mean = 14 trees ha^{-1}). The mean sustainable cutting cycles predicted in the three groups were significantly different and equal 27, 41 and 89 years in G1, G2 and G3 respectively. However, the respective mean annual extracted volumes were similar: 1.6, 1.8 and 1.4 m^3 ha^{-1} year^{-1}, respectively in G1, G2 and G3. The model suggests that a 40 year cycle, extracting 8 trees ha^{-1} (60 m^3 ha^{-1}) and an annual volume of 1.5 m^3 ha^{-1} year^{-1} is the best option to preserve ecological integrity of the forest, to ensure yield sustainability and, according to existing cost analysis, economic profitability. This result is also consistent with other studies which already demonstrated that logging damage reduction using RIL techniques could be only significant with a moderate felling intensity not exceeding 8 trees ha^{-1}. This felling intensity threshold can be easily achieved by applying simple harvesting rules.

dipterocarp forest / sustainable logging intensity / East Kalimantan / TPTI, modeling / reduced-impact logging (RIL) / matrix models

Résumé – Durée de rotation et production durable d'une forêt mixte à Diptérocarpacées de Bornéo. En nous basant sur un suivi de 6 ans de la dynamique d'une forêt mixte à Diptérocarpacées, de Kalimantan Est (1990–1996), nous avons construit un modèle matriciel pour établir la période de rotation durable en fonction de l'intensité de l'exploitation et des dégâts engendrés. Les parcelles ont été classées dans trois groupes de dégâts et d'intensités d'exploitation. Le groupe G1 rassemble des parcelles ayant subi des dégâts peu importants et ayant conservé une surface terrière ≥ 80 % de l'originale (intensité moyenne d'exploitation = 6 arbres ha^{-1}). Les parcelles de G2 ont une surface terrière résiduelle variant entre 70 et 79 % de l'originale (intensité moyenne = 8 arbres ha^{-1}). Enfin G3 regroupe des parcelles fortement perturbées avec une surface terrière inférieure à 70 % de l'originale et ayant subi une intensité d'exploitation beaucoup plus élevée (14 arbres ha^{-1}). Les durées moyennes de rotation dans les trois groupes sont significativement différentes et s'élèvent à 27, 41 et 89 ans respectivement dans G1, G2 et G 3. Cependant, les volumes annuels prélevés sont statistiquement similaires : 1.6, 1.8 et 1.4 m^3 ha^{-1} an^{-1}, respectivement dans G1, G2 et G3. Le modèle suggère qu'un cycle de 40 ans, avec une extraction moyenne de 8 arbres ha^{-1} (60 m^3 ha^{-1}) et un volume annuel prélevé de 1.5 m^3 ha^{-1} an^{-1} constitue la meilleure option permettant d'assurer l'intégrité écologique de la forêt, ainsi qu'une production constante et, selon les études de coûts existantes, économiquement rentable sur le long terme. Ce résultat conforte par ailleurs les études précédentes ayant démontré que les dégâts d'exploitation ne pouvaient être réduits de façon significative grâce à l'EFI (exploitation à faible impact) qu'à condition de limiter l'intensité d'extraction à 8 arbres ha^{-1}. Des règles simples permettent de respecter cette intensité.

forêt mixte à Diptérocarpacées / intensité d'exploitation durable / Kalimantan Est / TPTI / modélisation / exploitation à faible impact (EFI) / modèles matriciels

1. INTRODUCTION

In Borneo where primary lowland forests exhibit a high density of harvestable trees (23 ha^{-1} > 50 cm dbh and 16 ha^{-1} > 60 cm, diameter cutting limit depending on the type of forest), logging operations commonly damage more than 50% of the original stand [4, 22, 30, 32, 37]. These heavy cuts result in a seriously depleted residual stand, which is unlikely to reach an acceptable harvesting volume within a cutting cycle of 35 years as set up by the Indonesian regulations [16, 42]. The low economic value of those intensively logged forests makes them prone to be converted into agriculture lands. Moreover, large canopy openings and heavy vine invasion occurring in over-logged forests increase vulnerability to fire

as was dramatically demonstrated in Indonesia during the recent past successive El Niño drought events [25]. Detailed observations over several decades of forest dynamics processes after logging, based on permanent sample plots where ecological conditions were recorded before and after harvesting, are still lacking in South East Asia and, generally speaking in tropical forests [18, 34, 44]. This situation led to develop a wide range of forest dynamics models to predict forest yield and dynamics after disturbance [39, 52, 53]. These models were individual-based models with space-independent [9, 20, 23, 34, 39, 51, 54] or space-dependent [18, 28, 35, 36] interactions, as well as distribution-based (or matrix) models [5–8, 15, 16, 21]. During this last decade, these models originally research oriented, have been developed to a more practical approach integrating silvicultural and logging practices, to become effective management tools [1, 26]. Contrary to individual-based models, matrix models provide limited insights into the possible processes that drive the forest dynamics. However, they offer the advantage to use mostly discrete diameter distributions which are easy to assess in the field on relatively large areas. Moreover, matrix models can also predict in a robust way and as reliably as other approaches, stand structure (density, basal area and diameter distribution) and are mathematically more tractable than individual-based models.

For these reasons these models are generally considered as efficient tools for the management of tropical forests, which generally include large production areas but where inventories are very limited. This paper aims at simulating the impact of logging intensity and associated damage to assess the most suitable felling cycle able to ensure a long-term sustainable timber production. This will help to evaluate the Indonesian Selective System, better known as TPTI, recommending a 35-year felling cycle period. For this, we built a matrix model based on a 6 year monitoring of a mixed dipterocarp forest in East Borneo (1990–1996).

2. STUDY SITE AND METHODS

2.1. The STREK experimental design

2.1.1. Study site

The study area is located in the Indonesian province of East Kalimantan (Borneo Island), in the district of Berau, near Tanjung Redeb (2° N, 117° 15E), within a 500 000 ha forest concession [3]. The climate is equatorial with a mean annual rainfall of about 2000 mm. August is the driest month with a mean of 90 mm rainfall and January the wettest with 242 mm (data for Tanjung Redeb over the period 1984–1993). The bedrock is primarily alluvial deposits (mudstone, siltstone, sandstone and gravel) dating from the Miocene and Pliocene. Soils are mainly Ultisols (87.3%), with some Entisols (10.7%) and Inceptisols (2%). The topography is gently undulating to hilly in the north, changing to steep slopes with elevations reaching 500 m above sea level in the south.

2.1.2. Experimental design and treatments

A 5% inventory of the 1000 ha zone scheduled for logging provided the database for sample plot selection [3]. Twelve 4 ha plots (200 m × 200 m) each divided into four 1 ha squares or subplots, were set up from 1990 to 1991. All trees with dbh ≥ 10 cm were measured

(girth at 1.30 m or 20 cm above buttresses), numbered and mapped on a scale of 1/200. In control plots, all trees were identified to species from 1990 to 1993 whereas in the other 9 logged plots, tree identification was performed to species for dipterocarps but to genus or family level only for the other taxa [43].

Logging operations were carried out from November 1991 to May 1992, in the 1000 ha annual coupe area including the permanent sample plots. Four different treatments were defined, each treatment being replicated three times. Treatments included two Reduced-Impact Logging techniques (2 × 3 plots), a conventional logging method (3 plots) and, finally, an unlogged control treatment including 3 plots [4]. Owing to the Indonesian silvicultural system, harvesting was limited to trees larger than 60 cm of the following dipterocarp species *Anisoptera* spp., *Dipterocarpus* spp., *Dryobalanops beccarii*, *Hopea* spp., *Parashorea* spp. and *Shorea* spp. Two years after logging (1994), in the logged plots, all trees with bad damage such as those leaning or with a broken bole were cut (trees with dbh ≤ 20 cm) or poisoned (dbh ≥ 20 cm). On average, for the 36 subplots concerned, 19 trees ha^{-1} (SD = 9.8) or 0.70 m^2 ha^{-1} (SD = 0.42) were removed during this treatment. This was not taken into account for the calculation of "natural mortality" after logging.

2.1.3. Plot monitoring

Four successive measurements were carried out between 1990 and 1996. The first one occurred before logging, during plot set up in 1990–1991. The second was performed 3 months after logging between May and August 1992, the third and fourth ones every two years in 1994 and 1996 respectively and during the same year period (May–August). At each census, we recorded girth of all living individuals ≥ 10 cm dbh to the nearest mm with a fibreglass girth tape, new trees with dbh ≥ 10 cm, dead trees and causes of mortality. During the entire census period, 1990–1996, a total of 28657 trees were measured, monitored and recorded in the database.

2.1.4. Subplots groupings

There was a positive and significant correlation between the proportion of stems damaged and basal area removed ($R^2 = 0.62$, $P = 0.01$, $n = 36$, [4]). This result suggested that felling intensity was an important feature in the damage caused by logging regardless of the technique (reduced-impact logging or conventional, [42]). Two years after logging, there was a negative correlation between post-logging mortality (% year^{-1}) and the proportion of remaining basal area after logging ($R^2 = 0.43$, [29]). To assess the effect of logging damage intensity on forest dynamic processes, regardless of the logging techniques, we ordered the 48 subplots according to the proportion of remaining basal area (basal area after logging/original basal area before logging in %). The average remaining basal area of all the plots being 74% of the original one, we defined the three groups to obtain a fair distribution of the 48 subplots, as follows:

Group 0 (G0): Control plot, unlogged, no damage, 100% of the initial basal area ($n = 12$ subplots);

Group 1(G1): Low damage rates with a remaining basal area ≥ 80% of the original one ($n = 11$ subplots);

Group 2 (G2): Moderate damage rates with a remaining basal area = 70–79% of the original one ($n = 14$ subplots);

Group 3 (G3): High Damage rates with a remaining basal area < 70% ($n = 11$ subplots) of the original one.

Before logging, mean (± SD, $n = 48$ subplots) tree density (dbh ≥ 10 cm), basal area and standing volume in the 12 plots were respectively 530 ± 71.6 stems ha^{-1}, 31.5 ± 4.2 m^2 ha^{-1} and 402.0 ± 61.0 m^3 ha^{-1} (Tab. I). In the plots, logging intensity ranged from 1 to 17 ha^{-1} (9 m^3 ha^{-1} to 247 m^3 ha^{-1}) and averaged 9 trees ha^{-1} (86.9 m^3 ha^{-1}, [4]). Mean density of harvested trees varied from 6 trees ha^{-1} in G1 to 14 trees ha^{-1} in G3 and were significantly different in the three groups

Table I. Mean stand characteristics of the four groups of plots (± SD) before (year 1990) and after (year 1992) logging.

	Group 0	Group 1	Group 2	Group 3
Number of 1 ha subplots	11	11	14	11
Pre-harvest (1990)				
Mean density (1990)	527.9 ± 56.9	557.7 ± 71.9	540.2 ± 80.3	481.9 ± 55.6
Mean basal area (m² ha⁻¹)	30.7 ± 3.1	32.8 ± 4.9	31.8 ± 5.5	29.5 ± 1.7
Mean density of dipterocarps (trees ha⁻¹)	109.3 ± 23.0	139.4 ± 43.0	113.1 ± 35.1	104.5 ± 28.1
Mean basal area of dipterocarps (m² ha⁻¹)	14.5 ± 2.9	15.5 ± 3.6	14.8 ± 3.6	15.7 ± 3.1
Post harvest (1992)				
Mean felling intensity (harvested trees ha⁻¹)	–	5.8 ± 2.3	8.2 ± 3.3	13.9 ± 3.0
Mean % of injured trees	–	15.3 ± 5.6	21.5 ± 6.0	25.4 ± 5.5
Mean % of trees killed	–	14.8 ± 4. 6	22.0 ± 4.9	33 ± 6.7
Mean % of basal area remaining	–	86.2 ± 4.6	75.4 ± 19.7	58.6 ± 7.7
Mean density after logging (trees ha⁻¹)	524.1 ± 54.7	486.4 ± 80.3	429.4 ± 65.4	331.0 + 64.2
Mean basal area after logging (m² ha⁻¹)	30.7 ± 3.2	28.3 ± 4.9	23.9 ± 3.6	17.3 ± 2.7
Mean density of dipterocarps (trees ha⁻¹)	108.1 ± 23.0	117.9 ± 34.9	85.8 ± 26.1	63.6 ± 20.8
Mean basal area of dipterocarps (m² ha⁻¹)	14.5 ± 3.1	12.4 ± 3.3	9.3 ± 2.2	6.4 + 2.3

(ANOVA, $F = 22.71$ $P < 0.001$, Tab. I). After logging, mean basal areas remaining in the three groups varied from 17.3 m² ha⁻¹ in G3 to 28.3 m² ha⁻¹ in G1 (Tab. I).

2.2. Theoretical growth model: General concept

We used a Usher matrix model [48, 49] with the modifications by Buongiorno and coworkers [10–12, 15], that is based on species groups and density-dependent coefficients. A living tree of species group s, in the diameter class i at time t will at time $t + \Delta t$, either:

- die with the probability $m_{si}(t)$,
- stay alive and move up from class i to class $i + 1$ with the probability $a_{si}(t)$,
- stay alive in the same diameter class i with the probability $1 - m_{si}(t) - a_{si}(t)$.

Let $y_{si}(t)$ be the number of trees of species group s in diameter class i at time t, $F_{s\,i\rightarrow j}(t)$ the number of trees of species group s moving from diameter class i to j ($= i + 1$) between t and $t + \Delta t$, and $F_{s\,i\rightarrow dead}(t)$ the number of trees of species s in diameter class i that die between t and $t + \Delta t$. Following the Markov chain interpretation model, ($F_{s\,i\rightarrow i+1}$, $F_{s\,i\rightarrow i}$, $F_{s\,i\rightarrow dead}$) is a random vector that follows a multinomial law with parameters ($y_{si}, a_{si}, 1 - m_{si} - a_{si}, m_{si}$). The Usher model may also be formulated in a deterministic way by writing: $F_{s\,i\rightarrow i+1} = a_{si}y_{si}$, $F_{s\,i\rightarrow i} = (1 - m_{si} - a_{si})y_{si}$ and $F_{s\,i\rightarrow dead} = m_{si}y_{si}$. In both stochastic and deterministic way, the stand dynamics between t and $t + \Delta t$ is expressed by the following equation:

$$y_{s\,i}(t + \Delta t) = F_{s\,i-1\rightarrow i}(t) + F_{s\,i\rightarrow i}(t). \qquad (1)$$

Taking into account the number of trees newly recruited in the first diameter class, equation (1), in the deterministic case, can be written in its matrix form as:

$$\mathbf{Y}_s(t + \Delta t) = \mathbf{A}_s(t)\,\mathbf{Y}_s(t) + \mathbf{r}_s(t), \qquad (2)$$

where $\mathbf{Y}_s$ is the vector of the number of trees in each diameter class for species group s, $\mathbf{A}_s$, the transition matrix containing the m_{si} and a_{si} probabilities, $\mathbf{r}_s$ the vector for recruitment.

The expression for the $\mathbf{A}_s$ matrix is:

$$\begin{bmatrix} 1 - a_{s1} - m_{s1} & & & & 0 \\ a_{s1} & \ddots & & & \\ & \ddots & 1 - a_{si} - m_{si} & & \\ & & a_{si} & \ddots & \\ 0 & & & \ddots & 1 - m_{sk} \end{bmatrix}$$

and for the $\mathbf{r}_s$ vector:

$$\begin{bmatrix} r_s \\ 0 \\ \vdots \\ 0 \end{bmatrix}.$$

From equation (2), the dynamics of the whole stand can be written as follows:

$$\mathbf{Y}(t + \Delta t) = \mathbf{A}(t)\,\mathbf{Y}(t) + \mathbf{R}(t) \qquad (3)$$

where $\mathbf{Y}$ is the vector of the whole tree population, $\mathbf{R}$ is the vector [$\mathbf{r}_1...\mathbf{r}_S$] and $\mathbf{A}$ is the transition matrix containing the transition matrices $\mathbf{A}_s$:

$$\begin{bmatrix} \mathbf{A}_1 & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \mathbf{0} \\ \mathbf{0} & \cdots & \mathbf{0} & \mathbf{A}_S \end{bmatrix}$$

where S is the number of species.

Taking into account the number of harvested trees and those destroyed during logging operations, included in the vector $\mathbf{H}(t)$, equation (3) becomes:

$$\mathbf{Y}(t + \Delta t) = \mathbf{A}(t)\,[\,\mathbf{Y}(t) - \mathbf{H}(t)\,] + \mathbf{R}(t). \qquad (4)$$

Thus $\mathbf{Y}(t) - \mathbf{H}(t)$ includes the undamaged trees and the damaged trees (i.e. the trees wounded by logging operations but still standing).

2.3. Construction of the model using STREK data

2.3.1. Species grouping

Three main groups of species, called S_1, S_2, S_3 were distinguished.

S_1 gathers all pioneer species that are defined here as those requiring full penetration of light to the forest floor for the germination of seeds and establishment of seedlings [45]. The most common species in the study area were *Anthocephalus chinensis* (Lam.) Rich., *Duabanga moluccana* Bl., *Macaranga gigantea* (Reichb. f. & Zoll.) Muell. Arg., *M. hypoleuca* (Reichb. f. & Zoll.) Muell. Arg., *M. triloba* Muell. Arg., *Octomeles sumatrana* Miq. S_2 includes all dipterocarps, except the genus *Vatica* which, in contrast with all the other dipterocarps, has no commercial value. S_3 represents all the other species including those of the genus *Vatica*.

This species grouping mainly aimed to follow separately the dynamics of the commercial species (i.e. dipterocarps) and that of pioneers after logging but not to reflect the changes in species composition or diversity after logging. Group S_1 gathers species with a very similar ecological behaviour, as they all require full light to germinate and to develop. This group is homogeneous enough to be considered as a guild of species. Although dipterocarps include a wide range of species, they share common ecological behaviour that allows for their categorisation in the same guild of regeneration. Seeds require partial canopy shade protection for germination and early survival but they also require an increase of light, as this occurs after logging, for further establishment and growth [2, 17, 27, 31, 47]. Response of dipterocarps in the later development stage is also strong as growth of trees (dbh $\geq$ 10 cm) is clearly stimulated by canopy opening resulting from logging [29, 41]. Compared with the other two groups, S_3 is undoubtedly the most heterogeneous, including different species with different ecological behaviours. This group cannot be therefore regarded as a guild or functional group as commonly defined in ecological studies.

2.3.2. Specific equations

The basic unit of the model is each subplot of 1 ha ordered into the four groups of damage. Time step Δt is 2 years, the time interval between the two successive post-logging measurements. The diameter classes width was adjusted according to the group of species in order to obtain fluxes $F_{s\ i \rightarrow i+1} = a_{si}y_{si}$ large enough. For the dipterocarps (S_2), we defined 9 classes ranging from 10 to 90 cm dbh with a constant 10 cm width, the last one gathering all trees with dbh $\geq$ 90 cm. For the pioneer species group (S_1), only 3 dbh classes were defined (10–20, 20–30 and $\geq$ 30 cm) as only very few trees reach a dbh $\geq$ 30 cm. For S_3, the sample of trees was large enough to define 10 dbh classes with a constant 5 cm width for the dbh between 10 and 55 cm, the last class including all trees with dbh $\geq$ 55 cm.

Upgrowth transition probabilities $a_{is}(t)$ are density-dependent. Linear and non-linear relations were tested with $Y(t)/Y_0$ or $B(t)/B_0$ as independent variables, $B(t)$ being the cumulative basal area of the subplot at time t, B_0 the cumulative basal area at the assumed steady state (before logging), $Y(t)$ the number of trees in the subplot at time t, and Y_0 the number of trees at steady state (before logging). The following best equation was retained:

$$a_{is}(t) = \alpha_{0is} + \alpha_{1is} B(t) / B_0. \tag{5}$$

The recruitment rate r_s is also density-dependent and the fitting equations are:

$$r_s(t) = \gamma_{0s} + \gamma_{1s} B(t)/B_0 \quad \text{for species groups } S_2 \text{ and } S_3 \tag{6a}$$

and

$$\ln[r_s(t)] = \gamma_{0s} + \gamma_{1s} B(t)/B_0 \quad \text{for pioneer species } (S_1). \tag{6b}$$

Plot monitoring clearly showed that logged-over forest suffered a much higher mortality than undisturbed stands, mainly because of a higher mortality of damaged trees [41]. For this reason, the post-logging mortality was considered as the sum of two entities: (1) the mortality of undamaged trees (= natural mortality rate) m_{0is}, and (2) the mortality rate of trees damaged by logging, calculated as the proportion of damaged trees that died during the post logging period. This was expressed by the equation:

$$m_{si}(t) = m_{0si} + \Delta m_{si} \, \mathbf{I}(0 < t - t_{logging} \leq 2 \, \Delta t) \tag{7}$$

where $\mathbf{I}(p)$ is the indicator function of proposition p (= 1 if p is true and 0 otherwise) and $t_{logging}$ the time of the last logging operation. Linear relations between Δm_{si} and the cumulative basal area immediately after logging was selected according to the species groups as follows:

$$\Delta m_{si} = -\beta_s + \beta_s B(t_{logging}) / B_0 \quad \text{for } S_2$$

and

$$\Delta m_{si} = -\beta_s + \beta_s Y(t_{logging}) / Y_0 \quad \text{for } S_3.$$

There was no evidence of a post logging over-mortality of pioneer species.

The cumulative basal area B and the total number of trees are given by:

$$Y(t) = \mathbf{1}'\mathbf{Y}(t) \text{ and } B(t) = \overline{\mathbf{B}}' \, \mathbf{Y}(t)$$

where $\mathbf{1}$ is the vector of length 22 whose all elements equal unity, and $\overline{\mathbf{B}}'$ is the vector of the average basal areas of each diameter class and species group.

2.3.3. Parameter estimations

The upgrowth transition probability a_{is} was estimated as the proportion of trees of species group s and diameter class i that move to class $i + 1$ between two successive post-logging measurements. Let a_{isjn} be the estimate of a_{is} obtained from subplot j ($j = 1, ..., 48$) between two successive measurements n and $n + 1$ ($n = 2, 3$). We now focus on a given dbh class and species group to drop the indices i and s. To estimate α_0 and α_1 (Eq. (5)) we perform the regression:

$$a_{jn} = \alpha_0 + \alpha_1 B_{jn} / B_{j1} + \varepsilon_{jn} \tag{8}$$

where B_{jn} is the cumulative basal area of subplot j at measurement n, considering that forest structure before logging, at measurement 1, represents the steady state. In equation (5) $\alpha_0 + \alpha_1 > 0$, but if this condition is not met, equation (8) is replaced by:

$$a^*_{jn} = \alpha_1 (B_{jn} / B_{j1} - 1) + \varepsilon_{jn} \tag{9}$$

where $a^*_{jn} = a_{jn} - \mu$ and μ is the average of a_{jn} calculated in the control plots. These regressions include the 48 subplots for the measurements 2–3 and 3–4. Each plot therefore appears twice in equations (8) or (9). For this reason, the residuals ε_{jn} cannot be regarded as independent, impeding to perform a standard linear regression. The alternative is a longitudinal data analysis [14]. We suppose that the vector of residuals follows a multinormal law with means zero. As there are only two repetitions in time (i.e. two successive post-logging measurements), the variance/covariance structure can simply be expressed as:

$$\text{Var}(\varepsilon_{jn}) = \sigma^2$$
$$\text{Cov}(\varepsilon_{jn}, \varepsilon_{j'n'}) = 0 \quad \text{for } j \neq j'$$
$$\text{Cov}(\varepsilon_{jn}, \varepsilon_{jn'}) = \rho\sigma^2.$$

The estimates of α_0, α_1, σ and ρ were then calculated by the maximum likelihood method ([14], Tab. II). For the greatest diameter classes, α_1 was not significantly different from 0 and was therefore abandoned. The regression was then performed with the data of the control plots only.

Table II. Parameter estimates of the upgrowth transition probabilities.

				Pioneers S_1			
				α_1			
Dbh class	m	$\alpha_0 = \mu - \alpha_1$		Value	SD	Pr $(> |T|)$	Pseudo-R^2
10–20	0.0313	0.3906		–0.3594	0.0721	< 0.0001	0.25
20–30	0.0083	0.0083		0	–		–

				Dipterocarps S_2				
	α_0			α_1				
Dbh class	Value	SD	Pr $(> |Value|)$	Value	SD	Pr $(> |Value|)$	ρ	Pseudo-R^2
10–20	0.1644	0.0285	< 0.0001	–0.1253	0.0350	0.0002	0.2971	0.14
20–30	0.1747	0.0382	< 0.0001	–0.1237	0.0469	0.004	8×10^{-5}	0.07
30–40	0.1690	0.0627	0.0035	–0.1088	0.0765	0.0773	8×10^{-5}	0.02
40–50	0.3618	0.0937	< 0.0001	–0.2893	0.1151	0.0060	8×10^{-5}	0.06
50–60	0.0701	0.1006	0.0012	0	–	–	–	–
60–70	0.0615	0.0925	0.0017	0	–	–	–	–
70–80	0.0644	0.0958	0.0055	0	–	–	–	–
80–90	0.0810	0.0810	0.0266	0	–	–	–	–

				Others S_3				
	α_0			α_1				
Dbh class	Value	SD	Pr $(> |Value|)$	Value	SD	Pr $(> |Value|)$	ρ	Pseudo-R^2
10–15	0.2889	0.0165	< 0.0001	–0.2492	0.0203	< 0.0001	8×10^{-5}	0.61
15–20	0.2903	0.0223	< 0.0001	–0.2306	0.0274	< 0.0001	0.0475	0.44
20–25	0.3016	0.0292	< 0.0001	–0.2442	0.0358	< 0.0001	0.0338	0.33
25–30	0.3172	0.0406	< 0.0001	–0.2299	0.0499	< 0.0001	0.0095	0.18
30–35	0.3520	0.0485	< 0.0001	–0.2839	0.0595	< 0.0001	0.1547	0.21
35–40	0.2752	0.0511	< 0.0001	–0.2005	0.0628	< 0.0001	8×10^{-5}	0.10
40–45	0.0703	0.1025	0.0014	0	–	–	–	–
45–50	0.0756	0.1197	0.0031	0	–	–	–	–
50–55	0.1096	0.2596	0.0368	0	–	–	–	–

Table III. Parameter estimates for the recruitment rates.

		γ_0			γ_1			
Groups	Variable	Value	SD	Pr $(> |T|)$	Value	SD	Pr $(> |T|)$	R^2
Pioneers (S_1)	$\ln(r)$	6.0088	0.6082	< 0.0001	–6.0613	0.7924	< 0.0001	0.52
Dipterocarps (S_2)	r	19.7668	2.2785	< 0.0001	–16.3320	2.7988	< 0.0001	0.27
Others (S_3)	r	59.4484	4.5254	< 0.0001	–45.5798	5.5587	< 0.0001	0.42

To estimate the parameters of recruitment, we performed the regression:

$$r_{jn} = \gamma_0 + \gamma_1 B_{jn}/B_{j1} + \varepsilon_{jn} \qquad \text{for } S_2 \text{ and } S_3$$

$$\ln(r_{jn}) = \gamma_0 + \gamma_1 B_{jn}/B_{j1} + \varepsilon_{jn} \qquad \text{for } S_1$$

where r_{jn} is the number of recruited trees in subplot j at measurement n for a given species groups (S_1, S_2 or S_3). In the longitudinal analysis, ρ estimates are so small ($< 10^{-8}$) that we finally use a standard linear regression for the estimation of γ_0 and γ_1 (Tab. III).

Mortality rate of trees in primary forest and that of undamaged trees in logged-over stand were not significantly different during the post logging census period [41]. The natural mortality rate m_{0si} in logged-over forest was therefore regarded similar to that in the steady state. We considered the steady state where $y_{si}(t + \Delta t) = y_{si}(t)$ and Equation (1) therefore becomes [19]:

$$\forall i > 1, \ m_{0si} = a_{si-1} y_{si-1} / y_{si} - a_{si} \qquad (10a)$$

$$m_{0s1} = r_s / y_{s1} - a_{s1}. \qquad (10b)$$

For the estimation of m_{0si}, we estimated y_{si} from the data of the first measurement (i.e. 48 subplots still under primary forest) and we computed a_{si} and r_s from equations (5) and (6).
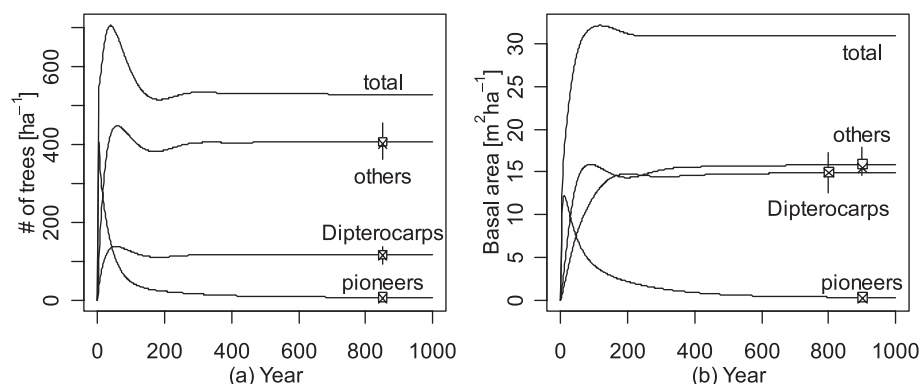
Figure 1. Prediction by the matrix model of the dynamics of a 1 ha subplot initially empty over 1000 years. (**a**) density in number of trees ha^{-1} of each species group (from top to bottom: total density, others, dipterocarps, pioneers); (**b**) cumulative basal area (m^2 ha^{-1}) for each species group (same legends as a). Time steps: 2 years; — predictions by the matrix model; crosses (×): median of the 48 subplots at first inventory, square (□): mean of the 48 subplots at first inventory, the wiskers indicating the first and third quantile. The predicted mean (not post-sample) always falls within the 95% confidence interval of the mean estimated from the 48 subplots.

Table IV. Value of the mortality rate parameters m_0 (probability of natural death between t and $t + 2$ years) and β (parameter of the additional mortality due to logging damage).

| | | Dipterocarps | | | | | | Pioneers | | | Others | | | | |
| | | β | | | | | | | | | | β | | | |
Dbh (cm)	m_0	Value	SD	PR (> |T|)	R^2	Dbh (cm)	m_0	Dbh (cm)	m_0	Value	SD	PR (> |T|)	R^2
10–20	0.0259	–0.3107	0.0483	< 0.0001	0.54	10–20	0.2534	10–15	0.0315	–0.3847	0.0318	< 0.0001	0.8
20–30	0.0510	–0.2062	0.0557	0.0007	0.28	20–30	0.0575	15–20	0.0353	–0.4497	0.0408	< 0.0001	0.78
30–40	0.0285	–0.4074	0.0721	< 0.0001	0.48	≥ 30	0.0115	20–25	0.0498	–0.3109	0.0389	< 0.0001	0.65
40–50	0.0160	–0.1113	0.0485	0.0279	0.13	–	–	25–30	0.0033	–0.3064	0.0429	< 0.0001	0.59
50–60	0.0142	–0.3747	0.1081	0.0015	0.27	–	–	30–35	0.0729	–0.4385	0.0564	< 0.0001	0.63
60–70	0.0302	0	–	–	–	–	–	35–40	0.0178	–0.4438	0.0674	< 0.0001	0.55
70–80	0.0225	0	–	–	–	–	–	40–45	0.0452	–0.4545	0.1000	< 0.0001	0.37
80–90	0.0005	0	–	–	–	–	–	45–50	0.0353	0	–	–	–
≥ 90	0.0513	0	–	–	–	–	–	50–55	0.0306	0	–	–	–
–	–	–	–	–	–	–	–	≥ 55	0.0447	0	–	–	–

To estimate the additional mortality caused by logging damage, we estimated the mortality rate in each dbh class i and species group s observed between measurements 2 and 3. Let m_{isj} be the estimate obtained from a logged plot j and m'_{is} the estimate obtained from all the 12 control subplots. We now focus on a given diameter class and species group to drop the indices i and s. To estimate β, we perform the linear regression:

$$\Delta m_j = \beta \, (X_{j2} / X_{j1} - 1) + \varepsilon_j \qquad (11)$$

where $\Delta m_j = m_j - m'$ and $X = B$ for S_2 or Y for S_3. For the greatest dbh classes, β was not significantly different from 0. The parameter values are given in Table IV.

3. RESULTS

3.1. Model verification

In a simulation starting from an empty 1 ha subplot, pioneer species (S_1) invade very rapidly at the beginning, followed by species of S_3 and finally by the dipterocarps (S_2, Fig. 1). Nevertheless,

Table V. Densities and basal areas of the groups of species at year 300 (starting from an empty plot) and at stationary state.

	Dipterocarps	Pioneers	Others
Year 300 density (ha^{-1})	114.8	14.9	403.0
Stationary state density (ha^{-1})	116.1	6.2	405.4
Year 300 basal area (m^2 ha^{-1})	14.4	1.3	15.2
Stationary state basal area (m^2 ha^{-1})	14.9	0.3	15.8

initiating the simulation from bare land is an extreme extrapolation compared to the range of observations; we mainly did this simulation to get a majored estimate of the time till the stationary state. Although stand density and basal area reach a stationary level only after 840 years, their respective values at year 300 are very close to that of the steady state (Fig. 1 and Tab. V). However, pioneers density remains twice higher at $t = 300$ years than in the stationary state (Tab. V). The mean values of density
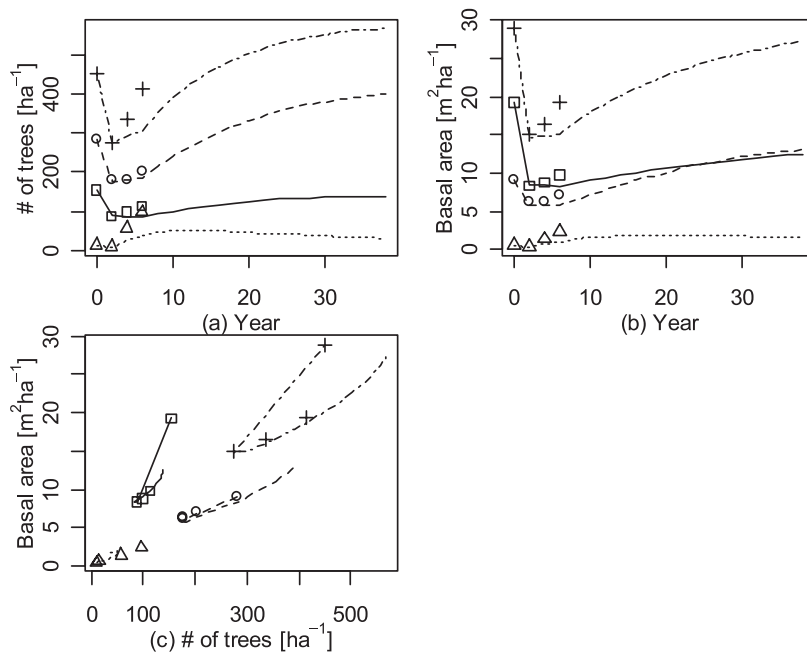
Figure 2. Predictions by the model of the stand dynamics of subplot 2 of plot 8 over 40 years according to species groups. (**a**) density, (**b**) basal area, (**c**): basal area × number of trees. The symbols stand for the observed values in the field: squares (□): dipterocarps; circles (○): others; triangles (△): pioneers; crosses (+): all stand. The lines show the values predicted by the model: — dipterocarps, --- others, ···· pioneers, ----- all stand.

and basal area at the steady state, predicted by the model are not significantly different from those recorded in the 48 subplots before logging (Fig. 1). The matrix model prediction therefore fits with the observed main structural characteristics of the primary forest.

The capacity of the model to predict stand dynamics after logging was tested on the 48 subplots. Subplot 2 of plot 8 was taken here as an example because it showed the strongest contrast between the model predictions and the field data. The predicted steady density and basal area are lower than those recorded in the field, particularly for pioneers at measurements 3 and 4 (Figs. 2a and 2b). However in the "number of trees × basal area" space, predictions fit with the measurements (Fig. 2c), suggesting that the model simply introduces a delay. This means that the model tends to overestimate the return time and consequently the cutting cycle lengths, provided that forest dynamics modelled from a 4-year observation period may be extrapolated to a medium term. It is worth noting that subplot 2 of plot 8 faced the highest logging intensity as well as the highest level of damage of the whole STREK device (17 harvested stems ha^{-1}, 52% of the original basal area remaining). The discrepancy between model predictions and field data decreases as logging damage decreases. Model predictions fit best with subplots of group G1 with low damage and low harvesting rates.

3.2. Return time

The model was used to estimate the time after logging required to reach 90% of the steady state density and volume of harvestable dipterocarps (dbh ≥ 60 cm). This time was called the return time of harvestable stems or volume. We required to reach 90% only (rather than 100%) of the density because the variations of the density become very slow when approaching the stationary value. It results that a small

increase of the threshold above 90% may increase drastically the return time. The return times for density vary from 66 in G1 to 96 and 106 years respectively in G2 and G3, and for volume from 82 in G1 to 115 and 125 years in G2 and G3 respectively. Return times for density in G1 and G2, and those in G2 and G3, are not significantly different, whereas those in G1 and G3 are (Ryan-Einot-Gabriel-Welsh multiple range at 5% level). Return times for volume in G1 and G2 or G3 are different whereas those of G2 and G3 are similar (Ryan-Einot-Gabriel-Welsh multiple range at 5% level).

After logging, density of pioneers increases in proportion with the amount of damage, the most damaged stands showing the highest density (Fig. 3a). In all 3 groups, pioneers reach their highest density 20 years after logging and their maximum basal area at 30 years (Fig. 3b). Past 30 years, pioneer populations decrease in all three groups. The time to reach the original density of pioneers (6.6 trees ha^{-1}) varies significantly in the three groups from 92 in G1, to 170 and 263 years in G2 and G3 respectively (ANOVA F = 20.07, df = 2, $P < 0.001$).

In all 3 groups, dipterocarps reach a maximum density of about 125 stems ha^{-1} at $t = 50$ years (Fig. 4a). At $t = 50$ years, in contrast with density, G1 shows the highest dipterocarp basal area (13.9 m^2 ha^{-1}, 94.5% of the original), followed by G2 (12.7 m^2 ha^{-1}, 86.4% of the original) and G3 (11.7 m^2 ha^{-1}, 79.6% of the original; ANOVA, $F = 16.04$, df = 35, $P < 0.01$, Fig. 4b). The time required for all dipterocarps (dbh ≥ 10 cm) to reach 90% of their original basal area varies significantly among the groups (ANOVA, $F = 7.58$, df = 35, $P < 0.001$), from 45 years in G1 to 65 in G2 and 85 years in G3 (Fig. 4b).

3.3. Sustainable felling cycle

In each of the 36 logged subplots, we simulated successive felling cycles with a constant period T, as many times as
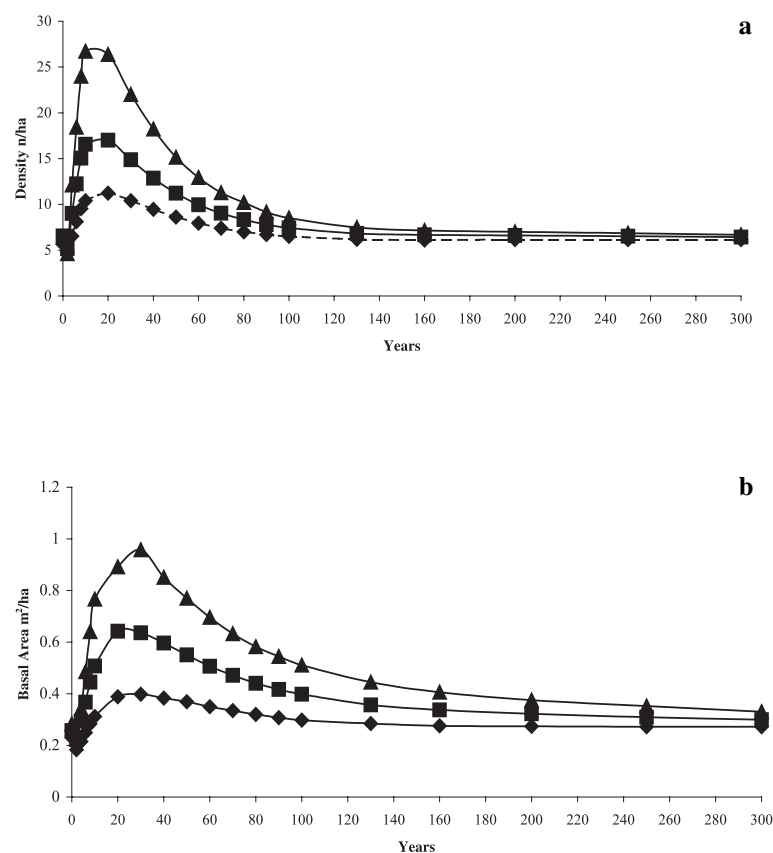
Figure 3. Simulation of pioneer density (**a**) and basal area (**b**) dynamics in the three groups of logging damage (G1: lozenges, G2: squares, G3: triangles).

needed to reach a periodic stationary regime, which actually occurred after 10 cycles. The number of harvested trees at each felling cycle and the rates of damage were those measured in the field in each subplot during the first harvesting (see [4] for methods). We denote $V(t)$ the standing commercial volume at time t (i.e dipterocarps with dbh $\geq$ 60 cm) calculated from the average volume of dipterocarps in each dbh-class tabulated in [16]. Under a constant extraction rate, $V(t)$ stabilizes to a periodic shape, with its maximum every $t = iT$ (just before logging) and its minimum every $t = iT + \Delta t$ just after logging. The standing commercial volume at the end of a cycle $V(iT)$ can be considered as the maximum harvestable volume under a constant felling regime (figure 5). We consider the felling regime sustainable as long as the maximum standing commercial volume $V(iT)$ is greater than the total dipterocarp volume removed (extracted and destroyed) during logging ($V_{removed}$).

The maximum standing commercial volume $V(iT)$ increases with the cutting cycle length T. The shortest sustainable felling period T_{sust} is reached when $V(iT_{sust}) = V_{removed}$. We computed $V(iT_{sust})$ for each logged subplots (n = 36) by computing $V(iT)$ for various periods T. We define the annual extracted volume of dipterocarps under a sustainable felling regime, as $V_{annual} =$ (extracted volume) / $T_{sust} = (V(iT_{sust}) -$ destroyed volume) / T_{sust}. The volume V_{annual} allows us to compare plots with different logging intensities. The extracted volume and the destroyed volume are inputs of the model, whereas $V(iT)$ is the output. In high extraction regimes, T was sometimes too short for the stand to reach the initial extracted volume at the end of the cycle period. In this case, the model removed all the avail-

able standing volume $V(iT)$. Three subplots showed remarkable high standing volume which resulted in very high extracted volume during the first felling that could never be reached afterwards. The stationary volume of these subplots was lower than that removed at first harvesting. Because for these three subplots, it was not possible to compute T_{sust} (and subsequently V_{annual}), we did not include them in the analysis of variance.

Figure 5 shows the predicted mean standing commercial volume $V(t)$ of the three groups of logging damage, under a constant regime cycle of 35 years (i.e. the cutting cycle of the Indonesian silvicultural system, TPTI). In the three groups of damage, the stationary volume is reached at the third felling operation ($t = 70$ years, Fig. 5). The mean stationary volumes removed at each cycle (from $t = 70$ years to $t = 385$ years) in the three groups are much lower than the volumes harvested during the first logging operation (35, 41 and 36 m^3 ha^{-1} vs. 44, 78 and 130 m^3 ha^{-1} respectively in G1, G2 and G3). Plots of G2 show the highest stationary volume ($t = 8.23$, df = 18, $P <$ 0.001 for G1 vs. G2; $t = 8.98$ df = 18, $P < 0.001$ for G2 vs. G3), whereas those of G1 and G3 are statistically similar ($t = 1.22$ df = 18, $P = 0.11$).

The mean sustainable periods T_{sust} in the three groups were significantly different and equalled 27, 41 and 89 years in G1, G2 and G3 respectively ($F = 16.9$, df = 32, $P < 0.001$). In contrast, the respective mean annual extracted volumes (V_{annual}) were not significantly different: 1.6, 1.8 and 1.4 m^3 ha^{-1} year^{-1}, respectively in G1, G2 and G3 ($F = 0.65$, df = 32, $P = 0.52$). The sustainable period T_{sust} increased with extracted volume: the
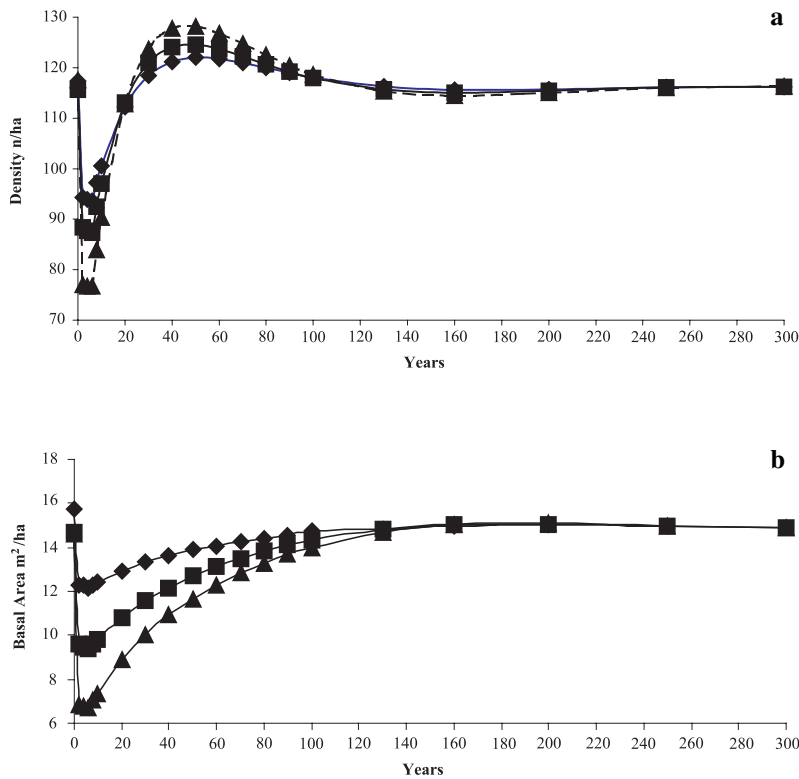
Figure 4. Simulation of dipterocarp density (**a**) and basal area (**b**) dynamics in the three groups of logging damage in Berau (G1: lozenges, G2: squares, G3: triangles).
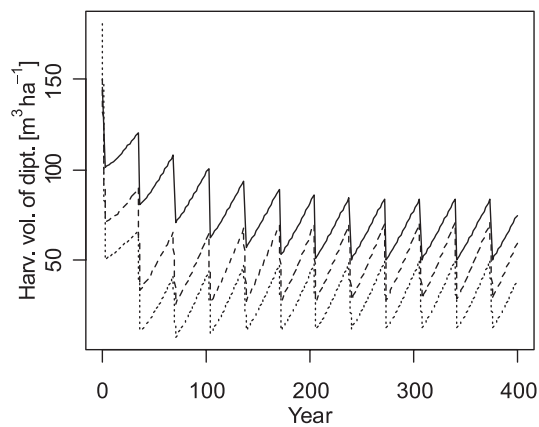

Figure 5. Simulation over 400 years of the mean standing commercial volume $V(t)$ (dipterocarps with dbh $\geq$ 60 cm) under a 35 year constant felling regime in the three groups of damage: — group G1, --- group G2, ···· group G3; $V(iT)$ = mean maximum harvesting volume at each cycle (see text).

more intensive the logging, the longer the felling cycle (Fig. 6). An exponential relationship between sustainable period and logging intensity was adjusted (Fig. 6a). The sustainable extracted annual volume was then computed as a function of logging intensity (Fig. 6b). According to the model predictions, yield sustainability within a 35-year cutting cycle, as that prescribed in the Indonesian selective logging system

(TPTI), can be achieved only under a moderate logging intensity of about 8 trees ha^{-1} (7.6) and a mean annual volume of 1.6 m^3 ha^{-1} year^{-1} (Figs. 6a and 6b).

3.4. Species groups dynamics

The impact of logging on the dynamics of the three groups of species was assessed by computing the proportion of each species group for different cutting cycles. The proportions were calculated as the share of the species group in the basal area of the whole forest, averaged over a complete cutting cycle in the stationary cutting regime. Figure 7 shows the proportion in basal area of the dipterocarps and pioneers, depending on the damage group and the cutting cycle period. Longer periods and lower damage favour dipterocarps. The proportion of dipterocarps in basal area in G1 and G2 were very close and clearly higher than that recorded in G3 (Fig. 7). The proportion of pioneers varies in an opposite way to dipterocarps. However, it does not vary much for $T > 35$ years, for any of the damage groups. Below that threshold, the proportion of pioneers increases sharply as T decreases.

4. DISCUSSION AND CONCLUSION

The time needed for a forest stand to come back to its original structure, that we assimilated here to the return time, proved to be much longer than the sustainable cutting cycle period. However, our simulations demonstrated that sustainable yield regime does not necessarily require to come back to
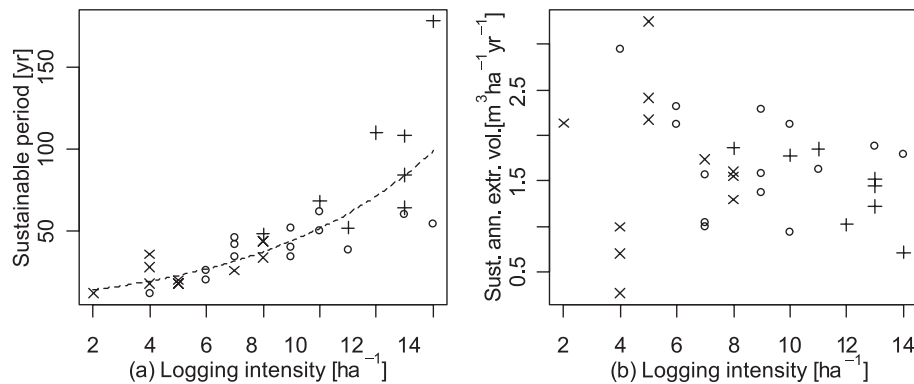
Figure 6. (**a**) Sustainable period T_{sust} (years) a function of the logging intensity LI (trees/ha). (**b**) Sustainable annual extracted volume of dipterocarps V_{annual}, as a function of logging intensity (LI). Each point represents a subplot: × subplot of G1; ○ subplot of G2; + subplot of G3. The equation of the function is $T_{\text{sust}} = 10.2 \exp(0.162 \text{ LI})$ (linear regression between $\log(T_{\text{sust}})$ and LI: $R^2 = 0.76$, $F = 97.0$, df = 32, $P < 0.001$), where T_{sust} is expressed in years and "LI" is the logging intensity in tree ha^{-1}. In each plot there are 33 points (two of them are superimposed in plot (a)).
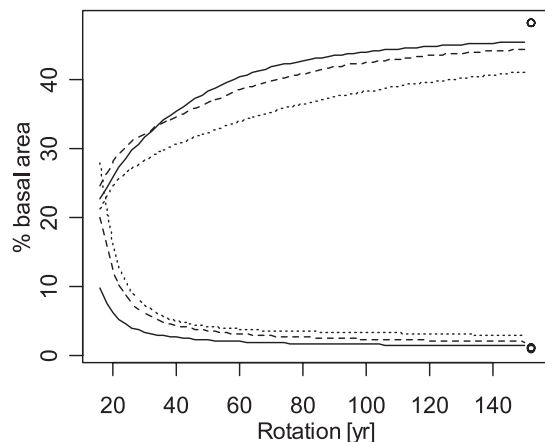

Figure 7. Proportion of dipterocarps (top curves) and pioneers (bottom curves) for different cutting cycles and mature forest (○) and for the different groups of logging damage: — group 1, --- group 2, ···· group 3. The proportions are calculated as the share of the species group in the basal area of all stand. Each value is the average over the 11 to 14 subplots of the group of damage of the mean proportion over a complete cutting cycle in the stationary cutting regime.

pristine conditions at each felling cycle. Although the model was not built to assess species composition changes during forest recovery some general trends of the dynamics of our three groups of species provide some interesting information. However, according to our simulations, the time required to return to pristine pioneer population characteristics is even under low harvesting intensities at least 90 years. This suggests that under successive logging operations at relatively short period intervals (40 years), forest stand will probably evolve towards structures and species compositions differing from that of pristine forests. High extraction rates favour light-demanding dipterocarps as well as pioneer species [20]. This was confirmed in this study as pioneer density was the highest in heavily damaged stands (G3, Fig. 3). Repeated logging operations similar

to those recorded in G3 would stabilize or even increase this phenomenon. In contrast, it is reasonable to assume that a moderate logging intensity associated with controlled and planned logging operations to limit damage, will probably not affect stand diversity or species composition in an irreversible manner. However, the need to preserve substantial areas of primary forest in any forest management plan remains essential to preserve landscape and ecosystem biodiversity within production areas. This corroborates conservationists recommendation to reserve areas within forest concession [38].

As the model was calibrated on this short 4-year period, it may be unable to reproduce specific mid- and long-term processes, especially as far as the behaviour of pioneers populations are concerned. The 4-year post logging observation period of this study corresponded to an expanding stage of pioneer populations stimulated by canopy openings resulting from harvesting operations [41]. Only longer term monitoring would provide a correct estimation of the lifespan of this group of species and allow for a more accurate description of its dynamics.

The Indonesian selective system (TPTI), that recommends a 35-year cutting cycle, would allow an extraction rate of 7 to 8 trees ha^{-1} to ensure yield sustainability. However, in TPTI, the Annual Allowable Cut (AAC) is simply determined by the density of harvestable timber size trees (mainly dipterocarps with dbh ≥ 60 cm). Because primary dipterocarp forests of Borneo exhibit a high density of harvestable trees (23 ha^{-1} above 50 cm and 16 ha^{-1} above 60 cm, [13, 31, 43]), any selective logging based on the minimum diameter cutting limit will therefore result in high felling intensities, ranging from 10 to 14 trees ha^{-1}. Under such high extraction rates (G3 case), yield sustainability requires a 90-year felling cycle. In terms of economic profitability, it is generally admitted that cutting cycles longer than 60 years have lower returns than shorter ones [20]. Taking this economic profitability aspect, the best option, according to our study, and within the Indonesian forestry regulation (TPTI), would be a 40-year felling cycle, for a yield of about 67 m^3ha^{-1} (8 trees ha^{-1}) or 1.6 m^3ha^{-1} year^{-1}. These values are also consistent with other

studies related to yield analyses in mixed dipterocarp forests of the region [20, 34]. High extraction regimes also involve major impacts on dynamics processes and forest composition. There is scant evidence that any commercial dipterocarp species benefits canopy openings greater than those created by single-tree selection cutting practices (500–600 m^2) to establish and maintain good growth, especially those of commercial value [24, 41, 46, 50]. High extraction rates by creating big canopy openings rather stimulate the growth of pioneer competitors and create drought conditions [33], hindering the establishment and growth of dipterocarps. Moreover, large openings are more subject to lianas invasion which can be a serious obstacle to tree regeneration. Big canopy openings in heavy logged-over forests increase fire risks and propagation, particularly during a long period of drought as this periodically occurs in South East Asia during El Niño events.

Previous study on logging damage in the study area demonstrated that RIL efficiency to keep logging damage under a reasonable threshold of 25% of the original stand [4] was quite limited if felling intensity exceeded the threshold of 8 trees ha^{-1} [42]. It is therefore worth noting that both in terms of immediate damage reduction during harvesting operations and long-term yield sustainability, this threshold of 8 trees ha^{-1} remains valid. Practical rules based on minimum spacing distance between harvested trees and maximum diameter cutting have been recommended by [40] to keep felling intensity under this threshold and to limit gap size to less than 500–600 m^2.

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