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EVALUATION OF LOGGING IN A DIPTEROCARP RAIN FOREST USING THE FORMIND FOREST MODEL AND MULTICRITERIA DECISION ANALYSIS

Andreas Huth, Martin Drechsler and Peter Köhler
UFZ Centre for Environmental Research Leipzig-Halle,
Department of Ecological Modelling
P.O. Box 500 136, D-04301 Leipzig, Germany
Huth@oesa.ufz.de
MartinD@oesa.ufz.de
pkoehler@awi-bremerhaven.de

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Summary: *Sixty-four different logging scenarios for an initially undisturbed forest stand at Deramakot (Malaysia) were simulated with rain forest growth model FORMIND. The scenarios differ regarding the logging cycle, logging method, cutting limit and logging intensities. We characterise the impacts with four criteria describing the yield, canopy opening and changes in species composition. Multicriteria decision analysis was used to evaluate the scenarios and identify the efficient ones.*
Our results plainly show that reduced-impact logging scenarios are more 'efficient' than the others, since in these scenarios forest damage is minimised without significantly reducing yield. Nevertheless there is a trade-off between yield and achieving a desired ecological state of logged forest; the ecological state of the logged forests can only be improved by reducing yields and enlarging the logging cycles. Our study also demonstrates that high cutting limits or low logging intensities cannot compensate for the high damage caused by conventional logging techniques.

1. Introduction

Timber harvesting in tropical rain forest is widely discussed. Timber logging, land clearing, high population pressure, forest fragmentation and climate change are all threats to tropical rain forest. Reducing these impacts and changing to sustainable development are needed to reduce extinction of various plants and animals in the tropics (Laurance et al. 1997; Whitmore 1998).

The certification of tropical timber is one way of supporting sustainable forest management. The controversial discussion over how to achieve sustainable forest management is still underway (Boot and Gullison 1995; Putz and Viana 1996; Putz and Putz 2000). Economic factors still play an important role in forest management decision-making. One main option seems to be to decrease logging damage by using 'reduced-impact' logging techniques. Such management is based on the detailed planning and supervision of logging operations combined with special wood transport systems (e.g. skyline yarding). Computerised simulation models designed to estimate the long-term impact of logging scenarios are useful tools for clarifying this discussion.

In recent years several simulation studies have been published focusing on logging in tropical rainforests. Liu and Ashton (1999) analysed the consequences of timber harvesting on tree species diversity under different seed dispersal assumptions. Pinard and Croper (2000) simulated the effects of logging on carbon storage in Dipterocarp forest. Boscolo et al. (1997a) calculated the economic costs of carbon storage in forests. Huth and Ditzer (2001) analysed impacts of conventional and reduced-impact logging scenarios.

To obtain a better understanding of the manifold ecological and economic effects of logging, a large number of logging scenarios have been considered in this study (64 scenarios). Each scenario is defined by four different options to reduce logging impacts: reducing logging damage, increasing logging cycles, increasing the cutting threshold and decreasing logging intensity. The impacts are evaluated using 18 indicators reflecting timber yield, canopy opening and the change of species composition in the forest.

One particular problem of sustainable forest use is balancing ecological and economic objectives. There will generally be trade-offs and the 'optimum' logging scenario is very likely to depend on the priorities or weight assigned to those objectives. The analysis of such a complex decision problem where a large number of scenarios has to be evaluated and ranked with respect to several conflicting objectives or criteria is known as 'multicriteria decision analysis' (MCDA) (Bana e Costa 1990). As far as we are aware, in this study MCDA is applied to a forest management problem and combined with a rain forest model for the first time.

Since MCDA can handle the integrated consideration of a large number of criteria, it does not require all the criteria to be measured on the same scale as most of the other assessment tools commonly used do (such as cost-benefit analysis, which has just one single monetary scale and requires the monetarisation of all ecological and social effects). Examples where MCDA has been applied in an ecological context can be found in Ralls and Starfield (Ralls and Starfield 1995; Beinat and Nijkamp 1998; Drechsler 2002).

MCDA usually starts with a matrix whose elements contain the effects of the scenarios in the various criteria. This multicriteria matrix can then be analysed in a large variety of ways, including utility-based methods such as the multi-attribute value theory, outranking methods, interactive and explorative methods (Stewart 1992; Gal et al. 1999). In the present study we use a two-step approach. In the first step multi-attribute value theory is applied to aggregate a large number of indicators in a few criteria, which in a second step are analysed in an exploratory analysis.
The forest simulation model used in this study is the process-based forest growth model FORMIND (Köhler and Huth 1998; Kammesheidt et al. 2001). It was used to evaluate the approach of the more aggregated model FORMIX3 (Huth et al. 1998). The model is individual-oriented and simulates the spatio-temporal dynamics of an uneven-aged mixed forest stand(Ditzer et al. 2000; Huth and Ditzer 2000). Tree species are aggregated into 13 plant functional types (Köhler et al. 2000). The tree growth modul was tested against permanent sampling file data of Sabah (Köhler et al. 2001). The recent model version FORMIND 2.0 was analysed and applied to forest harvesting studies in Malaysia, Venezuela and French Guyana (Kammesheidt et al. 2001; Köhler et al. 2002).

The forest model and decision analysis are used to answer the following questions:
(1) How are the forest structure and species composition modified by logging as a function of logging method, length of cutting cycle, cutting threshold and logging intensity?
(2) Is there an optimum combination of logging parameters which maximises yields and minimises changes in the forest structure at the same time, or is there a trade-off between timber yield and ecological objectives?

2. Methods

2.1 The site

We simulate growth and logging of the tropical rain forest of the Deramakot Forest Reserve (DFR) situated in Sabah (North Borneo,Malaysia, 117°30' E, 5°5' N, 130–300 m asl.). Deramakot has a per-humid climate with a mean annual temperature of 27° with little seasonal variations. The average annual precipitation is about 3500 mm, with no pronounced dry season. The soils are low in nutrients and prone to erosion once left devoid of tree cover. The dominant prevailing forest type is lowland Dipterocarp forest. Commercial logging started in the 1950s with varying intensity and damages.

2.2. Model description

Formind2.0 is an individual-oriented, process-based forest growth model which simulates the spatial and temporal dynamics of uneven-aged mixed forest stands. A complete model description has already been published (Köhler and Huth 1998; Köhler 2000). The general model behaviour including stability and sensitivity analysis (Kammesheidt et al. 2001) and a comparison of model behaviour against growth data of permanent sampling plots in Sabah (Köhler and Huth 1998) were already analysed.

The model simulates a forest stand as a mosaic of interacting patches of 20 m × 20 m in size. Within these patches, trees are not spatially-explicitly distributed, and thus compete for light and space following the gap model approach. The carbon balance of each individual tree is modelled explicitly including the main physiological processes (photosynthesis, respiration). Allometric relationships relate the above-ground biomass, the stem diameter, the tree height and the crown diameter. Growth process equations and physiological parameters are taken from the related model Formix3-Q (Ditzer et al. 2000). Tree mortality can occur either through self-thinning in dense patches, senescence, or large trees falling (gap formation). We assumes constant seed input rates which is correlated with the reproductive success at minimum diameter of 1 cm (Nathan & Muller-Landau 2000). Thus, the seed production rate lumps together several regeneration stages: fecundity, seed survival, germination and possible predation upon young seedlings. Incoming seeds update a seed pool, taking into account the dormancy variability across functional groups.

The more than 400 different tree species found in Deramakot were aggregated into 13 plant functional types (PFT) using three different successional stages and maximum tree height as grouping criteria (Köhler et al. 2000). The abundance of these different successional stages and the PFT were used as indicators in our MCDA (see below).

2.3. Simulated logging scenarios

We simulated 64 different logging scenarios (Table 1). The scenarios differ in the logging method (conventional logging with high damage and reduced-impact logging with low damage), logging cycle (time period between two logging events), cutting limit (only trees with a higher diameter above the cutting limit are logged) and logging intensities (number of remaining harvestable trees in the stand). The area size was kept constant at 9 ha; we assumed the boundary conditions to be periodic.

Table 1: Simulated logging scenarios.

Scenario[a]		Logging method	Logging cycle [yr]	Cutting limit [cm]	Number of remaining trees after logging [ha^{-1}]
A	R20-	Reduced impact (RIL)	20	30, 40, 50, 60	0
	C20-	Conventional (CON)	20	30, 40, 50, 60	0
	R40-	RIL	40	30, 40, 50, 60	0
	C40-	CON	40	30, 40, 50, 60	0
	R60-	RIL	60	30, 40, 50, 60	0
	C60-	CON	60	30, 40, 50, 60	0
	R80-	RIL	80	30, 40, 50, 60	0
	C80-	CON	80	30, 40, 50, 60	0
B	R20-	RIL	20	60	0, 3, 6, 9
	C20-	CON	20	60	0, 3, 6, 9
	R40-	RIL	40	60	0, 3, 6, 9
	C40-	CON	40	60	0, 3, 6, 9
	R60-	RIL	60	60	0, 3, 6, 9
	C60-	CON	60	60	0, 3, 6, 9
	R80-	RIL	80	60	0, 3, 6, 9
	C80-	CON	80	60	0, 3, 6, 9

[a] A: scenarios assuming different cutting limits, B: scenarios assuming different numbers of remaining trees after every logging operation**.**

Logging method. We distinguish two methods: highly damaging conventional logging (CON), which generally uses heavy machinery and unskilled workers but little planning, and reduced-impact logging (RIL), where substantial planning for road construction, felling directions etc. is performed. In RIL, tree removal usually implies the use of winching cables or airborne cable systems. The differences modelled between the two

methods represent the logging impact on the residual stand. We distinguished: (1) Damage proportional to the crown size through tree felling. The felling direction was chosen randomly in CON, but directed to neighbouring gaps in RIL whenever possible. (2) Skidding damage in the patch of a felled tree (25% and 50 % for RIL and CON respectively). (3) Land loss due to road construction and log landings (25% and 50 % for RIL and CON respectively). (4) Increased mortality rates for ten years after each logging event accounting for damaged but not instantly destroyed tree (RIL: 2x; CON: 3x)
Logging cycle, cutting limit and logging intensity. The time between two logging operations was constant, but differed between the scenarios (20, 40, 60, 80 years). All commercial trees of the mid- and late-successional species above a certain minimum diameter – the cutting limit (30, 40, 50, 60 cm) – were removed in a logging operation. The logging intensity was varied by defining a number of remaining harvestable trees in the forest for each scenario (0, 3, 6, 9 trees/ha).

2.4 Indicators and multicriteria decision analysis

Table 2 shows the 18 indicators used to evaluate the scenarios. In order to derive forest management recommendations from the results of the exhaustive model analysis, these 18 indicators have to be aggregated and important relationships detected. This is done in two steps.

Table 2: Criteria and indicator list

Criteria	Indicator Index	Description		height class [m]	Value for undisturbed forest [%]
yield Y	1	total harvested stem volume in 240 years			
canopy opening O	2	Changes [a] of fraction of area with trees no higher than 25m			4
species composition SC1	3	Changes [a] in the stem volume of	Early successional spp.		0.7
	4		Mid-successional spp.		69.6
	5		Late-successional spp.		29.7
species composition SC2	6	Changes [a] in the stem volume of	Shrub mid-successional spp.	0-5	0.0
	7		Understorey early-successional spp.	5-15	0.0
	8		Understorey mid-successional spp.	5-15	6.9
	9		Understorey late-successional spp.	5-15	6.4
	10		Lower canopy early-successional spp.	15-25	0.7
	11		Lower canopy mid-successional spp.	15-25	18.8
	12		Lower canopy late-successional spp.	15-25	0.2
	13		Upper canopy early-successional spp.	25-36	0.0
	14		Upper canopy mid-successional spp.	25-36	6.6
	15		Upper canopy late-successional spp.	25-36	3.6
	16		Emergent early-successional spp.	>36	0.0
	17		Emergent mid-successional spp.	>36	37.0
	18		Emergent late-successional spp.	>36	19.5

[a] Changes are calculated for the different indicators as follows: $|\underline{C}_i - P_i|$ with P_i indicator value for an undisturbed forest and $\underline{C}_i$ mean value obtained for indicator C_i over the whole simulation period of five repeated runs initialised with different random numbers. Yield is calculated in m³/ha, area fraction in % and stem volume in m³/ha.

First the 18 indicators are aggregated into 4 meaningful criteria C which encompass the most important features of the decision problem. The first criterion and second criteria are identical to the first and second indicators: the yield and the canopy opening. The third criterion and forth criteria (species composition SC1 and SC2) are obtained by aggregating the three/13 indicators for the coarse/ fine tree species groups, respectively. To aggregate the indicators into the four criteria we use the multi-attribute value theory

(MAVT), where the total value of an attribute is the weighted sum of the properly scaled indicator values (Ralls and Starfield 1995).

In the following we describe how this theory is applied to aggregate the indicators I_3, I_4 and I_5 into criterion SC1. For each scenario S_i the performance in the indicators I_3, I_4 and I_5 is denoted as $v_3(S_i)$, $v_4(S_i)$ and $v_5(S_i)$, respectively. First the values achieved by the scenarios in indicator I_3 are rescaled to the interval [0,1], which is done by the transformation

$$v_3(S_i) \rightarrow \frac{v_3(S_i) - \min_i v_3(S_i)}{\max_i v_3(S_i) - \min_i v_3(S_i)}$$

(1)

where the minima $\min_i$ and maxima $\max_i$ are taken over the values $v_3(S_i)$ of all scenarios S_i in indicator I_3. The same transformation is carried out for indicators I_4 and I_5 and ensures that the scales of the three indicators are comparable. Now we calculate for each scenario S_i a score $V_{SC1}(S_i)$ which is the average of the values $v_3(S_i)$, $v_4(S_i)$, and $v_5(S_i)$.
This score measures the performances of the scenario S_i in criterion SC1 (note that by using the average in the aggregation of indicators I_3-I_5 we assume that each of these indicators has equal weight). Lastly, the scores $V_{SP1}(S_i)$ are rescaled to the interval [0,1] using the analogon of Eq. (2).

Thus, the scenario that performs worst in criterion SC1 has a score of 0 while that which performs best has a score of 1. The indicators I_6-I_{18} are aggregated into criterion SC2 in the same way: first the values $v_6(S_i)$-$v_{18}(S_i)$ are rescaled to the interval [0,1] according to Eq. (2), and the mean of these values is calculated to obtain $V_{SC2}(S_i)$ (cf. Eq. (3)) which finally is rescaled to the interval [0,1] (Eq. 4). To obtain the performances of the S_i in the second criterion, O, we simply apply Eq. (2) and rescale the values $v_2(S_i)$ to the interval [0,1]. Instead of the yield criterion Y being modified, the original data are used in the analysis.

In the second step, conflicts between the four criteria Y, O, SC1 and SC2 are examined. This includes identifying the efficient management scenarios. A scenario S is termed efficient if there is no other scenario S' that is at least as good as S in each criterion, and strictly better than S in at least one criterion (cf. Fig. 3). Here a scenario S is termed "at least as good as a scenario S' in a criterion C_j" if the values of S and S' are either equal or if the value of S exceeds that of S'. The former case is termed "indifference between S and S' in C_j" and the latter "preference of S over S' in C_j" (Bana e Costa 1990). In the analysis some scenarios may differ only slightly in their values V. For instance, there may be two scenarios S_i and $S_{i'}$ such that S_i only has a marginally higher value in a criterion C_j ($Cj \in \{Y, O, SC1, SC2\}$) than scenario $S_{i'}$. In this case deciding that S_i is better than $S_{i'}$ in C_j is possible. Instead the two scenarios should be regarded as indifferent in C_j, as long as the difference between the values of the two scenarios, $|V_{Cj}(S_i)- V_{Cj}(S_{i'})|$ does not exceed some threshold called the 'indifference threshold' (Bana e Costa 1990). In the present decision problem we chose a 'resolution' of 10%: If in a particular criterion C_j two scenarios differ by less than 10% of the maximum range of values in that criterion ($\max_{ii'}|V_{Cj}(S_i)-V_{Cj}(S_{i'})|$), these two scenarios are regarded as indifferent in C_j.

3. Results

Fig. 1 shows the development of forest stem volume, species group composition and obtained yield for two scenarios. Each logging event results in a strong decline of the stem volume. In the first 20 years after each logging the early-successional species are very abundant, and in the conventional logging scenario (CON) the general level of this group is much higher than in the reduced-impact scenario (RIL). Yields are very low but stable in the CON scenario, whereas in the RIL scenario the second and third logging events lead to lower yields as the forest needs a long time to regenerate after the first logging event (year 0). The extremely low yield after the first logging event in the conventional logging scenario is a strong indicator that here the forest is being overexploited.

In following, we analyse the analysis economic and ecological impacts of logging. Fig. 2a shows yield Y and the ecological state E for the scenarios with different cutting limits. E is calculated as the direct sum of the three ecological criteria canopy opening O, species composition SC1 and SC2. The scenarios plotted by large dots that are efficient, i.e. no increase in any criterion (Y, O, SC1, SC2), are possible without at least one of these four criteria being decreased. Scenarios with high yields are shown on the right of the diagram, scenarios with low yields on the left. Scenarios with a good ecological state E are shown in the upper half; scenarios resulting in a bad state are plotted in the lower half of the diagram. The reduced impact logging scenario with a logging cycle of 80 years and a cutting diameter of 60 cm produces the best ecological state for the logged forest (scenario R80-60). The highest yields can also be obtained in a reduced-impact logging scenario assuming a cutting limit of 40 cm and a logging cycle of 20 years (scenario R20-40). All the efficient scenarios are in the upper right-hand corner of the diagram, which indicates that ecological improvement comes at the cost of reduced yield (cf. definition of efficiency above). Obtaining the best ecological state means cutting yield by nearly 50% (cf. scenarios R20-40 and R60-80). Interestingly, all the efficient scenarios are reduced-impact logging scenarios.

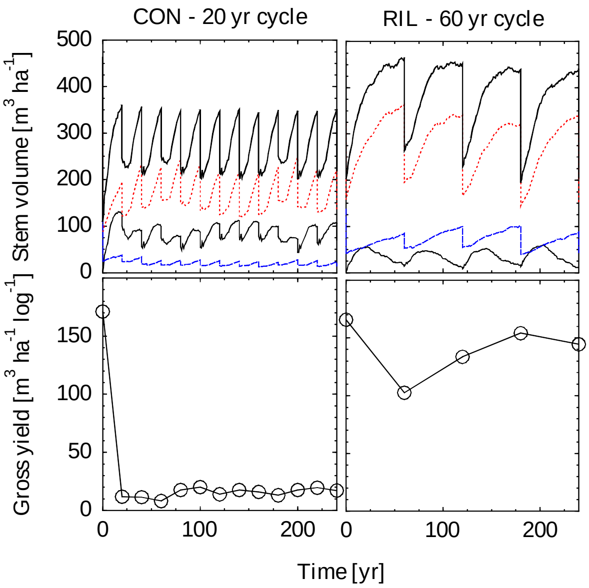

Figure 1 Two examples of simulated logging scenarios. Left: scenario with conventional logging (CON) and a logging cycle of 20 years. Right: scenario with reduced-impact logging methods (RIL) and a logging cycle of 60 years. Cutting limit = 60 cm and no remaining harvestable tree in both scenarios. Top: Stem volume over time for all tree species (bold black line), the early-successional (black line), mid-successional species (short-broken line) and the late-successional species (long broken line) Bottom: yields for each logging event.

Fig. 2b shows the ‘trade-off’ diagram for the scenarios assuming different logging intensities. As expected the best ‘ecological’ scenarios leading to the best ecological state are those using low impact logging methods and low logging intensities (scenarios R60-9. R80-9, R60-6, R60-3 with 3-9 harvestable trees per hectare remaining in the forest). Although the scenarios with the highest yields (R60-0, R80-0 and R40-0) assume higher logging intensities, the ecological state of the logged forest does not differ greatly from those with the best ecological performance. Similar to Fig. 3a, the reduced-impact logging scenarios are generally the efficient ones. Two interesting exceptions are the conventional logging scenarios (C20-0 and C20-3), which have a low ecological state *E* but are efficient with respect to the four criteria Y, O, SC1 and SC2. The reason is that these are best in terms of the coarse species composition SC1. Although most of the other scenarios lead to a better overall ecological state E (which is the sum of O, SC1 and SC2) and a higher yield Y, they are worse in SC1. This shows it is not enough to consider just the overall ecological state; the individual criteria also need to be considered because they do not always correlate with the overall ecological state E.

4. Discussion

Rainforest growth models are useful tools for analysing and comparing the long-term impact of logging strategies. Combined with multicriteria decision analysis, they can be used to evaluate logging impacts with a large number of indicators describing ecological and economical benefits. Our results clearly show that reduced-impact logging scenarios are more ‘efficient’ than the others as they minimise ecological damage to the forest. Nevertheless, there is a trade-off between ecological state and yields such that in the efficient reduced-impact logging scenarios, an improvement in the ecological state comes as the price of reduced yield. Our study also shows that high cutting limits or low logging intensities cannot compensate for the high damage caused by conventional logging techniques. Our study confirms the advantages discussed of low-impact logging methods (Putz et al. 2000). However, longer logging cycles are needed to protect the structural diversity of tropical rainforest, at least in parts of the logged areas. The simulation results suggest that for Dipterocarp lowland forest in North Borneo a logging cycle of 60 years combined with low-impact logging methods may be an appropriate compromise between economical and ecological interests.

In this study we used three indicator describe changes in the forest structure: canopy opening, and species group composition on two different scales (SC1 and SC2). Species composition as calculated here seems to be a rather complex indicator. In several cases we observed contrary trends for these two indicators with example SC1 exhibiting large changes and SC2 only small ones – and vice versa. It seems possible that small changes at the small scale mount up to effect large changes on the broader scale. In addition, the level of species shift tolerable in relation to forest conservation is not clear.

Discussion over useful indicators is ongoing. Pretzsch et al. (1997; Mendoza and Prabhu 2000; Pommerening et al. 2000) introduced some indicators describing the spatial heterogeneity of the forest. Boscolo et al. (1997a; 1997b) only used changes in the above-ground forest biomass as an indicator. Indicators describing changes in tree size distribution might also be useful. Several criteria lists have been developed for individual countries, selected to aid the development of policies that would support sustainable forest management at the national level and provide a common framework for monitoring and assessing trends. For example the "Santiago Declaration" (Miles 2002) by twelve countries includes five criteria groups which deal with ecological aspects of forestry: (1) conservation of biological biodiversity, (2) maintenance of production capacity of forest ecosystems, (3) maintenance of health and vitality, (4) conservation and maintenance of soil and water resources, (5) maintenance of forest contributions to the global carbon cycle. Similar criteria are used by the Forest Stewardship Council (Mendoza and Prabhu 2000).

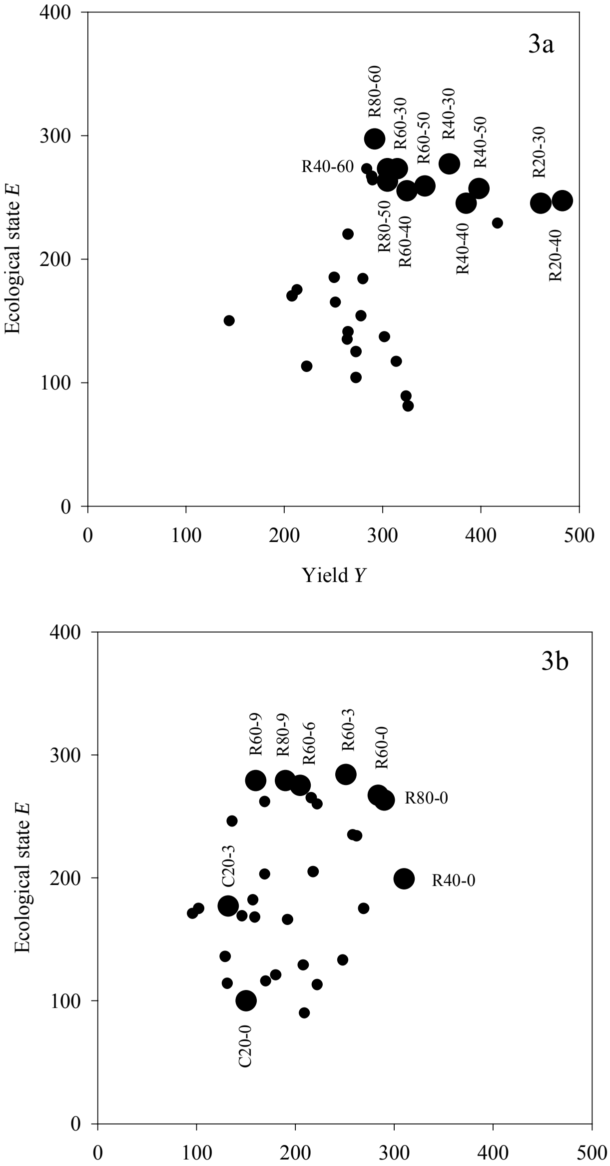

Figure 2 All 32 scenarios plotted by the yield Y and the ecological state E they produce (where E is the direct sum of the three ecological criteria canopy opening O, species composition SC1 and SC2, and ranges from 0 to 300). (a) shows the scenarios assuming different cutting limits and (b) different logging intensities. The efficient scenarios are represented by large dots.

The certification of forest management units closely depends on the evaluation of experts (Mendoza and Prabhu 2000). We believe that growth and yield studies using forest simulators and multicriteria decision analysis can help reduce 'subjective errors and misjudgements' in expert evaluation and so improve the quality of their decisions. Furthermore, formalising the decision problem in multicriteria decision analysis allows a large number of criteria and logging options to be analysed, which is important in the current situation where exactly what criteria and indicators are the main ones is not clear(Mendoza and Prabhu 2000).

Decision analysis allows not only the evaluation of trade-offs between different objectives at a given time, but also discussion of issues of time preference: should future costs or benefits be valued higher, the same or lower than present ones? Sometimes the argument is put forward that economic benefits, such as timber yield, should be discounted, making future yield less valuable than present yield. However, if at the same time the ecological effects are not discounted, this leads to a situation in which future ecological costs are accepted to achieve a high present economic benefit (Hanley and Spash 1993). From the angle of sustainability and intergenerational equity this is unacceptable, prompting others to argue that discounting should not be applied (Portney and Weyant 1999).

The simulation results in this study may be optimistic regarding harvesting impacts, because the model assumes the soil provides suitable conditions for seeds to germinate and become established. Due to logging soil may be partly compacted, reducing the establishment and germination of seeds. Compacted soils may lose their nutrients due to erosion. Another problem might be the extraction of nutrients due to harvesting. In the logged Dipterocarp forest on Borneo, it will take 20–60 years to restore the normal amount in the ecosystem (Glauner 1999). In other regions nutrient input due to precipitation or rock decomposition may be much lower. Moreover , we currently know little about the nutrient levels trees need in the tropics (Whitmore 1998).

In future additional problems due to climatic change and population pressure may have a strong impact on logging impacts and yields. Curran et al. (1999) observed very low recruitment rates due to El Niño events. Shortened rain seasons can cause severe drought stress to trees. The mortality of large trees is much higher in the border zone of fragmented forest (Laurance et al. 1997) and the fragmentation of tropical forests is still continuing. Two simulation studies which include these additional disturbances are in progress (Köhler et al. 2003a, 2003b).

Field studies are inadequate for testing whether a logging system is sustainable. The fact that some logging systems still exist after many years does not mean the current harvest is sustainable, because often we do not know whether current extraction levels are the same as previous ones. Static comparisons of tree populations in harvested and unharvested forests only show the effects of logging on stand structure, not necessarily the sustainability of harvesting. Dynamic data on growth, mortality and regeneration are needed to assess sustainability. The time period for which demographic data are available is on the scale of years to decades. This is much shorter than the time scale needed to assess the sustainability of a harvesting strategy. Thus the only option we have is to incorporate these data into simulation models to determine the long-term consequences for forest structure and dynamics.

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