Analysis of logging strategies for tropical rain forests with FORMIND

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Abstract

Estimation of the production and dynamics of tropical rain forest is an important issue for a sustainable management of these forests. In this paper we use the forest model FORMIND for analysing logging strategies. The model describes growth, mortality, recruitment of trees and competition between trees. The calculation of tree growth is based on a carbon balance. Dying large trees fall down and create gaps in the forest. Tree species are grouped in plant functional types.
Different management strategies for Dipterocarp rain forest in Malaysia were analysed. The scenarios differ regarding the logging cycle, logging method, cutting limit and logging intensities. We characterise the impacts with three 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. 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.

Introduction

Sustainable forest management has been widely discussed during the last decade as one key strategy of reducing the ongoing destruction and depletion of tropical rain forests. Several certification systems based on criteria and indicators have since been established to evaluate whether a forest management practice is sustainable (Mendoza & Prabhu, 2000a).
But how can it be evaluated whether a certain long-term strategy is sustainable? Although a logging system may still produce good yields after many years, this does not necessarily make it sustainable, because normally we do not know whether current yield levels are the same as previous ones. In addition, it goes without saying that sustainable management must ensure not only stable yields but also conserve various forest functions on which an intact forest structure depends. Different lists of criteria and indicators have been worked out (Miles, 2002; Mendoza & Prabhu, 2000a), but what kinds of criteria are important and what are the trade-offs among them (Boot & Gullison, 1995; Putz & Viana, 1996; Putz & Putz, 2000; Pearce *et al.*, 2003)?
One option towards sustainable management seems to decrease logging damage by using 'reduced-impact' logging techniques. Other proposals towards sustainability include reducing logging intensity, or lengthening the cutting cycle, or increasing the lower cutting limit (of the stem diameter of harvested trees). Reduced impact logging involves the detailed planning and supervision of logging operations combined with special timber transport systems to reduce logging damage (e.g. skyline yarding). Several empirical studies have shown that

such logging methods have many positive effects on the conservation of biodiversity and the stability of yields in the short term (Pinard & Putz, 1996, Pulkki, 1997, Putz et al., 2001).
The problem is that all such field studies only cover a time period of several years to a few decades at best, yet to assess the sustainability of forest management, we need knowledge about the long-term impacts of management strategies on forests.
In our view, there are two ways of dealing with this problem: (a) analysing forest stands whose disturbance history is known in detail (Saldarriaga *et al.*, 1988; Brown & Lugo, 1990; Moran *et al.*, 2000), (b) using computer simulation models to estimate the long-term impact of management.
In recent years, several studies have been published using the latter approach. 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 the carbon storage in a Dipterocarp forests. Boscolo et al. (1997) and Healey et al. (2000) calculated the economic costs of carbon storage in forests. Huth and Ditzer (2001) analysed the impacts of conventional and reduced-impact logging scenarios.
In this study, we also take the simulation approach. In the last two decades, a lot of data on the dynamics of growth, mortality and regeneration of Dipterocarp rain forests have been published (e.g. Monokaran & Swaine, 1994; Phillips & Gentry, 1994; Newbery *et al.,* 1996; Whitmore, 1998). We incorporate these data into an existing simulation model to estimate the long-term consequences of different management strategies on forest structure and dynamics.
To obtain a better understanding of the manifold impacts of logging, 64 different logging scenarios were analysed here. Each scenario was defined by a combination of four different options to reduce logging impacts: reducing logging damage, reducing logging intensity, lengthening logging cycles, and increasing the lower cutting limit. The impacts are evaluated using three indicators reflecting timber yield, canopy opening and the change of tree species composition in the forest.
We use MCDA – multicriteria decision analysis (Bana e Costa, 1990; Stewart, 1992; Munda, 1995; Beinat & Nijkamp, 1998; Gal *et al.*, 1999) – to evaluate and rank the logging scenarios with respect to three potentially conflicting objectives: maximising timber yield, minimising canopy opening, and minimising deviation from natural species composition. Examples where MCDA has been applied in an ecological context are contained in Ralls and Starfield (1995, Steuer & Schuler 1981, Siitonen et al. 2003, Drechsler, 2003b). The main advantage of MCDA is that it can handle the integrated consideration of a large number of criteria and, and does not require all the criteria to be measured on the same scale unlike most other assessment tools such as cost-benefit analysis (Beinat & Nijkamp, 1998; Drechsler, 2003a).
The forest simulation model used in this study is the process-based forest growth model FORMIND (Köhler & Huth, 1998), which has been employed to evaluate the approach of the more aggregated model FORMIX3 (Huth *et al.*, 1998; Ditzer *et al.*, 2000; Huth & Ditzer, 2000; Kammesheidt *et al.*, 2002; Glauner *et al.*, 2003). The model is individual-tree-oriented and simulates the spatiotemporal dynamics of an uneven-aged mixed forest stand. Tree species are aggregated into plant functional types (Köhler *et al.*, 2000). The recent model version, FORMIND 2.0, was analysed and used to study disturbed forest dynamics in Malaysia, Venezuela and French Guiana (Kammesheidt *et al.*, 2001; Huth *et al.,* 2003; Köhler *et al.*, 2001, 2003; Köhler & Huth, 2003).
The forest model and decision analysis are used here to answer the following questions:
(1) What are the main changes to the forest structure caused by logging, and how do they depend on the management strategies (logging method, cutting cycle, cutting limit and logging intensity)?
(2) What tree harvesting scenarios are best with respect to various priorities at conserving forest functions?
(3) Is there an optimum scenario that performs well under a wide range of different priorities? Which scenarios represent a good compromise?

Methods

The site

The tropical rain forest stands simulated in this study are part of the Deramakot Forest Reserve (DFR) 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°C with little seasonal variation. The average annual precipitation is about 3500 mm, with no pronounced dry season. The soils are low in nutrients and prone to erosion whenever devoid of tree cover. The dominant forest type is lowland Dipterocarp forest. Field data from a mature forest stand were taken for model initialisation (Schlensog, 1997).

Model description

The individual-oriented and process-based forest growth model FORMIND 2.0 simulates the spatial and temporal dynamics of uneven-aged mixed forest stands (Köhler & Huth, 1998; Köhler, 2000). The model’s general dynamics include stability and sensitivity analysis were already analysed (Kammesheidt *et al.*, 2001). The model’s behaviour has been compared to growth data from permanent plots in Sabah, and simulated and observed stand data were found to tally well (Köhler *et al.*, 2001).
The model simulates a forest of several hectares as a mosaic of interacting patches whose size is 20 m × 20 m, corresponding to the crown size of mature trees. Within the patches, trees are not distributed in a spatially explicit manner, and thus they all compete for light and space following the distance-independent gap model approach (Shugart 1998). The carbon balance of each individual tree is modelled explicitly, including the main physiological processes (photosynthesis, respiration). Allometric functions relate the above-ground biomass, the stem diameter, the tree height, the crown diameter and the stem volume. Growth process equations and physiological parameters are taken from the model Formix3-Q (Ditzer *et al.*, 2000). Tree mortality can occur either through self-thinning in dense patches, senescence, or gap formation by large trees falling. Gap formation and seed dispersal by mature trees link neighbouring patches together. The seed production rates of mature trees are effective rates regarding the recruitment of seedlings at a diameter (at breast height) threshold of 1 cm, with seed loss through predation and other processes already being implicitly incorporated.
An overview of the functions and parameters used in FORMIND 2.0 is contained in the appendix. The 468 different tree species found in Deramakot were classified into 13 plant functional types (PFT) using three different successional stages and five tree height classes as the grouping criteria (Köhler *et al.*, 2000). We distinguish between early-, mid- and late-successional species using information on tree growth and light demands. The height classes can be defined according to the canopy layers in which mature trees of a species can been found: emergents (h_{max} > 36 m), upper main canopy (25 m < h_{max} ≤ 36 m), main canopy (15 m < h_{max} ≤ 25 m), understorey (5 m < h_{max} ≤ 15 m) and shrubs (h_{max} ≤ 5 m, h_{max} maximum height of a mature tree). Altogether this makes for 15 PFT, from which only 13 did occur in our species list.

Simulated logging scenarios

Sixty-four different logging scenarios were simulated (Table 1). The scenarios differ regarding the following features: (A) logging method, (B) logging cycle, (C) cutting limit and (D) logging intensity. Our modelling of logging practices was motivated by several studies (e.g. Hendrison, 1990, Crome et al., 1992, Cannon et al., 1994, Johns et al., 1996, Pinard & Putz, 1996, Johns, 1997, Bertault & Sist, 1997, Sist et al., 1998).
(A) Logging method: Either highly damaging conventional logging CON (involving the use of heavy machinery, unskilled workers and little planning) or reduced-impact logging RIL (including substantial planning for road construction, felling directions, tree removal etc.) was

Table 1 Simulated logging scenarios.

Scenario[a]		Logging method	Cutting limit [cm]	Number of remaining trees after logging [ha^{-1}]	Logging cycle [yr]
A	R*-30	RIL (reduced impact)	30	0	20, 40, 60, 80
	R*-40	RIL	40	0	20, 40, 60, 80
	R*-50	RIL	50	0	20, 40, 60, 80
	R*-60	RIL	60	0	20, 40, 60, 80
	C*-30	CON (conventional)	30	0	20, 40, 60, 80
	C*-40	CON	40	0	20, 40, 60, 80
	C*-50	CON	50	0	20, 40, 60, 80
	C*-60	CON	60	0	20, 40, 60, 80
B	R*-0	RIL (reduced impact)	60	0	20, 40, 60, 80
	R*-3	RIL	60	3	20, 40, 60, 80
	R*-6	RIL	60	6	20, 40, 60, 80
	R*-9	RIL	60	9	20, 40, 60, 80
	C*-0	CON (conventional)	60	0	20, 40, 60, 80
	C*-3	CON	60	3	20, 40, 60, 80
	C*-6	CON	60	6	20, 40, 60, 80
	C*-9	CON	60	9	20, 40, 60, 80

[a] A: scenarios assuming different cutting limits, B: scenarios assuming different numbers of trees remaining after each logging operation. An asterisk * in the scenario name is a placeholder for the value of the logging cycle, e.g. R20-30 means reduced-impact logging with a cycle of 20 years and a cutting limit of 30 cm.

simulated. The methods differed in their impact on the residual stand: (1) Felling damage was proportional to the crown size of the logged tree. The felling direction was chosen randomly in CON, but directed towards neighbouring gaps in RIL whenever possible. (2) Skidding damage in the patch of a felled tree was assumed to destroy 25% and 55% of stem numbers for RIL and CON, respectively. (3) Land loss due to road construction and log landings cleared 12% and 33% of all patches for RIL and CON, respectively. (4) Increased mortality rates (RIL: 2x; CON: 3x) for ten years after each logging event accounted for damaged but not immediately destroyed trees.

(B) Logging cycle: The time between two logging operations was constant within a scenario, but differed among the scenarios (20, 40, 60, 80 years).

(C) Cutting limit: All commercial trees of the mid- and late-successional species above a certain minimum diameter (30, 40, 50, 60 cm), the cutting limit, were removed in a logging operation.

(D) Logging intensity: The logging intensity was varied by defining the number of remaining harvestable trees in the forest after each logging event (0, 3, 6, 9 trees/ha).

Each simulation was run for 240 years over an area of 9 ha and was repeated five times to account for random effects. From the simulation we calculate yield, canopy opening, and species composition in terms of relative standing stem volume (Table 2). Changes in species composition and canopy opening were calculated for the different variables as follows: $|\underline{C}_i - P_i|$, where P_i is the value for an undisturbed forest and $\underline{C}_i$ is the mean value obtained for variable C_i over the whole simulation period of five repeated runs initialised with different random numbers.

Table 2 Indicator list

Indicators	Basic variables Index	Description		Value for undisturbed forest [%]
Yield Y	1	Total harvested stem volume in 240 years		0
Canopy opening C	2	Changes [a] of fraction of area with trees no higher than 25m		4
Species composition B	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

[a] Changes are calculated for the different variables as follows: $|\underline{C}_i - P_i|$, where P_i is the value for an undisturbed forest and $\underline{C}_i$ is the mean value obtained for variable C_i over the whole simulation period of five repeated runs initialised with different random numbers. Yield is calculated in m³/ha, canopy opening as the area fraction in %, and species composition as the fraction of stem volume of the successional groups of total stem volume. The values for the undisturbed forest are from Schlensog 1997.

Indicators and multicriteria decision analysis

Three indicators – yield Y, canopy opening C and species composition B – were calculated from the simulation results (Table 2). The aim is to maximise Y while minimising C and B, as they measure deviation from the natural state of the forest.
The species composition indicator B is based on the standing stem volume of three successional species groups numbered i=3–5 (cf. Table 2). We rescale the means m_i and standard deviations □$_i$ (i=3–5) of the changes in stem volume by dividing them by the value v_i of the undisturbed forest (4.1, 313.1 and 138.3 m³/ha, respectively) to obtain relative changes $x_i=m_i/v_i$ and y_i=□$_i/v_i$. Relative changes are best aggregated through a geometric mean and so the mean of the indicator B is $m_B=(x_3x_4x_5)^{1/3}$.
As we aim to consider the uncertainties in the indicator values, we choose for multicriteria decision analysis the stochastic extension (Klauer *et al.*, 2001; Drechsler, 2003a) of the so-called PROMETHEE method (Brans & Mareschal, 1990), which belongs to the family of outranking methods (Roy, 1990; Gal *et al.*, 1999). For details of this methods see Huth et al 2005.

Results

The temporal dynamics of species group composition, canopy opening and harvested wood volume are shown for two scenarios in Fig. 1. Each harvesting operation results in a sharp decline in total stem volume. In the first 20 years after each logging operation, the early-successional species are very abundant. For conventional logging, the average abundance of this group is much higher than in the RIL scenarios. Each logging operation causes an opening of the forest canopy which is larger in the CON than the RIL scenarios. Yields are low in CON scenarios, whereas in RIL yields are higher but different in each logging operation.
Fig. 2 shows the results of the scenarios assuming different logging methods, logging cylces and logging intensities using as indicator yield, species diversity and canopy opening (for details see methods).

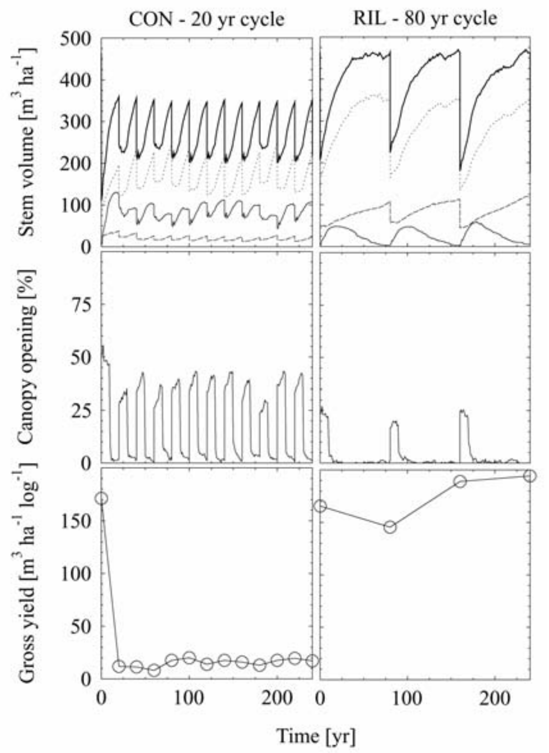

Fig. 1 Two examples of simulated logging scenarios. Left: scenario with conventional logging (CON) and a logging cycle of 20 years. Right: scenario with reduced-impact logging methods (RIL) and a logging cycle of 80 years. Cutting limit = 60 cm and no remaining harvestable tree in both scenarios. Top: 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). Middle: canopy opening. Bottom: yields for each logging event.

Different results are found for the conventional and reduced-impact logging scenarios. Reduced-impact logging always leads to higher yields than conventional methods. The highest yields are obtained for logging cycles of 40 years or more. The low yields in the conventional logging scenarios can be improved by applying long logging cycles (C80-*). As already shown in other studies (Huth & Ditzer, 2001), yield is low for short cycles because this management approach does not give the forest enough time to regenerate – a classic instance of overexploitation.

In the CON scenarios, a decrease in the logging intensity improves the species composition of the forest, but larger improvements are achieved by applying long logging cycles . For RIL,. a strong increase in the species composition indicator B with increasing cycle length. Only in the scenarios with the lowest logging intensity (R*-9) is the influence of the logging cycle on species composition reduced.

Canopy opening C shows similar trends as in the cases with different cutting limits (Fig. 2a). For both conventional and reduced impact logging scenarios, the canopy opening decreases sharply with the logging cycle, but is much lower in RIL (highest values of C). The scenarios with the lowest logging intensities show a slightly different behaviour (R*-9, C*-9). Here, an increase in logging cycles increases canopy opening (low values of C).

Similar results are obtained for logging scenarios with different cutting limits (not shown). In the following, we analyse which scenarios are optimal when different weights are assigned to the three indicators Y, C and B (cf. Eq. 2). For each combination of weights $\{w_Y, w_C, w_B\}$, Figures 3 and 4 show the 'winner', i.e. the scenario with the highest net flux among the 64 scenarios. Depending on the specific weightings, different scenarios are optimum within this three-dimensional weight space.

The analysis for the scenarios with different logging intensities results in five optimum scenarios (all RIL), of which two cover nearly the entire weight space (Fig. 4). If similar weight is given to all three indicators ($w_B \approx 1/3$, $w_Y \approx 1/3$, $w_C \approx 1/3$, middle of the diagram), the following two scenarios are optimum: reduced-impact logging with high logging intensity (number of remaining harvestable trees =0) and a logging cycle of 60 or 80 years. If we assign species composition very high priority (left corner, $w_B \approx 1$), the logging intensity needs to be reduced (R80-9). By contrast, if we are mainly interested in high yields (right corner,

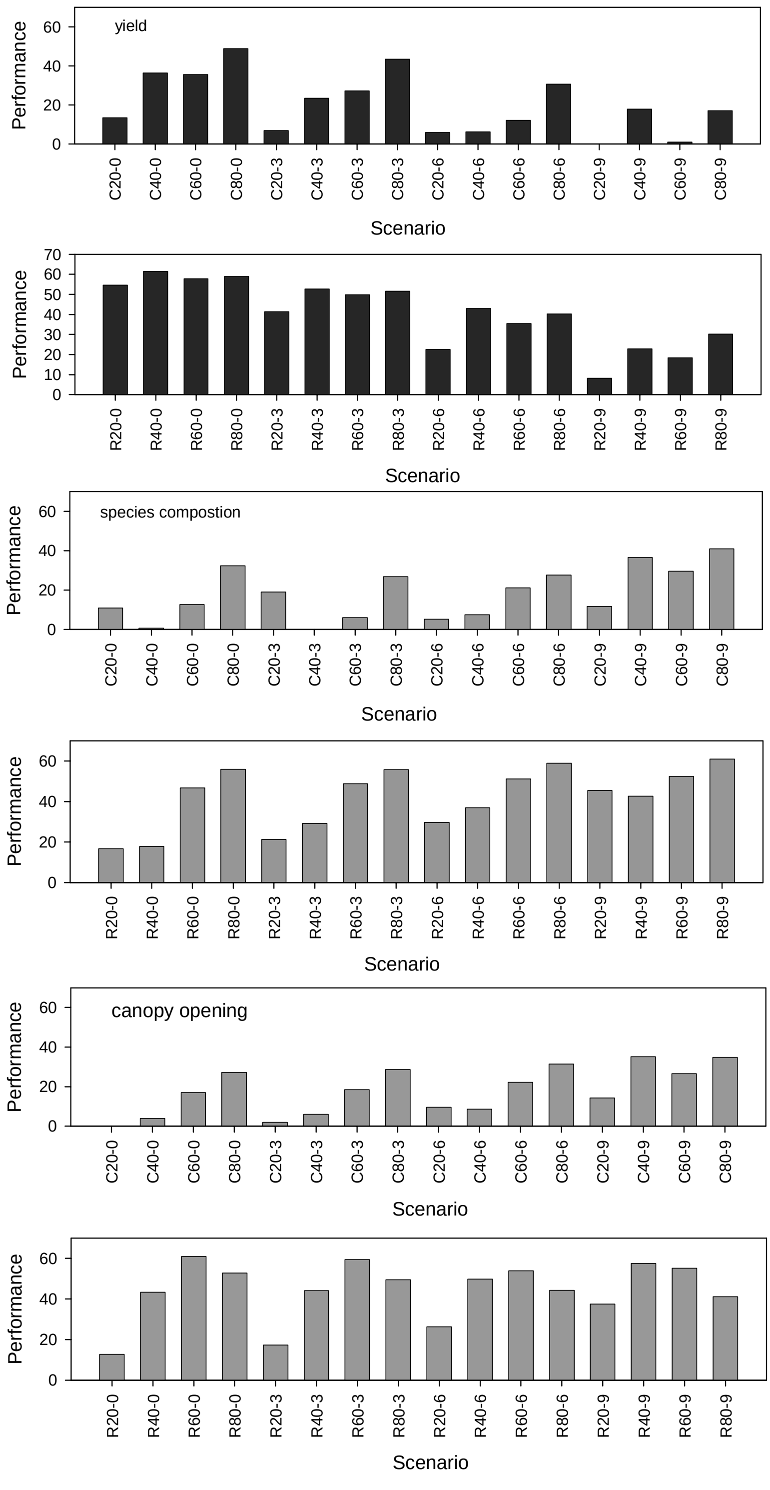

Fig. 2 Performance of scenarios for logging with different logging intensities. The scores for each of the three indicators species composition B, canopy opening C and yield Y range from 0 to 100. In the notation of the scenarios, C stands for conventional, R for reduced impact; the first number indicates the length of the logging cycle in years; the last number r the number of remaining harvestable trees per ha.

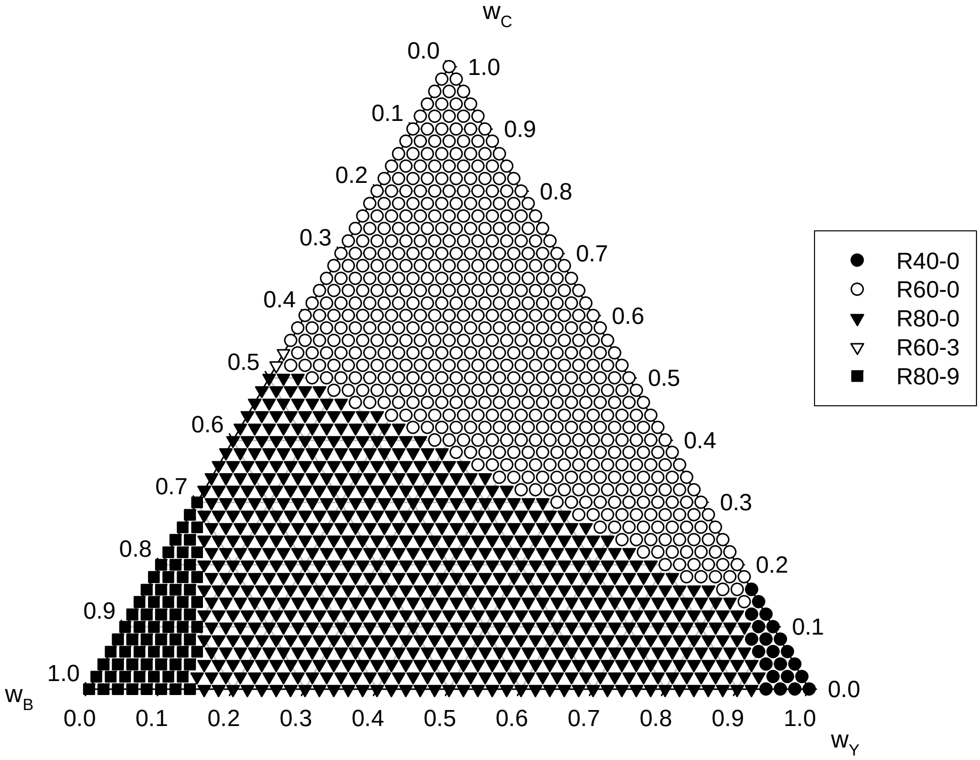

Fig. 3 Optimum scenarios for 32 different management strategies (scenarios including different logging intensities). Depending on the weights for the indicators species composition w(B)canopy opening w(C) and yield w(Y), we get in total 4 optimum scenarios. For further explanation see text.

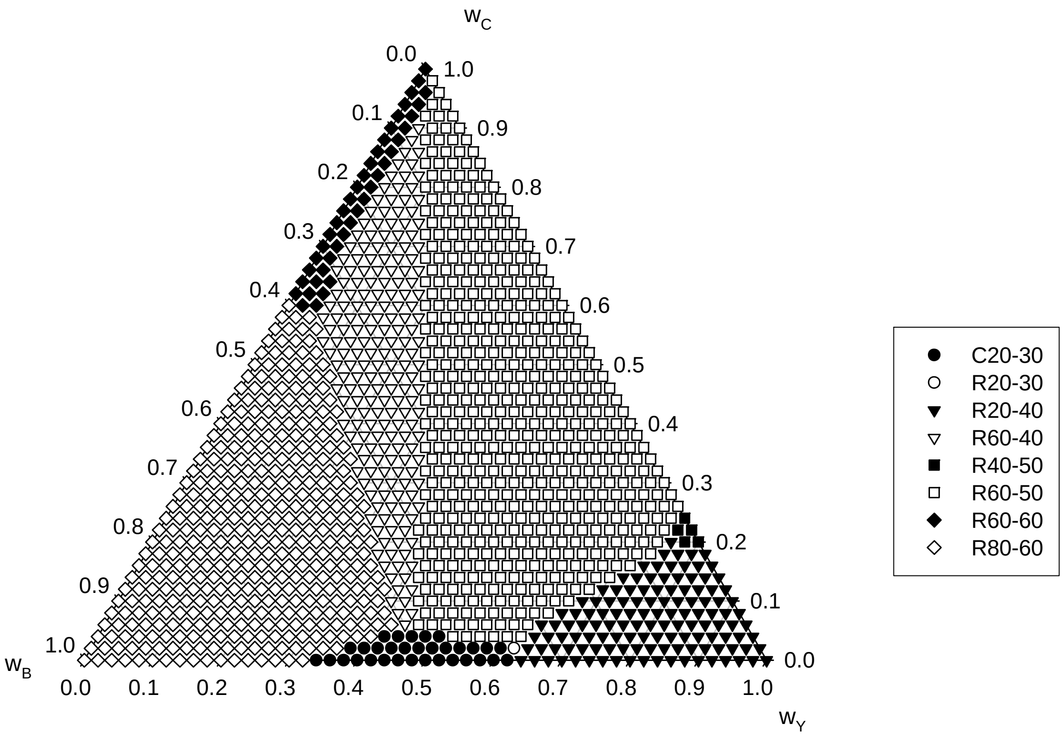

Fig. 4 Optimum scenarios for 32 different management strategies (scenarios including different cutting limits). Depending on the weights for the indicators species composition w(B), canopy opening w(C) and yield w(Y) we get in total 8 optimum scenarios. For further explanation see text.

w_Y≈1), a shorter logging cycle (40 years) combined with high logging intensity is needed (R40-0).
In the scenarios with different cutting limits, we only get eight optimum scenarios (Fig. 4). Most of the entire weight space is covered by four reduced-impact logging scenarios. If we are only interested in yield (right corner, w_Y≈1), a reduced impact logging scenario with a cycle of 20 years and a cutting limit of 40 cm is best. Assuming similar weights for all three indicators (centre of the diagram, w_B≈1/3, w_Y≈1/3, w_C≈1/3), two scenarios are optimum: RIL with a logging cycle of 60 cm and a cutting limit of 50 cm or 40 cm. Only one of the optimum scenarios assumes conventional logging methods (C20–30). This scenario is optimum if we suppose similar weights for species composition and yield, but do not consider canopy opening (w_C ≈0).

Discussion

Our results clearly show that in most cases reduced-impact logging methods are the optimum choices. From a total of 13 optimum management scenarios, only one is based on conventional logging, while all the others involve reduced-impact methods. Eight of the 13 optimum scenarios are characterised by cycle lengths of 60 or 80 years. The cutting limit does not show any trend; optimum scenarios were determined for each cutting limit. Nearly all optimum scenarios assume a high logging intensity, meaning that all harvestable trees have been logged. The scenarios in which a number of harvestable trees remain in the forest only produce optimum results in a few cases.
Even if we are mainly interested in yield, reduced-impact scenarios with long cycles nearly always produce the best results. When it comes to searching for compromises, the ‘weight space’ analyses presented here seem to be a very promising tool. Five of the 13 optimum scenarios only cover a small area in the weight space (e.g. R40-50), and so these scenarios only have reduced relevance. We showed that two or three scenarios dominate nearly the entire weight space. In other words, these selected scenarios are optimum for a large range of different preferences with which different forest functions have to be maintained. These dominating scenarios use reduced-impact methods with long logging cycles (between 60 and 80 years) and high cutting limits (50 or 60 cm).
Beyond these optimum scenarios, can these results be condensed into some rules of thumb? Can rules be drawn up which constitute the most effective methods to protect certain forest functions? Is a high cutting limit more important than a reduced logging intensity or long logging cycles for forest conservation?
There are no simple answers to these questions. The answers depends on the management strategy currently applied and the economic and ecological targets the future strategy is intended to fulfil. Assuming we are looking for a compromise between ecological and economic interests and the current practice is conventional logging with a cycle of 20 years and a cutting limit of 60 cm (which frequently corresponds to the current situation in Malaysia), the following recommendations can be formulated: reducing logging intensity only slightly improves the overall performance, while shifting to reduced-impact logging methods and long logging cycles (80 years) has the largest effects. Decreasing the cutting limit also has a positive effect, but only if applied in scenarios with short logging cycles.

In general, our study shows that high cutting limits or low logging intensities cannot compensate for the high damage caused by conventional logging techniques and short logging cycles. Our study confirms the advantages of low-impact logging methods (Putz *et al.*, 2000; Healey *et al.*, 2000). However, longer logging cycles are needed to protect the species diversity and canopy structure of tropical rainforest, at least in parts of the logged areas.

We used three indicators to characterise the management scenarios: species group composition, yield, and changes in the canopy opening. These indicators have various advantages and disadvantages, which are discussed below.
The index for species composition calculated here produces reasonable results and clear trends. Only in one case (C20-30) are astonishing results achieved for this indicator (species composition is fairly good). Nevertheless, calculating this indicator is simple as we use only three successional species groups. An index based on a more detailed classification of the tree species (13 species groups) used in another study showed more complex results (Huth *et al.*, 2003), e.g. for some species groups the variation of logging intensity resulted in no clear trend (tree species groups have been classified by using three different light demand classes and five height classes). In addition, we suggest for future studies that a certain level of species shift which can be tolerated in forest management should be included in the indicators.
Changes in the canopy opening as calculated here can be used as an indicator of the erosion risk. Erosion depends on several factors such as vegetation cover, slope and soil compaction. The canopy opening index is used here as an indicator of vegetation cover, even though it is also influenced by other factors.
The yields calculated in the present study are long-term yields (harvested stem volume in 240 years). This is certainly a useful indicator for questions of sustainable management. If we simulate longer periods the obtained results will be similar (assuming constant environmental conditions). An analysis of sustainability over longer time periods may also include effects of climatic change, but this was not investigated in this paper.
The simulation results in this study may be optimistic regarding harvesting impacts, because the model assumes that the soil provides suitable conditions for seeds to germinate and subsequently for seedlings to become established – yet logging may cause the soil to be partly compacted, reducing the establishment success (Cannon *et al.*, 1994; Pinard & Cropper, 2000). Compacted soils may lose their nutrients due to erosion (Malmer, 1996). 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 (Ruhiyat, 1989; Glauner, 2000). In other regions, nutrient input due to precipitation or rock decomposition may be much lower (Bruijnzeel, 1991). Moreover, we currently know little about the nutrient levels required by trees in the tropics (Whitmore, 1998; Ashton & Hall, 1992).
For management questions, indicators such as the short-term yields or the annual fluctuations in yields would also be of interest. It is known that short logging cycles result in strong fluctuations of the yields from each logging event (Huth & Ditzer, 2001).
It is also possible to use indicators describing the economic yield (Boscolo & Buongiorno, 1997; Healey *et al.*, 2000). In the context of sustainability, whether ecological indicators should be discounted is still being discussed (Hanley & Spash, 1993; Portney & Weyant, 1999). In some studies, indicators characterising the spatial heterogeneity of the forest have been proposed (Pretzsch, 1997; Mendoza & Prabhu, 2000a; Pommerening *et al.*, 2000). Indicators describing changes in tree size distribution might also be useful.
The discussion about useful indicators for sustainable forest management is still ongoing. Several lists of criteria have been developed for individual countries in order to aid the development of policies that would support sustainable forest management at the national level. For example, the Santiago Declaration (Miles, 2002) includes five groups of criteria dealing with ecological aspects of forestry: (1) conservation of biological diversity, (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. Another list of criteria has been put forward by the Forest Stewardship Council or CIFOR (Mendoza & Prabhu, 2000a).
Although most of these criteria are not clearly defined, they contain many interesting suggestions for new indicators which could be measured in the field or calculated from the output of forest simulation models. In our opinion, we need an intensive discussion on measurable indicators. Closely related to this topic is the question of how large the forest

area measured needs to be to obtain a good estimate for certain indicators. Several hectares provide good values for some indicators, e.g. biomass (Huth, 1999; Keller *et al.*, 2001), but more work has to be done.
An other important question is whether some of the indicators are correlated. By searching for such correlations, key indicators can be determined and the indicator lists can be cleared of redundant information. Our vision is a short list with measurable key indicators. Forest simulation models may have a crucial role for determining such key indicators (by determining correlations between indicators).
The present study demonstrates the advantages of combining simulation modelling with (multicriteria) decision analysis (cf. Drechsler & Burgman, 2003). Decision analysis helps to structure the results of the model study so that guidelines can be derived for optimum environmental management. A problem that usually occurs in the application of multicriteria analysis in environmental management is that the outcome of the analysis depends on the weights given to the individual indicators and that these weights vary among people. One solution is to engage in a participatory process where these weights are provided in discussions among decision-maker(s) and analysts (e.g. Beinat & Nijkamp, 1998, Proctor & Drechsler, 2004). Such processes, however are not always technically feasible, one reason being the associated financial costs. Another solution to the weighting problem is to deliver the Pareto-optimum solutions (cf. Fig. 3) to the decision-makers and let them decide on their own. The problem that occurs in this approach is that the modellers and analysts may not be aware of all the constraints. For example, the solution offered as optimum for a given combination of weights may not be feasible and the analysis useless to the decision-maker due to the non-availability of technical equipment. As modellers and analysts cannot anticipate all conceivable constraints, a sensible way out of this problem is to use substitutability indices as proposed in the present study (cf. Figs. 3b and 4b). If one of the scenarios that are optimum in theory turns out to be infeasible in practice, Figs. 3b and 4b offers a number of substitute scenarios that have very similar indicator values and thus meet the decision-maker's preferences to almost the same degree. Hence the results provide much more insight and flexibility to forest managers without overly complicating the model or decision analysis.
The current certification of sustainable forest management units closely depends on the evaluation of experts (Mendoza & Prabhu, 2000b; Lindenmayer *et al.*, 2000). We believe that growth and yield studies using forest simulators and multicriteria decision analysis can help to reduce subjective errors and misjudgements in expert evaluation, and by doing 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 in which what criteria and indicators are crucial is unclear.

Appendix

Details of the model simulations

Species grouping

We use the two criteria 'successional status' and 'maximum tree height' to assign the 468 different shrub and tree species in the study site to 13 plant functional types (PFT, Table 2, Köhler *et al.*, 2000). Assuming the independence of the two criteria, aggregation into the three different successional states (early, mid or late) is possible. The latter were determined through diameter growth rates under various light regimes and a literature survey of wood densities as an indicator for growth rates in cases of lacking data (Meijer & Wood, 1964). The full species list is available at http://www.usf.uni-kassel.de/usf/archiv/dokumente.en.htm. Similar grouping concepts are found in the literature (Swaine & Whitmore, 1988; Thomas, 1996). Furthermore, we assume that 80% of the mid- and late successional species are commercial species.

Model equations and parameters

The main model equations are explained in Tables A1 and A2. The parameter set used in our simulations is shown in Tables A2 and A3. The references used to parameterise the model are documented in other studies (Köhler & Huth, 1998; Köhler, 2000; Köhler & Huth, 2003).

Initialisation

To initialise the simulation, we used field data from an undisturbed forest stand (Schlensog, 1997). This stand has a stem volume of 464 m³/ha (for all trees with diameter > 10cm) and contains almost no early-successional species, abundance being highest in the mid-successional species group (70%, Table 2). The seed pool was filled with average seed numbers determined in long-term simulations of undisturbed forest stands.

Table A1 Main equations of the forest model FORMIND. Constants are explained in the model parameter list; see Table A2.

Equations	Description
$\frac{dN_i}{dt} = -(M_B + M_D) \cdot N_i - M_F$	Changes in number N_i of trees in cohort *i* due to mortality M_B (basic rate), M_D (diameter dependent rate), M_F (dying caused by large trees falling).
$\frac{dB_i}{dt} = P_i\ c_l\ \left(1 - R_g\right) -\ r_1 B_i$	Changes in above-ground biomass B_i of a tree in cohort *i*, including photoproduction P_i, growth limitation factor c_l, growth R_G and maintenance respiration r_1B_i.
$B_i = \frac{\pi}{4} d_i^2 h_i \frac{\rho_i \cdot \gamma}{\tau_i}$	Tree geometry relation between height h_i, diameter d_i and above-ground biomass B_i (ρ_i is the stem wood density, γ the form factor and τi fraction of stem-wood to total above-ground biomass).
$I_i = I_o \cdot e^{-k_i \cdot L_i}$	Light I_i available for tree *i* in relation to total leaf area index L_i above tree *i* and insolation I_0 (k_i constant).
$A_i = \frac{l_1 \cdot d_i + l_2 \cdot d_i^2 + l_3 \cdot d_i^3}{d_{ci}^2 \pi /\ 4}$	Leaf area index A_i of tree *i* in relation to diameter d_i and crown diameter d_{ci} (l_i are fitting constants).
$P_i = \int_{L_i}^{L_i + A_i} \frac{\alpha \cdot I_i(L)}{1 + \frac{\alpha}{P_M} I_i(L)} dL$	Total photoproduction Pi of tree i calculated by the integration of photoproduction of leaves over the whole tree canopy (*PM* and α are constants).

Table A2 Brief description of parameters including functional relationships.

Parameter	Description
Environmental parameters	
k	Light extinction coefficient
I_0	Light intensity above canopy
S_D	Day length
Recruitment parameters	
D_S	Initial diameter of seedlings
I_S	Minimal light intensity required for germination
N_S	Ingrowth rate of seeds into seed pool
x_R	Average seed dispersal distance
D_R	Minimum diameter of mother tree
Mortality parameters	
M_B	Basic mortality rate
M_S	Mortality rate of seeds
M_D	Size-dependent mortality rate ($M_D = M_{D0} - M_{D0}/M_{D1} \cdot d$)
W	Probability of a dying tree (d>10 cm) falling
Tree-physiognomic parameters	
H_M	Maximum height
c_p	Crown length fraction (in relation to tree height)
τ_j	Site-dependent fraction of stem-wood biomass to total above-ground biomass ($\tau = \tau_1 + \tau_2 \cdot h(d = 120cm)$)
h_0 and h_1	Height = f(diameter) ($h = d/(1/h_0 + d/h_1)$)
γ_j	Form factor = f(diameter) ($\gamma = \gamma_0 \cdot \exp(\gamma_1 \cdot d^{\gamma_2})$)
f_j	Crown diameter = f(diameter) ($d_c = (f_0 + f_1 \cdot d^{f_2}) \cdot d$)
l_j	Leaf area = f(diameter) ($l = l_1 \cdot d + l_2 \cdot d + l_3 \cdot d$)
LAI_M	Maximum leaf area index of single tree
Biomass production parameters	
P_M and α	Photosynthetic capacity and efficiency in light response curve ($P_i(I_i) = \alpha \cdot I_i/(1 + \alpha I_i/P_M)$)
ρ	Stem wood density
r_1	Maintenance respiration = f(biomass) ($R_m(B_i) = r_1 B_i$)
R_G	Growth respiration as part of biomass
m	Leaf transmittance
g	Conversation factor g_{CO2} to g_{odm}
c_l	Growth limitation factor ($c_l=1-(1-c)(d/D_M)^2$), D_M maximum diameter, c is calculated from $d(d=D_M)/dt = 0$

Table A3 Parametrisation for Sabah (Malaysia). Parameters with subindex vary with successional status (*s*) of an individual tree, potential height (*h*), or different functional coefficients (*j*).

Parameter	Subindex	Units	Values				
Environmental parameters							
k		[-]	0.7				
I_0		[μmol(photons)/ m^{2}s]	642.0				
S_D		[h]	12.0				
Recruitment parameters							
D_S		[m]	0.01				
I_{Ss}	s=1-3	[fraction of I_0]	0.20	0.04	0.01		
N_{Ss}		[ha^{-1} y^{-1}]	150	625	50		
x_R	s=1-3	[m]	100	75	50		
D_R	h=1-5	[m]	0.04	0.10	0.18	0.40	0.50
Mortality parameters							
$M_{Bs,h}$	s=1; h=1-5	[y^{-1}]	0.00	0.12	0.10	0.08	0.06
$M_{Bs,h}$	s=2; h=1-5	[y^{-1}]	0.06	0.05	0.04	0.03	0.025
$M_{Bs,h}$	s=3; h=1-5	[y^{-1}]	0.00	0.04	0.03	0.02	0.015
M_{Ss}	s=1-3	[y^{-1}]	0.1	0.5	1.0		
M_{Dj}	j=0-1	[y^{-1}, m^{-1}]	0.2	0.1			
W		[-]	0.40				
Tree-physiognomic parameters							
H_{Mh}	h=1-5	[m]	5	15	25	36	50
c_p		[-]	0.358				
τ_j	j=0-1	[-, m^{-1}]	-0.035	0.0139			
h_{0h}	h=1-5	[cm m^{-1}]	1.24	1.18	0.97	1.08	1.33
h_{1h}	h=1-5	[m^{-1}]	38.5	43.6	88.6	57.3	70.5
γ_j	j=0-2	[-, cm^{-1}, -]	2.575	-1.409	0.0358		
f_j	j=0-2	[-, -, -]	0.132	0.933	-0.6615		
l_j	j=1-3	[m/cm,m/cm^2, m/cm^3]	3.197	0.0684	-0.000379		
LAI_M		[-]	2				
Biomass production parameters							
P_{Ms}	s=1-3	[μmol(CO2)/ m^{2}s]	19.4	9.3	6.8		
α_s	s=1-3	[μmol(CO2)/ μmol(photons)]	0.043	0.043	0.043		
ρ_s	s=1-3	[Mgodm m^{-3}]	0.37	0.55	0.75		
r_{1s}	s=1-3	[-]	0.12	0.05	0.02		
R_G		[-]	0.25				
m		[-]	0.1				
g		[godm g$^{-1}_{CO2}$]	0.63				

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