



Financial and ecological analysis of management options for logged-over Dipterocarp forests in Indonesian Borneo

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Abstract

The sustainable management of areas of logged-over tropical forests requires an understanding of the potential yield from the forest and likely financial performance of the management system. This paper describes an analytical approach that involves the linkage of a simulation model of forest growth and yield to a financial model based on data from a forest concession in East Kalimantan (Indonesian Borneo). The growth and yield model SYMFOR (silviculture and yield management for tropical forests) was linked to a financial model derived for a forest concession managed under the Indonesian selective logging and replanting system (TPTI). This combined approach was used in this study to predict the likely timber yield for contrasting management regimes and then to calculate estimates of the financial performance described as the internal rate of return (IRR) and net present value (NPV) of the forest estate.

This approach was used in a study that compared the standard TPTI system with alternatives that combined reduced impact logging (RIL) techniques with alternative systems of yield regulation. The TPTI system regulates timber yield using a single diameter limit given for each type of forest (currently two categories for lowland Dipterocarp forests and one for swamp forest). The alternative systems that were evaluated included one defined by a maximum of eight harvested stems per hectare and others based on maximum volume extracted of either 50 or 60 m³ ha⁻¹. Each of these systems was evaluated for cutting cycle lengths of 25, 35 and 45 years. These management regimes were implemented for a simulated period representing three additional cutting cycles. The impacts of alternative management regimes were compared through statistical analysis of the results from the simulations that was able to remove the effect of the very significant variability between experimental plots.

The results of this analysis clearly demonstrated that the conventional TPTI management system failed to achieve criteria of sustainability for timber yield and financial performance. Average yields dropped from over 80 m³ ha⁻¹ for the first simulated harvest from the logged-over area (second harvest) to between 35 and 40 m³ ha⁻¹ for the third and fourth harvests. The financial analysis showed that this system was not viable after the second harvest leaving the only financially viable alternative of land conversion after clear felling of the remaining forest.

The alternative management regimes based on reduced impact logging and more effective systems of timber yield regulation performed much better. The study suggested that management systems based on a cutting cycle of 35 years with yield regulated to 50 m³ ha⁻¹ or 45 years with yield regulated to 60 m³ ha⁻¹ were the best alternatives to the current TPTI system. Neither of these two alternatives was able to consistently achieve the desired internal rate of return of 16% unless there were also decreases in wastage associated with the harvesting and timber extraction.

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Optimisation techniques were used to determine the combination that would produce an internal rate of return of at least 16%. This process suggested that the concession studied would be able to achieve or exceed this criterion over all harvests when (a) a management regime involving a cutting cycle of 45 years is combined with a yield regulation system harvesting a maximum of 60 m³ ha⁻¹ and (b) the efficiency of timber conversion increases from 52 to 60%. It is considered that this is readily achievable using existing methods and appropriate training.

The methods described in this paper can be transferred to other concessions or countries and may be modified to utilise alternative growth and yield or financial models. The paper also indicates that the approach could be adapted to consider a wider range of goods and services provided by forests to extend the analysis into a more comprehensive economic analysis. A preliminary consideration of these issues demonstrated that the system of management selected on the basis of timber yield and financial performance will also provide benefits for the environment and local communities.

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1. Introduction

Tropical forests cover around 1571 million ha of the Earth's surface (representing 12% of the land area, 2000 data) (FAO, 2001a) and as such represent one of the world's largest terrestrial biomes. Tropical forests are commercially significant with timber produced from the management of natural forests by the major producer countries estimated to be 185 million m³ in 2000 with an export trade worth US\$ 9265 million (ITTO, 2001). The benefits and income from this type of forest management tends to be captured by large industrial concerns and governments, rather those living near the forest. Communities living in or near forests that may derive additional benefits include harvesting of timber and non-timber forest products, a source of employment, religious or cultural values of forests, the impact of forests on health, and their impact on the local environment. Forests are also extremely important at local, regional and international scales in terms of their role in environmental protection (for example, watersheds) and as a store of carbon in the global carbon cycle (Phillips et al., 1998; Malhi and Grace, 2000).

This paper considers the management of tropical moist forests in Indonesia. The extent of these forests varies between regions of the globe with the main extant areas of forest being in Latin America (The Amazon) and south-east Asia (mainly in Indonesia) (FAO, 2001b). Extraction of significant volumes from the Amazon commenced during the 1980s, whilst in Indonesia, this commenced a decade earlier. The Indonesian selective logging and replanting system

(TPTI) has a set cutting cycle of 35 years (Departemen Kehutanan, 1993) for this reason much of the projected future production will be harvested from areas of logged-over forest. There is, however, much discussion on how this may be achieved in a way that both meets the needs of most stakeholders, whilst still being ecologically and financially viable. The current study will present such an analysis for an area of logged-over forest in the Indonesia province of East Kalimantan on the island of Borneo.

The Indonesian provinces of Kalimantan on the island of Borneo have approximately 16.4 million ha of forest zoned for commercial production from natural forests, representing 34% of the estimated national total (Gautum et al., 2000). Lowland Dipterocarp forests dominate these production forests. There have been several projects implemented to support the development of sustainable forest management of these forests and other similar forest types in the region (Appanah and Weinland, 1990; Bertault et al., 1998; Department for International Development, 2000c). The STREK project (Silvicultural Treatment for the Regeneration of logged-over forests in East Kalimantan) (Bertault and Kadir, 1998) was established to investigate methods supporting better management of logged-over forests in the region (Bertault et al., 1998) in collaboration with a state-owned forestry concession PT Inhutani I. This project subsequently became the Berau Forest Management Project supported by the European Union (<http://www.bfmp.or.id>).

These projects aimed to develop systems for the sustainable management of forest concessions, but initially tended to consider this in terms of sustainable

timber production (STREK project) and then considering timber production and the financial viability (BFMP) for a commercial forest management operation. This move has necessitated the development of tools that have the ability to make predictions of the future production of the biological system and link this to predictions of the financial viability of the management system. This paper describes the first such system developed for a forest management system in Indonesia through the linkage of a simulation model for forest management (Phillips et al., 2003) with a financial model of a forest concession (Fadilah, 1997). The paper considers the results of such an approach and then proceeds to discuss the implications for other stakeholders in the forest.

1.1. Management systems for tropical forests

The approaches to forest management have changed in recent years to emphasise the importance of the effective participation of all relevant stakeholders in decisions relating to the forest. This is seen to be essential for ensuring that forests play their role in poverty reduction (Department for International Development, 2000b; Blaser and Douglas, 2001) and that forest resources are maintained to maximise environmental benefits (Department for International Development, 2000a). The move to consider the needs of wider stakeholder groups as well as a range of goods and services from forests has required a shift in the methods of analysis utilised in both research and developmental projects. The current paper will contribute to the knowledge pool available to stakeholders to support their management decisions and thus contribute to sustainable forest management.

A range of management systems are applied for the sustainable management of natural tropical forests (Catinot, 1997; Whitmore, 1998). Those applied to the Dipterocarp forests of south-east Asia have been developments of the Selective Management Systems (SMS, from 1915) and Malaysian Uniform System (MUS, from 1949) originally implemented for Peninsular Malaysia (Wyatt-Smith and Panton, 1995), but since adapted for use elsewhere in the region as well as in Africa and Latin America (Catinot, 1997). The Malaysian Uniform System (Wyatt-Smith and Panton, 1995; Catinot, 1997) aims to convert primary forest to one approaching an even-aged forest through an initial

heavy harvest (usually with a minimum log diameter limit of 45 cm), followed by a series of tending treatments over a cutting cycle of around 60 years. The Selective Management System applied in Malaysia has a much shorter cutting cycle (25–40 years), removing trees with a minimum diameter between 50 and 60 cm aiming to maintain a mixed size class structure of the resulting forest.

1.2. Forest management systems in Indonesia

The Indonesian selective logging and replanting system is applied to all areas of natural forest being managed for sustainable production (Departemen Kehutanan, 1993). TPTI is based around a simple yield regulation system stating that all commercial species (groups 1–5, Table 1) may be harvested above a critical diameter limit. In practice, it is similar to the Malaysian Selective Management System (Catinot, 1997). For the Indonesian Dipterocarp forests, the diameter limit for harvesting is 50 cm in areas zoned as “full production” and 60 cm in areas where the average slope exceeds 40% which are zoned as “limited production”. Commercial species (Table 1) are defined by regulations issued by the Indonesian Ministry of Forestry, but local implementation may result in only a subset of those permitted being harvested. Early forest management in Kalimantan tended to emphasise the selection of stems from *Dipterocarpus* and some *Shorea* species. In recent years, as market demand has increased, a wider range of species are being harvested, including other Dipterocarp genera and non-Dipterocarp commercial species.

The length of the cutting cycle in the TPTI system is set at an arbitrary 35 years, based on the assumptions that the diameter increment of potential merchantable species (commercial) is 1 cm per year and the volume increment is at least 1 m³ ha⁻¹ per year. Additional post-logging treatments are specified, including liberation clearing, thinning and replanting but in practice these are seldom applied as forest managers question their effectiveness in both financial and ecological terms (van Gardingen, 1998).

A number of modifications to the TPTI system have been proposed. The move towards international codes of practice for harvesting (Dykstra and Heinrich, 1996) has led to the increased adoption of reduced

Table 1
Species groups used in this study

Group	Name	Typical species or genera
Commercial		
1	Meranti (Dipterocarps)	Most <i>Shorea</i> species
2	Fast growing Dipterocarps	<i>Dryobalanops</i> and <i>Hopea</i>
3	Slow growing Dipterocarps	<i>Dipterocarpus</i>
4	Non-Dipterocarps	<i>Madhuca</i> , <i>Palaquium</i> and <i>Agathis</i>
5	Minor commercials	<i>Diospyros</i> and <i>Beilschmiedia</i> sp.
6	Protected	<i>Durio</i> sp. and <i>Shorea pinanga</i>
7	Non-commercials	Wide range
Ecological		
1	Fast growing <i>Shorea</i>	<i>Shorea johorensis</i> , <i>S. leprosula</i>
2	<i>Dipterocarpus</i>	<i>Dipterocarpus</i> , some <i>Shorea</i>
3	Other large Dipterocarps	<i>Shorea</i> , <i>Parashorea</i> , <i>Dryobalanops</i>
4	Small Dipterocarps	<i>Hopea</i> , <i>Vatica</i> , <i>Dipterocarpus</i>
5	<i>Anthocephalus</i>	<i>Anthocephalus chinensis</i>
6	<i>Macaranga</i>	<i>Macaranga</i>
7	Gap small trees	<i>Aglaia</i> , <i>Knema</i> , <i>Artocarpus</i>
8	Other small trees	<i>Diospyros</i> , <i>Dacryodes</i> , <i>Polyalthia</i>
9	Shade small trees	<i>Macaranga lowii</i> , <i>Kayea</i>
10	Unknown	Unknown

Commercial groups are based on timber marketing in East Kalimantan (Rombouts, 1998b) and the ecological grouping was developed for SYMFOR and is described by Brash et al. (2000) and Phillips et al. (2002).

impact logging (RIL) practices in many countries including Indonesia (Sist et al., 1998a). The move towards systems of timber certification will increase the pressure to adopt RIL techniques along with the realisation that such systems may increase efficiency and reduce costs (Matikainen et al., 1998). An analysis of the early results from the STREK reduced impact logging trial suggested that a system based on a maximum extraction of 8 stems ha⁻¹ would maximise the environmental benefits of RIL treatments (Sist et al., 1998c). The same recommendation was obtained from trials conducted in similar forests in Central Kalimantan from studies investigating regeneration of Dipterocarps following logging (van Gardingen et al., 1998a). This system of yield regulation was compared in preliminary studies using the SYMFOR framework (silviculture and yield management for tropical forests) and found to be effective in producing more consistent yields between harvests (Susanty and Sardjono, 2000; Suyana and Sukarya, 2000; van Gardingen, 2000a). These studies also suggested that a system based on a system of yield regulation with a maximum harvest of 50 m³ ha⁻¹ gave equally promising results.

1.3. Growth and yield models for tropical forest management

There are many models that have been developed to describe the growth and ecology of tropical forests, but only a relative few have been applied to support forest management or policy. Early approaches for Malaysian forests (Appanah et al., 1990; Bossel and Krieger, 1991) and the tropical zone in Queensland, Australia (Vanclay, 1989, 1994b) were notable for their evaluation of forest management options. These models were included in comprehensive reviews of models used to predict the growth and yield of tropical forests (Vanclay, 1994a, 1995). More recently other models (Ong and Kleine, 1995; Rombouts, 1998a; Huth and Ditzer, 2000; Kohler, 2000) have been applied in studies of the management of Dipterocarp forests in Malaysia and Indonesia (Kleine and Heuvelod, 1993; Huth and Ditzer, 2001; Kohler et al., 2001). The results of these studies have all suggested that current implementation of forest management in the region will not lead to sustainable yields and recommended a combination of longer cutting cycles (up to 100 years) and/or lower harvesting intensities.

The SYMFOR framework used in the current study is a system based around an individual tree model describing the ecology of lowland Dipterocarp forests in East Kalimantan, Indonesia (Phillips et al., 2003). This is linked to a forest management model (Phillips and van Gardingen, 2001) that allows users to realistically simulate management decisions. The model operates using permanent sample plot data, typically for an area of 1 ha. Running the model on replicate plots provides statistical rigour, whilst replicate runs are required for each plot in order to obtain accurate estimates of mean responses because of the stochastic (statistical) nature of components of the model. The SYMFOR framework is freely available and may be downloaded (Phillips and van Gardingen, 2000) along with all associated documentation (Phillips et al., 2000). The model was developed based on permanent sample plot data collected from the Labanan concession (Sist and Bertault, 1998; Bertault et al., 1998; Nguyen-The et al., 1998).

One of the features of the SYMFOR framework used in the current study is a facility to enable replicated simulations with the model to permit statistical comparison between treatments. Of the models described above that have been previously applied to forest management studies, only the work in Queensland (Vanclay, 1994b) reports estimates of uncertainty associated with the simulated results. As the Queensland model was deterministic, the variation in that study resulted from variation between plots used in the simulations. More recent models have included stochastic representation of recruitment and mortality events and hence multiple simulations should be performed for each plot. The development of a model for Malaysia (Liu and Ashton, 1998) included such information in a description of the model, but to date, results of the application of this model to forest management have not been published. Applications of the FORMIX-3 (Huth and Ditzer, 2001) and FORMIND (Kohler et al., 2001) models with Malaysian data do not report estimates of statistical uncertainty associated with the modelled estimates. The FORMIX-3 study reported the means of twenty replicate runs (Huth, personal communication) but did not include standard errors as these were small. In contrast the FORMIND study did not use replicate runs as the authors considered that the stochastic elements of their model did not significantly influence their results (Kohler, personal communication).

The current study aims to demonstrate that statistical analysis of results from the application of simulation modelling to forest management is essential and presents advantages over conventional analysis of field trials. The modelling study in Queensland (Vanclay, 1994b) demonstrated the statistical variations between plots are significant whilst the impacts of stochastic elements was demonstrated by (Liu and Ashton, 1998). These two sources of statistical variation must be treated differently in order to avoid statistical bias and artificial replication. The experimental unit (Sokal and Rohlf, 1981) (or unit of replication) for a simulation modelling study should be the experimental plot used to initialise the runs. For this reason, the effects of stochastic variation within a model should be removed by averaging the results of repeated simulations within a plot. The average results from the simulations for each plot can then be analysed using conventional statistical approaches such as analysis of variance.

Results from forestry field trials have historically been difficult to analyse because of the variation between plots, pre-existing before experimental treatments are applied. The design of experiments and their analysis have commonly used analysis of covariance (ANCOVA) techniques sometimes combined with a randomised block experimental design. The analysis of covariance approach usually relies on the assumptions that: (1) there is a linear relationship between the result variable (e.g. yield) and covariate (e.g. stand basal area before the treatment is applied) and (2) that the linear relationships between the result variable and covariate have identical slopes (i.e. the lines are parallel). In many studies these assumptions are not met, reducing the statistical power of the technique and the value of the analysis. A similar problem exists for the application of experiments using randomised block experimental designs. This approach relies on the assumption that variation between plots within a block is very small when compared to that between blocks, a condition that is seldom met in experimental trials in tropical forests.

The application of simulation modelling to forest management studies provides an opportunity to utilise alternative statistical approaches that are potentially much more powerful. It is possible when utilising a simulation model, to apply alternative treatments to identical plots. If the simulations are then applied to

replicate plots (which differ) it is possible to treat the experiment as a simple form of a split-plot experimental design (Sokal and Rohlf, 1981). This type of analysis of variance can be very effective in removing between-plot variation when considering the effects of experimental treatments and was applied in this study. It is noteworthy that the computation of a split-plot analysis for a factorial experimental design as used in this study, is identical to that which would be used for a blocked experiment, where each plot represents an experimental block.

1.4. Financial analysis

There have been few studies describing either the financial performance of tropical forest management and to date, only one study describes a very simple financial analysis linked to the results from a growth and yield modelling exercise (Huth and Ditzer, 2001). Financial models that can be linked with yield estimates, should normally be developed for the region under investigation. In Indonesia, there are only two suitable models, both of which have been developed for forest concession in Kalimantan (Fadilah, 1997; Scotland and Whiteman, 1997). Additionally, a very simple financial analysis was carried as part of the original STREK project (Karsenty, 1998). All of these approaches utilise cost–benefit analysis.

The financial model of the Labanan concession (Fadilah, 1997) was originally developed in order to investigate the interactions between forest productivity and total area managed on the financial viability of the concession. The same model was subsequently modified to investigate the financial implications of thinning treatments (Fadilah, 1999) that are specified as part of the Indonesian selective logging and replanting system (Departemen Kehutanan, 1993). The financial model developed was linked with results provided from SYMFOR (McLeish et al., 2002) to develop a financial analysis of alternative management regimes for the concession (McLeish and Susanty, 2000).

There is much debate on appropriate methods for financial and economic analysis to include considerations of the value of non-timber goods and services from forests (Davies and Richards, 1999). It is beyond the scope of this paper to review these issues, but the implications of the results of the study for this debate will be discussed.

1.5. Objectives of the current study

This study aimed to evaluate options for managing the logged-over forest in the Labanan concession in Berau, East Kalimantan, a region typical of many areas covered by lowland Dipterocarp forests. Specific objectives were therefore to

- develop and illustrate a system that combined a biological growth and yield model, with a concession financial model to evaluate ecological and financial criteria for sustainable forest management;
- develop a statistical approach for the analysis of results from simulation studies for forest management that can be used to compare the effects of alternative management regimes;
- apply this approach to compare the current conventional management practice in Indonesia with alternatives applying a combination of reduced impact logging and timber yield regulation;
- use this analysis to suggest the best alternative management regime(s).

The criteria for selection of the best alternative management regime was the system that sustained yield from logged-over forest, whilst maximising the financial internal rate of return (IRR) and net present value (NPV) of the forest.

And finally the study aimed to

- extend the ecological and financial analysis to a discussion of the economic costs and benefits of the alternative management regimes and likely impact of social criteria of sustainable forest management, in particular the livelihoods of rural forest dependent communities.

2. Methods

2.1. Data

Data were obtained from permanent sample plots in the Berau Regency (Kabupaten) of East Kalimantan in Indonesian Borneo. Plots were established in the Labanan concession of PT Inhutani I between 1989 and 1991 as part of the STREK (Bertault and Kadir, 1998). The first enumeration (measurement campaign)

was completed in 1991 and plots were then remeasured at 2-year intervals. The analysis in this paper is based on data collected up to the fourth measurement campaign collected in 1997.

The structure and composition of the STREK plots have been described elsewhere (Sist and Saridan, 1998, 1999) and have been shown to be dominated by members of the Dipterocarpaceae and Euphorbiaceae families with a mean basal area of $31.5 \text{ m}^2 \text{ ha}^{-1}$ and 531 stems ha^{-1} (diameter at breast height, DBH > 10 cm). These values are very similar to values of $35.5 \pm 2.8 \text{ m}^2 \text{ ha}^{-1}$ and 521 ± 36 stems ha^{-1} documented for 11 locations in Borneo and Peninsular Malaysia (Newbery et al., 1992) and $34.4 \pm 1.4 \text{ m}^2 \text{ ha}^{-1}$ and 583 ± 19 stems ha^{-1} documented for 15 plots in Central Kalimantan (van Gardingen et al., 1998a).

The STREK experiment was designed to investigate silvicultural options for the management of logged-over forest (Bertault et al., 1998) for the lowland Dipterocarp forests typical of Borneo and in many other regions of south-east Asia. Two sets of plots were established. One set was established in an area of logged-over forest that had been harvested in 1979 (RKL-1). Twenty-four plots, each of 1 ha, were established and used for a subsequent thinning trial (Sist and Abdurachman, 1998). The plots were arranged in square groups of four plots with six groups distributed within a relatively uniform area of logged-over forest. Thinning treatments were applied to 16 plots in 1992.

The current study utilised the plots from the logged-over forest in RKL-1 before the thinning treatments were applied. These data were collected in 1991, 12 years after the original harvesting meaning that all 24 plots were available for the study. Data describing stand structure at the start of the simulation (i.e. the data from the field enumeration in 1991) show an average basal area for the plots in RKL-1 of $25.2 \text{ m}^2 \text{ ha}^{-1}$ (Sist and Saridan, 1998). Previous studies suggest that the first harvest of the RKL-1 area was at a relatively low intensity with an average of 4 stems ha^{-1} (Nguyen-The et al., 1998) using standard harvesting practice prevalent in the region at that time.

A second set of 48 plots were established in nearby primary forest (RKL-4) and used in an investigation of the impacts of logging in 1992 comparing conventional harvesting techniques with reduced impact

harvesting (Bertault and Sist, 1997; Sist and Bertault, 1998; Nguyen-The et al., 1998). Implementation of reduced impact logging included activities for yield regulation, directional felling and construction of planned skid trails. There was no pre-cutting of climbers in the reduced impact logging treatments because climber density was low and there was no previous evidence that such treatments were effective in the region. Data from the STREK trial were used to develop and calibrate the growth and yield model (SYMFOR) used in this study (Phillips et al., 2002, 2003).

The data used in the simulation represented each tree in terms of its species (ecological and commercial groups) (Phillips et al., 2002), diameter at breast height and location in the plot. All trees were assigned a lifelong value between 0 and 1 for stem quality from a uniform random distribution.

2.2. Growth and yield simulation model

This study utilised a growth and yield model for East Kalimantan developed from the STREK data and hosted within the SYMFOR framework (Phillips and van Gardingen, 2000, 2001) (<http://www.symfor.org>). The framework contains an ecological model for East Kalimantan (Phillips et al., 2003) and a management model (Phillips and van Gardingen, 2000, 2001; van Gardingen et al., in press) used to simulate the Indonesian selective logging and replanting system (Departemen Kehutanan, 1993; van Gardingen et al., 1998b; van Gardingen, 2000b).

The ecological model used in this study is spatially explicit, representing all trees in the stand with a DBH greater than 10 cm. The model simulates the processes of growth, recruitment and mortality. Diameter increment growth is modelled as a function of competition, recruitment is represented as a stochastic process modified by localised competition and mortality is represented as a stochastic process. Each of these processes are calibrated separately for the 10 ecological species groups used in the study (Brash et al., 2000; Phillips et al., 2002). The management model utilises a separate species grouping based on commercial characteristics of the main timber trees (Rombouts, 1998b). The groupings are summarised in Table 1. Sensitivity analysis of growth and yield estimates from the model for East Kalimantan are described in Phillips et al. (2003).

Table 2
Settings for the SYMFOR models simulations used in this study

	Conventional DBH 50 cm	RIL DBH 50 cm	RIL maximum 8 stems	RIL maximum 50 m ³
Ecological model	Kaltim	Kaltim	Kaltim	Kaltim
Management modules				
Felling	Undirectional	Directional	Directional	Directional
Planskidtrials	Straight	Branched	Branched	Branched
Calcskidcorners	No cutcorners	Cutcorners	Cutcorners	Cutcorners
Management parameters				
Logging specification				
Dbhthreshold (groups 1–5) (cm)	50	50	50	50
Minquality (groups 1–5)	0.3	0.3	0.3	0.3
Logselect: nlogmax	500	500	8	500
Logselect: maxextract (m ³)	500	500	500	50
Skidding (extraction)				
Maxdbhdamage (cm)	40	30	30	30
Skidprepradius (m)	5	3	3	3
Skidwidth (m)	7	5	5	5

Four management regimes were defined as shown. The reduced impact logging (RIL) regimes were characterised by having directional felling and planned skid trails (*management modules*), narrower skid trail width (*skidwidth*) and less damage surrounding the stump (*skidprepradius*). Reduced impact logging treatments were also defined to have less damage on the residual stand by only damaging trees with a DBH of less than 30 cm compared with 40 cm for conventional logging. Two additional management regimes were defined to harvest either a maximum of 8 stems ha⁻¹ (*nlogmax*) or 50 m³ ha⁻¹ volume (*maxextract*) from trees of commercial groups 1–5 (Table 1) where the DBH was greater than 50 cm (*dbhthreshold*) and stem quality exceeded 0.3 (*minquality*).

2.3. Management regimes

The study used a baseline of a simulation of conventional logging (Table 2). This simulated the harvesting of all potentially commercial trees with a diameter at breast height exceeding 50 cm with the condition that the stem quality exceeded 0.3 (on a scale of 0–1.0). This was used to simulate the observation (Matikainen, personal communication) that around 30% of the stems present in the forest are likely to be left standing because of bad form, defect or other undesirable characteristics (Troekbrodt et al., 2002).

The system of log extraction following harvesting (skidding) under the conventional management regime simulated high levels of disturbance to the residual stand resulting from wide skid trails (7 m) and the probability of damage of trees up to 40 cm diameter in the residual stand. There was no planning for either felling direction or skid trail construction.

The remainder of the management regimes simulated reduced impact logging. These regimes imple-

mented directional felling and planned skid trails. The skid trails were narrower (5 m) and only trees with DBH less than 30 cm were likely to be damaged by the skidding operation. The reduced impact logging treatment was combined with three systems of yield regulation. The “DBH 50 cm” option was the same as the conventional logging system where all potential commercial trees were harvested. Two alternatives were implemented, one where a maximum of 8 stems ha⁻¹ were extracted, the other limiting yield to a maximum of 50 m³ ha⁻¹.

A total of 10 sets of simulations were implemented (Table 3) applying the regimes described above to up to three lengths of cutting cycle ranging from 25 to 45 years (Table 3). The first year of the run was set as being 12 years after logging. Harvests were then implemented at the prescribed cutting cycle until three additional harvests had been completed.

An additional four sets of simulations were performed to describe changes in the ecological structure of the forest that would be predicted by the model. Two sets describe the predicted ecological impacts if

Table 3
Combinations of management regimes simulated in this study

Cutting cycle (years)	Conventional DBH 50 cm	RIL DBH 50 cm	RIL maximum 8 stems	RIL maximum 50 m ³
25		●	●	●
35	●	●	●	●
45		●	●	●

The settings shown in Table 2 were applied for three lengths of cutting cycle for reduce impact logging regimes, but only for a 35-year cutting cycle for conventional logging. These regimes were applied for a total of three cutting cycles.

the forest was logged once and then allowed to recover for a period of 150 years. A second set of simulations was conducted to demonstrate the likely effects of repeated harvesting with a cutting cycle of 35 years.

In all of these simulations, the harvest was implemented 20 years after the simulation commenced so that data describing the stand could be output for analysis at set intervals of 10 years. These settings meant that the first simulated harvest of logged-over forest was implemented at 32 years after the first harvest from primary forest. Earlier results had shown that the difference of 3 years would not significantly impact on this analysis. A comparison was made between the conventional system with yield regulation with a diameter limit of 50 cm and RIL with yield regulated to a maximum of 50 m³ ha⁻¹.

2.4. Simulation settings

Each set of simulations shown in Table 3 was applied to each of the 24 plots. Twenty replicate simulations were performed for each plot to allow for the stochastic nature of components of the SYM-FOR framework. The model was programmed to store data describing the status of the stand at intervals throughout the simulation. These were: at the start of the run, and then immediately before and after logging, for each replicate simulation. These data describing all “live trees” in the stand are summarised in Table 4. An additional set of data describing the trees that had been harvested during each simulation run were stored at the end of each replicate simulation (Table 4).

The model output two derived estimates. Basal area (g, m²) was calculated from the simulated DBH (*d*, cm).

Table 4
Data attributes output during each replicate simulation in this study

Attribute	Live trees	Harvested trees
Runnumber	●	●
Dumpnumber	●	●
Outreason	●	
Year died		●
Speciesgrp	●	●
Utilgrp	●	●
Dbh	●	●
Basal area	●	●
Volume	●	●
Quality	●	●

Data for all live trees were output at the start of the simulation and immediately before and after each simulated harvest. Data for all harvested trees were output at the end of each simulation. The *runnumber* and *dumpnumber* data were used to calculate the identity for each plot and simulation replicate. *Outreason* was output for live trees to indicate when data were output within each simulation. *Speciesgrp* represented the ecological group of the trees and *utilgrp* the commercial species (Table 1). *Dbh* represented the simulated diameter at breast height of the trees at intervals during the simulation (live trees) or when harvested (harvested trees). Volume was calculated from diameter using a volume equation developed previously for this concession (Enggelina, 1994, 1998). The quality factor was assigned at random to trees either at the start of the simulation or when small trees were recruited into stand (DBH > 10 cm).

Stem volume was calculated from volume equations previously derived for the Labanan concession of PT Inhutani I (Enggelina, 1994, 1998).

For the simulations describing ecological structure, data describing all the live trees in the stand (Table 4) were output at the start of the simulation, and then at regular 10-year intervals during the simulation. The data output in year 20 of the simulation (before logging) were supplemented with data immediately following logging.

2.5. Statistical analysis

The statistical analysis of the simulated data in this experiment was designed to maximise the power of the experiment (the ability to differentiate between treatments) whilst avoiding experimental or systematic bias or false replication. The occurrence of events such as the loss of volume from the stand resulting from the death of large trees may bias the resulting means (Phillips et al., 2003). In this previous study, it

was shown that large numbers of replicate simulations are required to prevent such bias and to obtain reliable estimators of the mean and standard error. In this study, 20 replicates were used for each of 24 plots, meaning that 480 separate simulations were completed for each treatment in the experiment. The experimental unit, was however still the plot, and the number of replicates was therefore 24. For this reason data were processed for each individual plot within a treatment to calculate the mean of 20 replicates. It was this mean that was used in subsequent analysis.

The periodic annual increment (PAI, $m, m^3 ha^{-1}$ per year) for volume was calculated for either commercial volume or the whole stand. The commercial PAI was calculated for only those stems in the commercial groups 1–5 (Table 1) with a diameter at breast height greater than 50 cm and stem quality of greater than 0.3. The PAI for the whole stand was calculated based on all stems in the stand (DBH > 10 cm). The PAI (p) was calculated using Eq. (1), where the subscripts 1 and 2 represent the start and end of a measurement interval, respectively. For harvest 2 this was the start of the simulation and immediately preceding harvesting. For harvests 3 and 4 these were immediately following the harvest and preceding the next harvest:

$$p = \frac{\sum V_2 - \sum V_1}{t_2 - t_1} \quad (1)$$

where $\sum V$ is the sum of volume ($m^3 ha^{-1}$) and T the year of simulation (year).

Statistical analysis of the data was performed using the SAS statistical package. The SUMMARY procedure (SAS Institute Inc., 1990) was used to calculate the total basal area, volume and number of stems for each plot. The GLM procedure (SAS Institute Inc., 1989) was used to calculate an analysis of variance (ANOVA) and associated treatment means, standard errors and orthogonal planned comparisons. The analysis of variance was implemented as a split-plot design where each treatment was applied to identical initial data for each of 24 plots.

Two sets of analysis of variance were calculated. The first was a one-way comparison of all four treatments with a 35-year cutting cycle (Table 3). The main effect had three degrees of freedom permitting the same number of orthogonal comparisons of means (Sokal and Rohlf, 1981; SAS Institute Inc., 1989). These comparisons are summarised in Table 5. Planned orthogonal comparisons were presented as they provide more robust comparison of treatment means compared to the usual approach utilising unplanned multiple range comparisons.

The interaction between the two treatment main effects was examined using graphical analysis if the interaction term of the analysis of variance was significant.

2.6. Financial analysis

A simple financial analysis was applied to the management regimes applied in these experiments.

Table 5
Orthogonal planned comparison of means calculated for each analysis of variance

Attribute	Main effect	d.f.	Planned comparisons
Experiment 1 (one-way)	Management	3	(1) Conventional \times RIL DBH 50 cm
			(2) RIL 8 stems \times 50 $m^3 ha^{-1}$
			(3) RIL DBH 50 cm \times (8 stems + 50 $m^3 ha^{-1}$)
Experiment 2 (two-way)	Management	2	(1) RIL 8 stems \times 50 $m^3 ha^{-1}$ (2) RIL DBH 50 cm \times (8 stems + 50 $m^3 ha^{-1}$)
	Cutting cycle	2	(1) 25 years \times 35 years (2) 35 years \times 45 years

The number of comparisons were limited to the number of degrees of freedom (d.f.) for each treatment main effect. Codes are: conventional, conventional logging (yield regulated to minimum diameter of DBH 50 cm); RIL, reduced impact logging; DBH 50 cm, yield regulated with a minimum diameter limit of 50 cm DBH; 8 stems, yield limited to a maximum of 8 stems ha^{-1} ; 50 $m^3 ha^{-1}$, yield limited to a maximum volume of 50 $m^3 ha^{-1}$. The comparison RIL DBH 50 cm \times (8 stems + 50 $m^3 ha^{-1}$) compared the RIL treatments of no yield regulation against the average of the 8 stems and 50 $m^3 ha^{-1}$ treatments.

Data from the SYMFOR simulations were used as input to an existing spreadsheet financial model for the Labanan concession of PT Inhutani I (Fadilah, 1997). The methods linking the SYMFOR and financial models are detailed in a separate technical report (McLeish et al., 2002). This method requires input data describing the annual expected yield and length of cutting cycle. Other data were supplied to describe the normal management practice at the Labanan concession. The financial model used in this study, calculated costs and income estimated on the basis of the volume harvested (as opposed to per unit stem). For this reason the different costs associated with reduced impact logging were estimated using a percentage change (increased or decreased depending on the activity). These data are summarised in Table 6. The financial model calculated an estimated financial IRR and NPV of the forest resource. The NPV of the forest becomes positive when the IRR exceeds the current discount rate used in the analysis. A value of

16.0% was selected for the discount rate used in the current study following previous studies (Fadilah, 1999, 2000). All costs and prices were based on 1997 data used in the original financial study of the Labanan concession (Fadilah, 1997). The choice of the 16% discount rate also reflects the high cost of borrowing and rates of inflation prevalent in Indonesia at the time represented by the financial model.

3. Results

The results in this paper have been presented giving the number of harvests since the forest was first logged. For this reason the first simulated harvest in this study is labelled harvest 2.

3.1. Growth and yield

The results of the comparison of four different management regimes on an area of logged-over forest are shown for a cutting cycle of 35 years as Table 7. The highest volume yield (a) for the second harvest (first simulated harvest of the logged-over forest) was observed for the two treatments with yield regulation of DBH 50 cm (conventional and reduced impact logging). The comparison between 8 stems ha⁻¹ and 50 m³ ha⁻¹ yield regulation methods showed a significantly higher yield for 8 stems ha⁻¹ in harvest 2 but this pattern was reversed for subsequent harvests when the 50 m³ ha⁻¹ had the highest yields.

The average diameter (b) of harvested stems tended to be lower when the DBH 50 cm system of yield regulation was applied but by harvest 4 these differences had reduced. The largest stems were produced by the 50 m³ ha⁻¹ treatment for harvests 2 and 3, but in harvest 4 there were no significant differences between this and the 8 stems ha⁻¹ treatment.

The number of stems (c) harvested per hectare varied between harvests in all treatments except for the 8 stems ha⁻¹ treatment. The eight stems and 50 m³ ha⁻¹ treatments tended to harvest fewer stems than the DBH 50 cm treatments for all harvests, however the 50 m³ ha⁻¹ treatment had an increased number of harvested stems at each harvest indicating that the average size of commercial stems was decreasing.

The periodic annual increment (d) for commercial volume was not significantly different from zero for

Table 6

Parameters used in the financial analysis of the results from the simulations of yield from logged-over forest utilising the SYMFOR framework

Parameter	Conventional	Reduced impact logging
Area of concession (ha)	53000	53000
Cutting cycle (years)	35	25, 35, 45
Yield (m ³ ha ⁻¹)	From model	From model
Harvest efficiency (%)	52	52
Log price (US\$)	90	90
Discount factor (%)	16	16
Cost modifiers (%)		
Felling and topping	0	+15
Skidding	0	-25
Road planning	0	+10
Pre-felling inventory	0	+10
Staff training	0	+20

The parameters *cutting cycle* and *yield* were obtained from the SYMFOR simulation. All other parameters use figures that are typical for the concession. The harvest efficiency represents the proportion of the total felled volume (yield from SYMFOR) that is actually extracted from the forest and marketed. A value of 52% means that 48% of the felled volume is currently lost through wastage in the forest. The cost modifiers were used to modify the costs when implementing reduced impact logging techniques. Significant cost savings are expected for skidding (extraction costs) but need to be balanced against additional costs associated with felling, planning activities and staff training.

Table 7

Comparison of results from simulations over three harvests using a 35-year cutting cycle

	Harvest 2	Harvest 3	Harvest 4
(a) Volume ($\text{m}^3 \text{ha}^{-1}$)			
Conventional (DBH 50 cm)	81.8	35.6	40.0
RIL (DBH 50 cm)	81.6	35.4	43.5
RIL 8 stems ha^{-1}	64.4	36.2	37.7
RIL 50 $\text{m}^3 \text{ha}^{-1}$	50.9	43.6	46.0
Standard error (\pm)	3.0	1.3	0.8
(1) Conventional \times RIL DBH 50 cm	n.s. ^a	n.s.	**
(2) RIL 8 stems \times 50 $\text{m}^3 \text{ha}^{-1}$	**	***	***
(3) RIL DBH 50 cm \times (8 stems + 50 $\text{m}^3 \text{ha}^{-1}$)	***	**	n.s.
(b) Mean DBH (cm)			
Conventional (DBH 50 cm)	71.8	59.2	58.5
RIL (DBH 50 cm)	72.4	57.8	57.9
RIL 8 stems ha^{-1}	80.5	64.1	64.3
RIL 50 $\text{m}^3 \text{ha}^{-1}$	87.8	68.6	64.3
Standard error (\pm)	1.1	1.0	0.8
(1) Conventional \times RIL DBH 50 cm	n.s.	n.s.	n.s.
(2) RIL 8 stems \times 50 $\text{m}^3 \text{ha}^{-1}$	***	**	n.s.
(3) RIL DBH 50 cm \times (8 stems + 50 $\text{m}^3 \text{ha}^{-1}$)	***	***	***
(c) Number of stems (ha^{-1})			
Conventional (DBH 50 cm)	12.5	8.8	10.3
RIL (DBH 50 cm)	12.2	9.3	11.5
RIL 8 stems ha^{-1}	7.7	7.3	7.8
RIL 50 $\text{m}^3 \text{ha}^{-1}$	5.7	8.1	10.0
Standard error (\pm)	0.6	0.4	0.2
(1) Conventional \times RIL DBH 50 cm	n.s.	n.s.	***
(2) RIL 8 stems \times 50 $\text{m}^3 \text{ha}^{-1}$	*	n.s.	***
(3) RIL DBH 50 cm \times (8 stems + 50 $\text{m}^3 \text{ha}^{-1}$)	***	**	***
(d) Periodic annual increment ($\text{m}^3 \text{ha}^{-1}$ per year)			
Conventional	-0.10	1.02	1.14
RIL no yield regulation	-0.05	1.03	1.26
RIL 8 stems ha^{-1}	-0.07	0.94	1.30
RIL 50 $\text{m}^3 \text{ha}^{-1}$	-0.04	0.85	1.36
Standard error (\pm)	0.03	0.03	0.02
(1) Conventional \times RIL DBH 50 cm	n.s.	n.s.	**
(2) RIL 8 stems \times 50 $\text{m}^3 \text{ha}^{-1}$	n.s.	*	n.s.
(3) RIL DBH 50 cm \times (8 stems + 50 $\text{m}^3 \text{ha}^{-1}$)	n.s.	***	n.s.

Data are presented as the mean (\pm standard error) for 24 plots using a one-way analysis of variance of a split-plot experimental design to remove between-plot variance. Levels of significance are presented for three planned comparisons (Table 5).

^a Not significant ($P > 0.05$).

* $P < 0.05$.

** $P < 0.01$.

*** $P < 0.001$.

the period of growth up to the second harvest. The average volume increment ranged between 0.85 and 1.03 for harvest 3 and between 1.14 and 1.36 $\text{m}^3 \text{ha}^{-1}$ per year for harvest 4. The growth rate of commercial stems was significantly higher for the treatments with the diameter-based yield regulation system at harvest

3, but at harvest 4 there was no significance difference for this comparison.

The results from the analysis of the reduced impact logging treatments in a two-way factorial design are shown in Tables 8 and 9 and Fig. 1. The main effect of the management regime treatment was highly

Table 8

The main effect of management regime for reduced impact logging treatments averaged three cutting cycles (25, 35 and 45 years) for three harvests

	Harvest 2	Harvest 3	Harvest 4
(a) Volume ($\text{m}^3 \text{ha}^{-1}$)			
RIL (DBH 50 cm)	81.1	36.2	26.9
RIL 8 stems ha^{-1}	63.5	36.1	42.4
RIL 50 $\text{m}^3 \text{ha}^{-1}$	51.2	42.6	53.6
Standard error (\pm)	1.6	0.8	0.5
(1) RIL 8 stems \times 50 $\text{m}^3 \text{ha}^{-1}$	***	***	***
(2) RIL DBH 50 cm \times (8 stems + 50 $\text{m}^3 \text{ha}^{-1}$)	***	**	***
(b) Mean DBH (cm)			
RIL (DBH 50 cm)	71.8	57.8	57.8
RIL 8 stems ha^{-1}	80.0	64.5	64.7
RIL 50 $\text{m}^3 \text{ha}^{-1}$	87.3	69.1	65.6
Standard error (\pm)	0.6	0.6	0.5
(1) RIL 8 stems \times 50 $\text{m}^3 \text{ha}^{-1}$	***	***	n.s. ^a
(2) RIL DBH 50 cm \times (8 stems + 50 $\text{m}^3 \text{ha}^{-1}$)	***	***	***
(c) Number of stems (ha^{-1})			
RIL (DBH 50 cm)	12.4	9.2	11.2
RIL 8 stems ha^{-1}	7.7	7.1	7.4
RIL 50 $\text{m}^3 \text{ha}^{-1}$	5.8	7.8	8.7
Standard error (\pm)	0.3	0.2	0.2
(1) RIL 8 stems \times 50 $\text{m}^3 \text{ha}^{-1}$	***	*	***
(2) RIL DBH 50 cm \times (8 stems + 50 $\text{m}^3 \text{ha}^{-1}$)	***	***	***
(d) Periodic annual increment ($\text{m}^3 \text{ha}^{-1}$ per year)			
RIL (DBH 50 cm)	-0.10	1.00	1.22
RIL 8 stems ha^{-1}	-0.10	0.92	1.24
RIL 50 $\text{m}^3 \text{ha}^{-1}$	-0.04	0.84	1.28
Standard error (\pm)	0.04	0.02	0.02
(1) RIL 8 stems \times 50 $\text{m}^3 \text{ha}^{-1}$	n.s.	**	n.s.
(2) RIL DBH 50 cm \times (8 stems + 50 $\text{m}^3 \text{ha}^{-1}$)	n.s.	**	n.s.

Data are presented as the mean (± 1 standard error) for 24 plots using a two-way analysis of variance of a split-plot experimental design to remove between-plot variance. Levels of significance are presented for two planned comparisons (Table 5).

^a Not significant ($P > 0.05$).

* $P < 0.05$.

** $P < 0.01$.

*** $P < 0.001$.

significant for volume, mean DBH and the number of stems (Table 8). Significant differences were only found for the periodic annual volume increment for harvest 3.

The timber yield at harvest 2 was highest when the DBH 50 cm treatment was applied and lowest in the 50 $\text{m}^3 \text{ha}^{-1}$ treatment. By harvest 4 this trend had reversed. The mean diameter of harvested stems in all treatments was lower for harvests 3 and 4 than for harvest 2 with the largest stems consistently being produced by the 50 $\text{m}^3 \text{ha}^{-1}$ treatment. By harvest 4, however, the difference between the 8 stems ha^{-1} and 50 $\text{m}^3 \text{ha}^{-1}$ treatments was not significant.

The decrease in average stem diameter was matched by an increase in the number of stems harvested for the DBH 50 cm and 50 $\text{m}^3 \text{ha}^{-1}$ treatments for harvests 3 and 4.

The periodic annual volume increment for commercial volume was close to 0 for harvest 2, between 0.84 and 1.0 $\text{m}^3 \text{ha}^{-1}$ per year for harvest 3 and exceeded 1.2 $\text{m}^3 \text{ha}^{-1}$ per year for harvest 4. The only significant differences between treatments were observed for harvest 3, where the highest volume increments were observed in the DBH 50 cm and the lowest for the 50 $\text{m}^3 \text{ha}^{-1}$ treatment.

Table 9
The main effect of length of cutting cycle averaged over three reduced impact logging treatments (Table 2) for three harvests

	Harvest 2	Harvest 3	Harvest 4
(a) Volume ($\text{m}^3 \text{ha}^{-1}$)			
25 years	64.2	27.6	26.9
35 years	65.7	38.4	42.4
45 years	65.9	49.0	53.6
Standard error (\pm)	1.6	0.8	0.5
(1) 25 years \times 35 years	n.s. ^a	***	***
(2) 35 years \times 45 years	n.s.	***	***
(b) Mean DBH (cm)			
25 years	78.8	60.7	57.6
35 years	80.2	63.5	62.1
45 years	80.0	67.3	68.3
Standard error (\pm)	0.6	0.6	0.5
(1) 25 years \times 35 years	n.s.	***	***
(2) 35 years \times 45 years	n.s.	***	***
(c) Number of stems (ha^{-1})			
25 years	8.7	6.3	7.1
35 years	8.5	8.2	9.7
45 years	8.6	9.6	10.5
Standard error (\pm)	0.3	0.2	0.2
(1) 25 years \times 35 years	n.s.	***	***
(2) 35 years \times 45 years	n.s.	***	**
(d) Periodic annual increment ($\text{m}^3 \text{ha}^{-1}$ per year)			
25 years	-0.20	0.71	1.05
35 years	-0.05	0.94	1.31
45 years	0.02	1.12	1.39
Standard error (\pm)	0.04	0.02	0.02
(1) 25 years \times 35 years	**	***	***
(2) 35 years \times 45 years	n.s.	***	**

Data are presented as the mean (± 1 standard error) for 24 plots using a two-way analysis of variance of a split-plot experimental design to remove between-plot variance. Levels of significance are presented for two planned comparisons (Table 5).

^a Not significant ($P > 0.05$).

** $P < 0.01$.

*** $P < 0.001$.

The main effect of cutting cycle length is shown in Table 9. The means for harvest 2 tend not to show any significant differences between cutting cycle lengths, presumably because the periodic annual volume increment for commercial stems in the stand is near zero. There is a consistent pattern for harvests 3 and 4, where the volume, mean DBH and number of stems harvested all increase significantly with the length of the cutting cycles.

Interactions between the main treatments (management regime and cutting cycle length) are shown in

Fig. 1. Significant interactions are indicated when the lines on the graphs are not parallel. No significant interactions are observed for harvest 2. The 8 stems ha^{-1} and 50 $\text{m}^3 \text{ha}^{-1}$ treatments reacted in the same way to the treatments but differed from the DBH 50 cm treatment. This treatment tended to perform poorly for harvests 3 and 4 at short cutting cycles, but had the highest yield and number of stems harvested for a cutting cycle of 45 years. The DBH 50 cm treatment consistently had the lowest mean diameter of harvested stems.

3.2. Financial analysis

The internal rate of return and net present value of the forest enterprise are shown in Tables 10 and 11, respectively. Net present values were calculated using a discount factor of 16%. At harvest 2, most treatments produced an IRR greater than 16% and hence a positive NPV. The exception was the RIL 50 $\text{m}^3 \text{ha}^{-1}$ treatment which only managed to break even on the shortest cutting cycle. The NPV for harvests 3 and 4 were negative for all combinations of treatments. In several cases the IRR became undefined when the total costs exceeded the total income and the business ran at a net loss.

3.3. Ecological analysis

A separate ecological analysis was conducted comparing the conventional DBH 50 cm and 50 $\text{m}^3 \text{ha}^{-1}$ treatments where the stand was logged in year 20 of the simulation (32 years after harvest 1) and then allowed to recover for a further 150 years. Data for the volume, basal area and number of stems are shown for the whole stand and commercial trees (DBH > 50 cm, quality > 0.3) are shown in Fig. 2.

This figure shows that the conventional system showed the most significant changes in the period immediately following logging with lower average basal area, volume and initially number of stems. Ten years after logging, the stand managed with the conventional system had a very significant increase in the number of stems, which must have been small, as the total basal area and volume was still lower at this time. There were more significant differences observed for the commercial stems immediately after logging, but it is interesting to note that that the

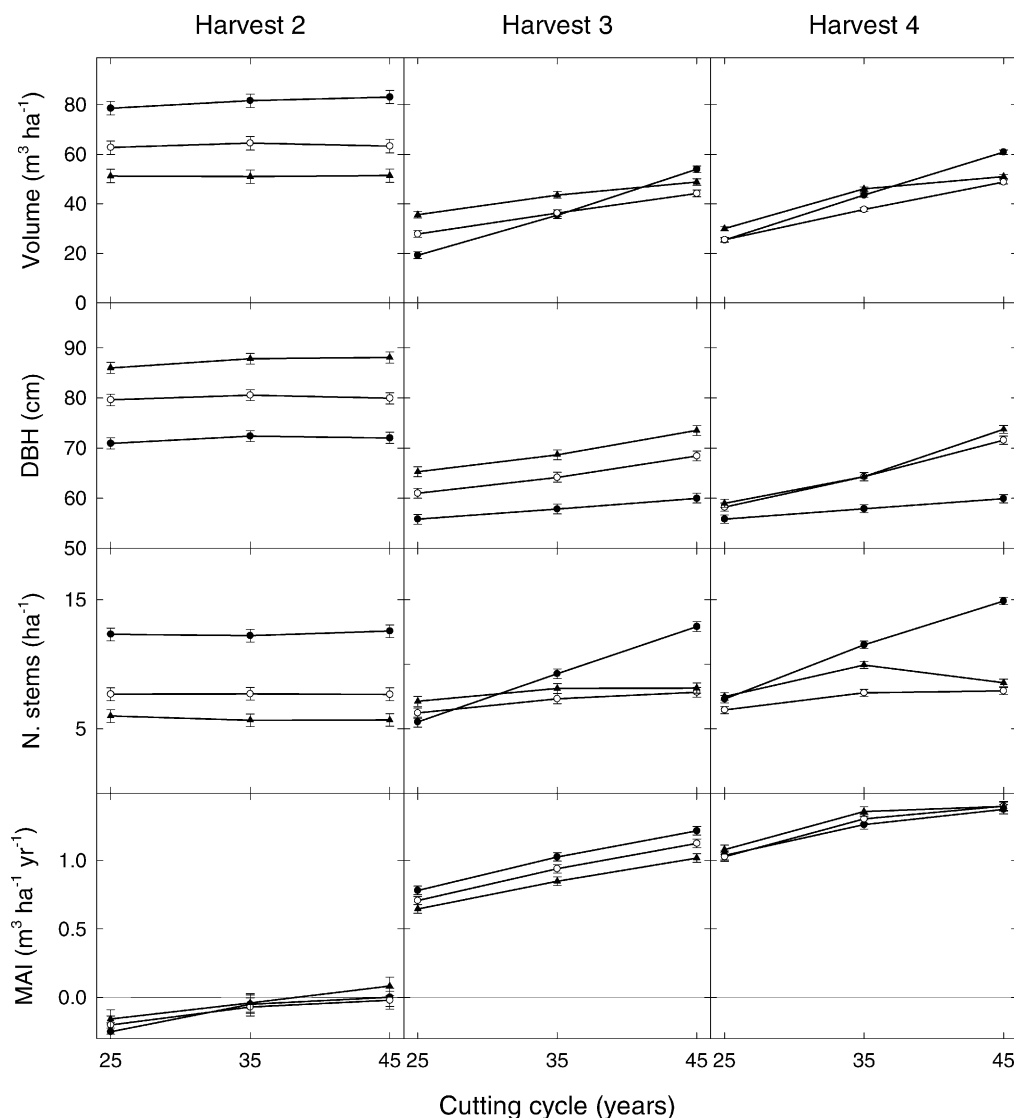


Fig. 1. Interactions between management regime and length of cutting cycle. Data represent the mean obtained from 24 plots in a two-way split-plot ANOVA experimental design. Treatments were yield regulated with a diameter limit of DBH 50 cm (●) or yield regulated to a maximum of 8 stems ha^{-1} (○) or maximum volume of $50 \text{ m}^3 \text{ ha}^{-1}$ (▲). Error bar represents ± 1 standard error. The means for the treatment main effects are listed in Table 8 (management regime) and Table 9 (cutting cycle length).

conventional management system ended the simulation with higher commercial volumes.

The basal areas shown in Fig. 2 have been subdivided according to their ecological species group (Table 1) and are presented in Fig. 3. The results for the three main groups (groups 1–3) show that the $50 \text{ m}^3 \text{ ha}^{-1}$ treatment has higher basal area of the main Dipterocarp species for up to 40 years following

harvesting, but that this reverses subsequently. The simulations are predicting significant changes in the composition of the forest from the starting point of the simulation up to the harvest. It must however be remembered that the first year of the simulation uses data collected from a forest 12 years after the first harvest in primary forest and as such it would be in a dynamic state.

Table 10

Internal rate of return (IRR, %) calculated using the yields shown in Table 7 and Fig. 1 and financial parameters as detailed in Table 6

	Cutting cycle (years)		
	25	35	45
Harvest 2			
Conventional (DBH 50 cm)	– ^a	26.3	–
RIL (DBH 50 cm)	31.2	26.4	24.5
RIL 8 stems ha ⁻¹	23.5	20.1	16.3
RIL 50 m ³ ha ⁻¹	17.6	13.4	10.1
Harvest 3			
Conventional (DBH 50 cm)	–	n.c. ^b	–
RIL (DBH 50 cm)	n.c.	n.c.	12.0
RIL 8 stems ha ⁻¹	n.c.	n.c.	2.3
RIL 50 m ³ ha ⁻¹	2.0	7.2	8.1
Harvest 4			
Conventional (DBH 50 cm)	–	2.3	–
RIL (DBH 50 cm)	n.c.	7.1	15.4
RIL 8 stems ha ⁻¹	n.c.	n.c.	8.1
RIL 50 m ³ ha ⁻¹	n.c.	9.5	10.1

^a Not simulated.

^b Not calculated when the management system operated at a net loss.

The data shown in Fig. 2 were used to calculate an estimate of the periodic annual volume increment at 10-year intervals for the whole stand (a) and for commercial stems (b) shown in Fig. 4. The PAI is highest in the conventional logging treatment. The rate of volume increment for the whole stand simulated by the model is highest in the period immediately following logging and then steadily declines. At the peak of over 4 m³ ha⁻¹ per year the volume increment of the stand was more than four times greater than the commercial volume increment. The simulated commercial periodic annual volume increment plateaus at just over 1 m³ ha⁻¹ per year after logging and only starts to decline around 80 years after logging for the 50 m³ ha⁻¹ treatment and 120 years after logging for the conventional treatment.

The results shown in Figs. 1–4 demonstrate ecological aspects of the impact of a single logging event on the forest, and the subsequent process of recovery of the forest stand. The forest management regimes applied in this study utilised multiple harvests with cutting cycles of between 25 and 45 years. Such repeated logging operations are likely to further influence the ecology and structure of the forest. Results of

Table 11

Net present value (NPV, US\$ per hectare) calculated using the yields shown in Table 7 and Fig. 1 and financial parameters as detailed in Table 6

	Cutting cycle (years)		
	25	35	45
Harvest 2			
Conventional (DBH 50 cm)	– ^a	51	–
RIL (DBH 50 cm)	88	55	35
RIL 8 stems ha ⁻¹	41	19	1
RIL 50 m ³ ha ⁻¹	8	–11	–21
Harvest 3			
Conventional (DBH 50 cm)	–	–57	–
RIL (DBH 50 cm)	–114	–57	–14
RIL 8 stems ha ⁻¹	–77	–54	–38
RIL 50 m ³ ha ⁻¹	–44	–31	–26
Harvest 4			
Conventional (DBH 50 cm)	–	–42	–
RIL (DBH 50 cm)	–89	–31	–2
RIL 8 stems ha ⁻¹	–88	–49	–26
RIL 50 m ³ ha ⁻¹	–67	–26	–21

^a Not simulated.

a simulation with a cutting cycle of 35 years are shown in Fig. 1 showing changes in basal area for the same ecological species groups as shown in Fig. 3. These results predict a gradual shift in the ecological composition of the forest with reductions in the total basal area of the fast growing *Shorea* species balance with increases in other commercial groups. Very significant differences in the presence of pioneer species (*Anthocephalus* and *Macaranga* groups) are predicted between the conventional treatment and the reduced impact logging treatment with yield regulated to 50 m³ ha⁻¹. The conventional logging appears to create sufficient disturbance to maintain a presence of these pioneers in the stand. In contrast, the lower intensity harvesting combined with reduced impact harvesting techniques only produces small numbers of pioneers in the stand.

4. Discussion

The discussion will first consider an ecological and financial analysis of conventional logging before moving to evaluate the range of possible alternatives simulated in this study.

Management of logged-over Dipterocarp forests

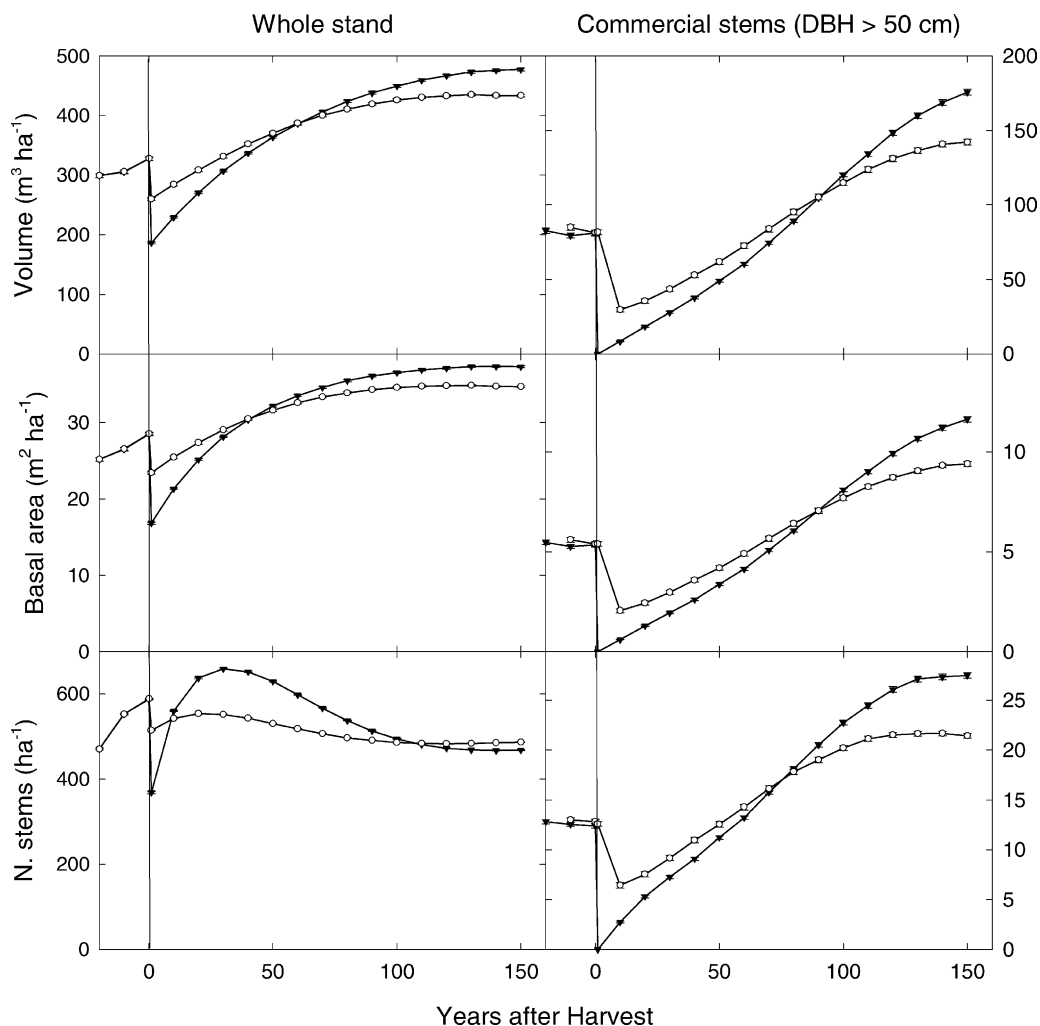


Fig. 2. Stand structure over a 150-year simulation where the stand is harvested once in year 20. Two management regimes are shown: conventional logging with yield regulated with a minimum diameter limit of DBH 50 cm (\blacktriangledown) and reduced impact logging with yield regulated to a maximum volume of $50 \text{ m}^3 \text{ ha}^{-1}$ (\circ). Data show the mean (± 1 standard error) for all trees in the stand compared with commercial stems with DBH > 50 cm and quality > 0.3. The means were calculated as the average of 24 plots.

4.1. Conventional management

The conventional management system uses a simple yield regulation system based on a diameter limit of 50 cm. The results show that the second harvest (first simulated harvest) on logged-over forest produced a predicted yield of over $80 \text{ m}^3 \text{ ha}^{-1}$ (Table 7). This value is much higher than that predicted for the

second harvest using the same simulation model when commencing with data from primary forest (Susanty and Sardjono, 2000). The likely reason for this is that the plots used in the current study were harvested in 1979 when the levels of extraction were much lower than are currently practised. For this reason it is likely that many potentially harvestable stems were left in the forest at the time of the first harvest.

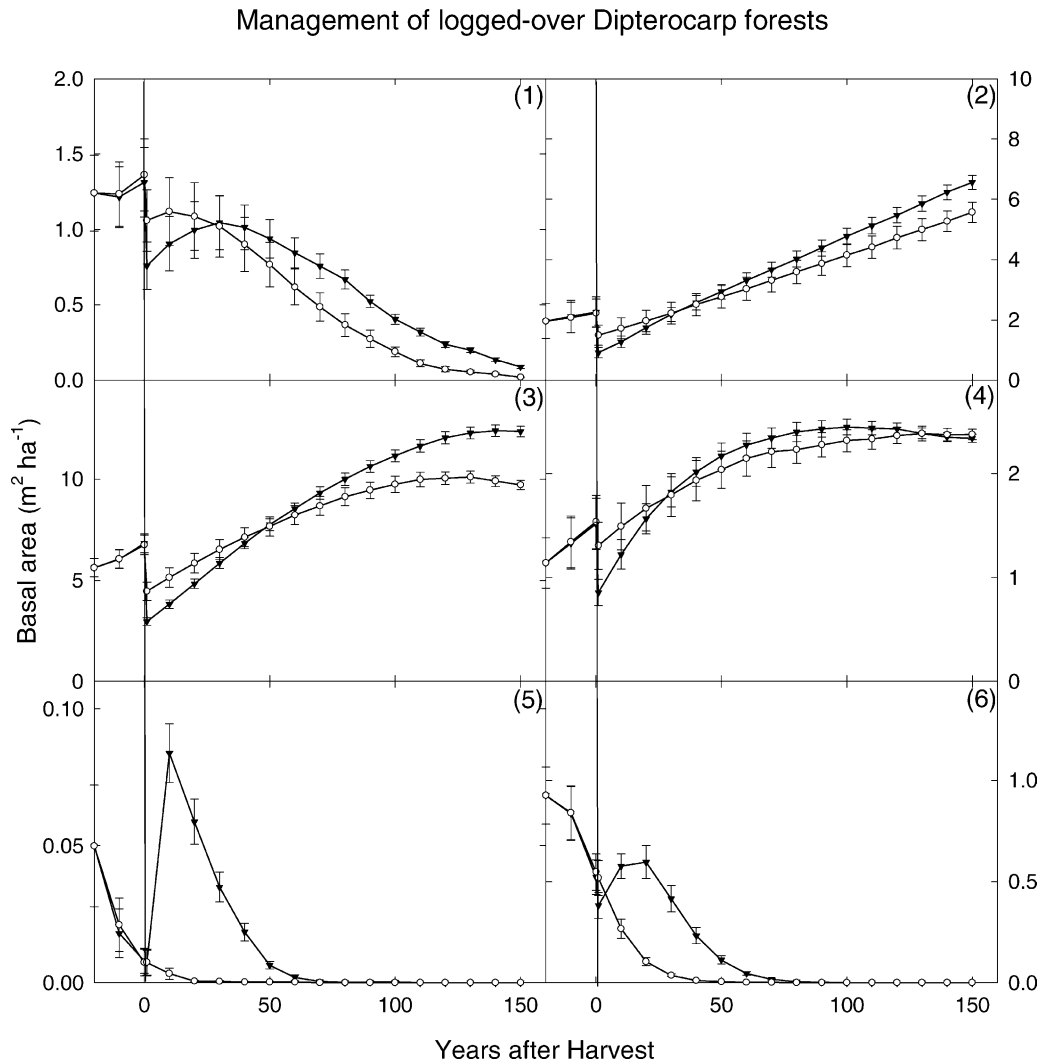


Fig. 3. Basal areas of key ecological species groups for the data shown as in Fig. 2. Data show the mean (± 1 standard error) conventional harvesting with yield regulated with a minimum diameter limit of DBH 50 cm (\blacktriangledown) compared with reduced impact logging with maximum volume of $50 \text{ m}^3 \text{ ha}^{-1}$ (\circ). The means were calculated as the average of 24 plots. Numbers refer to the ecological species groups defined in Table 1: (1) fast growing *Shorea*; (2) *Dipterocarpus*; (3) other large Dipterocarps; (4) small Dipterocarps; (5) *Anthocephalus*; (6) *Macaranga*.

This conclusion was supported by a survey of the plots during the early stage of the STREK trial which suggested that an average of four stems had been harvested per hectare (Nguyen-The et al., 1998).

The relatively low rate of extraction of commercial timber from the plots at the time of the first harvest would have left the canopy relatively intact and may be a reason that the annual volume increment for all treat-

ments was near zero just before harvest 2. This would suggest that for this area of forest there was little benefit in waiting for the full 35-year cutting cycle to be completed, before commencing the second harvest. This leads to the conclusion that the length of the cutting cycle should be more flexible and be linked to data from regular static inventory from the forest. Data from untreated plots in the silvicultural experiment set

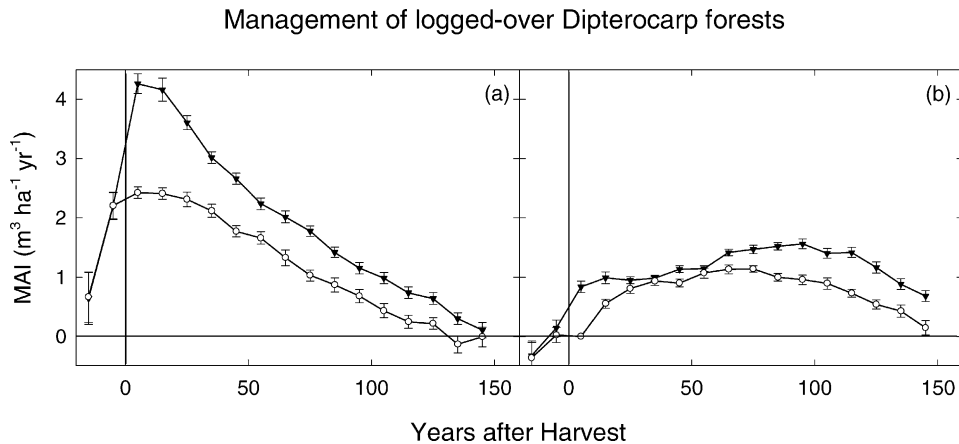


Fig. 4. Mean annual volume increment (PAI) for volume calculated from the data shown in Fig. 2. Data show the mean (± 1 standard error) for (a) all trees in the stand compared with (b) commercial species with DBH > 50 cm and quality > 0.3. Two management regimes are shown: conventional logging with yield regulated to a minimum diameter of DBH 50 cm (\blacktriangledown) and reduced impact logging with yield regulated to a maximum volume of $50 \text{ m}^3 \text{ ha}^{-1}$ (\circ). The means were calculated as the average of 24 plots.

up in 1992 (1 year after the data used in this study were collected) also show very low commercial volume increments over a period of 8 years (van Gardingen, 1999a,c).

The conventional management system leads to a variable yield, where the predicted yields for the third and fourth harvests are less than half that of harvest 2. This is associated with very significant reductions in the average diameter of the harvested stems (Table 7). This system does not fulfil the criteria for sustainable production of timber, and has the worst financial performance of any of the systems tested with a 35-year cutting cycle (Tables 10 and 11). We can conclude that the conventional management system will not be sustainable based on this simple analysis of yield and associated financial viability. The low predicted yield (Table 7) and large negative net present value (Table 11) suggest that the only commercially viable option for the forest after the second harvest under the conventional management system would be to clear the forest and convert it to alternative uses such as planted forests or agriculture.

The rest of this paper will consider a matrix of nine alternative management regimes. All of the alternative systems considered in this paper are modifications of the original TPTI, first by implementing reduced impact logging and then through the application of alternative yield regulation systems in combination with cutting cycle lengths of 25, 35 and 45 years.

4.2. Reduced impact logging (DBH 50 cm)

The least radical change to the conventional management regime simulated in this study was the RIL (DBH 50 cm) regime. The only change was that RIL techniques were simulated including directional felling and construction of planned skid trails, the system of yield regulation remained unchanged. This system was applied at three cutting cycle lengths. With a 35-year cutting cycle there were no significant differences between the conventional management and RIL treatments for the second and third harvests in this study (Table 7). Only at the fourth harvest was there evidence of slightly higher yields and periodic annual volume increment. This could be expected, as the reduced impact logging treatments tend mainly to affect regeneration and the survival of small trees. These trees are typically less than 30–40 cm diameter, and these can take 40–50 years to become large enough to be harvested. This means that the effect would only be expected to be observed in the last simulated harvest of this study (70 years after the first simulated harvest).

The financial performance of the RIL (DBH 50 cm) treatment is marginally better than the conventional treatment reflecting the lower total costs associated with well-planned reduced impact activities. The calculated internal rate of return (Table 10) and net present value (Table 11) indicate that this treatment once again cannot be considered to be sustainable

on the basis of either sustained yield or financial performance. The worst net present value (US\$ –114 per hectare) observed in this study was predicted for this treatment when using a 25-year cutting cycle.

This analysis reflects that the reduced impact logging system does not offer any significant benefits in long-term productivity or financial performance associated with future harvests under this system compared with conventional management when applied using the diameter-based system of yield regulation. The same conclusion was drawn from early analysis of data from the STREK trial in terms of the potential for the reduction of damage to the residual stand (Bertault and Sist, 1997). It can be suggested that the financial benefits of reduced impact logging must be realised immediately through lower operating costs, rather than expectations of higher potential yield from future harvests. This previous study and the current results also leads to the conclusion that the real benefits of reduced impact logging will only be achieved when it is combined with an effective system for yield regulation. The next section will consider two such alternatives.

4.3. Alternative systems of yield regulation

The comparison of different systems of yield regulation is summarised as the main effects of management regime (Table 8), cutting cycle (Table 9) and their interaction (Fig. 1), and as a financial analysis giving the resulting internal rate of return (Table 10) and net present values (Table 11). These results showed significant variation between the combinations of yield regulation system and length of cutting cycle. The first criterion for sustainability applied in this study was that the management system should have a sustainable timber yield over several cutting cycles.

The average basal area observed in RKL-1 of $25.2 \text{ m}^2 \text{ ha}^{-1}$ observed 12 years after logging is similar to the basal area observed in the more recent logging trial in RKL-4 only 5 years following logging (van Gardingen, 1999b), in spite of the RKL-4 trial removing significantly more stems (Sist and Bertault, 1998). This suggests that harvesting activities RKL-1 differed from subsequent activities in that whilst a small number of stems were removed, the resulting damage was very great. This conclusion is further supported by the relative large number of stems and basal area for light

demanding pioneer species, *Anthocephalus chinensis* in the plots in RKL-1 indicating high levels of disturbance associated with harvesting. These observations are consistent with what is known as the logging operation at the time, where it is reported by local people, that the forest was exploited by removing only the best stems of a few species, with little consideration for the environment or future productivity of the stand.

The standard of forest management in this region has consistently improved since the early 1980s when the plots in RKL-1 were harvested. This can be seen by the observation that plots harvested using conventional techniques for the logging trial in 1992 (RKL-4), had less damage even though more stems were extracted. For these reasons it must be concluded that the yield simulated for the second harvest simulated in this study would not be representative of other areas of forest logged more recently and heavily. In these stands it would be expected that yields would be lower, more similar to those observed for the third or fourth harvests simulated in this study.

The general trends in yields are that the 25-year cutting cycle results in a significant reduction in timber yield to an average level of around $27 \text{ m}^3 \text{ ha}^{-1}$ by harvest 4 (Table 9). For both the 35- and 45-year cutting cycles there appears to be a recovery in yield by harvest 4 to produce average yields of 42 and $54 \text{ m}^3 \text{ ha}^{-1}$, respectively. These results suggest that only the 35- and 45-year cutting cycles should be considered as being potentially sustainable under the management systems considered in this study.

There were statistically significant interactions between management regime and cutting cycle length as shown in Fig. 1. These results suggest when applying a 35-year cutting cycle that only the RIL treatment with yield regulated to $50 \text{ m}^3 \text{ ha}^{-1}$ should be considered to result in sustainable yields. In contrast, all reduced impact logging treatments produced evidence of sustained yield with a 45-year cutting cycle. In order to further differentiate these treatments it is necessary to consider other aspects of their performance.

There are very significant differences between treatments in the number of stems and their average diameter that combine to produce the harvested yield (Fig. 1). By harvest 4, the treatment with yield regulated to DBH 50 cm, resulted in a stand consisting of many small stems. Hence, whilst the DBH 50 cm treatment has the highest yield in harvest 4, it requires

the most effort and expense to harvest and would produce the most damage to the residual stand. In contrast, both the 8 stems ha^{-1} and 50 $\text{m}^3 \text{ha}^{-1}$ treatments are able to sustain yields without very significant increases in the number of stems harvested, or reductions in the average diameter of the harvested stems.

Forest managers would benefit because lower numbers of stems harvested reduces costs and increases profit per unit volume. Larger diameter stems are easier to market and may receive a price premium that further increases the potential profit. Yield regulation systems based on a maximum number of stems extracted do, however, have advantages over volume-based systems, in being easier to specify, implement and monitor.

4.4. Statistical analysis of results from growth and yield simulations

The introduction to this paper indicated that there have been very few reports that have made statistical comparisons of forest management treatments utilising simulation models. Of these only the work in Queensland (Vanclay, 1994b) permits effective comparison. The combination of variation between plots used to initialise simulations and the stochastic components of many simulation models means that such approaches should be applied in all applications of models to support management or policy development. The approach described in this paper provides a method that can very significantly reduce the experimental error associated with variation between plots. An initial comparison was made with results from the simulations to contrast the statistical power of the split-plot design compared to an ANCOVA experimental design often used to analyse similar field trials. The experimental variance was very much smaller than that obtained using the ANCOVA analysis meaning that the approach described in this paper was much more likely to resolve differences between simulated treatments.

4.5. Financial analysis

The financial analysis used in this study was based on a cost–benefit analysis to produce estimates of the financial internal rate of return (Table 10) and

net present value (Table 11). This analysis produces several key conclusions. The first is that a 25-year cutting cycle is not financially viable. The high net present value and internal rate of return for the second harvest appears to be derived from pre-existing natural capital, that is the commercial stems that were left standing after the first harvest in primary forest. After that natural capital has been depleted, the expected yields are such that the business will make an operating loss when applying a 25-year cutting cycle. The 35-year cutting cycle produces better financial results, but the net present value is negative for all treatments in harvests 3 and 4. Only the 50 $\text{m}^3 \text{ha}^{-1}$ treatment produces an annual operating profit for the third harvest (with an IRR of 7.2%). By harvest 4, most of the treatments are producing annual operating profits with internal rates of returns between 2.3 and 9.5%. Only the 8 stems ha^{-1} treatment is producing a loss. The reason for this is that as the average stem diameter decreases with all of the treatments, it is no longer possible to obtain sufficient yield with 8 stems ha^{-1} to make a profit. This suggests that the 8 stems ha^{-1} treatment will not be viable for long-term sustainable management of the resource under current market conditions if applied with a 35-year cutting cycle. The long-term financial performance of all of the systems was best under a 45-year cutting cycle, but again none managed to meet the target internal rate of return of 16% and produced negative net present values for harvests 3 and 4. Once again, the 50 $\text{m}^3 \text{ha}^{-1}$ treatment produced the most consistent results with an internal rate of return of between 8 and 10%. Ways of further improving this result will be considered later.

One of the most important conclusions in the current study is the quantification of the opportunity cost associated with the alternative systems of yield regulation. A comparison between the DBH 50 cm and 50 $\text{m}^3 \text{ha}^{-1}$ reduced impact logging treatments show a predicted lost profit of between US\$ 66 and 80 per hectare associated with the 50 $\text{m}^3 \text{ha}^{-1}$ treatment depending on the length of the cutting cycle. The time horizon for management decisions is such that any commercial manager would be unlikely to accept this opportunity cost unless given some other incentive or else the presence of a strong and effective regulatory framework. Neither of these options are effective in Indonesia at present, timber certification will certainly

help, but it will not be able to address the issue for all forest management enterprises. There needs to be more effort directed towards capturing distant benefits (in time and space) such as environmental services associated with good forest management. Schemes such as carbon credits may have a role to play, but it is debatable how quickly and widely such a scheme could be applied. For this reason it is suggested that modifications to the policy and regulatory framework supporting forest management are likely to be more effective. There is a need to move to a system that is more flexible, recognises outcomes (Bennett, in press) and penalises poor management either through the loss of a performance bond (Davies and Richards, 1999) or the loss of the right to manage the forest. All of these approaches have the characteristic of giving much more immediate financial return rewarding good management and significant costs linked to poor performance. The opportunity to link this to schemes of certification and market access should remove the current opportunity cost and thus provide a real incentive for forest managers to adopt better management practices.

The cost–benefit analysis was chosen as being the financial measure of most direct relevance to commercial forest managers and decision makers. It is recognised that this approach suffers from not considering the value of other goods and services produced by forests and that there are alternative economic methods that could be used to support more inclusive economic analysis (Davies and Richards, 1999). These were not used in the current study for the reason that the forest management system in Indonesia has no way at present to capture these added benefits. Davies and Richards (1999) also question the appropriate discount factor applied in financial analysis of forest management. Many practitioners will consider the value of 16% used in this study excessive, however, it does represent a realistic value for the managers involved with the forest when considering the opportunity costs associated with the decision of investing in good management compared to other alternatives. The estimates of the internal rate of return reported in this study will allow stakeholders to make objective comparisons of management options that are independent of the choice of discount factor.

The potential controversy associated with the application of fixed discount rates in such analysis can be avoided through the discussion of results in terms of

the internal rate of return. This approach has the advantage of better informing management and policy decisions through the provision of predictions on the likely rate of return on investment.

The analysis used in this study captured information on taxes and levies applied by the government and as such is sensitive to the changing policy environment in Indonesia. The model was found to be insensitive to the impacts of some other aspects of forest management. The most important issue identified in this study was that the costs associated with all forest management activities were calculated on a volume basis rather than on an activity basis. This meant that the true benefits of reduced impact logging and yield regulation tend to be underestimated by the current model. An examination of an alternative model for Kalimantan showed that it also suffers from this problem (Scotland and Whiteman, 1997). Neither model produces a price premium for larger diameter logs, a factor that means that the benefits of the $50 \text{ m}^3 \text{ ha}^{-1}$ treatment (and to a lesser extent the 8 stems ha^{-1} treatment) tend to be underestimated when compared with either of the treatments using a DBH 50 cm system of yield regulation.

4.6. Stand structure, ecological impacts and sustainability

The ecological impacts of contrasting management systems are illustrated in Figs. 2–5. These figures contrast the most extreme management regimes used in this study (conventional harvesting with yield regulation of $\text{DBH} > 50 \text{ cm}$) with the reduced impact logging with yield limited to a maximum of $50 \text{ m}^3 \text{ ha}^{-1}$. The conventional management regime is associated with more severe disturbance to the forest and shifts in species composition. This is clearly demonstrated by the increase in basal area of pioneer species *Anthocephalus chinensis* after logging in the conventional treatment (Fig. 3). Both treatments took up to 150 years following logging to come to a new equilibrium in stand structure. Similar results have been reported from other simulation studies for Malaysian forests (Appanah et al., 1990; Huth and Ditzer, 2001).

The observed periodic annual volume increments are higher for the conventional treatment for both the whole stand and commercial stems, but the difference in the commercial volume remaining after the harvest

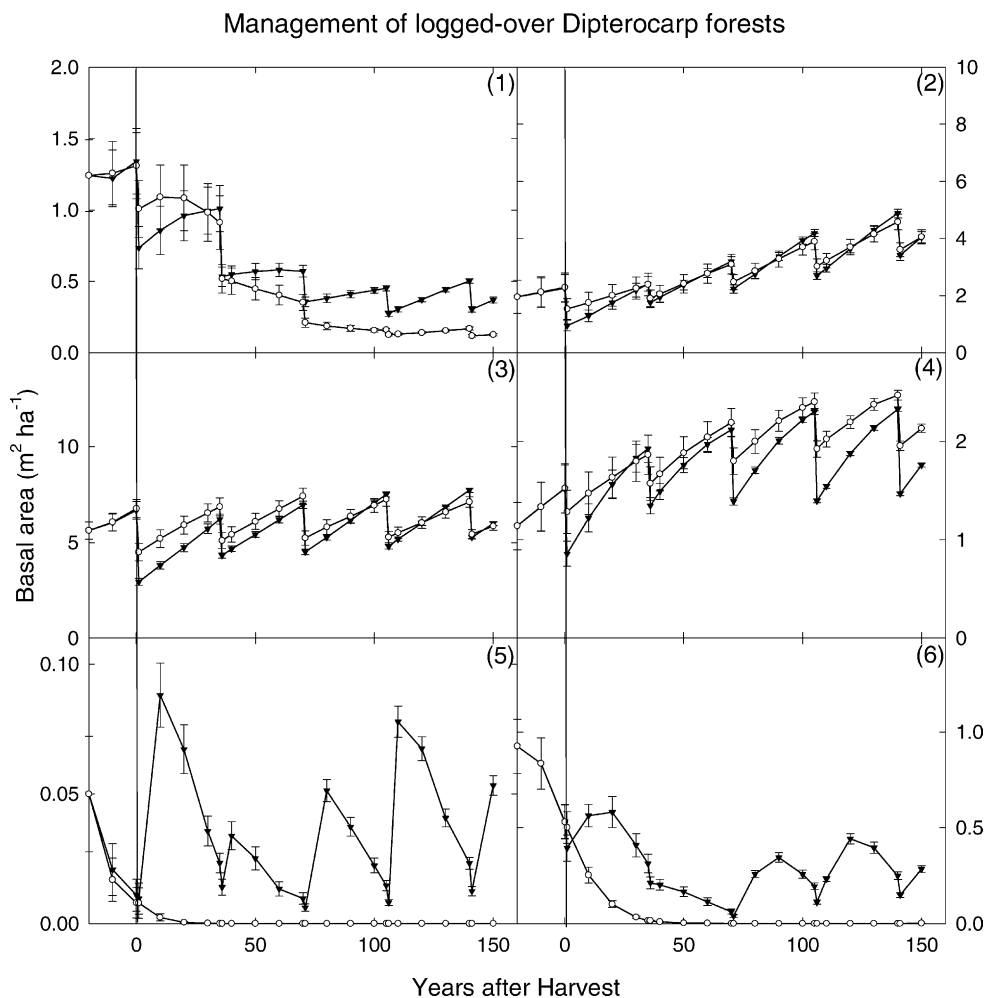


Fig. 5. Basal areas of key ecological species groups for simulations with a 35-year cutting cycle for simulated treatments with yield regulated with a minimum diameter limit of DBH 50 cm (\blacktriangledown) compared with reduced impact logging with maximum volume of $50 \text{ m}^3 \text{ ha}^{-1}$ (\circ). Numbers refer to the ecological species groups defined in Table 1: (1) fast growing *Shorea*; (2) *Dipterocarpus*; (3) other large Dipterocarps; (4) small Dipterocarps; (5) *Anthocephalus*; (6) *Macaranga*. Other details as for Fig. 3.

means that the $50 \text{ m}^3 \text{ ha}^{-1}$ treatment has a higher commercial volume for up to 80 years following the harvest.

The choice in harvesting method and system of regulation very clearly has impacts on the ecology of the forest. The RIL $50 \text{ m}^3 \text{ ha}^{-1}$ treatment has much less impact on the forest stand and would be expected to be associated with higher value associated on the ecological and environmental services of the forest. This may be very important for local and traditional communities who derive income from non-timber forest products.

4.7. Social impacts: sustainability and opportunities

The likely social impacts associated with each of the management regimes considered could only be derived by inference in this study. One method is to consider the outcomes in terms of likely effects on measures of natural, financial and social capital (Carney, 1998). A comparison between the conventional management system and the RIL $50 \text{ m}^3 \text{ ha}^{-1}$ suggests that the conventional system results in a rapid decline in natural capital (the forest and environment). Local communities are often not involved in this type

of forest management and they are unlikely to receive significantly increased income (and resulting financial capital) from this option. The alternative RIL system with yield regulated to a maximum of $50 \text{ m}^3 \text{ ha}^{-1}$ has a number of very significant benefits. Most importantly it sustains the natural resource base (capital) and associated opportunities for income from timber, non-timber forest products and employment. This system results in a greater choice of livelihood strategies for individuals and thus reduces their vulnerability.

4.8. Improving the forest management system

This study has clearly demonstrated that the conventional forest management system applied in Indonesia cannot be sustained for the Labanan concession used in this study. The options to improve the system include, increasing the length of the cutting cycle, imposing stricter controls on the yield and requiring reduced impact logging techniques. Previous studies in Malaysia (Appanah et al., 1990; Huth and Ditzer, 2001) have suggested that the length of the cutting cycle would need to increase much more than suggested in this study, perhaps up to 100 years. The reason for this apparent discrepancy from similar forest types is that these studies simulated very high levels of extraction, often greater than $100 \text{ m}^3 \text{ ha}^{-1}$, such as would be expected under the Malaysian Uniform System of management. When allowances are made for the differences in harvesting intensity, the results and predicted productivity of the forests are very similar to those obtained in the current study.

If the TPTI system continues to be applied as currently specified in Indonesia, it will lead to a rapid deterioration in the structure of the forest to a point where the only financially viable option left would be clearance of the land to be replaced by either agriculture or planted forests. The alternatives based on reduced impact logging and improved systems of yield regulation do appear to be much more viable, but still do not reach the desired 16% internal rate of return used in this study. This leaves two options for sustainable and equitable forest management: either accepting a lower return; or looking for ways to increase the profitability of the system.

The Indonesian TPTI system includes replanting and thinning treatments that are designed to increase future productivity of the stand. Financial analysis of

these treatments has suggested that an increase in resulting yield of around $70 \text{ m}^3 \text{ ha}^{-1}$ is required before these treatments would be financially viable (Fadilah, 1999). This is highly unlikely considering that it would represent a doubling of current yields from primary forest and is not supported by existing trial results (van Gardingen, 2000a).

The results from this study suggest a number of areas where current regulations and technical guidelines could be improved. There are apparently contradictory results relating to the length of the cutting cycle in this study. The lack of any net volume increment leading up to harvest 2 suggests that a shorter cutting cycle would be appropriate for that harvest. In contrast for harvests 3 and 4, the cutting cycle needed to be at least 35 years, with 45 years seeming preferable. The appropriate response to these results is to propose a more flexible system of setting the length of the cutting cycle that should be linked to regular static inventory and a system of yield prediction for the management unit. A prototype system using this approach has been developed for the Labanan concession (Rombouts, 1998a) and is being used to suggest revised management plans. Unfortunately, this approach may not be adopted more widely until regulations have been amended to allow the desired flexibility.

The choice of an appropriate system of yield regulation is apparently crucial for the development of sustainable management. The existing system based on diameter limits has been demonstrated to lead to a significant decline in productivity. Similar systems are being applied in many other tropical countries (Catinot, 1997). The alternative systems of either 8 stems ha^{-1} or $50 \text{ m}^3 \text{ ha}^{-1}$ performed much better for the 35- and 45-year cutting cycles. This paper aimed to test the hypothesis that the 8 stems ha^{-1} system of yield regulation was best for the forest. The analysis, however, shows that this system may not be sustainable in the long term because a decline in average stem diameter may reduce timber yield to below a level currently required for financial viability. The alternative system with a maximum volume $50 \text{ m}^3 \text{ ha}^{-1}$ performed better for both the 35- and 45-year cutting cycles and should be preferred on the basis of yield and financial performance.

The choice of yield regulation system should also consider the ease of application. A system based on

the number of stems harvested per hectare has the advantage of being linked to a criterion that is very simple to apply and monitor in the field. A volume-based criterion is much more difficult as it depends on a diameter measurement and the availability of a suitable volume table or calculation. The equation used in this study, calculated volume based only a measurement of diameter (Enggelina, 1998). Most other concessions in Indonesia use simple equations or tables that require estimates of bole height. These are subject to significant estimation errors. It is preferable to use a criterion that can be either recorded directly (such as number of stems) or measured with more accuracy. Stem basal area may be considered preferable to volume as it can be calculated directly from diameter and will be associated with much lower error. Further study and dialogue between the various stakeholders is required to identify the optimal system in terms of performance, ease of implementation and effective monitoring.

This study suggests that the best overall performance is obtained with a management regime based on regulation yield to a maximum of $50 \text{ m}^3 \text{ ha}^{-1}$ with a cutting cycle of either 35 or 45 years. The possibility of increasing the maximum yield for a 45-year cutting cycle was tested in one additional simulation leaving all other variables unchanged. This simulation produced yields of 58.7, 54.3 and $57.6 \text{ m}^3 \text{ ha}^{-1}$ for harvests 2, 3 and 4, respectively. The associated internal rates of return obtained were very close to the desired 16%, at 14.2, 12.0 and 14.0% for each of the three simulated harvests.

Sensitivity analysis of the financial model used in this study identified an opportunity for forest managers to improve the profitability of their business. The current analysis was based on the observed low conversion efficiency for felled timber (52%). Optimisation techniques were used to identify how much this must be increased by in order to achieve the desired 16% internal rate of return for the $50 \text{ m}^3 \text{ ha}^{-1}$ yield regulation system. This analysis showed that the $50 \text{ m}^3 \text{ ha}^{-1}$ treatment with a 35-year cutting cycle will return an IRR of at least 16% over all harvests if the conversion from 52 to 66%. The subsequent analysis of a system of yield regulation of $60 \text{ m}^3 \text{ ha}^{-1}$ and a 45-year cutting cycle produced an internal rate of return of at least 16% when the efficiency increased to only 60%. Increases in efficiency of this magnitude

are considered readily obtainable through a combination of better training and planning that are associated with implementation of reduced impact logging approaches.

4.9. Transferring the results, conclusions and approaches

This study describes results from an analysis based on data for one concession in East Kalimantan in Borneo. It was noted that the nature of the forest in the Berau region is similar to many other areas in Borneo and Peninsular Malaysia, so the general results and trends are likely to be widely applicable through the region.

The detail of the results will, however, depend on factors such as the structure and productivity of the forest, and for the financial analysis total area of the concession and level of investment in physical plant and equipment. The numeric results therefore cannot be directly transferred elsewhere, but the approach can, and should be, transferred to other concessions and regions. There are also very important lessons from this study that are transferable. The first is that simple systems of yield regulation based on diameter limits are unlikely to result in sustainable forest management. There is evidence that diameter-based systems may even contribute to the decline in forest resources observed in many regions. More effective systems of yield regulation based on volume, basal area or even number of stems are likely to produce much better results. The second is that there is no evidence that systems of reduced impact logging will increase the yield of timber from forests, although increases in efficiency will improve profitability. Finally, only the *combination* of reduced impact logging techniques *and* effective yield regulation can lead to a system of management that meets criteria for production, ecological and financial sustainability and contribute to socially responsible forest management.

The forests in south-east Asia are recognised as having the highest potential commercial volume of any tropical forests currently managed for production. The financial analysis in this paper clearly demonstrates that the financial performance of even these forests is marginal under current market conditions. When combined with the very high opportunity costs associated with the adoption of effective yield

regulation demonstrated in this study, there is clearly an urgent need to develop policies and approaches that reward improved forest management and capture the benefits for all those involved.

5. Conclusions

This paper demonstrates the development of a system of analysis combining a biological model of forest growth and yield with a financial model for a forest concession in East Kalimantan, Indonesia. The results clearly demonstrate that the current management system prescribed by National Regulations is not sustainable in terms of timber production, ecological, financial and social criteria. A number of alternatives management regimes were evaluated and the analysis suggests that a system based on reduced impact logging techniques combined with an effective system of yield regulation is required. The study concludes that the two best options for the concession evaluated in this study would be to limit yield to $50 \text{ m}^3 \text{ ha}^{-1}$ with a 35-year cutting cycle or $60 \text{ m}^3 \text{ ha}^{-1}$ for a 45-year cutting cycle. It is suggested that this system may not be the simplest to implement or monitor and it should be compared to alternatives based on limiting basal area removed or remaining.

The study aimed to evaluate a system of yield regulation set to a maximum harvest of 8 stems ha^{-1} suggested previously for this forest (van Gardingen et al., 1998a; Sist et al., 1998b). This system was rejected on the basis of poor financial performance in harvests 3 and 4 resulting from a gradual decrease in average stem diameter and volume leading to yields below the level of financial viability. A problem of smaller diameter harvested stems was also apparent in the two treatments based on a diameter cutting limit where yield could only be sustained through the harvesting of large number of stems over a long cutting cycle.

Financial analysis demonstrated that none of the management systems investigated would produce a financial return equal to or exceeding the desired 16% internal rate of return. The best and most consistent performance was obtained by the systems using a volume-based system of yield regulation. The financial performance was best with either a yield regulation system of $50 \text{ m}^3 \text{ ha}^{-1}$ combined with a 35-year cutting cycle, or $60 \text{ m}^3 \text{ ha}^{-1}$ with a 45-year cutting cycle.

Sensitivity analysis of the financial model showed that both of these systems could produce internal rates of returns exceeding 16% if the efficiency of timber conversion was increased, by 14–66% for the 35-year cycle ($50 \text{ m}^3 \text{ ha}^{-1}$) and by only 8% (to 60%) for the 45-year cycle ($60 \text{ m}^3 \text{ ha}^{-1}$).

Even with the sustainable production of timber and an increase in conversion efficiency, this study demonstrates the very high opportunity costs for forest managers associated with the adoption of improved systems of yield regulation. There is little incentive for better practice from current market conditions and forest management policy. The failure of both markets and policy to regulate forest management indicates that major changes are required in these areas.

This study has shown that it is possible to have a system of sustainable management for Dipterocarp forests in Indonesia that will deliver against criteria for ecological, production, financial and social sustainability. The problem is that such a system is currently much less profitable than completing alternative land uses and hence the forest is likely to be lost. There is a need for better policies and incentives to guide the decision making processes of key stakeholders if managed natural forests are to be retained on the landscape. Key necessary changes are:

- Forest management systems need to become more flexible with yield regulation and cutting cycle lengths based on static inventory and associated predictions of yield.
- The opportunity costs associated with improved forest management need to be balanced through the combination of appropriate incentives and policies. These should emphasise opportunities for local stakeholders to capture the benefits associated with good forest management and the costs derived from bad practice.
- The financial models used in the current study need to be improved to better represent the costs and opportunities associated with various forest management regimes. Two areas need attention: (1) the capture of the value of non-timber products and environmental services and (2) a revision of the financial analysis of logging so that it reflects the true activity cost (such as the extraction of individual stems) as opposed to providing estimates based on volume averages.

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References

- Appanah, S., Weinland, G., 1990. Will the management systems for hill Dipterocarp forests, stand up? *J. Trop. For. Sci.* 3, 140–158.
- Appanah, S., Weinland, G., Bossel, H., Krieger, H., 1990. Are tropical rain forests non-renewable? An enquiry through modelling. *J. Trop. For. Sci.* 2, 331–348.
- Bennett, C.P.A. Outcome-based regulations to encourage reduced-impact logging. In: Proceedings of the International Conference on the Application of Reduced Impact Logging to Advance Sustainable Forest Management.
- Bertault, J.G., Kadir, K., 1998. Silvicultural research in a lowland mixed dipterocarp forest of East Kalimantan. CIRAD Foret, Montpellier, 250 pp.
- Bertault, J.G., Sist, P., 1997. An experimental comparison of different harvesting intensities with reduced-impact and conventional logging in East Kalimantan, Indonesia. *For. Ecol. Manage.* 94, 209–218.
- Bertault, J.G., Sist, P., Nguyen-The, N., 1998. STREK Project objectives and methodology. In: Bertault, J.G., Kadir, K. (Eds.), CIRAD Foret. FORDA, Inhutani I, Jakarta, pp. 29–49.
- Blaser, J., Douglas, J., 2001. A future for forests. *ITTO Trop. For. Update* 10 (4), 9–15.
- Bossel, H., Krieger, H., 1991. Simulation model of natural tropical forest dynamics. *Ecol. Model.* 59, 37–72.
- Brash, T.E., Phillips, P.D., van Gardingen, P.R., 2000. Species groups for use with the SYMFOR modelling framework (<http://meranti.ierm.ed.ac.uk/g&y/speciesgroups>).
- Carney, D., 1998. Implementing the sustainable rural livelihoods approach. In: Carney, D. (Ed.), *Sustainable Rural Livelihoods. What Contribution Can We Make?* Department for International Development, London, pp. 3–23.
- Catinot, R., 1997. *The Sustainable Management of Tropical Tainforests*. Scytale Publishing, Paris, 100 pp.
- Davies, J., Richards, M., 1999. The use of economics to assess stakeholder incentives in participatory forest management: a review. European Union Tropical Forestry Paper 5. Overseas Development Institute, London, 45 pp.
- Departemen Kehutanan, 1993. Pedoman dan petunjuk teknis Tebang Pilih Tanam Indonesia (TPTI) pada hutan alam daratan. Direktorat Jenderal Pengusahaan Hutan. Departemen Kehutanan, Jakarta, Indonesia, 113 pp.
- Department for International Development, 2000a. Achieving sustainability. Poverty elimination and the environment. Department for International Development, London, 56 pp.
- Department for International Development, 2000b. Halving world poverty by 2015. Economic growth, equity and security. Department for International Development, London, 54 pp.
- Department for International Development, 2000c. Indonesia, towards sustainable forest management. Final report of the Senior Management Advisory Team and the Provincial Level Forest Management Project, vol. 1. Department for International Development, Jakarta, 58 pp.
- Dykstra, D.P., Heinrich, R., 1996. *FAO Model Code of Forest Harvesting Practice*. Food and Agriculture Organisation of the United Nations, Rome, 97 pp.
- Enggelina, A., 1994. Species–volume equation: a prerequisite to build up stand tables. In: Proceedings of the STREK Workshop on From the Concept to the Field Reality: The Contribution of R&D Activities in the Natural Forest Management, Jakarta, 28–29 June 1994, 12 pp.
- Enggelina, A., 1998. Volume equation. In: Bertault, J.G., Kadir, K. (Eds.), *Silvicultural Research in a Lowland Mixed Dipterocarp Forest of East Kalimantan*. CIRAD Foret, FORDA, Inhutani I, pp. 127–135.
- Fadilah, D., 1997. Minimum area model. A financial approach to determine minimum area of forest management unit. Report and user guide. Berau Forest Management Project, Jakarta, 36 pp.
- Fadilah, D., 1999. Economic implications of the TPTI implementation—a financial approach to determine the feasibility of thinning in the Labanan Concession PT Inhutani I. EU Berau Forest Management Project, Jakarta, 16 pp.
- Fadilah, D., 2000. The economics of thinning natural production forests. In: Purnama, B., Ginting, A.Ng., Pratiwi, Sukardi, D., Soeparno, W., Rochadi, D., Panjaitan, J.H., Septiani, Y. (Eds.), *Proceedings of the Expose of Research Results of International Cooperation Projects*, Jakarta, 24–25 November 1999. Forestry and Estate Crops Research and Development Agency, Ministry of Forestry and Estate Crops, Jakarta, pp. 1–20.
- FAO, 2001a. *Global forest resources assessment 2000*. Main Report FAO Forestry paper 140. FAO, Rome, 479 pp.
- FAO, 2001b. *State of the World's Forests 2001*. FAO, Rome, 188 pp.
- Gautum, M., Lele, U., Kartodihardjo, H., Khan, A., Erwinsyah, R.S., 2000. *Indonesia. The Challenges of World Bank Involvement in Forests*. The World Bank, Washington, DC, 142 pp.
- Huth, A., Ditzer, T., 2000. Simulation of the growth of a lowland Dipterocarp rain forest with FORMIX-3. *Ecol. Model.* 134, 1–25.

- Huth, A., Ditzer, T., 2001. Long-term impacts of logging in a tropical rain forest—a simulation study. *For. Ecol. Manage.* 142, 33–51.
- ITTO, 2001. ITTO Annual Report 2001. ITTO, Yokohama, Japan (<http://www.itto.or.jp/inside/report2001/>).
- Karsenty, A., 1998. The economic implications of reduced impact and conventional logging. In: Bertault, J.G., Kadir, K. (Eds.), *Silvicultural Research in a Lowland Mixed Dipterocarp Forest of East Kalimantan*. CIRAD Foret, Inhutani, pp. 163–170.
- Kleine, M., Heuvelodp, J., 1993. A management planning concept for sustained yield of tropical forests in Sabah, Malaysia. *For. Ecol. Manage.* 61, 277–297.
- Kohler, P., 2000. Modelling anthropogenic impacts on the growth of tropical rain forests. Der Andere Verlag, Osnabruck, 216 pp.
- Kohler, P., Ditzer, T., Ong, R.C., Huth, A., 2001. Comparison of measured and modelled growth on permanent plots in Sabah rain forests. *For. Ecol. Manage.* 144, 101–111.
- Liu, J.G., Ashton, P.S., 1998. FORMOSAIC: an individual-based spatially explicit model for simulating forest dynamics in landscape mosaics. *Ecol. Model.* 106, 177–200.
- Malhi, Y., Grace, J., 2000. Tropical forests and atmospheric carbon dioxide. *Trends Ecol. E* 15, 332–337.
- Matikainen, M., Herika, D., Muntoko, E., 1998. Logging trials in compartment 17, RKT 1997/98. In: Muljadi, A., Fraser, A.I. (Eds.), *Proceedings of the Joint Workshop on Silviculture and Reduced Impact Logging and Workshop on Silviculture, Growth and Yield and Reduced Impact Logging*, Department for International Development, Jakarta, pp. 78–102.
- McLeish, M.J., Susanty, F.H., 2000. Yield regulation options for Labanan. A financial and economic analysis of yield regulation options for logged over forest at PT Inhutani I, Labanan Concession. Berau Forest Management Project, Tanjung Redeb, 45 pp. (<http://www.symfor.org/technical/yield6.pdf>).
- McLeish, M.J., Moran, D., van Gardingen, P.R., 2002. Linking SYMFOR with financial models for forest concessions. SYMFOR Technical Note Series 10. The University of Edinburgh, Edinburgh, 20 pp. (<http://www.symfor.org/technical/financial.pdf>).
- Newbery, D.M., Campbell, E.J.F., Lee, Y.F., Ridsdale, C.E., Still, M.J., 1992. Primary lowland dipterocarp forest at Danum valley, Sabah, Malaysia—structure, relative abundance and family composition. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 335, 341–356.
- Nguyen-The, N., Favrichon, V., Sist, P., Houde, L., Bertault, J.G., Fauvet, N., 1998. Growth and mortality patterns before and after logging. In: Bertault, J.G., Kadir, K. (Eds.), *Silvicultural Research in a Lowland Mixed Dipterocarp Forest of East Kalimantan*. CIRAD Foret, FORDA, PT Inhutani I, Jakarta, pp. 181–216.
- Ong, R., Kleine, M., 1995. DIPSIM. A Dipterocarp Forest Growth Simulation Model for Sabah. Forestry Department, Forest Research Centre, Sabah, Malaysia, 94 pp.
- Phillips, P.D., van Gardingen, P.R., 2000. SYMFOR 2000 (<http://www.symfor.org/symfor/home.htm>).
- Phillips, P.D., van Gardingen, P.R., 2001. The SYMFOR framework for modelling the effects of silviculture on the growth and yield of tropical forests. In: Rennolls, K. (Ed.), *Proceedings of the IUFRO 4.11 Conference on Forest Biometry, Modelling and Information Science*, University of Greenwich, London, pp. 1–12 (<http://cms1.gre.ac.uk/conferences/iufro/proceedings/>).
- Phillips, O.L., Malhi, Y., Higuchi, N., Laurance, W.F., Nunez, P.V., Vasquez, R.M., Laurance, S.G., Ferreira, L.V., Stern, M., Brown, S., Grace, J., 1998. Changes in the carbon balance of tropical forests: evidence from long-term plots. *Science* 282, 439–442.
- Phillips, P.D., Brash, T.E., van Gardingen, P.R., 2000. SYMFOR documentation and user manual (<http://www.symfor.org/symfor/Hlp/contents.html>).
- Phillips, P.D., Yasman, I., Brash, T.E., van Gardingen, P.R., 2002. Grouping tree species for analysis of forest data in Kalimantan (Indonesian Borneo). *For. Ecol. Manage.* 157, 205–216.
- Phillips, P.D., Brash, T.E., Yasman, I., Subagyo, S., van Gardingen, P.R., 2003. An individual-based spatially explicit tree growth model for forests in East Kalimantan (Indonesian Borneo). *Ecol. Model.* 159, 1–26.
- Rombouts, J., 1998a. Growth model components and integrated yield simulation system for the Berau Forest Management Project area (East Kalimantan). Berau Forest Management Project, Jakarta, 53 pp.
- Rombouts, J., 1998b. Species grouping based on diameter increment in East Kalimantan. GTZ Sustainable Forest Management Project, Samarinda, Kalimantan Timor, 47 pp.
- SAS Institute Inc., 1989. SAS/STAT User's Guide, vol. 2, GLM-VARCOMP Version 6, fourth ed. SAS Institute Inc., Cary, NC, pp. 891–1686.
- SAS Institute Inc., 1990. SAS Procedures Guide, Version 6, third ed. Cary, NC, 705 pp.
- Scotland, N., Whiteman, A., 1997. The ITFMP forest concession model operators manual. Indonesia–UK Tropical Forest Management Project, Jakarta, 62 pp.
- Sist, P., Abdurachman, 1998. Liberation thinnings in logged-over forests. In: Bertault, J.G., Kadir, K. (Eds.), *Silvicultural Research in a Lowland Mixed Dipterocarp Forest of East Kalimantan*. The contribution of the STREK project, CIRAD Foret, pp. 171–180.
- Sist, P., Bertault, J.G., 1998. Reduced impact logging experiments: impact of harvesting intensities and logging techniques on stand damage. In: Bertault, J.G., Kadir, K. (Eds.), *Silvicultural Research in a Lowland Mixed Dipterocarp Forest of East Kalimantan*. CIRAD Foret, Inhutani, pp. 139–161.
- Sist, P., Saridan, A., 1998. Description of the primary lowland forest of Berau. In: Bertault, J.G., Kadir, K. (Eds.), *Silvicultural Research in a Lowland Mixed Dipterocarp Forest of East Kalimantan*. The contribution of the STREK project, CIRAD Foret, pp. 51–94.
- Sist, P., Saridan, A., 1999. Stand structure and floristic composition of a primary lowland dipterocarp forest in East Kalimantan. *J. Trop. For. Sci.* 11, 704–722.
- Sist, P., Dykstra, D.P., Fimbel, R., 1998a. Reduced-impact logging guidelines for lowland and hill dipterocarp forest in Indonesia. CIFOR Occasional Paper No. 15. Center for International Forestry Research, Jakarta.
- Sist, P., Nolan, T., Bertault, J.G., Dykstra, D., 1998b. Harvesting intensity versus sustainability in Indonesia. *For. Ecol. Manage.* 108, 251–260.

- Sist, P., Nolan, T., Bertault, J.G., Dykstra, D.P., 1998c. Harvesting intensity versus sustainability in Indonesia. *For. Ecol. Manage.* 108, 251–260.
- Sokal, R.R., Rohlf, F.J., 1981. *Biometry*, second ed. Freeman, San Francisco, 859 pp.
- Susanty, F.H., Sardjono, E., 2000. Growth and yield production using the SYMFOR model. In: *Yield Scheduling to Support the Second Cycle of Forest Harvesting*. Berau Forest Management Project, Jakarta, pp. 60–75.
- Suyana, A., Sukarya, 2000. Simulating the development of logged-over standing stick using the SYMFOR model. In: *Yield Scheduling to Support the Second Cycle of Forest Harvesting*. Berau Forest Management Project, Jakarta, pp. 76–86.
- Trockenbrodt, M., Imiyabir, Z., Josue, J., 2002. Hollow logs and logging residues from Deramakot Forest Reserve, Sabah, Malaysia. *For. Ecol. Manage.* 165, 141–150.
- van Gardingen, P.R., 1998. TPTI implementation by Inhutani I Labanan: options for improving sustainable forest management. European Union, Berau Forest Management Project, Jakarta, 40 pp.
- van Gardingen, P.R., 1999a. Application of results from the STREK trial. The role of statistical analysis and simulation modelling. Berau Forest Management Project, Jakarta, 17 pp.
- van Gardingen, P.R., 1999b. Application of STREK permanent sample plot database for management purposes. Opportunities and challenges. Berau Forest Management Project, Jakarta, 52 pp.
- van Gardingen, P.R., 1999c. Growth and yield of logged-over dipterocarp forests after thinning treatments under the Indonesian TPTI system. Analysis of results from the STREK trial in PT Inhutani I. Berau Forest Management Project, Jakarta.
- van Gardingen, P.R., 2000a. Application of results from the STREK trial: the role of statistical analysis and simulation modelling. In: Purnama, B., Ginting, A.Ng., Pratiwi, Sukardi, D., Soeparno, W., Rochadi, D., Panjaitan, J.H., Septiani, Y. (Eds.), *Proceedings of the Expose of Research Results of International Cooperation Projects*, Jakarta, 24–25 November 1999. Forestry and Estate Crops Research and Development Agency, Ministry of Forestry and Estate Crops, Jakarta, pp. 21–36.
- van Gardingen, P.R., 2000b. Silvicultural systems for KPHP. In: Department for International Development (Ed.), *Indonesia, Towards Sustainable Forest Management*. Final report of the Senior Management Advisory Team and Provincial Level Forest Management Project, vol. 2. Department for International Development, Jakarta, pp. 137–153.
- van Gardingen, P.R., Clearwater, M.J., Nifinluri, T., Effendi, R., Rusmanto, W., Noor, M., Mason, P.A., Ingleby, K., Munro, R., 1998a. Impacts of logging on the regeneration of lowland dipterocarp forest in Indonesia. *Comm. For. Rev.* 77, 71–82.
- van Gardingen, P.R., Purnama, B., Rusmanto, W., Effendi, R., DeKock, R., Fraser, A.I., 1998b. Silvicultural benefits of reduced impact logging for sustainable forest management of lowland dipterocarp forests in Indonesia: synthesis of research results from Wanariset Sangai and the Indonesian Tropical Forest Management Programme. In: Muljadi, A., Fraser, A.I. (Eds.), *Proceedings of the Joint Workshop on Silviculture and Reduced Impact Logging and Workshop on Silviculture, Growth and Yield and Reduced Impact Logging*. Department for International Development, Jakarta, pp. 28–46.
- van Gardingen, P.R., Phillips, P.D., McLeish, M.J., Brash, T.E., Susanty, F.H., Gadas, S., Purnama, B., Sardjono, E., Yasman, I., 2002. SYMFOR: a silvicultural and yield management tool for tropical forests. *Integrated Manage. Neotrop. Rain For. Ind. Commun.*, in press.
- Vanclay, J.K., 1989. A growth-model for north Queensland rainforests. *For. Ecol. Manage.* 27, 245–271.
- Vanclay, J.K., 1994a. *Modelling Forest Growth and Yield: Applications to Mixed Tropical Forests*. CAB International, Oxford, 312 pp.
- Vanclay, J.K., 1994b. Sustainable timber harvesting-simulation studies in the tropical rain-forests of north Queensland. *For. Ecol. Manage.* 69, 299–320.
- Vanclay, J.K., 1995. Growth-models for tropical forests—a synthesis of models and methods. *For. Sci.* 41, 7–42.
- Whitmore, T.C., 1998. *An Introduction to Tropical Rain Forests*, second ed. Oxford University Press, Oxford, 282 pp.
- Wyatt-Smith, J., Panton, W.P., 1995. *Manual of Malayan Silviculture for Inland Forest*, vol. 1, second ed. Forest Research Institute, Kuala Lumpur.