

INCOME AND DIVERSITY TRADEOFFS FROM MANAGEMENT OF MIXED LOWLAND DIPTEROCARPS IN MALAYSIA

C. Denise Ingram

USDA Forest Service, Forest Products Laboratory, Madison, WI 53705-2398, United States of America

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Joseph Buongiorno

Department of Forestry, University of Wisconsin-Madison, 1630 Linden Drive, Madison, Wisconsin, United States of America

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INGRAM, C.D. & BUONGIORNO, J. 1996. Income and diversity tradeoffs from management of mixed lowland dipterocarps in Malaysia. Short-run and long-run effects of current management regimes in Southeast Asia were evaluated for their economic returns and diversity of tree size and species. A two-species (dipterocarp and non-dipterocarp), seven size-class growth model was constructed to agree in the steady-state with data from old-growth lowland dipterocarp forests in Peninsular Malaysia. Three options for Southeast Asian forest management systems were evaluated and compared to constrained optimum regimes. The evaluation criteria were the Shannon-Wiener index to measure diversity, minimum number of trees in any species-size class, soil rent, forest value, internal rate of return, and annual yield. Regimes were compared in the steady-state (long-run) and during convergence (short-run) of stands of different initial conditions to the steady-state. Regimes that gave the highest economic performance or maximum diversity in the steady-state also did so during conversion, for stands with either high or low initial basal area. To a great extent, the ability to harvest heavily and early in the conversion period determined the economic performance of a management regime. Among the regimes studied, a good compromise between economics and diversity was to cut mostly 30- to 40-cm trees of dipterocarps and non-dipterocarps every 10 years. This would maintain some trees in all size and species classes. Financial returns would be comparable to those of other investments in Malaysia and similar to the highest yield under current management regimes, but tree diversity would be much higher.

Key words: Forest management - Malaysia - dipterocarps - soil rent - diversity - linear programming

INGRAM, C.D. & BUONGIORNO, J. 1996. Pendapatan dan kepelbagaian perdagangan daripada pengurusan dipterokarp pamah campuran di Malaysia. Kesan jangka pendek dan jangka panjang regim pengurusan semasa di Asia Tenggara telah ditaksiran bagi pulangan ekonomi dan kepelbagaian saiz pokok dan spesies sebuah model. Dua spesies (dipterokarpa dan bukan dipterokarpa), tujuh pertumbuhan kelas saiz telah dibina untuk disesuaikan dengan keadaan mantap dengan data daripada hutan pamah dipterokarpa pertumbuhan lama di Semenanjung Malaysia. Tiga pilihan sistem pengurusan hutan Asia Tenggara ditaksiran dan dibandingkan dengan regim optimum berkonstren. Indeks Shannon-Wiener merupakan kriteria pentaksiran untuk

mengukur kepelbagaian, bilangan minimum pokok daripada mana-mana kelas saiz spesies, sewaan tanah, nilai hutan, kadar pulangan dalaman, dan hasil tahunan. Regim-regim dibandingkan ketika keadaan mantap (jangka panjang) dan semasa pemusatan (jangka pendek) dirian yang mempunyai keadaan awal yang berbeza hinggalah kepada keadaan mantap. Regim yang menunjukkan prestasi ekonomi tertinggi atau kepelbagaian maksimum di dalam keadaan mantap juga melakukannya semasa tempoh perubahan, bagi kedua-dua dirian dengan luas pangkal pemula tinggi dan rendah. Sehingga pada satu tahap, keupayaan untuk menebang dengan banyak dan awal semasa tempoh pertukaran menentukan prestasi ekonomi bagi regim pengurusan. Di antara regim yang dikaji, satu kompromi yang baik di antara ekonomi dan kepelbagaian ialah untuk menebang kebanyakannya pokok-pokok dipterokarpa dan bukan dipterokarpa bersaiz 30 hingga 40 cm setiap tahun. Ini dapat mengekalkan sesetengah pokok di dalam semua kelas saiz dan spesies. Pulangan kewangan setanding dengan pulangan pelaburan lain di Malaysia dan sama dengan hasil tertinggi di bawah regim pengurusan semasa tetapi kepelbagaian pokok akan jauh lebih tinggi.

Introduction

One of the many challenges facing stewards of the world's forests today is to manage their resources sustainably. Attempts to take on this challenge will encourage closer scrutiny of forest resource management policies and guidelines. Whether the approaches adopted use green certification of wood products, international criteria and indicators of sustainable forest management, or some other programme, sustainability remains centered on the concern for balance between the needs of present and future generations (World Commission on Environment and Development 1987). Further, there will be an attempt to find a balance among the different benefits produced by forests. Thus, the task in tropical and temperate forest management will be to develop methods that address both the ecological and economic dimensions of forest resources.

The issue of whether existing natural forest management practices in tropical countries are the "best" strategies, if applied fully, becomes important in this discourse, and it needs rigorous quantitative testing. Further, more attention needs to be given to broadening forest management analysis to include non-timber and non-revenue objectives, including biological diversity. In some cases, the attainment of non-revenue goals need not be mutually exclusive of forest production goals (Buongiorno *et al.* 1994).

Selective tropical forest management systems, like their temperate counterparts, depend critically upon the sustainable relationship between residual stocking and growth. The value of perpetually recurring future harvests is directly affected by the performance of a stand of trees after logging. Research has suggested that existing selective systems do not allow sufficient release for tropical species to obtain full growth potential (Miller 1981, Mendoza & Setyarso 1986, Appanah *et al.* 1990). The same studies indicated that evaluations based on existing management systems may greatly underestimate the economic potential of tropical forests. This is a critical issue, for the conservation of natural tropical forests may in part depend on the economics of management.

The objective of this study was to compare some economic and biodiversity trade offs of existing tropical forest management schemes, thus providing a basis for selecting optimum management approaches to achieve financial and ecological goals. This report describes a matrix growth model for lowland dipterocarp forests of Peninsular Malaysia. Different management scenarios, based on existing selective management systems in Southeast Asia, are compared in the steady-state, using this growth model and linear-programming methods. The short-run effects of converting different stands to sustainable management conditions are explored as well.

Previous studies

Most forest management systems applied in tropical countries employ a type of selective harvesting regime derived from systems of improvement fellings in Malaysia or timber stand improvement treatments in North America (Baur 1962). In Malaysia, the Malayan Uniform System (MUS) and the Selective Management System (SMS) are examples of the evolution of management systems that move away from the sheer mining of the tropical forest to its organisation for sustainable perpetual production. Variations of the SMS are by far the most prevalent in Southeast Asia (e.g. Indonesian Selective Cutting System, or TPI, and Selective Logging in the Philippines). Some studies in the last decade have questioned the ability of these regimes to sustain current yields in the future.

Appanah *et al.* (1990) analysed the MUS and SMS of Malaysia with empirical and physiological process growth models. The results suggested longer rotations were required to achieve sustainable, natural dynamics of Malaysian dipterocarp forests. Mendoza and Setyarso (1986) applied linear programming to design alternative management for Indonesia's tropical forests and questioned the ability of the TPI to provide sustainable yields. They showed that, with their model, it would not be possible to maintain the TPI prescribed minimum of 25 desirable trees per hectare after logging. The same study analysed management alternatives in terms of their effects on diameter distributions and harvest volumes, but not in terms of the critical economic returns.

Other growth and yield studies have contributed to the understanding of tropical forest dynamics (Caillez 1974, Soemarna 1977, Jonkers 1982, Bustomi & Soemarna 1986, Hutchison 1986, Mendoza & Gumpal 1987, Kingston & Nir 1988, Vanclay 1989, Wan Razali 1989, Manokaran & LaFrankie 1990). Yet, the missing link between these efforts and forest management planning has been the economic, and ecological, evaluation of different timber management practices. Methodologies developed for temperate forests provide a starting point for the analysis of tropical forest systems.

The basic objective most commonly set forth in economic forest management is to maximise net returns to fixed assets—land or forest. Matrix models, combined with linear programming, have been found useful for the analysis of economic objectives. Buongiorno and Michie (1980), Michie and Buongiorno (1984), and Michie (1985) strengthened the matrix growth approach by making ingrowth a

function of the stand state. This led to the ability to predict the steady-state diameter distribution of a stand, a key concept in dealing with sustainability. As a result, one could compute both the level of growing stock and the cutting cycle that would maximise soil rent.

Buongiorno and Lu (1990) concluded that the optimal stocking and cutting cycle in regulated versus non-regulated forests differed only for extreme values of the discount rate and fixed costs. Therefore, the cost of regulation was ignored in this study. Other applications of matrix growth modeling and optimisation have addressed the costs and benefits of intermediate treatments such as logging damage on residual stands in East Kalimantan, Indonesia (Sianturi 1990), and the relationship between tree diversity and economic returns in temperate hardwoods or mixed mountain forests (Buongiorno *et al.* 1994, 1995). The research reported here built on this experience with uneven-aged temperate forests to evaluate tropical forest management regimes.

A steady-state constrained matrix growth model for natural forests in Peninsular Malaysia

The growth model assumes that the state of a stand is defined by the number of trees, of each species if the data are available, in predetermined size classes. The growth of a tree from year t to $t+1$ is measured by its probability of staying in the same size class, a_i , or moving into the next higher size class, b_{i+1} , or dying, m_i . Ingrowth is highly variable, but its expected value from t to $t+1$ is influenced by the stand state, in particular its density (Husch *et al.* 1972, Chapter 16). Ignoring tree species for the moment, for simplicity, the functional form of ingrowth is:

$$I = \beta_0 + \beta_1 \sum_{i=1}^n B_i x_{i,t} \quad (1)$$

where β_0 is the number of recruits independent of stand state and β_1 is the effect on ingrowth of the stand density measured as basal area. B_i is the basal area of a tree in size class i , in which there are $x_{i,t}$ stems. The sign of β_0 is positive, while that of β_1 is negative as ingrowth is dampened by increased basal area and thus, competition.

An n -size class growth model is then:

$$x_{i,t+1} = G(x_t - h_t) + c, \text{ for } x_t > h_t > 0 \quad (2)$$

where G is a matrix of parameters that depend on the transition probabilities a_i and b_i and the parameters of ingrowth β_0 and β_1 (Buongiorno & Michie 1980). The column vectors x_t , and x_{t+1} , have entries $x_{i,t}$ and $x_{i,t+1}$, which represent the number of trees in the i th size class, $i = (1, 2, 3, \dots, n)$ at year t and $t+1$. The column vector h_t represents the number of trees harvested from each size class in year t

and c is a constant vector = $[\beta_0 \ 0 \dots 0]'$. The general form of this model for stand growth over p years is

$$x_{t+p} = G^p (x_t - h_t) + \sum_{i=0}^{p-1} G^i c \quad (3)$$

Depending on the detail of the measurements available, different techniques can be used to estimate the parameters of G and c (Michie & Buongiorno 1984, Lu 1992). Yet, these methods failed with the data available for this study. After estimating G and c , model (2) with no harvest ($h_t = 0$) yielded a steady-state that was totally different from the state of undisturbed, old-growth lowland dipterocarp stands (Ingram 1995).

Therefore, a method was sought that would require few data and ensure a predicted steady-state equal to the one observed in climax tropical forests. In this approach, mortality and transitional growth rates are assumed independent of basal area. This seemed acceptable according to results of statistical tests with this dataset (Ingram 1995). Also, the steady-state of a natural forest, x^* such that $x_{t+1} = x_t = x^*$, for all t was assumed to be known. Knowledge of the mortality rates and of the steady-state led to the following expressions for the transition probabilities.

With seven size-classes, the probability that a tree stays alive in the largest size-class from t to $t+1$ is

$$a_7 = 1 - m_7 \quad (4)$$

Then, the probability that a live tree in size-class 6 moves to size-class 7 must satisfy

$$x_7^s = b_7 x_6^s + a_7 x_7^s \quad (5)$$

or

$$b_7 = (1 - a_7) \frac{x_7^s}{x_6^s} \quad (6)$$

and the probability that a live tree stays in size-class 6 is

$$a_6 = 1 - m_6 - b_7 \quad (7)$$

By recursion we obtain

$$b_6 = (1 - a_6) \frac{x_6^s}{x_5^s} \quad (8)$$

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$$b_2 = (1 - a_2) \frac{x_2^s}{x_1^s} \quad (9)$$

$$a_1 = (1 - m_1 - b_2) \quad (10)$$

Therefore, all of the probabilities, $a_1, \dots, a_7$ and $b_2, \dots, b_7$, are determined once m and x are known. Further, letting I^s be the ingrowth in the steady-state, we must have

$$x_1^s = a_1 x_1^s + I^s \quad (11)$$

and, since from equation (1)

$$I^s = \beta_0 + \beta_1 \sum_{i=1}^7 \beta_i x_i^s \quad (12)$$

β_0 is defined, once a_1 and β_1 are known, by

$$\beta_0 = (1 - a_1) x_1^s - \beta_1 \sum_{i=1}^7 \beta_i x_i^s \quad (13)$$

Last, the parameter β_1 can be estimated from a set of stands with observations on ingrowth I^j and stand state x by noting that

$$I^j - I^s = I^j - (1 - a_1) x_1^s = \beta_1 \left(\sum_{i=1}^7 \beta_i x_i^j - \sum_{i=1}^7 \beta_i x_i^s \right) \quad (14)$$

which shows that the difference in expected ingrowth between a given stand and the steady-state stand is directly proportional to the difference in basal area. Equation (14), with an error term, allows estimation of β_1 by ordinary least squares, and then recovery of β_0 from equation (13).

The data to estimate the parameters came from ecological studies of lowland evergreen rain forests conducted by the Forest Research Institute of Malaysia. The red meranti-keruing forest type in the study area was located on relatively flat terrain and moderately well- to poorly-drained soils. Study plots were in mature to over-mature stands and representative of virgin forests (Wyatt-Smith 1966). Measurements, including the number of trees in 30-cm girth classes, were taken from seventeen 1/2-acre transects of primary forest, two 1/2-acre transects of disturbed forest, and two 1/2-acre transects of secondary forest. The data were grouped into 10-cm dbh classes on a per hectare basis for this analysis. All 21 plots were measured three times during the period 1947 to 1959, resulting in a total of 42 observations.

Economic and diversity values of tropical forest stands are affected strongly by their species composition, in addition to the diameter distribution. For purposes of economic management, Southeast Asian trees can be categorised roughly as dipterocarps and non-dipterocarps, dipterocarps being the most valuable. In principle, distinguishing between dipterocarps and non-dipterocarps is straight-

forward, within the model structure outlined by equations (1) and (2). The vectors $\mathbf{x}$ and $\mathbf{h}$ and the corresponding matrices $\mathbf{G}$ and $\mathbf{c}$ are simply partitioned between dipterocarps and non-dipterocarps. However, the Malaysian data did not contain information on species composition, which had to be inferred from scarce observations in the Philippines and Indonesia (Ingram 1995). Thus, in the following discussion, the diameter distributions by size only are always more reliable than those by size and species.

The parameters of the growth model with two species classes and $p = 1$ year are shown in Table 1. The parameter that measures the effect of stand basal area on ingrowth, β_1 , had the expected negative sign, which explains the negative parameters in Table 1, but was not statistically significant for either species. The magnitudes of the parameters in Table 1 are consistent with those in Wan Razali (1989), who found average annual diameter increments for dipterocarps 27% higher than for non-dipterocarps, for trees 10 cm dbh or larger, and ingrowth for non-dipterocarps more than 40% higher than for dipterocarps. Correspondingly, in Table 1 the probabilities of staying in a size-class (main diagonal) are larger for non-dipterocarp trees than for dipterocarps, and the ingrowth constant β_0 is also larger for non-dipterocarps.

Dynamic implications of the growth model

By construction, the model with the parameters in Table 1 predicts a steady-state that matches that of old, disturbed stands (Table 2, second column). This is a useful property since the model will be used extensively to compare regimes in the steady-state. The model also predicted correctly short-term growth on the plots for which two measurements were available, although it tended to overestimate the number of trees in the smallest size-class (Table 3). However, it is not easy to infer how the model predictions converge to that steady-state (climax forest). To explore these dynamics, three simulations were conducted. They predicted natural (undisturbed) growth, by applying equation (2) with the parameters in Table 1 to stands with initially low, medium, or high basal area (Table 2).

The predicted basal area converged to the steady-state, regardless of initial condition, and exhibited only small changes before reaching that state (Figure 1). The stands of low and high initial basal area were near the steady-state after 150 years. A steady decline in basal area of the high density stand and increases in the average tree size (Figure 2) suggested a heavy natural thinning of the smallest trees in the first 25 years. However, average tree size declined in the next 75 years, as total stand basal area decreased gradually, with the recovery of vigorous growth in the smallest size-class. The growth dynamics of the stand of low initial basal area was nearly symmetric to that of the high initial basal area, with smaller changes in average tree size during the first 100 years.

Another aspect of stand dynamics is the evolution of species composition. Figure 3 shows the 100-year development of dipterocarps and non-dipterocarps, by size, in the stand of high initial basal area. Throughout the projection period, about two-thirds of the trees were non-dipterocarps, but the largest trees were

Table 1. Annual growth parameters for lowland dipterocarp forests in Peninsular Malaysia

		G														
Species	Diameter class (cm)	Dipterocarp							Non-dipterocarp							c
		10	20	30	40	50	60	70	10	20	30	40	50	60	70	
Dipterocarp																
	10	0.95	-0.01	-0.03	-0.05	-0.08	-0.12	-0.16	0.00	-0.01	-0.03	-0.05	-0.08	-0.12	-0.16	8.52
	20	0.03	0.96													
	30		0.03	0.94												
	40			0.04	0.95											
	50				0.04	0.93										
	60					0.05	0.96									
	70						0.03	0.98								
Non-dipterocarp																
	10	-0.01	-0.02	-0.05	-0.09	-0.14	-0.20	-0.27	0.97	-0.02	-0.05	-0.09	-0.14	-0.20	-0.27	16.08
	20								0.01	0.97						
	30									0.01	0.97					
	40										0.01	0.97				
	50											0.01	0.98			
	60												0.00	0.97		
	70													0.02	0.98	

dipterocarps. The initial high basal area was due to the high frequency of 30- to 40-cm trees of both species. Ingrowth was dampened in the first 50 years due to overcrowding by the larger trees. As a result, the number of dipterocarps in the 10- to 20-cm classes fell to less than 15 trees after 50 years, less than half the initial condition. By year 100, the smaller trees recovered as the stand thinned its middle-sized, non-dipterocarp trees. By then, the stand was in a near steady-state.

Table 2. Tree distributions of selected lowland dipterocarp stands

Species	Diameter class (cm)	Old growth ^a	Low basal area	Medium basal area	High basal area
Dipterocarp		(trees ha ⁻¹)			
	10	30	53	47	39
	20	23	28	24	26
	30	10	7	11	23
	40	8	5	8	12
	50	4	1	6	7
	60	5	1	3	5
	70	9	3	5	10
Non-dipterocarp					
	10	160	136	122	100
	20	64	75	66	69
	30	27	15	23	48
	40	12	9	12	19
	50	7	1	6	7
	60	1	0	2	4
	70	1	2	3	6
Total		361	336	338	375
Basal area (m ² ha ⁻¹)		17.0	10.6	15.9	24.4

^aUndisturbed climax stands assumed to be in a steady-state.

Table 3. Mean error of growth model predictions for individual plots^a

	Diameter class (cm)						
	10	20	30	40	50	60	70
Mean error*	-9.08	-1.15	-0.73	-0.13	0.13	-0.09	0.42
Standard error	2.88	1.08	0.97	0.57	0.39	0.26	0.47

^aNote: Predictions on 42 plots over an average period of 5.5 years.

Long-term consequences of current management

To study the long-term (steady-state) effects of pursuing current management regimes, three options (Table 4) were derived from the Indonesian Selective

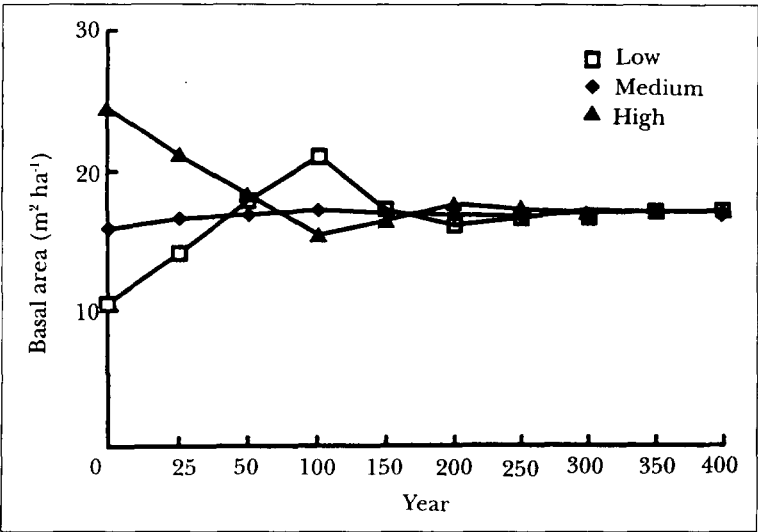


Figure 1. Predicted basal area of undisturbed stands with different initial conditions

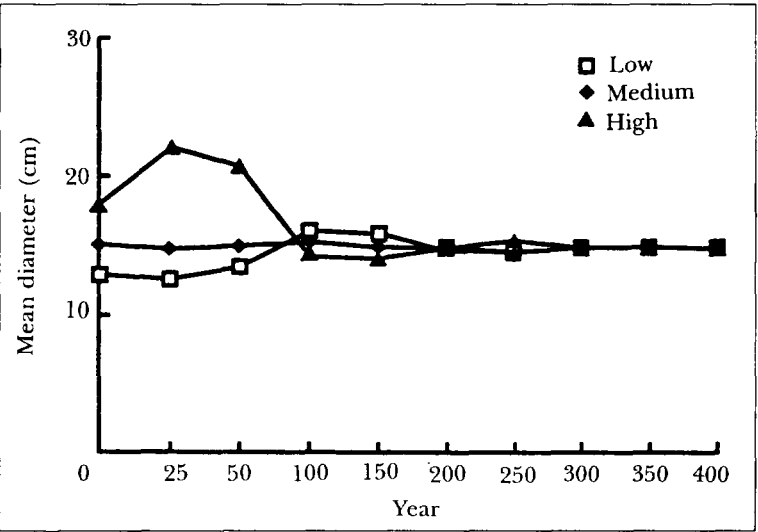


Figure 2. Predicted average diameter of trees in undisturbed stands with different initial conditions

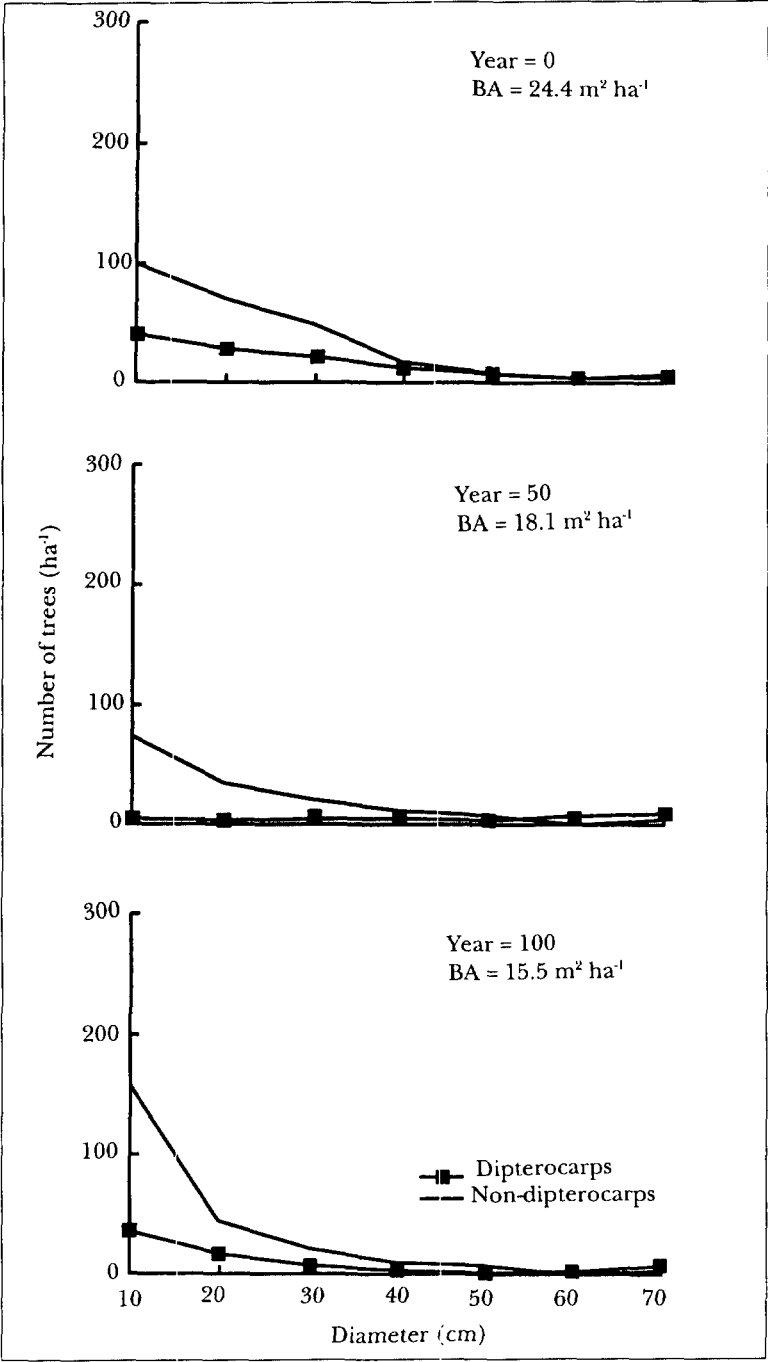


Figure 3. Predicted tree distribution in a stand of high initial basal area (BA), without management

Cutting System¹ (Tebang Pilih Indonesia-TPI) (Armitage & Kuswanda 1989). Here, the options are labeled M, N and O. The TPI options are defined broadly by three variables: cutting cycle, minimum number of trees to remain in the stand after harvest, and minimum size (diameter) for trees that may be harvested. TPI also suggests guidelines for stand improvement and replanting, which vary considerably with the condition of each stand; however, for simplicity, and to reflect the realities of forest management in many tropical forests, these other activities were ignored. In this study, the TPI options were viewed as constraints. Another constraint was that the harvest must be sustainable, in perpetuity. Within these constraints it was assumed that the maximum possible number of trees would be taken. Thus, the mathematical interpretation of the TPI management regimes was the solution of the following linear programme:

$$Max_{(x_i, h_i)} \sum_{j=1}^2 \sum_{i=k}^7 h_{i,j} \quad (15)$$

s.t.

$$x_t = G^p(x_t - h_t) + \sum_{i=0}^{p-1} G^i c \quad (16)$$

$$\sum_{j=1}^2 \sum_{i=1}^7 (x_{i,j} - h_{i,j}) \geq J \quad (17)$$

$$x_t - h_t \geq 0 \quad (18)$$

$$h_t \geq 0 \quad (19)$$

$$h_{i,t} = 0 \text{ for } i = 1, \dots, k-1 \quad (20)$$

where p is the cutting cycle, k is the diameter of the smallest tree that may be harvested under the TPI guide, and J is the minimum number of trees, with diameters greater than or equal to k , that must remain in the stand after harvest (Table 4). Equation (16) is the growth equation (3) with the steady-state condition ($x_t = x_{t+p}$). The objective function implies that all trees that may be cut are cut. Economic and diversity criteria were then calculated for the solution of equations (15) through (20).

¹Indonesia has modified the TPI and adopted other management regimes, such as the TPTI (Tebang Pilih Tanam Indonesia - Indonesian Selective Cutting and Planting System), the THPA (Tebang Habis Permudaan Alam - Clearcutting with Natural Regeneration System), and the THPB (Tebang Habis Permudaan Buatan - Clearcutting with Planting System). The TPI system was selected for this analysis because it reflects a range of options that encompass management in other countries, such as Malaysia.

Table 4. Definition of TPI management options

Management option	Cutting cycle (years)	Minimum dbh of harvested tree (cm)	Residual stocking requirement
<i>M</i>	35	50	at least 25 trees $\geq$ 40 cm dbh
<i>N</i>	45	40	at least 25 trees $\geq$ 40 cm dbh
<i>O</i>	55	30	at least 40 trees $\geq$ 20 cm dbh

Current trends in forestry emphasize ecosystem management. One of its dimensions, biological diversity, has two components: richness and evenness (Hunter 1990). For example, the species diversity of trees in a forest stand depends on the number of species present (richness) and the distribution of trees across species (evenness). A variety of gap sizes in the forest canopy, provided by fallen trees, is required for species to develop their individual specialisation in the maintenance of the forest (Leigh & Wright 1990). In addition to tree species diversity, tree size plays an important role in the diversity of tropical forests. Standing trees of different sizes provide a variety of habitats for different flora and fauna. Total tree diversity, therefore, provides habitat, food and shelter for the sustainability of many other species than trees in the forest (Hunter 1990).

One standard measure of diversity is the Shannon-Wiener Index (Schoonmaker & McKee 1988, Niese & Strong 1992, Hunter 1990, Buongiorno *et al.* 1994, 1995). With this index, a forest area with two tree species-classes and seven size-classes has a total stand diversity level of

$$H = - \sum_{i=1}^2 \sum_{j=1}^7 f_{ij} \log f_{ij} \quad (21)$$

where f_{ij} is the fraction of trees of species i and size j . The maximum value of this index occurs when there is an equal number of trees in each species and size class. However, such a stand would not be sustainable. Therefore, it seems more informative to express diversity relative to the diversity, H_s , that an undisturbed stand would have in the steady-state (Buongiorno *et al.* 1994):

$$H_r = \frac{H}{H_s} \cdot 100 \quad (22)$$

For example, with the data in Table 2, we get $H_s = 1.83$ and $H_r = 100\%$ for the steady-state stand, 93% for the stand of low basal area, 108% for the stand of medium basal area, and 120% for the stand of high basal area. A disturbed stand may have, as here, a higher (but transient) diversity than the steady-state. Basal area itself is an indicator of the ecological condition of a stand. Higher basal area implies a stand well-occupied by trees, but possibly to the detriment of other plant species.

A difficulty with Shannon's Index for optimisation is that it is highly non-linear in x_{ij} and it does not reflect the number of trees in a stand, only their relative distribution by size class. An alternative is to assess diversity from the minimum number of trees, N_{min} , after harvest, across species-size class (Buongiorno *et al.* 1995). The larger N_{min} , the higher the stand diversity. This indicator reflects both the distribution of trees and their absolute numbers. Furthermore, as a max-min criterion, it is easy to handle by linear programming.

The economic criterion to compare management regimes in the steady-state is the net present value. In uneven-aged stands, this is equal to the discounted income for all periodic perpetual harvests minus the value of the investment held in growing stock (Davis 1966).

$$NPV = \frac{v'h - F}{(1 + r)^n - 1} - v'(x - h) \quad (23)$$

where the parameter v is a column vector of tree values by size and species, for trees sold as stumpage. F is a constant representing fixed costs per hectare and r is the interest rate.

NPV is the fundamental criterion because it takes into account the cost of the capital tied up in growing stock. NPV is also useful to compare forestry with other land uses, since NPV is the implicit value of land to grow trees under uneven-aged management. Still, the first term of equation (23) is informative. It measures the income produced by the land and the trees held on it, i.e., the forest value FV .

Economic performance may also be judged from the internal rate of return. Setting NPV , in equation (23), equal to 0 and solving for r gives the internal rate of return, IRR . As with FV , maximising IRR does not lead to the best economic management, but knowing IRR is useful in decision-making. For example, a management regime is certainly non-economic if its IRR is less than the guiding rate of interest.

Estimates of tree value (v), fixed cost (F), and interest rate (r) were obtained from price and cost data for various years, converted to U.S. dollars, and adjusted to 1992 values. Stump age values were calculated by subtracting the costs of logging and processing of 1 m³ of final product from the export unit value. Data for logging and processing costs pertained to forestry and forest products industries in Indonesia (Institut Pertanian Bogor 1989). The assumption that dipterocarps could be used either for sawnwood or plywood gave an average stumpage value of \$59 m⁻³ for dipterocarps of ≥ 30 cm dbh. Trees in the 10-cm and 20-cm dbh classes for both species were assumed noncommercial. The unit price for non-dipterocarps was set at 75% that of dipterocarps, based in part on Kir (1989). The final prices of trees by size and species are listed in Table 5.

The fixed cost F was estimated at \$195 ha⁻¹, based on Indonesian data (Institut Pertanian Bogor 1989). The interest rate r was measured by the lending rate for Malaysia from 1976 to 1990, which was about 6% per year, net of inflation (International Monetary Fund 1993).

Table 5. Estimated prices of trees

Species	Diameter class (cm)	Volume/tree (m ³ tree ⁻¹)	Stumpage value ^a	
			(\$ m ⁻³)	(\$ tree ⁻¹)
Dipterocarp	10	0	0	0
	20	0.3	0	0
	30	0.7	59	40
	40	1.1	59	65
	50	1.6	59	92
	60	2.9	59	172
	70	4.3	59	255
Non-dipterocarp	10	0	0	0
	20	0.3	0	0
	30	0.7	44	30
	40	1.1	44	48
	50	1.6	44	69
	60	2.9	44	129
	70	4.3	44	191

^a1992 U.S. Dollars.

Solving model equations (15) to (20) with these data showed that TPI options *M* and *N* had poor economic performances, with negative *NPV* and *IRR* close to only 1% (Table 6). The negative soil rents (*NPV*) reflect the high cost of holding the commercial stock in size classes of 30 and 40 cm. Instead, management option *O* achieved a positive *NPV* of \$241 ha⁻¹ and an *IRR* of more than 18%. Under option *O*, all commercial trees were removed every 55 years, reducing pre-harvest stand basal area by about two-thirds. Thus, diversity would be very low after harvest (two-thirds that of an old-growth stand), though it would recover almost fully in 55 years (Table 6). Option *M* kept the highest diversity (89%) and the highest basal area (13 m² ha⁻¹) after harvest. Here, the tradeoffs between economic and ecologic benefits are obvious. Management option *O* sacrificed approximately 20% of the diversity possible under *M* or *N* in order to achieve higher economic returns.

Management to maximise steady-state diversity

The sustainable management regime that maximised diversity, defined by *N_{min}*, in the steady-state was found by solving

$$\text{Max}_{(x_i, h_i, N_{\min})} N_{\min} \quad (24)$$

s.t.

$$x_i = G^b(x_i - h_i) + \sum_{i=0}^{p-1} G^i c \quad (25)$$

$$x_i - h_i \geq Nmin \quad (26)$$

$$h_p, Nmin \geq 0 \quad (27)$$

where the objective is to maximise the minimum number of trees in any species-size class after harvest, in the steady-state.

Table 6. Steady-states under TPI management options

Species	Diameter class (cm)	Management options					
		<i>M</i>		<i>N</i>		<i>O</i>	
		Pre-harvest	Post-harvest	Pre-harvest	Post-harvest	Pre-harvest	Post-harvest
Dipterocarp		(trees ha ⁻¹)					
	10	42.1	42.1	39.2	39.2	68.1	68.1
	20	35.8	35.8	35.2	35.2	58.5	58.5
	30	15.8	15.8	15.8	15.8	24.8	0
	40	12.6	12.6	12.2	9.0	16.5	0
	50	5.8	0	5.6	0	7.4	0
	60	4.5	0	4.9	0	5.0	0
	70	1.8	0	2.4	0	2.7	0
Non-dipterocarp							
	10	205.0	205.0	199.3	199.3	220.5	220.5
	20	85.4	85.4	84.9	84.9	89.9	89.9
	30	36.1	36.1	36.0	36.0	32.8	0
	40	16.0	16.0	16.0	16.0	9.4	0
	50	5.0	0	5.8	0	2.6	0
	60	0.3	0	0.4	0	0.2	0
	70	0.1	0	0.1	0	0	0
Total		466.3	448.84	57.8	435.4	538.4	437.0
Basal area (m ² ha ⁻¹)		17.2	13.01	7.5	12.4	18.7	6.9
Yield (m ³ ha ⁻¹ y ⁻¹)		1.1		1.1		2.0	
<i>H_p</i> (%) ^a		98	89	99	86	99	67
<i>Nmin</i> (trees ha ⁻¹)		0.1		00.1	0	0	0
<i>NPV</i> (\$ ha ⁻¹)		- 3009		- 2873		241	
<i>FV</i> (\$ ha ⁻¹)		291		193		241	
<i>IRR</i> (% y ⁻¹)		1.3		1.3		18.4	
<i>m</i> (years) ^b		35		45		55	

^aRelative to diversity of old-growth natural stand (*H* = 1.83).

^bCutting cycle fixed by TPI regulation.

The highest *Nmin* was achieved with a cutting cycle of 5 years (Table 7). Shannon's diversity index after harvest was 78% of that in old-growth stands because the distribution of trees among species would be more uneven than that in an old-growth stand (Table 2). Although maximising *Nmin* left trees in all size classes, Shannon's index was worse than that under TPI options *M* and *N*, which left no tree of size 50 cm and above (Table 6). This shows the limitations of Shannon's index as an index of diversity. Here, *Nmin* seems to be a better indicator of how rich a stand is in trees of all species and sizes. So, maximising *Nmin* did lead to a diverse

stand, but economic performance was very poor (worse than any TPI option) because the solutions called for cutting only a few of the smallest dipterocarps of no commercial value. *NPV*, *FV*, and *IRR* were all negative (Table 7).

Table 7. Steady-state that maximises the minimum number of trees in any species-size class

Species	Diameter class (cm)	Pre-harvest	Post harvest
Dipterocarp		(trees ha ⁻¹)	
	10	15.6	5.9
	20	8.5	8.5
	30	3.6	3.6
	40	2.9	2.9
	50	1.4	1.4
	60	1.5	1.4
	70	1.5	1.4
Nondipterocarp			
	10	226.4	226.4
	20	92.1	92.1
	30	38.8	38.8
	40	17.3	17.3
	50	10.1	10.1
	60	1.4	1.4
	70	1.4	1.4
Total		422.5	412.7
Basal area (m ² ha ⁻¹)		14.8	14.7
Yield (m ³ ha ⁻¹ y ⁻¹)		0.2	
<i>H'</i> (%) ^a		81	78
<i>Nmin</i> (trees ha ⁻¹)		1.4	1.4
<i>NPV</i> (\$ ha ⁻¹)		- 4702	
<i>FV</i> (\$ ha ⁻¹)		- 466	
<i>IRR</i> (% y ⁻¹)		- 1.0	
<i>m</i> (years) ^b		5	

^aRelative to diversity of old-growth natural stand (*H* = 1.83).

^bBest cutting cycle.

To improve economic performance, the next solution maximised diversity (*Nmin*) with the requirement that the *IRR* be at least 6%. The objective was to achieve the highest level of diversity in the steady-state and maintain an investment in trees competitive with the rest of the Malaysian economy. This was obtained by introducing equation (23) as a constraint in model (24) to (27), with *NPV* = 0 and *r* = *IRR* = 0.06 y⁻¹. With this constraint, the best cutting cycle was longer (10 years), *Nmin* was reduced by about one-third (although trees still remained in every size class), and Shannon's index was reduced to 72% of old-growth stands (Table 8). However, economic returns were much improved, leading to a forest value of \$ 1070 ha⁻¹ from 2 m³ ha⁻¹ y⁻¹ of commercial yields (Table 8). Most of the cut was in the 30-cm diameter class of both species.

Table 8. Steady-state that maximises the minimum number of trees in any species-size class, while returning 6% per year

Species	Diameter class (cm)	Pre-harvest	Post harvest
Dipterocarp		(trees ha ⁻¹)	
	10	75.2	75.2
	20	58.2	58.5
	30	12.3	0.5
	40	2.5	0.4
	50	0.5	0.4
	60	0.5	0.5
	70	0.5	0.5
Non-dipterocarp			
	10	302.9	302.9
	20	121.7	121.7
	30	19.2	5.5
	40	5.5	5.5
	50	3.1	3.1
	60	0.5	0.5
	70	0.5	0.5
Total		603.1	575.4
Basal area (m ² ha ⁻¹)		13.2	11.1
Yield (m ³ ha ⁻¹ y ⁻¹)		2.0	
H_r (%) ^a		80	72
N_{min} (trees ha ⁻¹)		0.5	0.4
NPV (\$ ha ⁻¹)		0	
FV (\$ ha ⁻¹)		1070	
IRR (% y ⁻¹)		6.0	
m (years) ^b		10	

^aRelative to diversity of old-growth natural stand ($H = 1.83$).

^bBest cutting cycle.

Management to maximise steady-state income

The steady-state that maximised net present value, NPV, or soil rent, was found by solving

$$\text{Max}_{(x,h)} NPV = \frac{v h_t - F}{(1+r)^p - 1} - v'(x_t - h_t) \quad (28)$$

s.t.

$$x_t = G^p(x_t - h_t) + \sum_{i=0}^{p-1} G^i c \quad (29)$$

$$x_t - h_t \geq 0 \quad (30)$$

$$h_t \geq 0 \quad (31)$$

(Buongiorno & Michie 1980).

The best steady-state under this strategy (Table 9) was obtained by harvesting all 30- and 40-cm trees every 5 years. The *NPV* of this management was \$ 1433 ha⁻¹, six times that of the best TPI option. The *IRR* was undefined because the residual stock had no value. The high fixed cost of harvesting the stand frequently (every 5 years) was offset by the removal of close to 20 trees ha⁻¹ worth \$489 at each harvest. Commercial yields of 2.6 m³ ha⁻¹ y⁻¹ were gained, again at the expense of diversity, which was only 64% that of an old-growth stand. After harvest, no tree larger than 20 cm was left in the stand. Residual basal area was low (10 m² ha⁻¹), but still higher than under the most economic TPI option, 0. These results should be viewed with caution because of the heavy logging damage that might result in stands harvested so frequently. If the damage costs were included, these attractive economic returns would be lower (Sianturi 1990).

Table 9. Steady-state that maximises soil rent

Species	Diameter class (cm)	Pre- harvest	Post harvest
Dipterocarp		(trees ha ⁻¹)	
	10	90.1	90.1
	20	70.0	70.0
	30	8.4	0.0
	40	0.7	0.0
	50	0.0	0.0
	60	0.0	0.0
	70	0.0	0.0
Non-dipterocarp			
	10	345.8	345.8
	20	140.0	140.0
	30	9.6	0.0
	40	0.2	0.0
	50	0.0	0.0
	60	0.0	0.0
	70	0.0	0.0
Total		664.8	645.9
Basal area (m ² ha ⁻¹)		11.4	10.0
Yield (m ³ ha ⁻¹ y ⁻¹)		2.6	
<i>H_t</i> (%) ^a		71	64
<i>N_{min}</i> (trees ha ⁻¹)		0.0	0.0
<i>NPV</i> (\$ ha ⁻¹)		1433	
<i>IV</i> (\$ ha ⁻¹)		1433	
<i>IRR</i> (% y ⁻¹)		undefined	
<i>m</i> (years) ^b		5	

^aRelative to diversity of old-growth natural stand (*H* = 1.83).

^bBest cutting cycle.

Conversion to the steady-state

Up to this point, steady-state analysis was used to find management practices that achieved sustainable economic and ecological goals. Then, we evaluated the gains and losses due to converting different stands to the steady-state. First, the TPI management options were applied to stands of low and high initial basal areas (Table 2) by harvesting everything within the limits of each option. The consequences were described by the diversity of the stand after each harvest and by the present value of the income received during and after conversion. Next, regimes defined by optimal steady-states were evaluated, including the steady-state that maximised N_{min} , income, and N_{min} with an internal rate of return of 6%.

Despite its limitations, the Shannon-Weiner Index, relative to average unmanaged stands, was maintained as an indicator of diversity during conversion to the steady-state, in addition to the minimum number of trees in any species-size class, which seemed to be a better index of the stand diversity. The income from converting the stand to the steady-state is

$$FV = \sum_{t=0}^{T-1} \frac{v' h_t - F}{(1+r)^{tp}} + \frac{1}{(1+r)^{Tp}} \cdot \frac{v' h_T - F}{(1+r)^{p-1}} \quad (32)$$

where the period of conversion is equal to the length of the cutting cycle, p , times the number of cutting cycles, T . For an initial stand condition, x_0 , the net present value during the conversion is the sum of the discounted value of all harvests from $t = 0, 1, 2, \dots, T-1$, net of costs. Once the stand is in the steady-state, it produces a constant periodic perpetual harvest of which the present value is added to that of conversion harvests to yield the forest value, FV . For a given initial condition and harvest regime, FV is the forest value at time zero, inclusive of land and initial growing stock.

Conversion with TPI management options

The long-term effects of options M , N and O (Table 4) were simulated with stands of low or high initial basal area (Table 2). The simulated management cut all trees in and above the minimum diameter class, as long as the number of remaining trees met the requirements. If the number of trees exceeded the desired number for the residual stand, the higher-valued dipterocarps were cut before the non-dipterocarp trees. Stands with too few trees were left uncut until the beginning of the next cutting cycle.

The results of applying the TPI options, in terms of yield, income, and diversity during conversion, are shown in Table 10. The conversion to the steady-state took approximately 4 to 5 cutting cycles, i.e. 175 to 220 years, for all options. But, the economic and ecological consequences differed markedly between options.

Table 10. Yield, income, and diversity from TPI management options

	TPI management option		
	<i>M</i>	<i>N</i>	<i>O</i>
Cutting cycle	35	45	55
Low initial basal area (10.6 m ² ha ⁻¹)			
Year to steady-state	175	180	220
Average annual yield (m ³ ha ⁻¹ y ⁻¹)	1.1	1.1	1.1
PV of 1st harvest (\$ ha ⁻¹)	0	0	2 774
PV of 2nd harvest (\$ ha ⁻¹)	217	157	198
FV (\$ ha ⁻¹)	258	174	2 982
Average <i>N</i> _{min} (trees ha ⁻¹) ^a	0.0	0.0	0.0
Average <i>H</i> _p (%) ^a	90	91	68
High initial basal area (24.4 m ² ha ⁻¹)			
Years to steady-state	175	180	220
Average annual yield (m ³ ha ⁻¹ y ⁻¹)	1.4	1.6	1.9
PV of 1st harvest (\$ ha ⁻¹)	6 011	7 318	10 063
PV of 2nd harvest (\$ ha ⁻¹)	279	240	182
FV (\$ ha ⁻¹)	6 327	7 575	10 255
Average <i>N</i> _{min} (trees ha ⁻¹) ^a	0.0	0.0	0.0
Average <i>H</i> _p (%) ^a	93	86	67

^apost-harvest.

Option *O* produced substantially more yield compared to options *M* and *N* during conversion; the higher yields led to a *FV* 10 to 17 times greater than *M* or *N* for stands of low initial basal area. Here, the initial condition of the stand was a major factor, as well as the minimum diameter limit. Not only did harvesting occur early, but trees as small as 30 cm in diameter were cut. The high economic returns of option *O*, however, were gained at the expense of diversity. The average Shannon's Index was less than 70% that of an average old-growth stand and about 20% less than that under options *M* or *N*. Also, the ratio of economic gains under option *O* to the gains from *M* or *N* dropped to less than 2:1, with a stand of high initial basal area.

The relative performance of TPI management options for economic or ecologic criteria was the same in the steady-state (Table 6) as during conversion (Table 10). The TPI option that achieved the highest economic returns in the steady-state, option *O*, also led to the highest economic return during conversion. Average annual yield, *H*_p, and *N*_{min} were almost the same during conversion as they were in the steady-state, regardless of the initial state. The best choice of management for ecological benefits during conversion, was either *M* or *N*, regardless of initial state, which is also coherent with the steady-state results.

Conversion with optimal steady-state cutting guides

The consequences of conversion with cutting guides defined by the steady-states that maximised economic returns, diversity, or a combination of the two were also investigated. The steady-state solution $\mathbf{x}^*$ and $\mathbf{h}^*$ defined the stem distribution of

the residual stand, $x^* - h^*$, that gave a desired result in perpetuity. The conversion consisted of cutting back a stand to this level at intervals equal to the best steady-state cutting cycle, p , until the desired steady-state was obtained.

The results are summarised in Table 11. Cutting guides that maximised economic returns (Table 9), or maintained at least a 6% return on investment (Table 8), gave incomes from stands of high initial basal area 3 to 4 times those of stands of low initial basal area. The regime that maximised diversity (Table 7) generated a FV from the stand with high initial basal area 90 times that of the poorly stocked stand. Average yields during conversion were similar to those of the steady-state, for all guides and initial states. For the stand with high initial basal area, choosing TPI option O , instead of the one that maximised NPV in the steady-state, led to nearly the same forest value. But option O led to a much lower FV for a stand of low initial basal area.

Table 11. Yield, income and diversity from applying cutting guides that are optimum in the steady-state

	Study-state cutting guide		
	Maximise NPV	Maximise N_{min}	Maximise N_{min} , IRR 6%
Cutting cycle	5	5	10
Low initial basal area ($10.6 \text{ m}^2 \text{ ha}^{-1}$)			
Year to steady-state	180	220	170
Average annual yield ($\text{m}^3 \text{ ha}^{-1} \text{ y}^{-1}$)	2.3	0.9	1.8
PV of 1st harvest ($\$ \text{ ha}^{-1}$)	2 774	583	1 909
PV of 2nd harvest ($\$ \text{ ha}^{-1}$)	92	- 139	206
FV ($\$ \text{ ha}^{-1}$)	3 397	60	2 522
Average N_{min} (trees ha^{-1})	0.0	0.5	0.2
Average H_t (%) ^a	64	77	71
High initial basal area ($24.4 \text{ m}^2 \text{ ha}^{-1}$)			
Years to steady-state	185	180	170
Average annual yield ($\text{m}^3 \text{ ha}^{-1} \text{ y}^{-1}$)	2.3	0.8	2.0
PV of 1st harvest ($\$ \text{ ha}^{-1}$)	10 063	6 039	8 993
PV of 2nd harvest ($\$ \text{ ha}^{-1}$)	71	- 117	413
FV ($\$ \text{ ha}^{-1}$)	10 596	5 574	9 929
Average N_{min} (trees ha^{-1}) ^a	0.0	1.3	0.4
Average H_t (%) ^a	66	81	71

^apost-harvest.

The diversity of the stands converted with the optimal steady-state cutting guides ranged from 64 to 81% according to H_t . These management options ranked the same regardless of the initial state. Diversity levels measured by N_{min} ranked the same as measured by H_t ; therefore, the optimal steady-state regime that maximised diversity led to the highest diversity during conversion. This was true regardless of the initial state.

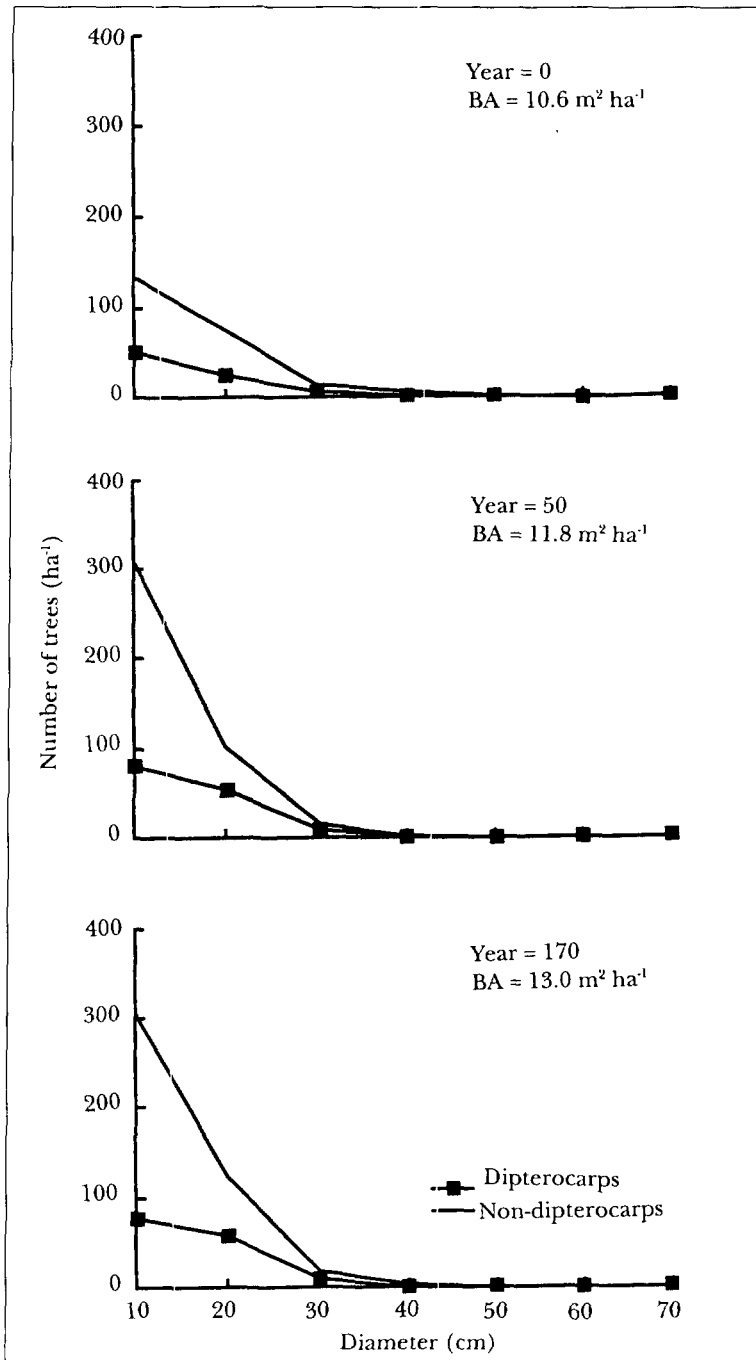


Figure 4. Predicted diameter distribution in a stand of low initial basal area (BA), managed under the steady-state regime that maximised N_{min} with IRR = 6%

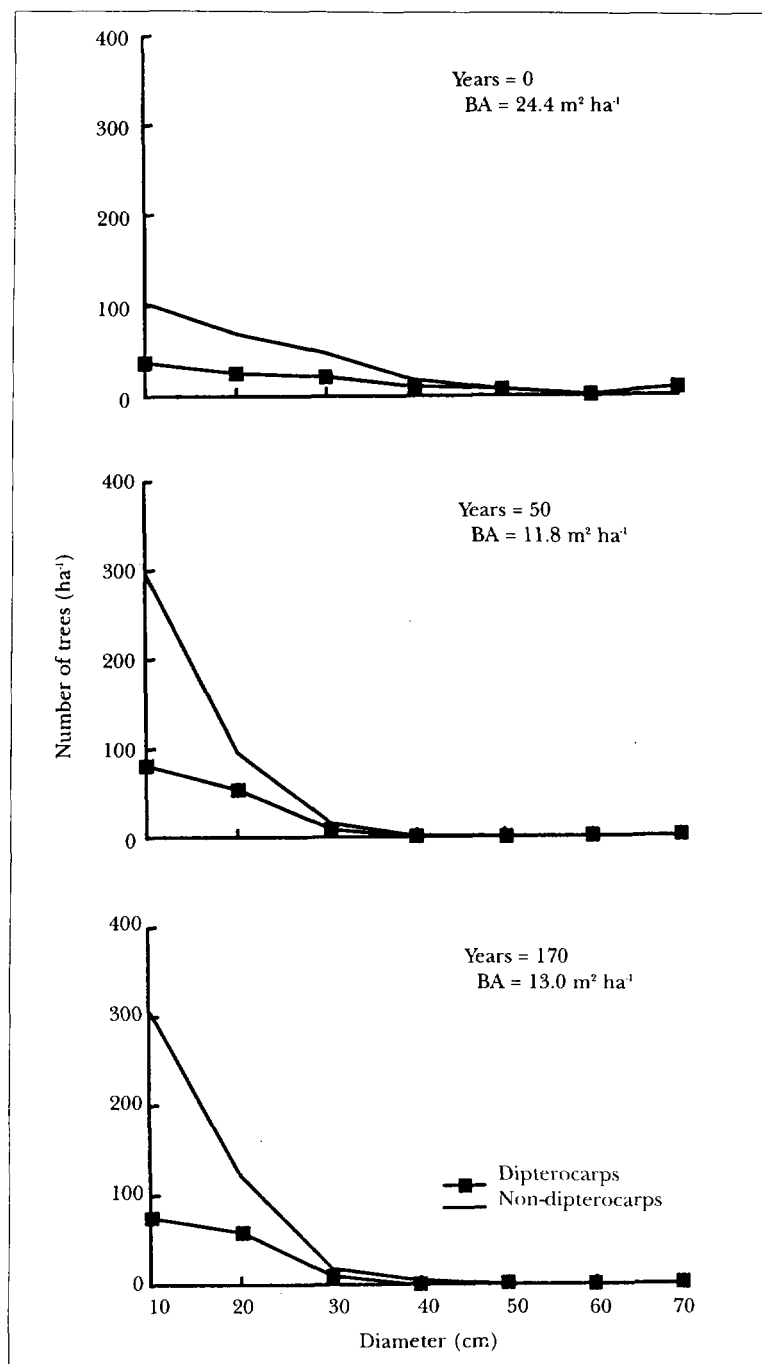


Figure 5. Predicted diameter distribution in a stand of high initial basal area (BA), managed under the steady-state regime that maximised N_{min} with IRR = 6%

The steady-state regime that maximised diversity with an *IRR* of 6% also gave good income and diversity during conversion. Figure 4 shows that in 50 years, the conversion of the stand of low initial basal area was nearly completed under this regime. After 170 years, total basal area had increased slightly to 13 m² ha⁻¹, predominantly in the non-dipterocarp species. The stand with high initial basal area (Figure 5) had its basal area reduced by almost 50% after 4 to 5 harvests before recovering to steady-state levels.

The evolution of diversity was similar for stands in different initial states. The difference was mainly the magnitude of diversity reduction. The diversity of the stand with high initial basal area fell from 120 to less than 80%. The stand of low basal area lost only about 13% of its diversity during conversion. H_t fluctuated about 10% between pre- and post-harvest levels once the stand growth stabilised (Figure 6).

The relative performance of the three steady-state regimes during conversion coincided with their performance in the steady-state, for both initial states. The regime that maximised diversity in the steady-state led to the highest diversity during conversion, as did the regime that maximised economic returns. The management regime that achieved a compromise between economic returns and ecologic diversity accomplished its objectives in the steady-state and during conversion.

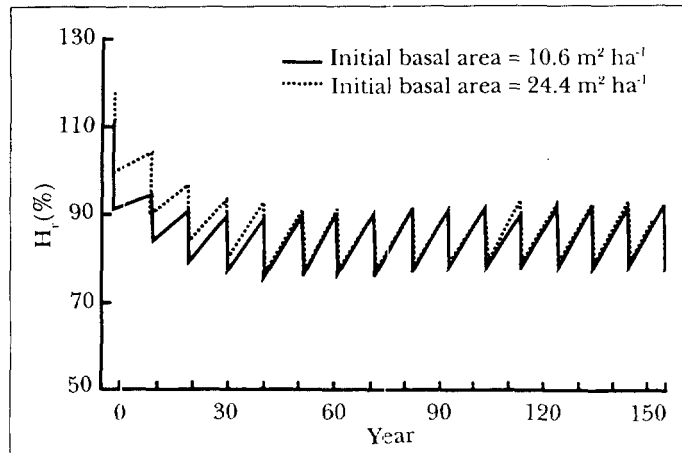


Figure 6. Predicted diversity, before and after harvest, when managing under the steady-state cutting guide that maximised *N_{min}* with *IRR* = 6%

Summary and conclusion

The lowland dipterocarp forests of Southeast Asia are among the most productive and species-rich tropical forests in the world. The objective of this study was to better understand how these forests grow, and how they could be managed for income and diversity. For this, a matrix growth model was developed, with trees

classified into dipterocarps, non-dipterocarps, and seven size classes. The model formulation insured that the predicted steady-state would be identical to that observed in old-growth stands. Model estimation required one single regression to predict the effect of basal area on ingrowth. Model validation suggested that it predicted plausible stand dynamics for lowland dipterocarp forests in Peninsular Malaysia.

The growth model was then applied to evaluate the effects of three selective management options derived from the Indonesian Selective System (TPI) on economic returns and diversity of tree sizes and species. Stand diversity was judged by Shannon's Index and the minimum number of trees in any species-size class (N_{min}). Financial performance was measured by soil rent, forest value, internal rate of return, and annual yield. Performance was evaluated in the steady-state and during conversion to the steady-state. In the steady-state, two TPI regimes (M and N) led to stands of high diversity compared to old-growth stands, at a high opportunity cost. The light harvest needed to maximise N_{min} would be costly, and so little would be gained that no management at all would be the best option to achieve high diversity.

Management that maximised economic returns resulted in average annual yields of almost $3 \text{ m}^3 \text{ ha}^{-1}$ and soil rents in excess of $\$1400 \text{ ha}^{-1}$. This was much higher than what would be obtained with the most profitable TPI option, and it would lead to about the same diversity. However, the diversity levels would be much lower than those of old-growth stands because no large trees would remain. A good compromise solution was found by maximising N_{min} , subject to getting returns on growing stock comparable to those of the rest of the economy in Malaysia (6% per year in 1992). Then, steady-state stands would have dipterocarp and non-dipterocarp trees in every size class.

The results of converting current stands to the steady-state with different regimes showed that the advantages or shortcomings revealed in the steady-state also appeared during conversion. For example, the regime that led to the highest economic performance in the steady-state did so during conversion, and so did the regime that maximised diversity, regardless of the initial state. However, the initial condition of the stand was the most influential factor of the economic performance during conversion. Given the same cutting guide, the ability to harvest heavily and early was the difference between an income of a few hundred dollars per hectare and more than several thousand dollars.

If the objective of management is to maintain a high level of diversity, the results suggest harvesting every 35 to 45 years leaving at least 25 trees per hectare of size 40 to 50 cm dbh, or, better yet, applying a regime that maximises N_{min} in the steady-state. To maximise income, it is best, among the guides considered here, to apply the one that maximises NPV in the steady-state, or utilise the most liberal cutting regime based on the TPI examples. This would generate incomes ranging from $\$2900 \text{ ha}^{-1}$ to $\$10\ 600 \text{ ha}^{-1}$, depending on the initial condition of the stand. It appears possible to generate attractive economic returns and maintain good levels of diversity when converting a stand to the steady-state, by applying the guide that maximises N_{min} while returning 6% per year in the steady-state. Regardless of

objectives, choosing a management regime from its steady-state properties leads to results during conversion that are consistent with those in the steady state.

In summary, existing selective logging systems in Southeast Asia could be improved. If applied consistently, the TPI guides can maintain a mix of dipterocarp and non-dipterocarp species in lowland tropical forests. Two options (*TPI-M* and *N*) could provide good diversity, but they have little chance to be sustainable in a developing economy because their economic returns are very low. Option *O* has acceptable economic indices, but poor diversity. These options could be replaced by one of the guides obtained in this study. It has been shown, for example, that maximum soil rent (much higher returns than option *O*) could be obtained, with higher diversity. The most attractive guide developed here is the one that maximises the minimum number of trees in any size class, while insuring a rate of return of 6% per year. Such a return should be enough to keep lowland dipterocarp forests in their current use.

Ecologic and economic objectives are not incompatible. The difficulty is to find the proper balance between the two. The methods presented in this paper are useful in that respect. They give a quantitative measure of the opportunity cost of diversity. To improve these management guides, better growth models should be developed with tree data from the specific forest area to be managed, with more detail in species composition. With a good growth model and adequate economic data, existing management regimes can be evaluated or alternative regimes can be defined from the steady-state analysis alone. Though a steady-state solution is not necessarily optimal during conversion, the results of this paper suggest that, in fact, not much is lost by assuming that it is so. In this way, much is gained in terms of simplicity since the steady-state cutting guide remains independent of the stand state.

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