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OPTIMISING TREE DIVERSITY AND ECONOMIC RETURNS FROM MANAGED MIXED FORESTS IN KALIMANTAN, INDONESIA

Guillermo A. Mendoza*,

Department of Natural Resources and Environmental Sciences, University of Illinois, Urbana, IL 61801, United States of America

Hayri Önal & Widyono Soetjipto

Department of Agriculture and Consumer Economics, University of Illinois, Urbana, IL 61801, United States of America

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MENDOZA, G. A., ÖNAL, H. & SOETJIPTO, W. 2000. Optimising tree diversity and economic returns from managed mixed forests in Kalimantan, Indonesia. This paper addresses the problem of optimising the management of uneven-aged forests under the dual objectives of economic returns and tree species and size diversity. Three models are developed: 1) Model I is aimed at maximising sustainable tree diversity; 2) Model II is formulated to maximise economic returns from harvesting while also ensuring sustainability of the stand; and 3) Model III is aimed at maintaining an exogenous level of tree diversity while at the same time maximising economic returns and ensuring the sustainability of the stand. The models are applied to an old-growth forest that contains trees belonging to the highly commercial family of species called Dipterocarpaceae located in the tropical forests of Kalimantan, Indonesia. Simulations based on the three models are used to examine some of the provisions and technical regulations contained in the Indonesian Selective Cutting System.

Key words: Optimum management - uneven-aged mixed forest - economic returns - tree diversity - steady state

MENDOZA, G. A., ÖNAL, H. & SOETJIPTO, W. 2000. Mengoptimumkan kepelbagaian pokok dan pulangan ekonomi daripada hutan campur yang terurus di Kalimantan, Indonesia. Artikel ini menyatakan masalah dalam mengoptimumkan pengurusan hutan yang tidak sama umur di bawah dua objektif iaitu pulangan ekonomi dan kepelbagaian spesies dan saiz pokok. Tiga model dibangunkan: 1) Model I bertujuan untuk memaksimumkan kepelbagaian pokok secara mapan; 2) Model II dirumuskan untuk memaksimumkan pulangan ekonomi daripada pengusahasilan di samping memastikan kemapanan dirian; dan 3) Model III bertujuan untuk mengekalkan peringkat eksogen kepelbagaian pokok dan pada masa yang sama memaksimumkan pulangan ekonomi dan menentukan kemapanan dirian. Model-model ini digunakan di hutan sudah lama tumbuh dan mengandungi spesies daripada famili yang bernilai komersial tinggi, dikenali sebagai Dipterocarpaceae yang terdapat di hutan tropika

**Author for correspondence.*

di Kalimantan, Indonesia. Simulasi yang berdasarkan tiga model digunakan untuk memeriksa beberapa peruntukan dan peraturan teknikal yang terdapat dalam Sistem Tebang Pilih Indonesia.

Introduction

The primary question addressed in this paper is: Is it possible to practise forest management with a harvest option that is sustainable with respect to tree diversity, and at the same time maximise long-term economic returns? To answer this question, a mathematical model is developed to examine prescriptive management strategies that simultaneously meet the dual objectives of generating acceptable economic return and maintaining a sustainable level of tree species and size diversity.

The tropical rain forest in Indonesia is concentrated mostly in four islands: Kalimantan, Irian Jaya, Sumatra and Sulawesi (Bunton 1983). The dominant species belong to the family Dipterocarpaceae which includes most of the highly commercial timber species. Since 1972, harvesting has been conducted under a system called Tebang Pilih Indonesia (TPI), or Indonesian Selective Cutting System (Direktorate Jenderal Kehutanan 1972). TPI regulations provide the structure under which the silvicultural system is conducted including how and when timber should be harvested and how forest regeneration should be implemented. In 1989, TPI was modified by adding a provision requiring tree planting. The system is now called Tebang Pilih dan Tanam Indonesia (TPTI) or Indonesian Selective Cutting and Replanting System. This system includes, among other things: (1) a 35-y cutting cycle for commercial tree species based on a 50-cm diameter-at-breast-height (dbh) limit on trees available for harvest; (2) a requirement that at least 25 trees per hectare must be left as residual trees distributed within the 20–49 cm dbh size classes; (3) a requirement that enrichment/restocking planting be conducted one year after harvesting; and (4) a timber stand improvement requirement, including poisoning liana and other plants that adversely affect regrowth.

Managing for tree diversity

Tree size and species diversity is one of the main issues in managing uneven-aged tropical forests. In this paper, tree diversity is formulated following the seminal work of Buongiorno *et al.* (1994). In that pioneering study, tree-size diversity, patterned after the Shannon index, is formulated as follows:

$$H = -\sum_{i=1}^{n} \frac{y_i}{\sum_{i=1}^{n} y_i} . \ln \frac{y_i}{\sum_{i=1}^{n} y_i} \qquad (1)$$

where i is the index of diameter size classes, n is the number of size classes considered, y_i is the number of trees in size class i, and $y_i/\sum y_i$, is the proportion of trees in the i^{th} size class. The minimum value of the Shannon index is zero, which occurs when all the trees are in a single class, and the maximum value is equal to ln (n), which occurs when all the trees are evenly distributed among size classes. In the present study, the above formulation is extended to incorporate tree species also, where tree groups are distinguished not only by size classes but also by tree species. This defines a measure of combined tree species and size diversity, which is simply termed as tree diversity.

Stand growth model

This study adopts a whole stand growth model developed by Buongiorno and Michie (1980) because of its simplicity for interpretation and application, and its compatibility with the uneven-aged conditions of the tropical rain forests in Indonesia (Setyarso 1984). The stand growth model is formulated as follows:

$$\mathbf{y}_{t+1} = \mathbf{G}(\mathbf{y}_t - \mathbf{h}_t) + \mathbf{c} \qquad (2)$$

where $\mathbf{y}_t$ is the stand structure (vector) in year t, $\mathbf{h}_t$ is the number of harvested trees in year t, $\mathbf{G}$ is the growth transition matrix described in the latter part of the paper; and $\mathbf{c}$ is the ingrowth (vector of new trees).

Growing stock and harvesting schemes

The entire stand of living trees per unit area at time t can be formulated as:

$$\mathbf{y}_t = (y_{it}), \qquad \text{for } i = 1, ..., n \qquad (3)$$

where y_{it} represents the number of trees of size class i per ha. The harvest (vector) at time t is represented by $\mathbf{h}_t$ which takes the form:

$$\mathbf{h}_t = (h_{it}), \qquad \text{for } i = 1, ..., n \qquad (4)$$

where h_{it} is the number of trees cut from diameter class i.

Ingrowth

Ingrowth is defined as the number of young trees that grow into the smallest diameter class during one growth period. The part of ingrowth that is independent of stand state is denoted by $\mathbf{c}$, which is an n x1 column vector. Ek (1974) found that ingrowth is a function of the basal area and the number of trees. Therefore, ingrowth is estimated using linear regression based on the following equation:

$$I_t = \alpha + \beta_1 \sum_{i=1}^{n} A_i (y_{it} - h_{it}) + \beta_2 \sum_{i=1}^{n} (y_{it} - h_{it}) \quad (5)$$

in which I_t is ingrowth. Basal area of diameter class i is represented by A_i. The α, β_1, and β_2 are regression coefficients.

Growth transition matrix and stand structure

A transition matrix G is an n xn matrix which consists of probability values indicating: (1) the probability that a tree in diameter class i will stay in the same diameter class after one growth period, denoted by a_i; and (2) the probability that a tree in diameter class i will shift to the next higher diameter class after one growth period, denoted by b_i. The summation of a_i, b_i, and the tree mortality in each diameter class i is equal to 1. Given the information on the growing stock, harvesting scheme, ingrowth and the probabilities of a_i and b_i, the number of trees for each tree group at time $t+1$ can be determined by the equations:

$$\begin{aligned} y_{1,t+1} &= I_t + a_1 (y_{1,t} - h_{1,t}) \\ y_{2,t+1} &= b_1 (y_{1,t} - h_{1,t}) + a_2 (y_{2,t} - h_{2,t}) \\ &\;. \\ &\;. \\ y_{n,t+1} &= b_{n-1} (y_{n-1,t} - h_{n-1,t}) + a_n (y_{n,t} - h_{n,t}) \end{aligned} \quad (6)$$

Substituting I_t from equation (5) into the first equation above leads to equation (7), which represents the changes in the smallest diameter class due to changes in the stand structure and the harvest as denoted by:

$$y_{1,t+1} = \alpha + e_1 (y_{1,t} - h_{1,t}) + \ldots + e_i (y_{i,t} - h_{i,t}) \quad (7)$$

where, $e_1 = a_1 + \beta_1 A_1 + \beta_2$, and $e_i = \beta_1 A_i + \beta_2$, for $i > 1$.

The coefficients in equations (6) and (7) can be transformed into a growth transition matrix, G, and ingrowth, c, which have the form:

$$G = \begin{bmatrix} e_1 & e_2 & e_3 & \cdots & e_{i-1} & e_i \\ b_1 & a_2 & & & & \\ b_2 & a_3 & & & & \\ & & & & & \\ & & & & a_{i-1} & \\ & & & & b_{i-1} & a_i \end{bmatrix}, \quad c = \begin{bmatrix} \alpha \\ 0 \\ 0 \\ . \\ . \\ . \\ 0 \end{bmatrix} \quad (8)$$

The coefficients in the first row of G indicate the effects of the basal area and the number of trees on ingrowth (i.e. first diameter class). When ingrowth is constant, as is the case for the young growth forest in this study, the first row of G contains only the percentage of trees staying in the smallest diameter class, a_1.

Stands in an equilibrium

The evolution of a stand for a given structure and harvesting regime is formulated by equation (2). In the long run, however, it is conceivable that each harvesting scheme could lead to an equilibrium stand where the distribution of trees is stable. This equilibrium, or steady-state condition, implies that the number of trees in each tree group, as well as the number of trees harvested, remains unchanged from one time interval to the next. This can be expressed mathematically as:

$$y_{i,t} = y_{i,t+1} = y^*_{i,t} \quad \text{for all } i \tag{9}$$

$$h_{i,t} = h_{i,t+1} = h^*_{i,t} \quad \text{for all } i \tag{10}$$

where y_i^* and h_i^* are the number of trees in class i and the number of harvested trees in equilibrium respectively. Therefore, equation (2) can be generalised to:

$$\boldsymbol{y} = \boldsymbol{G}\,(\boldsymbol{y} - \boldsymbol{h}) + \boldsymbol{c} \tag{11}$$

Technical harvest constraint

The technical harvest/stock balance requirement restricts the harvest not to exceed the number of trees available for harvest. This constraint can be stated mathematically as:

$$y_i \geq h_i, \qquad \text{for all } i = 1, \ldots, n \tag{12}$$

Residual damage

The success of selective logging depends on the survival of an adequate number of healthy trees after harvest (i.e. residual stand structure) and the regeneration of trees. The residual stand, in turn, determines the number of trees than can grow and be harvested in the next cutting cycle. This condition was described by Sianturi (1990) as:

$$(1 - d)\ (y_i - h_i) = z_i \ \text{for all } i = 1, \ldots, n \tag{13}$$

where d is the intensity of damage measured in percentage, z_i is the number of live trees in class i in the residual stand after harvest, and y_i and h_i are the number of trees before harvest and the number of trees harvested in class i respectively. The incorporation of residual damage in the analysis introduces a modification to the description of a stand in equilibrium condition. Equation (11) now takes the form:

$$\mathbf{y} = (1 - d)\mathbf{G}(\mathbf{y} - \mathbf{h}) + \mathbf{c} \tag{14}$$

Models for optimising uneven-aged forest management

Three optimisation models are developed in this study, using a tree diversity index and the stand growth model described above. The first model is aimed at maximising sustainable tree diversity. The second model aims at maximising the economic returns from harvesting without a tree diversity consideration, but ensuring sustainability of the forest. Finally, the third model aims at maintaining tree diversity at a specified level while maximising economic returns. These models are described in detail below.

Model I - The maximum sustainable tree diversity model

In this model, we maximise tree diversity subject to stand growth, steady state, and harvest constraints. Two species groups, i.e. dipterocarps and non-dipterocarps, and seven size categories (defined by diameter classes) for each species are considered. The mathematical programming model is presented below:

$$\text{Max } H = -\sum_{j=1}^{2}\sum_{i=1}^{7} \frac{y_{ij}}{\sum_{j=1}^{2}\sum_{i=1}^{7} y_{ij}} \cdot \ln \frac{y_{ij}}{\sum_{j=1}^{2}\sum_{i=1}^{7} y_{ij}} \tag{15}$$

subject to:

$$\mathbf{z} = (1 - d)(\mathbf{y} - \mathbf{h}) \tag{16}$$

$$\mathbf{y} = \mathbf{G}\,\mathbf{z} + \mathbf{c} \tag{17}$$

$$\mathbf{y} - \mathbf{h} \geq 0 \tag{18}$$

$$\mathbf{y}, \mathbf{z}, \mathbf{h} \geq 0 \tag{19}$$

The notation used in the above model is as follows: H is the Shannon index which is used here to measure the tree diversity; $\boldsymbol{y}=(y_{ij})$ is pre-harvest stock vector, where y_{ij} is the number of trees in diameter class i and tree species j; $\boldsymbol{h}=(h_{ij})$ is harvest vector where h_{ij} is the number of trees harvested in diameter class i and tree species j; $\boldsymbol{G}$ is a 14×14 matrix of growth coefficients; and $\boldsymbol{c}$ is the ingrowth vector which represents the number of trees added to the first size category of each species in each growth period.

The first summation ranges over the two species groups: dipterocarps and non-dipterocarps. The second summation in the objective function ranges over the seven diameter classes that exist in the old-growth forest data. Equation (16) is an accounting constraint. Equation (17) describes the steady state growth condition, while equation (18) requires that harvest cannot exceed the available stock. The objective function (15) is non-linear in y_{ij}, while all of the equations (16)–(18) are linear. Therefore, the above model is a non-linear program. The key decision variables are the harvest and stock variables, h_{ij}, and y_{ij}, for each species group j and diameter class i.

Model II - The economic harvesting policy model

An economic harvesting policy involves two features: (1) the harvesting cycle, and (2) the intensity of harvest. The harvesting cycle and intensity of harvest both influence the economic returns from a forest and its tree diversity.

For a given harvest cycle T, which is assumed to be a multiple of the growth period, we first form the following linear programming model that maximises the net present value (NPV) of harvest returns over an infinite horizon subject to the steady state equilibrium and harvest constraints [based on Buongiorno and Gilles (1987) and Sianturi (1990)]:

$$\text{Max NPV}(\boldsymbol{y}, \boldsymbol{h}) = [\boldsymbol{vh} - F]/[(1+r)^{T}-1] \tag{20}$$

subject to:

$$\boldsymbol{z} = (1-d)\ (\boldsymbol{y} - \boldsymbol{h}) \tag{21}$$

$$\boldsymbol{y} = \boldsymbol{G}^{K}\boldsymbol{z} + \sum_{k=0}^{K-1} \boldsymbol{G}^{k}\boldsymbol{c} \tag{22}$$

$$\boldsymbol{y} - \boldsymbol{h} \geq 0 \tag{23}$$

$$\boldsymbol{h}, \boldsymbol{y}, \boldsymbol{z} \geq 0 \tag{24}$$

where $\boldsymbol{v} = (v_{ij})$ represents the value of trees by species j and diameter class i; F symbolises the fixed cost of harvesting per ha, which is assumed to be independent of the amount of harvest; r represents the discount rate; and K is the number of growth periods within the cutting cycle. All other symbols are as defined earlier.

The above formulation does not take into account the economic value (opportunity cost) of the growing stock. An alternative formulation is to cast the problem as an investment decision-making problem where the growing stock is treated as initial investment. The problem is then to determine the optimum size of the initial stock and harvest policy that maximise the soil expectation value (SEV). SEV is defined as the sum of discounted net returns, which occur at time T and thereafter, minus the cost of the growing stock. In this case, the objective function (20) is replaced by:

$$\text{Max SEV}(y, \boldsymbol{h}) = [v\boldsymbol{h} - F]/[(1+r)^{T}-1] - v(y-\boldsymbol{h}) \qquad (20a)$$

The formulation described by equation (20a) discounts all net returns that would occur throughout an infinite horizon except the harvest value which occurs at time $t = 0$. The implicit assumption here is that the initial stock value could be invested elsewhere in the economy or the forest land can be used for alternative purposes.

An alternative formulation of the objective function incorporates all returns and costs throughout an infinite horizon, including the harvest value at time $t = 0$ as well as the initial cost. This leads to the following objective function specification:

$$\text{Max SEV}(y, \boldsymbol{h}) = [v\boldsymbol{h} - F](1+r)^{s} / [(1+r)^{s}-1] - v(y-\boldsymbol{h}) \qquad (20b)$$

As will be discussed later, the three objective function formulations described above imply dramatically different forest stands in terms of size and tree composition (i.e. the total number of trees in the forest and tree distribution by size and species).

Model III - The joint economic and tree diversity model

The optimum management of a forest stand can be determined by incorporating a tree diversity goal, namely by imposing an exogenously specified tree diversity level as a constraint in an economic optimisation model. The model considered here aims at maximising NPV, as described by equation (20), achievable with a given level of tree diversity and a given harvesting cycle. The mathematical structure of the model is the same as model II except that a tree diversity constraint which imposes a minimum stand tree diversity level, H_o, is appended. This constraint is given below:

$$-\sum_{j=1}^{2}\sum_{i=1}^{7} \frac{y_{ij}}{\sum_{j=1}^{2}\sum_{i=1}^{7} y_{ij}} \ln \frac{y_{ij}}{\sum_{j=1}^{2}\sum_{i=1}^{7} y_{ij}} \geq H_o \qquad (25)$$

The resulting model is again a non-linear program due to the non-linear terms involved in equation (25)[(1)].

Application of the models to Kalimantan forests

The study area

The sample area studied is a natural forest concession area owned by PT Inhutani II *(PT. Explotasi dan Industri Hutan II)*, a government-managed firm. It consists of dipterocarp species such as *Shorea* sp., *Dipterocarpus* sp., *Hopea* sp. and *Dryobalanops* sp., and non-dipterocarp species. such as *Eusyderoxilon zwageri*. The data were recorded during the period of 1976 to 1986.

The growth data

Data from Sianturi (1990) were utilised to study the economic and tree diversity aspects of an old-growth dipterocarp and non-dipterocarp forest. Here, a 5-y growth period was used for both species. The resulting transition matrix is shown in Table 1. Following Sianturi (1990), the stand-independent component of ingrowth is assumed to be 18.8 and 35.5 trees ha^{-1} 5 y^{1} for dipterocarps and non-dipterocarps respectively.

Predicting the growth of secondary stands

This section projects the evolution of a secondary forest (i.e. a forest after harvest), assuming no harvest during succeeding years. The stand projection model, based on the work of Buongiorno and Michie (1980), is expressed in vector form as:

$$y_{t+\sigma K} = G^K(y_t) + \sum_{k=0}^{K-1} G^k c \qquad (26)$$

where σ is the length of a growth period (years), K is the number of growth periods in a cutting cycle, and $y_{t+\sigma K}$ reflects the stand composition K growth intervals after the initial measurement. The variable y_t indicates the initial stand composition, and c and G^k denote ingrowth and the growth matrix based on k growth periods respectively.

The stand projections show that the total number of trees remains relatively stable over time, while the tree diversity increases gradually (Table 2). If there is no harvest over a long period, the number of trees in the smallest diameter classes would decrease. The number of trees in the middle classes would remain

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[(1)] GAMS/MINOS (Brooke *et al.* 1992) is used as the computational software to solve all the three models. It should be noted that GAMS/MINOS guarantees only local solutions for non-linear models.

Table 1. Five-year growth parameters for the old-growth forest model

Diameter class (cm)	G														Ingrowth (new trees) per ha
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Dipterocarps															
5–14	0.366	-0.243	-0.231	-0.215	-0.193	-0.166	-0.135	0.089	0.097	0.109	0.125	0.147	0.174	0.205	18.2
15–24	0.323	0.672													0.0
25–34		0.273	0.688												0.0
35–44			0.262	0.707											0.0
45–54				0.248	0.715										0.0
55–64					0.245	0.750									0.0
65+						0.220	0.965								0.0
Non-dipterocarps															
5–14	0.0356	0.0346	0.0329	0.0305	0.0274	0.0236	0.0191	0.643	-0.1254	-0.1271	-0.1295	-0.1326	-0.1364	-0.1409	38.5
15–24								0.168	0.770						0.0
25–34									0.170	0.774					0.0
35–44										0.171	0.786				0.0
45–54											0.164	0.802			0.0
55–64												0.153	0.820		0.0
65+													0.145	0.960	0.0

Source: Sianturi (1990).

somewhat stable, while the number of trees in the largest classes would increase. The growth of new trees (i.e. ingrowth and small trees) is also inhibited by the density of the canopy generated by the larger diameter classes. This results in a declining number of trees in the smallest diameter.

Table 2. Stand growth projection for dipterocarps and non-dipterocarps species in an old- growth forest

Diameter class (cm)	Y_0	Y_{25}	Y_{35}	Y_{45}
	← Trees per hectare →			
Dipterocarps				
5–14	43.0	33.4	29.7	28.1
15–24	34.6	38.6	34.8	31.4
25–34	22.1	32.4	32.6	31.0
35–44	13.4	23.3	26.3	27.5
45–54	8.0	14.7	17.8	20.5
55–64	5.0	9.5	12.0	14.7
65+	7.0	12.7	16.2	20.6
Non-dipterocarps				
5–14	144.0	64.2	56.9	53.9
15–24	80.6	70.9	60.4	52.4
25–34	41.0	55.6	53.8	49.7
35–44	19.9	34.2	38.1	39.6
45–54	10.2	18.3	22.2	25.7
55–64	5.0	9.2	11.6	14.3
65+	4.3	7.9	10.0	12.7
Total	438.1	424.8	422.3	422.0
Basal area (m^2 ha^{-1})	31.2	47.5	54.1	60.5
Diversity (*H*)	2.100	2.425	2.493	2.541

Note: Calculated based on Sianturi's data (1990).

Model I results: achieving maximum sustainable diversity

The maximum level of tree diversity was determined using the constrained optimisation model described by equations (15)–(19). The solution presented in Table 3, indicates that to achieve the maximum sustainable pre-harvest tree diversity (*H*=2.583), 3.5 dipterocarp trees ha^{-1} and 1.1 non-dipterocarp trees ha^{-1} should be cut from the 65+ cm dbh class[(2)].

[(2)] Buongiorno *et al.* (1994) find that in order to achieve highest diversity, no trees should be cut, and therefore the climax structure of a forest provides maximum tree size diversity in the case of northern hardwood forests. The results of the present study show that the above finding is specific to the forest considered in their study and should not be generalised.

Table 3 also demonstrates that the dipterocarp trees would achieve a nearly uniform diameter class distribution[3]. Compared to the current stand structure, the steady-state stand that maximises tree diversity would have fewer trees in the 5–14 and 15–24 cm diameter classes, but substantially more trees in the higher diameter classes[4].

Examining the solution for the non-dipterocarps, all diameter classes above 35 cm have more trees than the current distribution, while all diameter classes below 35 cm have fewer trees. The management practice generated by the model allows the cutting of only 1.1 trees out of 37.6 trees in the largest diameter class (Table 3).

Table 3. Stand structure and harvest which maximise tree diversity in an old-growth forest

Diameter class (cm)	Current structure	Pre-harvest structure	Harvest
	← Trees per hectare		→
Dipterocarps			
5–14	43.0	30.1	0.0
15–24	34.6	29.6	0.0
25–34	22.1	25.9	0.0
35–44	13.4	23.2	0.0
45–54	8.0	20.2	0.0
55–64	5.0	19.8	0.0
65+	7.0	28.0	3.5
Non-dipterocarps			
5–14	144.0	57.9	0.0
15–24	80.6	42.3	0.0
25–34	41.0	31.8	0.0
35–44	19.9	25.4	0.0
45–54	10.2	21.0	0.0
55–64	5.0	17.9	0.0
65+	4.3	37.6	1.1
Total	438.1	410.7	
Diversity (*H*)	2.100	2.425	
Relative diversity	81%	100%	

(3) A uniform stand structure may not always be a desirable goal. If the relations between tree diversity and ecosystem diversity are well understood and a desirable tree diversity is determined, an alternative approach is to minimise the deviation between the optimum stand structure that can be obtained from the estimated growth behavior and the exogeneously determined (goal) structure by employing goal programming techniques (see, for instance, Buongiorno *et al.* 1995, and Önal 1997).

(4) The steady state stand structure is expected to be closely reflected by the current structure since the forest has not been managed before. The results found here are not consistent with this expectation. This may be due to several reasons: i) the forest may not have achieved its climax composition yet; ii) the growth of the forest may have been disturbed by natural causes, such as climate, diseases, fire, etc., before or during the period the data were collected; iii) the sample data that have been used in the statistical estimation may not be truly representative for the whole forest. Ingram and Buongiorno (1996) report that a similar discrepancy was obtained in their study also. One can incorporate the assumption that the current structure reflects the steady state structure in the estimation procedure, and obtain the growth matrix coefficients accordingly. See Ingram and Buongiorno (1996) for details.

The maximum theoretical value of the diversity index is 2.639= ln(14). However, this maximum theoretical value could not be obtained by the model, indicating that such a stand would not be sustainable. Instead, the maximum sustainable tree diversity generated by the model was H=2.583. These results suggest that the optimum forest management practice would remove a small portion of the largest diameter classes to achieve maximum tree diversity.

Model II results: the economic harvesting policy

A fundamental element of forest management practice is the specification of the economic stocking level and harvest regime necessary to achieve both economic and yield-oriented objectives. The economic harvesting policy for dipterocarps and non-dipterocarps is determined by solving the linear programming model described by equations (20)–(24). Given this formulation, various simulations are performed using the basic model to see the impacts on the optimal solution of changing parameter specifications, including the discount rate, fixed cost and the residual damage.

Table 4 summarises the simulated results of different levels of forest management and economic parameters, specifically the discount rate and residual damage. For a 5% discount rate and 10% residual damage, the optimal harvesting cycle is found as 20 y. The pre-harvest stand would have 334.8 trees ha^{-1} in equilibrium. The corresponding pre-harvest tree diversity is 2.359, or 91% of the maximum sustainable diversity level. The optimum harvesting scheme would remove all trees in the classes of 55–64 and 65+ cm dbh for both species, giving a post-harvest diversity of 2.177. Net present value ranges from \$493.07 to \$456.78 ha^{-1} associated with the fixed cost values ranging from \$40 to \$100 ha^{-1} [(5)]. Neither the optimum cutting strategy nor the cutting cycle is affected when the fixed cost parameter is altered over the range \$40–100 ha^{-1}.

An increase in residual damage to 20% would shift the optimal harvesting cycle to 25 y. However, a delay in harvest would not result in a larger number of total trees or a higher value of tree diversity, as one might expect. The increase in residual damage would result in a decrease in the total number of trees ha^{-1} (318.3). The corresponding tree diversity is 2.267 before harvest, and 2.039 after harvest, which correspond to 88% and 79% of the maximum sustainable tree diversity respectively. It would be optimal to cut all dipterocarp trees in the classes of 55+ cm dbh. For non-dipterocarps, all trees in the 45+ cm dbh classes would be harvested. NPV's are about 30–32% less (ranging from \$337.70 to \$312.56 ha^{-1}) than those obtained with 10% residual damage for the same range of fixed costs.

[(5)] All values are in US dollars. The tree values used in the model differ by size class and species, and given by the vectors v = (0.47, 2.65, 7.28, 14.91, 26.01, 40.99, 60.22) for dipterocarps and v = (0.31, 1.68, 5.00, 9.05, 15.56, 24.24, 35.25) for non-dipterocarps. These values are obtained from stumpage prices for tropical non-coniferous timber. Details can be found in Soetjipto (1995).

Increasing the residual damage further to 30% would lengthen the harvesting cycle to 30 y. The total number of trees decreases to 313.7 ha^{-1}. The optimal solution indicates a cutting scheme where all trees above 45 cm dbh are harvested. A further decline in NPV is also indicated, ranging from $252.27 to $234.21 per ha or about 47–49% reduction, for the same range of fixed costs compared to the NPV obtained with 10% residual damage.

The impact and importance of the discount rate can be seen by comparing the first and last columns in Table 4. With the residual damage set at 10%, increasing the discount rate from 5 to 7% reduces the net present value by about 40% (all other parameters being equal). Furthermore, a high discount rate also leads to a shorter harvesting cycle, 15 y instead of 20 y.

Table 4. Optimal results of the economic harvesting policy model (Model IIA: excluding both initial returns and investment costs)

	Parameters examined[a]			
Discount rate	5%	5%	5%	7%
Residual damage	10%	20%	30%	10%
	Optimal stand structure ← Trees per hectare →			
Dipterocarps				
5–14	30.4	30.2	31.4	30.7
15–24	28.6	27.9	29.6	28.0
25–34	23.0	21.4	22.1	21.9
35–44	18.8	16.4	16.1	17.4
45–54	15.0	12.3	10.4[b]	13.5
55–64	9.5[b]	8.3[b]	5.5[b]	7.2[b]
65+	3.7[b]	4.2[b]	2.0[b]	1.8[b]
Non-dipterocarps				
5–14	73.3	79.0	80.7	75.1
15–24	49.4	51.4	52.0	48.4
25–34	33.1	32.1	30.9	31.3
35–44	23.6	21.1	19.1	21.5
45–54	17.2	10.4[b]	9.8[b]	15.1
55–64	7.5[b]	3.0[b]	3.3[b]	5.4[b]
65+	1.8[b]	0.5[b]	0.7[b]	0.9[b]
Cutting cycle[c]	20 y	25 y	30 y	15 y
Number of trees	334.8	318.3	313.7	318.0
Harvested trees	22.5	26.4		
Pre-harv. diversity	2.359 (91%)[d]	2.267 (88%)	2.226 (86%)	2.299 (89%)
Post-harv. diversity	2.177 (84%)	2.039 (79%)	1.939 (75%)	2.155 (83%)
NPV ($/ha)	480.97	329.32	246.26	285.66

Notes:

a/ all results are obtained with a fixed cost of $60 ha^{-1}.

b/ indicates a totally harvested diameter class.

c/ the cutting cycles assumed in each column are optimum values.

d/ figures in parentheses represent relative tree diversity values (percentage of the maximum sustainable diversity level, 2.583).

As expected, an increase in fixed costs results in a decrease in the net present value. The results of simulations using different levels of fixed costs, ranging \$30–250 ha^{-1}, suggest that fixed costs may also affect the optimum cutting cycle. For example, for 5% discount rate and 30% damage factor, the optimum cutting cycle is 30 y for fixed cost values up to \$170 ha^{-1}. For higher fixed cost levels, the optimum cutting cycle becomes 35 y. A 5-y delay in optimum cutting cycle was observed for other combinations of discount rate and damage factor when fixed costs were set at \$170 or higher. This result is expected because higher fixed costs per cutting cycle can be compensated by increased returns from harvesting more mature trees, which can be achieved by lengthening the cutting cycle.

The importance of alternative objective function specifications is investigated by incorporating equations (20), (20a), and (20b) in model II, and the results obtained from the model with a fixed set of parameter values (r = 5%, d = 20%, and F = \$100) are shown in Table 5. The solutions obtained by excluding and including the economic value of initial tree stock as an investment cost, i.e. the objective function specifications given by equations (20) and (20a), are given in the first two columns labeled as model IIA and model IIB respectively. The results indicate that if the first specification is valid, a 25-y cutting cycle would be optimum whereas the second specification implies a 30-y optimum cutting cycle. The optimum harvest schedule, size and composition of the forest are dramatically different in the two solutions. When the initial cost is not incorporated, the model IIA solution suggests that harvesting the largest two size categories of dipterocarps and the largest three categories of non-dipterocarps would be optimum. On the other hand, model IIB suggests that harvesting all trees except the smallest size classes of both species would be optimum. Discounting the net returns but incorporating the current value of the growing stock as an initial investment cost alters the relative importance of costs and returns in the objective function. When the forest growth rate is slow and the cutting cycle is long, future net returns will be discounted heavily even with a low discount rate r. Therefore, model IIB does not favor a large growing stock, which diminishes the size of the forest. A total of 142 trees would be harvested in each cutting cycle, as opposed to 26 trees in model IIA, yet the nominal economic value of the harvest in each cutting cycle is only \$522 ha^{-1}, as opposed to \$746. Although the harvest cycle is five years longer, the forest would be thinner (273 versus 318 trees) and contains fewer and younger trees. This is because young trees would be harvested early instead of allowing them to grow into larger diameter classes. Both pre-harvest and post-harvest tree diversity levels, particularly the latter, obtained with model IIB are substantially lower than the diversity levels obtained with model IIA (1.808 versus 2.267 pre-harvest diversity, and 0.580 versus 2.039 respectively). The third column of Table 5 displays the results of the model that incorporates equation (20b) in its objective function, where the returns include the harvest that occurs at time t = 0 and the initial value of the forest is considered as an investment cost. The first important observation is that there is no optimum cutting cycle with this specification, and discounted net returns increase indefinitely as longer cutting cycles are assumed. The solution reported in Table 5 assumes an arbitrarily specified 30-y cutting cycle. In terms of the forest size, harvest volume, and tree diversity measures, this alternative formulation yields a compromise solution between the models IIA and IIB solutions.

Table 5. Optimal stand composition, harvest schedule and tree diversity under alternative specification of the economic optimisation model[a]

	Model IIA	Model IIB	Model IIC[b]	Model IIB + TPI
	←	Trees per hectare		→
Dipterocarps				
5–14	30.2	35.0	32.6	30.7
15–24	27.9	32.8[c]	32.5	29.6
25–34	21.4	19.1[c]	23.7[c]	23.4
35–44	16.4	7.1[c]	12.8[c]	18.4
45–54	12.3	1.6[c]	4.5[c]	12.6[c]
55–64	8.3[c]	0.2[c]	1.0[c]	6.8[c]
65+	4.3[c]	n.s.[c]	0.1[c]	2.6[c]
Non-dipterocarps				
5–14	79.0	95.9	85.9	77.2
15–24	51.4	55.2[c]	58.8	52.3
25–34	32.1	20.6[c]	31.4[c]	33.8
35–44	21.1	4.9[c]	11.8[c]	22.8
45–54	10.4[c]	0.7[c]	2.8[c]	12.5[c]
55–64	3.0[c]	n.s.[c]	0.4[c]	4.3[c]
65+	0.5[c]	n.s.[c]	n.s.[c]	1.0[c]
Number of trees	318.3	273.1	298.4	328.0
Harvested trees	26.4	142.3	88.6	39.8
Pre-harvest diversity	2.267 (88%)[d]	1.808 (70%)	2.002 (78%)	2.285 (88%)
Post-harvest diversity	2.039 (79%)	0.580 (22%)	1.300 (50%)	1.966 (76%)
NPV ($/ha)	329.32	111.1	725.16	-707.21
Harvest value ($/ha)[e]	785.76	522.76	731.76	997.73

Notes:

a/ The models are solved with the parameter values of F = $100, r = 5%, d = 20%. A 25-y optimum cutting cycle is assumed when solving model IIA, and a 30-y cutting cycle (which is optimum for model IIB) is used when solving the remaining models.

b/ Model IIA incorporates discounted returns except the initial returns at $t = 0$ and excludes initial costs. Model IIB is the same as model IIA except that it incorporates initial investment costs. Model IIC includes all returns and costs including the ones at $t = 0$.

c/ Indicates a totally harvested diameter class, n.s. means positive but not significant.

d/ Figures in parentheses represent relative tree diversity values (percentage of the maximum sustainable diversity level, 2.583).

e/ Nominal harvest value per cutting cycle.

Model II is also used to investigate the impacts of the TPI regulations on optimum harvest strategy and associated tree diversity at steady state. To accomplish this, i) the harvest variables for all size classes smaller than 50 cm dbh are fixed at zero level, and ii) a constraint is added to reflect the TPI requirement that there must be at least 25 trees standing in the remaining groups after harvest. The optimum solution obtained with model IIA, with an optimum cutting cycle of 25 y, satisfies the TPI restrictions and therefore the additional constraint becomes redundant under that specification[(6)]. When a 35-y cutting cycle was imposed (as required by TPI), the size of the forest, harvest volume and economic value of the harvest per cutting cycle were all increased. However, the total net discounted returns over an infinite horizon was less than the solution reported in column one of Table 5. This implies that either the TPI represents a sub-optimum management strategy, or the policy objective is different than the one represented by equation (20). Consideration of the objective function specification given by equation (20b) results in a negative discounted net return for any cutting cycle, which means that retaining the forest in any form would not pay off the investment (value of the growing stock) and the society would be better off by clear-cutting the forest and investing the funds elsewhere[(7)]. However, when the harvest value obtained at time $t = 0$ (not accounted for in the optimisation process) is added to the discounted net returns, a positive economic value would be obtained for any cutting cycle longer than 25 y. The value of such ex-post calculated returns increases indefinitely as longer cutting cycles are used in the model. The results obtained from model IIB including the TPI constraint and assuming a 30-y cutting cycle are reported in the last column of Table 5. This solution is fairly close to the solution obtained from model IIA without the TPI constraint (column one in Table 5). The optimum solution obtained from the model when the initial harvest return is also accounted for in the optimisation, i.e. model IIC plus the TPI constraint, was identical to that solution[(8)]. A distinguishing feature of this solution is that the nominal value of optimum harvest returns per cutting cycle, which is the value of the initial harvest at $t = 0$, is substantially higher than the values obtained in the other three solutions reported in Table 5. These results suggest that, if the model parameters are truly representative, the TPI restrictions play an important controlling role and may be geared towards increasing medium term economic benefits rather than maximising discounted net returns over an infinite horizon.

[(6)] The tree size categories 5 and 12 considered in the model contain trees with 45–55 cm dbh. In these two classes, those trees with more than 50 cm dbh can be cut according to the TPI rules while others cannot be cut. The model allows full cutting of all trees in those groups. Therefore, the optimum harvest results reported in Table 5 are overestimates for those two groups.

[(7)] Ingram and Buongiorno (1996) report a similar finding, i.e. large economic losses (negative net returns), for a Malaysian old-growth forest when the TPI regulations were imposed. We do not have sufficient empirical evidence to generalise this result, but given that forests grow at a slow rate and cutting cycles are usually long, future returns would be discounted heavily even for a small discount rate and, therefore, may not pay off the investment (initial value of the growing stock) in most cases.

[(8)] This cannot be generalised, however. Somewhat different solutions were obtained from model IIB+TPI and model IIC+TPI when a 35-y cutting cycle was used.

Imposing the TPI regulations improves the tree diversity (particularly post-harvest diversity), as can be seen by comparing the last column with column two of Table 5. The pre-harvest diversity level, 2.285, is the highest diversity level obtained from model II under the three objective function specifications. Therefore, the TPI strategy represents a compromise solution in terms of tree diversity and long term economic objectives.

Model III results: joint economic and tree diversity concerns

This section investigates the optimum economic harvesting strategy that simultaneously maintains a specified level of tree diversity, as formulated by equations (20)–(25). Recall from the model III formulation that the objective is to maximise economic returns (i.e. NPV), while at the same time satisfying both the sustainability constraint and the minimum tree diversity target, denoted by H_0. Table 6 summarises the results under the following set of parameters: a 5% discount rate, a 30% residual damage, a fixed cost of \$60 ha^{-1} and a 30-y harvesting cycle. The table shows the results obtained with different target levels of relative tree diversity (i.e. tree diversity expressed as a percentage of the maximum sustainable tree diversity, H_{max}=2.583)[9].

The maximum NPV under a pre-harvest relative tree diversity of 86% (i.e. H_0 = 2.225) is \$246.26 ha^{-1}. When the tree diversity target, i.e. the right hand side of equation (25), is systematically increased, the results indicate that the optimum economic return would be constant for the values of H_0 up to 86% of the highest sustainable tree diversity level. Beyond the 86% level, the maximum NPV begins to decline. Table 6 shows the optimum stand distribution and harvest solutions maximising NPV at different levels of pre-harvest relative tree diversity from 86 to 92%. The reductions in NPV associated with increases in tree diversity are dramatic. Starting from 86% relative diversity, moving to relative diversity levels of 88, 90 and 92% results in reductions in NPV of \$6.7, 20.7 and 83.3 ha^{-1} respectively.

In terms of stand distribution, the optimal solutions obtained with different tree diversity targets suggest that the number of trees in the largest diameter classes of both species increases as the minimum diversity requirement is increased. Results from model II (i.e. maximise NPV without a tree diversity constraint) show that the optimum harvests involve either harvesting all trees in a given diameter class or none at all (see Table 4). On the other hand, model III results show that partial cutting would occur in some diameter classes. For example, under a 92% target relative diversity level, only 2.0 out of 8.9 trees in the 55–64 cm dbh class are to be harvested, thereby allowing the tree diversity level to improve by harvesting fewer trees. Optimal model III results also show partial cutting in the classes of 55–64 cm dbh for the non-dipterocarp species group at 90 and 92% relative diversity levels (Table 6).

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[9] The analysis here focuses on pre-harvest diversity. One can also impose a goal for post-harvest diversity. It may be possible to increase post-harvest diversity and NPV above the levels found here on a sustainable basis.

Table 6. Stand structure and harvest obtained by maximising NPV at different levels of pre-harvest tree diversity

	Trees/ha with tree diversity constrained at:							
	Pre-harvest 2.225 (86%)[a] Post-harvest 1.939 (75%)		Pre-harvest 2.273 (88%) Post-harvest 2.052 (79%)		Pre-harvest 2.325 (90%) Post-harvest 2.168 (84%)		Pre-harvest 2.376 (92%) Post-harvest 2.305 (89%)	
Diameter class (cm)	Pre-harvest structure	Harvest	Pre-harvest structure	Harvest	Pre-harvest structure	Harvest	Pre-harvest structure	Harvest
Dipterocarps								
5–14	31.4	0.0	31.7	0.0	31.4	0.0	31.6	0.0
15–24	29.6	0.0	30.0	0.0	29.6	0.0	29.8	0.0
25–34	22.1	0.0	22.5	0.0	22.1	0.0	22.3	0.0
35–44	16.1	0.0	16.4	0.0	16.1	0.0	16.3	0.0
45–54	10.4	10.4	10.8	9.1	11.5	0.0	11.6	0.0
55–64	5.5	5.5	5.9	5.9	8.0	8.0	8.9	2.0
65+	2.0	2.0	2.5	2.5	4.9	4.9	8.1	8.1
Non-dipterocarps								
5–14	80.6	0.0	79.2	0.0	78.4	0.0	77.0	0.0
15–24	52.0	0.0	51.0	0.0	50.4	0.0	49.4	0.0
25–34	30.9	0.0	30.3	0.0	30.0	0.0	29.4	0.0
35–44	19.1	0.0	18.7	0.0	18.5	0.0	18.1	0.0
45–54	9.8	9.8	11.5	1.3	11.7	0.0	11.5	0.0
55–64	3.3	3.3	5.6	5.6	6.9	2.0	7.3	0.0
65+	0.7	0.7	2.1	2.1	4.0	4.0	9.2	1.0
Total Trees	313.7	31.7	318.2	26.4	323.5	18.8	330.5	11.1
NPV ($/ha)[b]		246.26		239.62		225.51		163.55
Cost ($/ha)[c]		0.0		6.70		20.70		83.30

Notes: [a] In parentheses is the tree diversity relative to the maximum sustainable diversity (=2.583).
[b] NPV given a 5% discount rate, $60/ha fixed cost, 30% residual damage and 30-y harvesting cycle.
[c] Opportunity cost of the diversity constraint, reflected by declining NPV's, when minimum diversity is set beyond 86%.

Summary and conclusions

A mathematical programming model is developed in this study to investigate the optimal management practices for an uneven-aged natural mixed forest in Indonesia. The data set belongs to an old-growth forest in South Kalimantan, Indonesia. The study analyses optimum uneven-aged management under the dual objectives of tree diversity and economic returns.

Three versions of the programming model are used to analyse three main cases. The first case involves maximising tree diversity, subject to forest sustainability and harvest-stock balance constraints. The second case maximises economic returns, subject to the same sustainability and harvest constraints given specified levels of residual damage, fixed costs, discount rate and cutting cycle. The third case is designed to maximise economic returns, under the constraints of tree diversity, sustainability and harvest limitations. The Shannon index is used to measure the tree size and species diversity.

Results from the first model indicate that the maximum sustainable level of diversity (2.583) is obtained when the forest reaches a fairly uniform tree (species and diameter class) distribution. The skillful use of silvicultural practices, which in this case involve harvesting in the largest diameter class only, is necessary to create and maintain an uneven-aged forest stand with the maximum sustainable level of tree diversity.

The second model solves the problem of maximising economic returns under different scenarios. It was observed that the optimum management strategies are very sensitive to three key parameters used in the economic harvesting model, namely the discount rate, fixed cost and residual damage. The discount rate has a major impact on the optimal harvesting cycle and economic returns. The results show that the higher the discount rate, the shorter the optimal harvesting cycle and the lower the NPV would be. For instance, the optimal cutting cycle is shortened from 20 to 15 y when the discount rate is increased from 5 to 7%, while the NPV decreases by approximately 40%. In general, the fixed cost does not have an impact on the optimal economic stocking or harvest, but high fixed cost values can affect the optimum cutting cycle. The objective function of model II can be specified differently, depending on the purpose of the management policy, and may or may not incorporate initial harvest returns as well as the value of the growing stock as investment cost. The empirical results show that optimum strategies can be dramatically different under each specification. Therefore, an accurate representation of the policy objective is crucial for determining the optimum stocking and harvesting schedules. The model is also used for an evaluation of the TPI regulations in terms of the economic and tree diversity objectives. The results show that the optimum steady state solution under TPI represents a compromise strategy where economic returns decline somewhat at the expense of improved tree diversity (particularly post-harvest diversity). The results also show that the 35-y cutting cycle that is currently in effect is longer than the optimum values under most of the parameter specifications considered in the analysis.

When economic and tree diversity considerations are considered simultaneously, the solution from the third model reveals the following: 1) for a 5% discount rate, \$60 fixed cost and 30% residual damage, the maximum NPV of \$246.26 ha^{-1} can be obtained when the tree diversity is as high as 86% of the maximum sustainable diversity level; 2) the maximum net present value is also attainable (i.e. remains constant) even at all lower levels of relative tree diversity; and 3) net present value decreases as relative tree diversity increases beyond 86%. These insights suggest that tree diversity and economic returns are compatible when tree diversity is below 86%; beyond this level, a trade-off occurs where an increase in diversity can be achieved only at the expense of some economic returns. Similar results were obtained with other combinations of the discount level, fixed cost and residual damage parameters.

These results have important management implications. First, the dual objectives of managing for diversity and economic returns can be pursued and achieved. Hence, it is possible to manage a forest where both tree diversity and economic objectives can be improved. Moreover, management regimes can be developed so that economic returns are maximised and at the same time an acceptable level of tree diversity can be achieved. For example, Table 4 displays the optimal stand structures and cutting strategies for alternative values of discount rate, fixed costs and residual damage. For each of the scenarios considered in Table 4, a different management regime that results in a pre-harvest structure with a lower tree diversity value than obtained from the model would not be desirable because the tree diversity can be increased to a higher level without incurring economic losses.

Given the results of the three models described above, some remarks on the TPI system can be deduced. First, in spite of its weaknesses, the TPI system seems to perform well in managing tropical rain forests in Indonesia. Second, the model results seem to support the TPI technical regulation that only trees with 50 cm in dbh and bigger should be harvested and that 25 trees ha^{-1} in those size classes should be left standing (as seeding agents) after harvest, for commercial species. In addition, requiring a high value of tree diversity leads to a reduction in the portion of trees in the largest diameter classes that are harvested. These results suggest that some of the technical regulations of TPI regarding harvesting strategies, residual stand and diameter limit should be reviewed if very high residual damage can be expected. Also, optimum harvesting strategies would require a shorter cutting cycle than 35 y required by TPI under all the residual damage levels considered here (which were less than 30%).

Fixed harvesting costs are determined by the organisation of forest property, the technology used, timber sale preparation, or moving machinery and personnel to a particular site. Even though the fixed cost of harvesting is not seen to be as important as the discount rate, large fixed cost values may lengthen the optimal harvesting and lower the forest's NPV.

In all aspects of forest management and conservation, failure to follow prescribed management regimes has been a common cause of unnecessary damage to the site, growing stock and regeneration. Often, little attention is paid to the residual stock during harvesting. This frequently leads to significant damage to residual trees, which are often abandoned and left to decompose. This study shows that damage to the residual trees will decrease the NPV, lengthen the cutting cycle and lower the tree diversity level and diameter classes to be harvested.

While the current forest management policies of the Indonesian Selective Cutting and Replanting System may be performing well, its implementation could be modified to enhance conservation goals. This can be done by incorporating ecological considerations, such as the inclusion of tree diversity as an objective along with economic and forest sustainability goals. Addressing tree diversity concerns is essential for achieving sustainable yield; besides, it also enhances habitat conservation of a forest containing enormously valuable tree species. In conclusion, this study has developed models that address the primary question stated at the outset. It is possible to practise forest management that maintains forest sustainability and achieves the dual objectives of tree diversity and economic returns.

References

BROOKE, A., KENDRICK, D. & MEERAUS, A. 1992. *GAMS: A User's Guide (Release 2.25).* The Scientific Press. 289 pp.

BUNTON, J. 1983. *Building Indonesia: A Market Survey.* Construction Press, London.

BUONGIORNO, J., DAHIR, S., LU, H. C. & LIN, C. 1994. Tree size diversity and economic returns in uneven-aged forest stands. *Forest Science* 40(1):83–103.

BUONGIORNO, J. & GILLES, J. K. 1987. *Forest Management and Economics.* McMillan Publishing Co., New York. 285 pp.

BUONGIORNO, J. & MITCHIE, B. 1980. A matrix model for uneven-aged forest management. *Forest Science* 26(4):609–625.

BUONGIORNO, J., PEYRON, J., HOULLIER, F. & BRUCIAMACCHIE, M. 1995. Growth and management of mixed-species, uneven-aged forests in the French Jura: implications for economic returns and tree diversity. *Forest Science* 41(3):397–429.

DIREKTORATE JENDERAL KEHUTANAN. 1972. Surat Keputusan Dirjen Kehutanan No.35/KPTS/DP/I/72 tentang tebang pilih, Indonesia, tebang habis dengan penanaman dan tebang habis dengan permudaan alam (Letter from the Directorate of Forestry No. 35/KPTS/DP/I/72 about Indonesian selective logging and clearcutting with artificial and natural regeneration, in Indonesian). Jakarta.

EK, A. R. 1974. Nonlinear models for stand table projection in northern hardwood stands. *Canadian Journal of Forest Research* 4:23–27.

INGRAM, C. D. & BUONGIORNO, J. 1996. Income and diversity tradeoffs from management of mixed lowland dipterocarps in Malaysia. *Journal of Tropical Forest Science* 9(2):242–270.

MENDOZA, G. A. & SETYARSO, A. 1986. A transition matrix forest growth model for evaluating alternative harvesting schemes in Indonesia. *Forest Ecology and Management* 15:219–228.

ÖNAL, H. 1997. Trade-off between structural diversity and economic objectives in forest management. *American Journal of Agricultural Economics* 79:1001–1012.

SETYARSO, A. 1984. Development of Stand Growth Model and Alternative Harvesting Schemes in Indonesia. MS. thesis, University of the Philippines at Los Baños. 88 pp.

SIANTURI, A. 1990. An Optimal Harvesting Model to Evaluate the Indonesian Selective Logging System for Secondary Dipterocarp Forests. Ph.D. thesis, University of Washington, Seattle. 155 pp.

SOETJIPTO, W. 1995. Structural Diversity and Economic Returns of a Managed Forest in Kalimantan, Indonesia. MS. thesis, University of Illinois at Urbana-Champaign. 99 pp.