ARE TROPICAL RAIN FORESTS NON-RENEWABLE? AN ENQUIRY THROUGH MODELLING

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APPANAH, S., WEINLAND, G., BOSSEL, H. & KRIEGER, H. 1990. Are tropical rain forests non-renewable? An enquiry through modelling. Much controversy surrounds the management of tropical rain forests, and arguments that they are non-renewable are gaining currency. The solutions to such arguments lie in studying the long term changes and recovery of forests following specific silvicultural regimes. Such forest areas in the tropics have all vanished. An alternative and easier approach is by modelling. A mechanistic-process model was developed based on the five development stages of trees (seedling, sapling, pole and understorey layer, main canopy layer, and emergent tree), and the individual photosynthetic production at each layer. The simulations were validated satisfactorily with the stand characteristics found in nature.

Following the validation, the model was used to assess two silvicultural systems, the Malayan Uniform System (a tropical shelterwood system) and the Selective Management System (a selective felling), that have been used for managing the dipterocarp forests in Malaysia. The model's results, even with cautious acceptance, have several important implications to forest management practices. Dipterocarp forests are renewable, but only long rotations (*ca.* 100 years) are in step with the dynamics of the forest. This is because the recruitment process is very slow. More significantly, the model showed that the pole regeneration is ephemeral in time and space, implying that cutting dipterocarp forests when the poles are few or absent would endanger the timber sustainability of such forests.

Key words: Dipterocarp forests - management - non-renewable - mechanistic model - natural frequency - regeneration - poles

Introduction

That the tropical rain forests are non-renewable and should not be logged is being imputed by some workers. This, despite us managing the tropical rain forests for timber from the beginning of this century, should come as a surprise. But it is not. Today, nowhere in the wet tropics exists a forest management system that guarantees sustainability (see Wyatt-Smith 1987, Dawkins 1988).

Our failure to develop successful management systems for the multispecies forests of the wet tropics is caused by many problems, one of it being scientific. In the application of management systems, we have no methods to ascertain early on whether the management system being introduced is the appropriate one, since we cannot predict the response of forests in the long term to different management practices. As a result, we are easily persuaded towards management systems that are based on short term economic gain than sustainability.

Long term changes of forest to different management practices could be observed from old plots. But the tide of population growth and socio-economic changes in the tropics removed much of the forests, including many of the old research plots. Also a victim to the rapid change in forest policy was research and planning of the past. It could not be used any longer.

The above problems faced by foresters in the wet tropics can be clearly highlighted by the case for forest management in Peninsular Malaysia. In the 1960s the Malayan Uniform System (MUS) was developed for managing the lowland dipterocarp forests (Wyatt-Smith 1963). This can be regarded as a major development in the silviculture of tropical moist forests. However, its effectiveness was never tested. Before the MUS managed forest s underwent one rotation, the majority of the lowland dipterocarp forests were alienated for other land uses, and management was shifted to the hills.

Unfortunately, foresters were totally unprepared to manage hill dipterocarp forests when this sudden shift took place in the early 1970s. Very little information on management of hill dipterocarp forests was known at that stage (Burgess 1968). Nevertheless, the Selective Management System (SMS) was introduced to the hill dipterocarp forests of Peninsular Malaysia. The SMS is viewed both with optimism (Thang 1987, Anonymous 1989) and scepticism (Walton 1954, Fox 1967, Wyatt-Smith 1987, 1988). The optimists believe that under the SMS, output of timber can be sustained at about 35 year intervals and that the reproductive capacity of the forest is not diminished following logging. The sceptics argue that the SMS as it is practiced now is not feasible: it ignores stand quality, topography, logging methods, and quality of management. The theoretical basis of management cannot be ascertained, and doubts linger over its suitability.

Second, long term changes and recovery of forests, essential for validating management systems in both MUS and SMS, are lacking. The forests managed under MUS have mostly gone. Even research plots to monitor long term changes following SMS have little value. The virgin forests are logged before results become available. What may be more useful in this context is the problem of management of logged hill dipterocarp forests.

Therefore, methods by which we can rapidly ascertain the suitability of a management system and predict the long term changes resulting from the treatments would be very desirable. The results of such forecasts can be immediately implemented in practice, the forecasts can be validated and management can be progressively fine tuned. A management system based on sound theory has a better chance of success if properly implemented.

The above constraints can be overcome, partially, by using models. Currently, two types of models are in use. They are the empirical-predictive models and the mechanistic-process models. The former require large data sets, state or estimate "what has occurred, is occurring and may occur in the future, to provide yield predictions for planning and management" (Adlard *et al.* 1988). The latter, the mechanistic-process models, simulate interactions of growth processes. Growth of trees is formulated as a result of these interacting processes. They "explain how the system works and lead to an understanding of why it behaves in a particular manner to create a better understanding of the system modelled" (Landsberg & Parsons 1985: as in Adlard *et al.* 1988).

Some researchers (*e.g.* Adlard *et al.* 1988) have concluded that with regards to tropical forests, empirical models must remain the area of concern in the near future, and are sceptical of the value of mechanistic models. However, we regard that both models serve different objectives, and both should be examined, so they can complement each other. The process model is built on system concepts and physiological processes and is based on natural processes. The statistical model is built on data sets, from measurements of nature's growth processes. While the former tries to simulate nature's growth processes, the latter measures the results. The latter can be used to validate the former.

Development of a new mechanistic model

Through a collaborative project between the Forest Research Institute Malaysia and the University of Kassel, West Germany, a mechanistic model is being developed (H. Bossel & H. Krieger unpublished). While it is still in its infancy, it is robust enough to address known forest management concepts. In this paper we examine some issues concerning recovery of dipterocarp forests following different management regimes using the model. Only some aspects of the theoretical background of the model are given here; more details on the model will be published elsewhere (Bossel & Krieger 1990).

The model

At the heart of the canopy model used for the simulation of the long term dynamics of natural forest development is a description of the eco-physiological processes of energy assimilation, dissimilation and storage in the different tree layers making up the forest canopy. The model is based on the physical principles of energy and mass conservation. This approach automatically avoids serious errors which are possible in descriptive approaches (such as growth table models). The major difference setting this model apart from other forest models is the fact that it does not use any time-dependent formulations of growth [as in growth table models, or FORET-type gap models (Shugart 1984)], but that forest dynamics (and hence timepaths) are generated entirely endogenously by modelling real eco-physiological processes by their rates of change in terms of differential equations. The model is in the tradition of the plant-physiological models of the Wageningen school, which have been applied very successfully in agricultural production for almost two decades (Penning de Vries 1983).

The parametrization of the model is largely based on data for Pasoh forest, Peninsular Malaysia (Kira 1978). Energy flows are determined in terms of CO_2 assimilated, or their dry organic matter equivalent.

In the model, the total number of trees and their total (wood) biomass is disaggregated into five classes representing five more or less distinct canopy layers also corresponding to five more or less distinct development stages of emergent trees: seedlings, saplings, poles, main canopy trees, and emergent trees (Figure 1). Each canopy layer is characterised by a unique relative position with respect to the other layers; this position determines the amount of light received. Each canopy layer may have several leaf layers. The total number of leaf layers is the leaf area index of the forest.

The light attenuation within the forest canopy is approximated by the Monsi-Saeki formulation of the Lambert-Beer law of exponential light attenuation. This determines the incident radiation for each leaf layer as a function of the radiation above the canopy.

$$I = I_o \times \exp(-k \times l),$$

where I is the radiation at a certain level in the canopy, I_o is the radiation above the canopy, k the light attenuation parameter, and l the cumulative leaf area index between the canopy surface and the height level considered.

The light reponse curve of leaves is approximated by a Michaelis-Menton formulation. It provides the gross photoproduction rate as a function of the incident radiation.

$$p = m \times I/[1 + (m/p_{max}) \times I]$$

where p_{max} is the light response (maximum production) at light saturation and m is the initial production increase with increasing radiation (slope). The parameters m and p_{max} are determined by fitting experimental data. The parameters are species-dependent and differ in particular for shade tolerant and light seeking species (pioneers). For most tropical trees, the light response is characterised by a maximum net production at light saturation of 10 to 15 *mg* CO_2 /(diam.^{2} × height) (Kira 1978).

Inserting the expression for the light I received by each leaf layer into the equation for the leaf photoproduction p, and integrating formally over all leaf layers, provides an expression for the total photoproduction rate P of each canopy layer at each point of time as a function of the light received

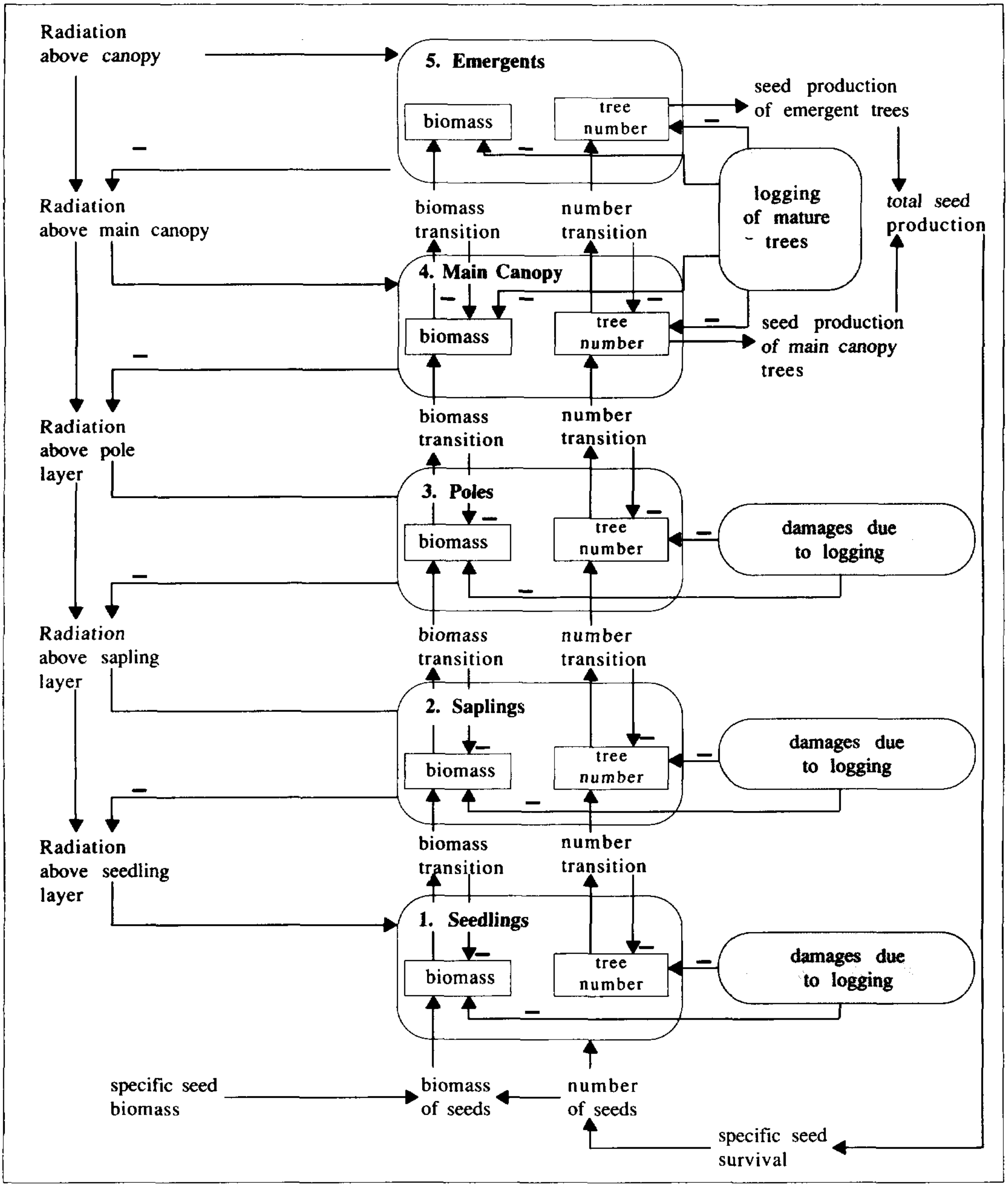


Figure 1. Influence diagram for the system modules contained in the FORMIX forest dynamics model (seedling, sapling, pole, main canopy, and emergent layer)

(with its diurnal and seasonal variation) (Kira 1978).

$$P = (p_{max}/k) \times \ln[(1+(m/p_{max}) \times I_o)/(1+(m/p_{max}) \times I_o \times \exp(-k \times LAI_t)].$$

Hence the incident solar radiation I_o, the light extinction coefficient k, the parameters of the light response curve (m and p_{max}), and the total leaf area index LAI_t of the forest canopy determine the total photoproduction in the canopy. The daily production is determined by time integration over all daytime hours; the annual production follows from an integration over all daytime hours of the year.

Over a given time period (*i.e.* year), the assimilated energy must balance exactly the energy lost to respiration, litter losses, and biomass increment. The respiration and litter losses can be grouped in two categories: a certain amount is proportional to leaf photoproduction and hence leaf area, and the remainder is (roughly) proportional to the current amount of total (wood) biomass. The following energy losses are (approximately) proportional to leaf area: leaf respiration (maintenance and photorespiration); respiration, renewal, and litter; small branch and small root respiration, renewal and litter; and fruit production. The remaining losses are (approximately) proportional to total tree biomass: stem respiration and litter; coarse branch respiration and litter; and coarse root respiration and litter.

In the model, each part of the forest corresponding to one of the canopy layers is represented by two state variables: biomass and tree number. This allows the calculation at any time of quantities important in forest management: biomass per tree, volume, diameter, height, basal area, crown area, leaf area *et cetera,* using well known parameters such as wood density, form factor, height-to-diameter ratio, crown-to-diameter ratio, and leaf area index.

Any energy surplus goes into biomass increment. On the other hand, trees die in each layer due to normal mortality, or due to higher crowding mortality. Furthermore, if there is sufficient increment in a layer, trees will eventually grow in height until they reach into the next higher layer - with different light and hence growth conditions. In both cases - mortality and transition - tree numbers and tree biomass in a layer must be reduced by the correct amounts, while in the case of transition to the next canopy layer, the tree number and biomass of the receiving canopy layer must be increased accordingly.

The dynamic model consists of a total of ten ordinary differential equations describing the rate of change of tree number and tree biomass in each of the five canopy layers. Each canopy layer is represented by two differential equations describing the temporal development of wood biomass and stem number in that particular layer,

$$dN_i / dt = TN_{i-1} - TN_i - M_i, \text{ and}$$

$$dB_i / dt = PB_i + TB_{i-1} - TB_i - R_i - MB_i.$$

Tree numbers N_i are calculated by integrating the transition rates TN_{i-1} and TN_i representing trees growing into this class from a lower stratum and leaving the class to the next canopy layer, and accounting for density-dependent tree mortality M_i. The transitions will be activated if the diameter of trees within a particular class exceeds a given threshold value. Additionally, the N_i may be influenced by the density-dependent mortality rate M_i.

Biomass B_i increases at the rate of biomass production by photosynthesis PB_i, where PB_i is the net assimilate production after accounting for leaf-proportional respiration, construction, and renewal losses. The biomass transfer TB_{i-1} is caused by ingrowth from the next lower level and can be derived directly from TN_{i-1}. Biomass is transferred to the canopy layer i+1 at the rate TB_i proportional to TN_i. Biomass losses occur due to biomass-proportional respiration and deadwood losses R_i (respiration demands for maintaining stems, branches, coarse roots; losses of dead branches and coarse roots). Again, B_i may be influenced by a density-dependent mortality rate MB_i derived from M_i.

For simulating natural forest development, the differential equations are integrated numerically over the time period of interest, starting from initial conditions specifying tree numbers and biomass in each canopy layer. Scenarios for seeding, thinning, cutting, and logging damage are introduced by specifying corresponding changes in the relevant state variables for specific points in time.

Results of simulating natural forest

The simulation results were compared for validation with natural forests for the following features:

Stand curve

The stand curve represents stem numbers in diameter classes. The model produced a stand curve typical for undisturbed natural forests, an inversed J-shaped curve (Figure 2). This neatly duplicates what is usually found in

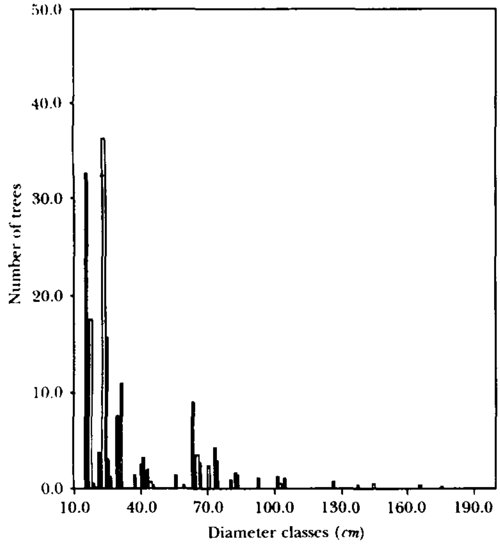


Figure 2. A FORMIX stand curve from a simulation for 500 years

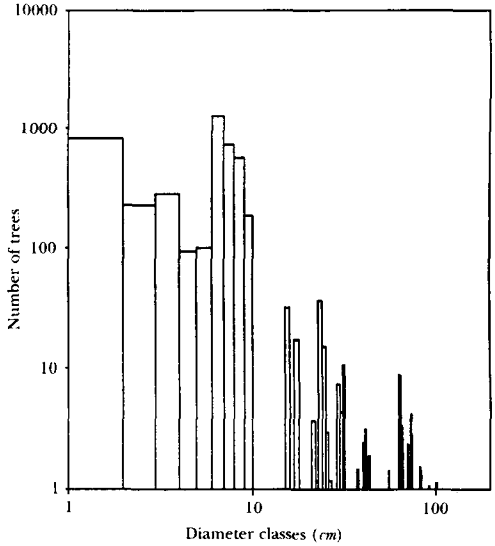


Figure 3. A FORMIX stand curve in double logarithmic scale from a simulation for 500 years

natural forest stands. When represented in a double logarithmic scale, the stand curve is a straight line with negative gradient (Figure 3). This is just as in natural situations too.

Usually, a semi-logarithmic curve is used to linearise the stand curve. However, in this case, a double logarithmic curve was needed for the best fit.

The normal stand curve of a selection stand corresponds to a declining geometric series (described by F. de Liocourt 1898 in: Assmann 1970):

$A;\ Aq^1;\ Aq^2 \ldots Aq^{n-1}.$

This stand curve can be fitted by an exponential function (Prodan 1965)

$N = Ke^{-\alpha d}.$

This function can be transformed into a linear relationship using a semi-logarithmic scale. In our case, instead the function

$N = ad^{-m}$

was used. This gave a good fit ($r = 0.977$). Therefore validation of the stand curve was done using this relationship (Figure 3). The problem was examined further using natural stands in Pasoh forest. Three randomly

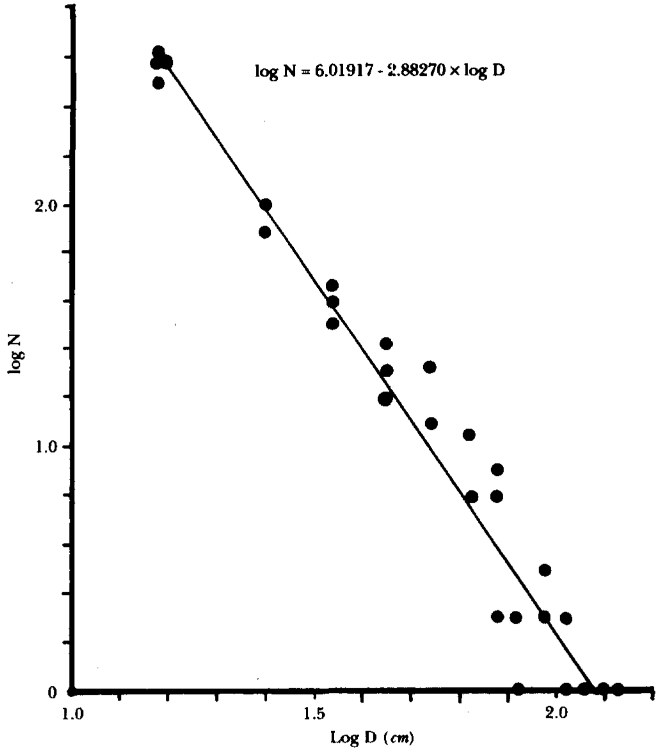


Figure 4. Relationship of stem number over diameter classes in double logarithmic scale (The relationship was derived from a lowland dipterocarp forest in Pasoh Reserve, Peninsular Malaysia; the data were from 1 *ha* each of plots 1, 4 and 7; the stems are 10 *cm* dbh and above)

selected 1-*ha* plots were fitted for semi-logarithmic and double logarithmic curves. The fitting was best in the latter case (Figure 4). Hence, the model produced a stand curve that duplicated stands of undisturbed tropical forests.

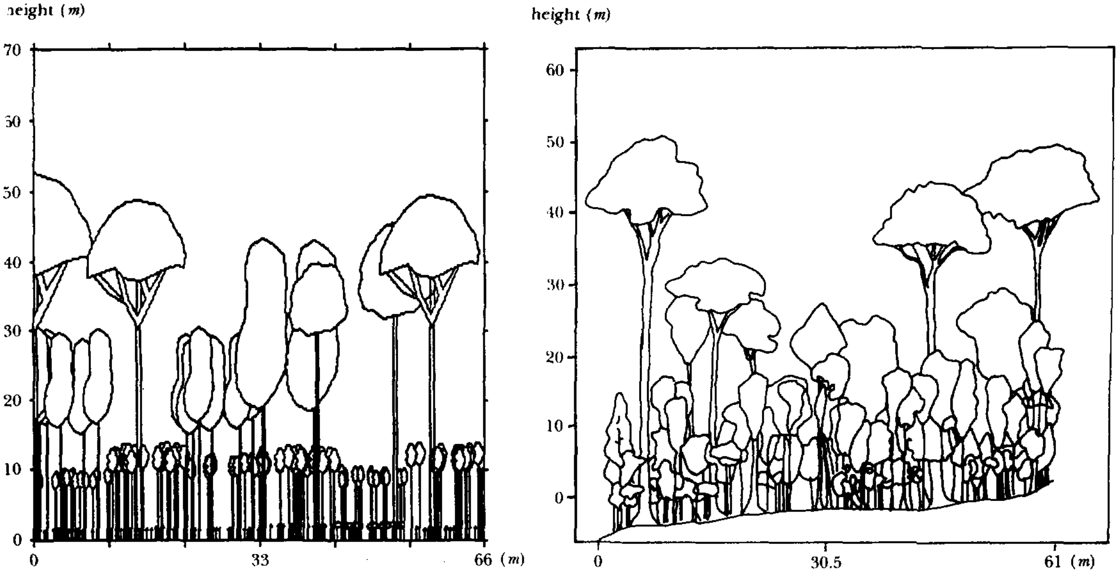
The above relationship suggests a probable difference between managed selection stands and undisturbed natural forests. Whereas the managed selection stands give straight lines for stand curves on semi-logarithmic scale this does not always hold for undisturbed natural stands (*e.g.* Loetsch *et al.* 1973, p. 63). This difference could be due to the shortage of stems of medium size in undisturbed natural forests.

Basal area

The simulated final basal area of a fully developed stand varied from 30 to 42 $m^2\ ha^{-1}$. This too accords well with results found in natural stands. For example, Pasoh forest has 36.87 $m^2\ ha^{-1}$, excluding trees below 9.5 *cm* dbh (Plot 4; subplots 1-25).

Stand profile

The height of the emergents was approximately 50 *m*, and the main canopy between 30 to 40 *m*. The understorey layer was around 10 *m*. These



(a) (b)

Figure 5. a). A FORMIX simulation of a stand profile composed of six cells of 8 × 11 *m* each in an artificial stand at the age of 210 years, the profile covers 66 × 8 *m*. **b)**. A stand profile of Kuala Belalong Forest, Brunei (Along Ridge, 550 *m* a.s.l.; trees exceeding 4.6 *m* only included); profile covers 61.0 × 7.6 *m* (Adapted from Ashton 1964)

heights are within the profiles of most dipterocarp forests. The simulation output of the stand profile (Figure 5a) compares favourably with one from a natural stand (Figure 5b).

Stand density

The density of the stand was as follows:

	Model	Pasoh
Seedlings (up to 1.3 *m*)	873	-
Saplings (1 - 10 *cm* dbh)	2706	-
Poles (10 - 25 *cm* dbh)	324	360
Main canopy (25 - 45 *cm* dbh)	38	86
Emergents (>45 *cm* dbh)	21	49

From the above table, it is obvious that a forest like Pasoh has more main canopy and emergents (*ca.* 2×) than given by the model. This would be due to a higher mortality in the model than in nature (Table 1). Another explanation could be that a portion of the basal area in undisturbed natural forests is composed of a large number of smaller trees belonging to non-dipterocarp families.

Table 1. Specific mortality rates introduced to the different canopy layers for uncrowded conditions (figures given as percentages of actual tree numbers per year, estimated)

	% y^{1}
Seedlings	10.0
Saplings	5.0
Poles	1.0
Main canopy	0.8
Emergent	0.5

Mortality rates

Figures for mortality in natural forest stands are needed to calibrate the model. Mortality data are needed under both normal and crowded conditions depending on the degree of crown closure. However, the parameters characterising the mortality due to crowding are less critical: they merely control the speed of release from crowding pressure and are replaced by the normal mortality rates (*cf.* Table 1) as soon as optimal conditions are reached again.

Biomass

The biomass varied between 400 to 510 $t\ ha^{1}$ oven dry weight. This value is comparable to that obtained for dipterocarp forests. For example, Pasoh has 475 $t\ ha^{1}$ (>4.5 *cm* dbh). This is for a forest having 35 - 40 *m* mean canopy height; that in the model is 42 *m*. Note that in the model, the biomass is contained in fewer trees than in Pasoh forest.

The heights, diameter, and crown to stem diameter ratios are within observable limits. Reasons for the excess biomass needs further investigation. Overall, the biomass fluctuated over time within a range of 400 - 500 $t\ ha^{-1}$; this occurred over a period of 400 years though. Thus, on an annual basis, the fluctuation was small.

In the first instance, applying the model to forests logged under different management regimes means simulating the dynamics of the vegetation within a single gap and interpreting the results on a hectare basis. In fact, this is a very crude simplification and the model has to be extended to represent a grid of different interacting gap-like cells of 100 - 400 m^2 in order to test the influence of the dynamics of the single-gap model on the overall behaviour of the modelled stand.

Further validation required

This model, surprisingly requires relatively simple measurements to validate it further. These are:

a) Mortality patterns for the different guilds or physiognomic groups (not a critical parameter);
b) Transition rates in each of the storeys and for all physiognomic groups (not a critical parameter);
c) Light response curves and other photosynthetic parameters for the different physiognomic groups;
d) Light extinction and light attenuation for the different canopy layers;
e) Crown projection areas and vertical profiles;
f) Crown-to-stem diameter ratios for the different layers;
g) h-d-ratios, form factors, and stem volumes;
h) Damage patterns for the different canopy layers;
i) Seed production, seed predation, seed dispersal, specific weight of seeds; and
j) Structure of the natural forest (physiognomic groups and height layering, stem diameters, species composition, commercial and non-commercial species).

Results of simulating logging

According to the Malayan Uniform System (MUS)

According to the MUS, logging operations require removal of all main canopy and emergent trees on a rotation of about 70 years (Wyatt-Smith 1963). The model was used to assess several such rotations. The simulations revealed that a 70 year rotation is not optimal (Figure 6). From the simulations, it is evident that the biomass composition at each rotation is quite different. Assuming a stemwood-to-total wood ratio of 0.7 (70% stemwood, 30% branches and coarse roots), the potential harvest (mainly consisting

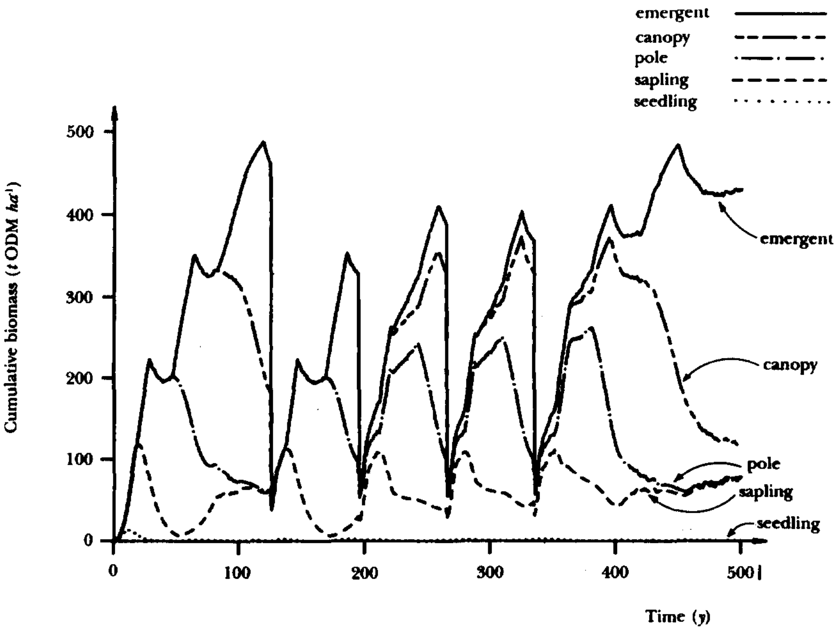


Figure 6. A FORMIX simulation of a forest stand's cumulative biomass under a Malayan Uniform System (MUS) 70-y logging rotation, the first logging was after a simulation of 125 years (Key to vegetation layers apply to rest of figures)

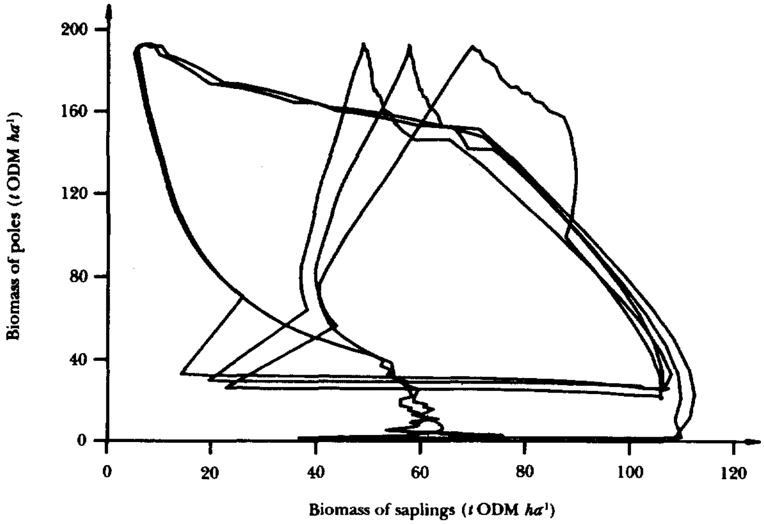


Figure 7. A FORMIX simulation showing a phase diagram of biomass of poles over biomass saplings of a forest stand managed under a MUS 70-y logging rotation (The trajectory represents the development of the biomass of poles over biomass of saplings in time; when all the phases overlap, the biomass development of the poles and saplings follows a stable cyclic behaviour; when the phases are not overlapping, as above, the development is not repeating itself in a regular pattern)

of main canopy trees) amounts to 160, 177 and 185 *t ha*^{1} of stemwood biomass at the second, third, and fourth cut, respectively. The lack of cyclicity is also shown in the phase plot of biomass of poles *versus* biomass of saplings which has an irregular trajectory (Figure 7).

With the MUS 100 year rotation, the cycle repeats itself after every logging (Figure 8). The phase plot for saplings has a regular trajectory too (Figure 9). This indicates that the 100 year rotation is in step with a

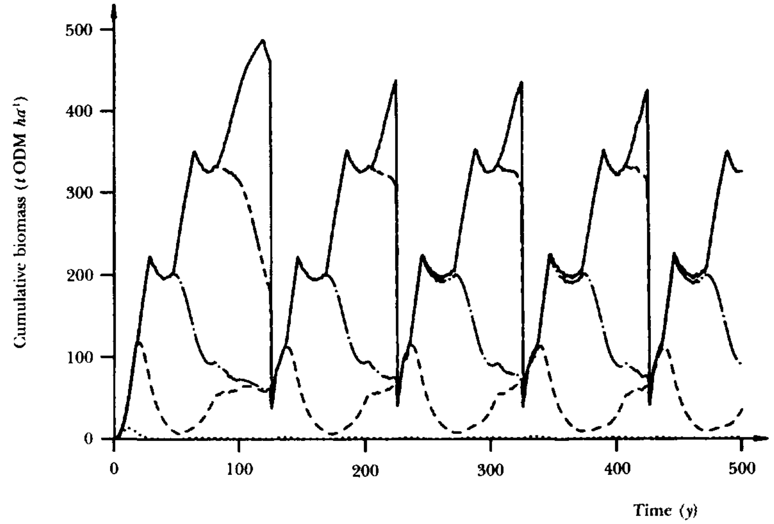


Figure 8. A FORMIX simulation of a forest stand's cumulative biomass under a MUS 100-*y* logging cycle (The first logging was after a simulation of 125 years)

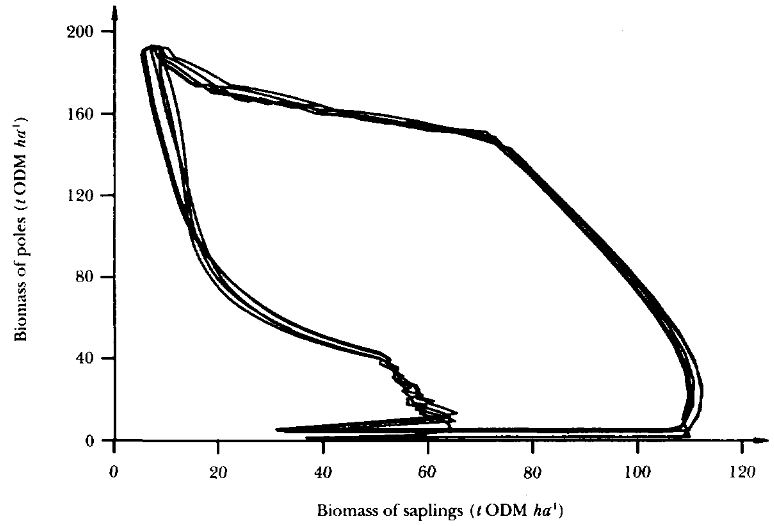


Figure 9. A FORMIX simulation showing a phase diagram of biomass of poles over biomass of saplings of a forest stand managed under a MUS 100-y logging cycle

'natural dynamics' (eigendynamics) of the forest. The potential harvest at each logging consists almost exclusively of main canopy trees (with exception of the first cut at 125 years growth). The total stem biomass is expected to be around 253 *t ha*^{1} for each logging.

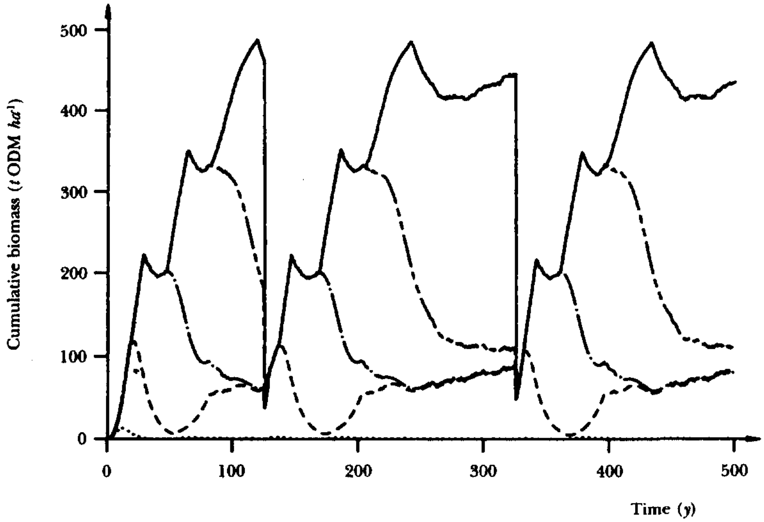


Figure 10. A FORMIX simulation of a forest stand's cumulative biomass under a MUS 200-y logging cycle (the first logging was after a simulation of 125 years)

For the 200 year MUS rotation (Figure 10), the natural cycle is maintained as well. It also produces a harvest with a very high fraction of emergents; stem biomass again is expected to be about 253 *t ha*^{1}.

According to the Selective Management System (SMS)

The SMS is based on a cutting cycle of approximately 35 years. All emergent and main canopy trees above 45 *cm* dbh are removed in the case of non-dipterocarps and above 60 *cm* dbh in the case of dipterocarps. A minimum number of residuals, which amount to 32 trees *ha*^{1} of between 30 to 45 *cm* dbh, are left behind. These will then form the harvest at the next cut 35 years later. Meanwhile, the poles will grow into the main canopy by the second cut.

Two SMS logging scenarios were simulated, one was for 35 years and another for 100 years. The biomass developments for the SMS 35 years and SMS 100 years are shown in Figures 11 and 12. Figure 13 reproduces the phase plot for poles over saplings for SMS 100 years. This approach obviously produces neither a uniform timber assortment, nor a reliable and uniform harvest volume. This can only be because the cutting cycles are completely out of phase with the forest's 'natural dynamics'. For the SMS 35 year cutting cycle, the logging results in continuous reduction in harvest of emergents after every successive cutting. In the SMS 100 year cutting regime, repetition of the results are shown every 200 years, that is at every second logging, and substantial volume of emergents (approximately 230 *t ha*^{1}) can be obtained in such alternate cuts. At the first, third, fifth *et cetera* cutting intervals, emergents represent only about one-third of the timber harvested.

When the SMS 200 year cutting cycle was simulated (Figure 14) this corresponded with biomass development in a 200 year MUS rotation. Note that in the MUS 100 rotation, the successive biomass contribution from emergents is declining but is not so in the case for MUS 200. This pattern

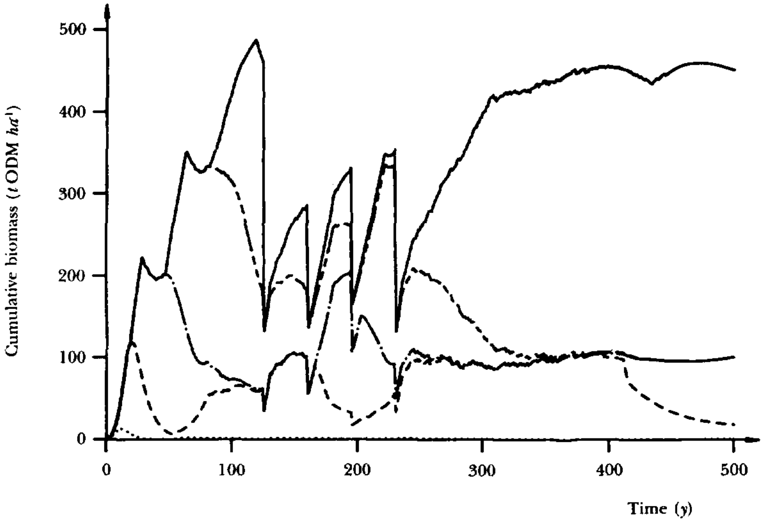


Figure 11. A FORMIX simulation of a forest stand's cumulative biomass under a Selective Management System (SMS) 35-y logging cycle (The first logging was after a simulation of 125 years, after four such loggings, the forest was left to grow)

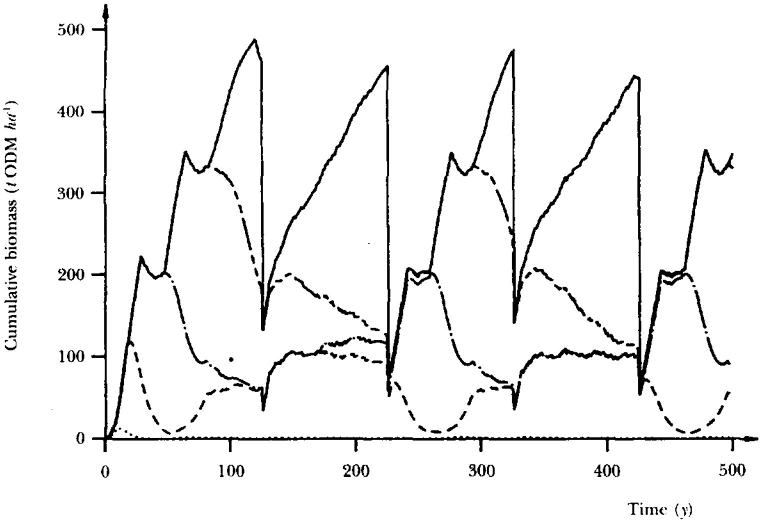


Figure 12. A FORMIX simulation of a forest stand's cumulative biomass under a SMS 100-y logging cycle (The first logging was after a simulation of 125 years)

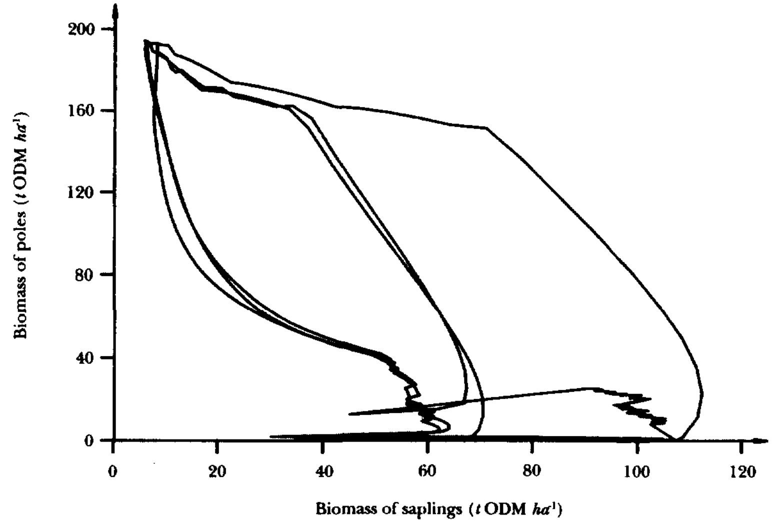


Figure 13. A FORMIX simulation showing a phase diagram of biomass of poles over a biomass of saplings of a forest stand managed under a SMS 100-*y* logging cycle

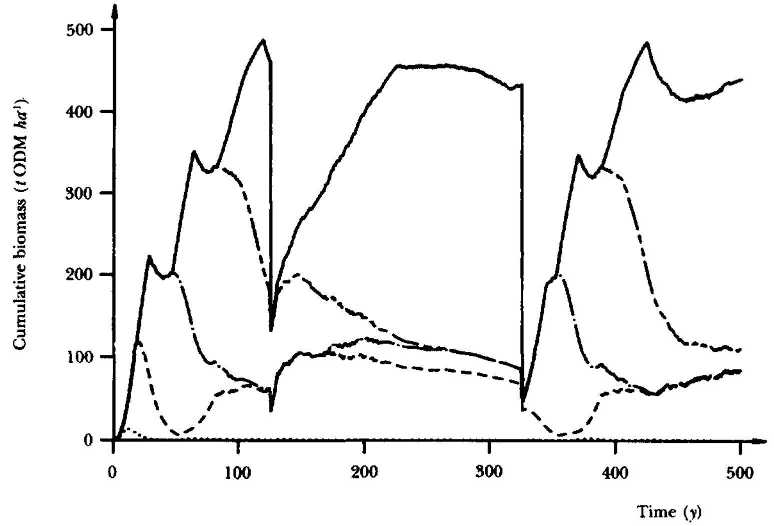


Figure 14. A FORMIX simulation of a forest stand's cumulative biomass under a SMS 200-*y* logging cycle (The first logging was after a simulation of 125 years)

more or less exhibits itself in the SMS 200 too. This means that a period of at least 200 years is required for the biomass to reestablish itself in the right proportions.

Conclusions

The results from these simulations should be interpreted with caution since the model is still in an early stage of development. According to the model, tropical forests such as the dipterocarp forests of the Far East are renewable, and can be managed, but only with long cutting cycles. Contrary to expectations of the SMS (a short cutting cycle concept), the recruitment process in the dipterocarp forest is too slow. Another critical point stands out clearly - in all simulations the pole regeneration is ephemeral in time and space. There is a clear danger in this: if cutting comes into a place at a time when the poles are small in number or absent, then no residual stand will develop for the third cut. That this may often be the case is supported by field observations (S. Appanah & G. Weinland personal observations).

From this exercise in modelling, it is clear that this development stage growth model has many advantages:

(a) It provides a holistic view of stand dynamics, based on patch units of a forest in various stages of growth cycle;
(b) It tests the long-term response of the forest to silvicultural and logging impacts; and
(c) Its validation helps researchers to focus on the essential parameters and to ignore less significant issues. It saves time, effort and energy. As such, research can be pursued with clearer directions.

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