Rain Forest Ecology

Rain Forest Growth Model FORMIX3: A Tool for Forest Management Planning Towards Sustainability

Model Development and Case Study for *Deramakot Forest Reserve* in Sabah, Malaysia

Tropenökologisches
Begleitprogramm (TÖB)

Deutsche Gesellschaft für
Technische Zusammenarbeit (GTZ) GmbH

Rain Forest Ecology

Rain Forest Growth Model FORMIX3: A Tool for Forest Management Planning Towards Sustainability

Model Development and Case Study for *Deramakot Forest Reserve* in Sabah, Malaysia

Andreas Huth
Thomas Ditzer
Hartmut Bossel

Eschborn 1997

TÖB-Seriennummer: TÖB ??

Herausgeber:	Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH Postfach 5180 D-65726 Eschborn
Verantwortlich:	Tropenökologisches Begleitprogramm (TÖB) Dr. Günter Riethmacher
Autoren:	Dr. Andreas Huth, Thomas Ditzer, Prof. Dr. Hartmut Bossel Center for Environmental Systems Research University of Kassel Kurt-Wolters-Str. 3 D-34109 Kassel
Lektorat:	Uwe Setje-Eilers (AGEG e.G.)
Redaktion:	Richard Haep

Table of contents

Appendix

List of Figures

Glossary

AAC	Annual Allowable Cut
a.s.l.	above sea level
cutting cycle	the period between two subsequent logging operations
DFR	Deramakot Forest Reserve
irradiance	amount of solar radiation (in terms of energy flux density) reaching a unit of horizontal area
ITTO	International Tropical Timber Organization
Long Distance Cable Crane System	an air-borne yarding equipment
PFE	Permanent Forest Estates
PSP	Permanent Sample Plot
photoproduction	gross amount of biomass produced by green plants in terms of organic dry mass accumulated by the leaves
respiration	amount of energy consumed by plants to maintain its life processes in terms of organic dry mass consumed
RIL	Reduced Impact Logging

Summary

The degradation and loss of tropical rain forests is one of the world´s most prominent environmental concerns. Considering the adverse impacts of deforestation, the development of appropriate concepts for the sustainable management of tropical forests is of tremendous importance. In order to elaborate sustainable forest management strategies the long-term impact of logging operations on the forest structure has to be known. The complexity of tropical forest ecosystems renders experimental approaches to study these long-term impacts extremely difficult. In this context, growth models are a useful forest management planning tool. The long-term impact of different harvesting strategies can be analysed and assessed for sustainability by simulating a variety of logging scenarios. In this way, data derived from growth modelling support the decision-making regarding an enhanced yield regulation and thus directly contribute to the development of sustainable forest management practices.

The most important growth model types are explained and related to the approach used by FORMIX3. FORMIX3, which synthesises the state-of-the art knowledge on forest growth, was developed to simulate the growth dynamics of lowland Dipterocarp rain forest in Sabah, Malaysia. The model can be divided into several components: species grouping, spatial structure, tree growth, competition, regeneration and mortality. The growth of the individual tree is based on a carbon balance, which includes photoproduction of the tree on the one hand and biomass losses on the other hand. The FORMIX3 model was extensively tested. The results of the test runs indicate

that the model produces realistic results and adequately reflects the growth behaviour of lowland Dipterocarp forests.

The growth simulations focused on eight typical stands representing different structural types of natural Dipterocarp forest, all of them located in the Deramakot Forest Reserve, Sabah: three stands of primary forest and five stands of more or less seriously disturbed secondary forest. The analysis of the simulation results shows that the model correctly simulates the growth of the investigated stands. The complete recovery of secondary stands takes at least 150 years, sometimes even much more depending on the degree of damage caused by the harvesting operations.

The impact of two different logging methods is analysed: conventional logging with high damages and reduced impact logging with low damages. Different cutting cycles of 20 to 100 years are simulated. For the comparison of the simulated logging scenarios, four indicators are used to assess their long-term sustainability: (i) total logged volume, (ii) logged volume per cut, (iii) species composition and (iv) opening of the forest canopy. The model output indicates that short logging cycles < 40 years have negative impacts on the forest stands, even if reduced impact logging methods are applied. Only long cutting cycles of 80 and 100 years in combination with careful logging methods ensure that the main characteristics of stand structure can be maintained. A logging cycle of 60 years seems to be an acceptable compromise between economic and ecological interests. This cycle produces higher harvestable volumes than short cycles, while causing comparatively low impacts on species composition and soil.

To extend the model´s range of application, additional refinements of FORMIX3 are recommended. The future development of the model should focus on the following topics: logging damages, site quality, regeneration, species composition and biodiversity. Most of these aspects are already reflected by the model, however, some of them in a rather simple way. It is important to keep in mind that models are always simplifications of reality and therefore have a specific range of application. In combination with professional judgement the FORMIX3 model can support sustainable forest management planning.

1 Introduction

1.1 Growth models in the context of sustainable forest management

The degradation and loss of tropical rain forests is one of the world´s most prominent environmental concerns (German Bundestag 1990). Considering the adverse impacts of deforestation, the development of appropriate concepts for the sustainable management of tropical forests is of tremendous importance. One of the main causes for the rapid depletion of the natural forest resources is the insufficient yield regulation as current forest policies often seem to overestimate the rate of forest growth. The cutting cycles are too short and do not allow an adequate regeneration of the logged-over forests. As a result, the timber harvesting is not sustainable and the resource is exploited.

In this context, growth models are a useful forest management planning tool. They serve to improve the yield prediction by providing reliable estimates of forest growth and yield. Besides, the long-term impact of different harvesting strategies can be analysed and assessed for sustainability by simulating a variety of logging scenarios. Based on the growth forecasts and harvesting simulations the sustainable annual allowable cut (AAC) can be calculated more precisely. In this way, data derived from growth modelling support the decision-making regarding an enhanced yield regulation and therefore directly contribute to the development of sustainable forest management practices.

1.2 Overview on common growth model types

For the elaboration of sustainable forest management strategies the long-term impact of logging operations on the tree population structure has to be known. The complexity of tropical forest ecosystems renders experimental approaches to study these long-term impacts extremely difficult. The main problems can be summarised as follows:

1. Tropical forests are characterised by a high species diversity and complex vertical and horizontal structures, usually stocking on a wide range of different site conditions.

2. The lifetime of many species is very long, typically some hundred years, and tree age is usually unknown.

3. There is a lack of long-term field data, usually derived from observations of Permanent Sample Plots (PSPs).

Despite these constraints, different modelling approaches have been developed in recent years, although the number of available models for tropical forests is still rather small compared to the existing models simulating the growth of temperate forests. In the following, the most important modelling concepts used for yield forecasts of tropical forests are briefly reviewed.

Stand table projection models

Stand table models represent the classical approach to project the development of uneven-aged forest stands. This traditional method describes the structure of a forest stand by a stem number - diameter distribution, called ´stand table`. The future stand composition is predicted from the current stand table by applying specific diameter increments for each diameter class. The estimation of the diameter increments is usually based on the analysis of historical data obtained from PSPs. Although this method is still very popular to forecast yields of tropical forests, stand table models feature certain weaknesses. The growth predictions are based on highly aggregated data and do not allow for varying environmental conditions. Traditional stand table models have been developed by Kofod (1982) and Howard & Valerio (1992). Recently a more sophisticated approach has been elaborated by Kohyama (1993), reflecting the impact of gaps created by dying trees.

Gap models

The basic concept of this model type is to describe the development of a forest on a small plot, called ´gap`, with a typical size of 0.1 ha. In this gap the growth of each individual tree is simulated, taking into consideration the tree competition for light and space, in some cases even for water and nutrients. The development of the whole forest can later on be estimated by repeated simulation of forest growth in the plot. Although this approach adequately accounts for the spatial heterogeneity and competition processes of tropical forests, it is difficult to implement because the maximum age for every simulated tree species is required. The gap model concept has been developed by Botkin (1972, 1993) and Shugart (1984). Special applications for tropical forests have been elaborated by Doyle (1981), Shugart et al. (1980) and Kürpick et al. (1997).

Cohort models

The basic idea of this modelling approach is that the trees of a forest stand are classified into various homogeneous groups, called ´cohorts`. Usually each cohort comprises trees of the same species group and size class. Trees remain in their initial cohort throughout the whole simulation, although the number of trees in a growth group will be reduced due to mortality and other factors. For the individual cohorts, growth rates are calculated by applying cohort-specific increment functions, usually derived from the analysis of available PSP data. These increment functions also include information about the impact of competition and site quality on diameter growth - supposed there are sufficient suitable field data. Examples for this modelling strategy have been developed by Vanclay (1989, 1994) and Ong & Kleine (1995).

Carbon balance models

The main feature of this modelling concept is that forest growth is calculated on basis of ecological and physiological processes. The biomass growth of a tree is usually described by calculating the photoproduction of leaves as a function of light climate. Other approaches attempt to include the impact of temperature and soil nutrient levels on growth into the modelling design. The development of carbon balance models is therefore only partly based on conventional PSP data, but requires mainly ecophysiological and environmental parameters. Based on this approach these models describe the competition between trees (e.g. for light and space) in detail. Due to the integration of environmental parameters the process-based approach allows for the accommodation of changes in the environmental conditions (e.g. soil nutrient level or temperature). This is an advantage compared with the more traditional methods (e.g. stand table projection models) which are not able to consider changing environmental parameters and can thus not adequately react to changes in the ecosystem. Unfortunately it might happen that some of the parameters required for the development of these models are not readily available. Hence, it is required to measure the lacking data in the field. An example of a carbon balance model for temperate forests can be found inValentine (1989). For tropical rain forest only Oikawa (1985) and Bossel & Krieger (1991, 1994) use such an approach.

FORMIX3 in relation to other growth models

The FORMIX3 model can be classified under the carbon balance modelling approach since the calculation of the individual tree growth is based on carbon balance. However, it is not purely process-oriented as the classical carbon balance models, but integrates the advantages of the other modelling concepts. In FORMIX3 trees compete for light in a similar way as in gap models. Gap dynamics as proposed by Whitmore (1990) are incorporated into the model design. Besides, the tree species are classified in a small number of functional groups, an approach which is used in stand table and cohort models. A more detailed description of the model is given in Chapter 2.

All these different model approaches may have the potential to give realistic predictions of forest growth. Certain differences in the model structure might indicate in which cases one model gives more realistic predictions than another. It can be concluded that there is no single methodology optimal for solving all questions related to growth of tropical forests. Each modelling approach has its own strengths and limitations. Hence, it is important to always carefully adjust the models to the local site, stand and management conditions. If the field data basis for the development and adjustment of the model is weak, the quality of the model will suffer.

1.3 Objectives and background of the study

Since the eighties the public becomes increasingly aware of the multiple causes for the depletion of tropical rain forests. The drastically decreased forest area, the loss of plant and animal species, the expulsion of indigenous people heavily depending on the local forest resource, and the adverse impacts of forest destruction on the global climate are the main reasons of public concern.

The forest resources of Malaysia are seriously affected by this adverse development (Aiken & Leigh, 1992). Commercial logging of the Malaysian rain forest, which belongs to the oldest and most complex ecosystems on earth, began in the fifties and sixties. Increasingly heavy machinery was employed during the seventies and eighties, accelerating the depletion of the resource. Today, the timber stock of commercial forests in e.g. Sabah is almost exhausted (Juin et al. 1994). In the coming years, the Sabah Government will be threatened by a serious decrease in timber revenues if the loss in production cannot be compensated by for instance higher prices. For the time being, Sabah´s natural forest resources still provide some 60 % of the State´s budget (Kleine 1994).

In order to stop the present trend of forest depletion, the Malaysian Government has committed itself to achieve the ITTO Target 2000, which implies that from the year 2000 onwards all areas under the Permanent Forest Estates should be managed in a sustainable way. This commitment includes the intention to reduce the logging damages and gradually scale down the present harvesting rates, which are considered to be far beyond sustainability, to a level corresponding to sustainable yield.

The bilateral Technical Co-operation Project *Malaysian-German Sustainable Forest Management Project* is directed to develop a system for the sustainable management of the Dipterocarp rain forests in Sabah. An important aspect of this sustainable forest management system is the elaboration of a yield regulation system, which adequately considers the actual growth rates of the forest. In the framework of the *Malaysian-German Sustainable Forest Management Project*, the FORMIX3 model was therefore developed to precisely estimate the growth rates of lowland Dipterocarp rain forest and to reliably quantify the sustainable annual allowable cut (AAC). In addition, the model aimed at simulating the long-term development of logged-over Dipterocarp stands under different logging scenarios.

2 Description of the FORMIX3 model

The FORMIX3 model was developed to simulate the growth dynamics of lowland Dipterocarp rain forests in Sabah, Malaysia (Huth et al. 1994, Ditzer et al. 1995, Huth et al. 1996). It is a successor of the FORMIX model (Bossel & Krieger 1991, 1994, Appanah et al. 1990). Some of the parameters required for the elaboration of FORMIX3 were identified on the basis of general Dipterocarp forest characteristics reported in literature, others were derived from locally available data or were specifically measured. Chapter 2 contains a short description of the location where FORMIX3 was developed and a simplified overview of the main features of the model. For a comprehensive review of relevant literature and a more detailed description of the model see Huth et al. 1996.

2.1 The site

The Deramakot Forest Reserve, where most of the field data have been collected, is situated in Sabah, Malaysia (117°30' O, 5°25' N; Figure 1). Located close to the equator, Deramakot has the typical perhumid climate of the inner tropics. Mean annual temperature is 27° and mean annual rainfall is about 2500 mm. The geology of Deramakot is characterised by tertiary sediments, mostly mud- and sandstone. The soils are mainly Acrisols. They are poor in nutrients and easily eroded, especially when the protective plant cover is removed. The Deramakot Forest Reserve is situated in altitudes between 130 and 300 m a.s.l.. The prevailing forest type is lowland Dipterocarp forest. Commercial logging started in 1956 with varying intensities. At present, most of the area has been logged at least once.

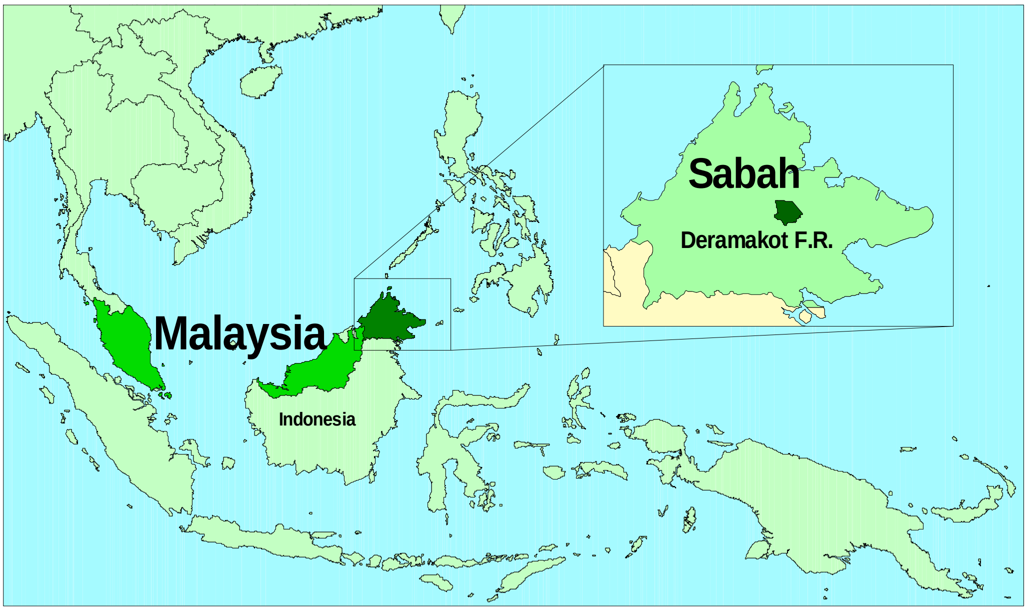


Figure 1: Location of the site of model application: Deramakot Forest Reserve in Sabah, Malaysia.

2.2 Main components of the FORMIX3 model

The FORMIX3 model can be divided into several components: species grouping, spatial structure, tree growth, competition, regeneration and mortality. In the following the modelling approach and its individual components are briefly explained. A detailed list of the parameters used for the development of FORMIX3 is given in Appendix B.

Species grouping and spatial structure

Tropical forests in South-East Asia are composed of a large number of tree species. For the investigation of forest dynamics it is useful to classify the numerous species into a small number of functional groups, as it is impractical to assess growth parameters for each individual tree species. Based on three essential growth characteristics (potential height, light demand and regeneration) for species grouping, 5 different groups were derived for the Dipterocarp forest at Deramakot. Group 1 is composed of the largest shade-tolerant species with mature heights of 36 m and more, while Groups 4 and 5 comprise the smallest light demanding pioneer species and the lower understorey crown layer (Appendix A; see Huth et al. 1996 for more details).

For the simulation of the spatial structure the forest stand is divided into small patches, each covering an area of 20 x 20 m. Hence, the growth simulation of a forest stand with a size of 1 ha is based on 25 patches. The area of one patch (400 m^2) corresponds to the approximate crown area of one big tree and thus has a size typical of natural gaps created by the collapse of dying large trees. In the vertical direction, the model stratifies trees of the same species group according to their height into 5 different height layers.

Summarised, FORMIX3 describes the stand structure in the following way: tree species are aggregated into five **species groups**. The vertical structure of the canopy is separated into five **height layers**, while the spatial heterogeneity across the stand area of one hectare is represented by 25 **patches** of 20 x 20 m.

Individual tree growth

The model calculates the development of a forest stand based on collectives of trees, each comprising the trees of one species group in a certain height layer of a single patch. Each collective is characterised by its number of trees and by the size of one specific representative tree, reflecting the average biomass of the tree collective. The biomass data provided by the model were adapted to meet the specific local site conditions by comparing them with respective data for nearly undisturbed forest at Deramakot.

The growth of the individual tree is based on a carbon balance. The carbon balance includes photoproduction of the tree on the one hand and biomass losses on the other hand (Bossel & Krieger 1991, 1994). Photoproduction is calculated based on the tree´s leaf area and its specific productivity which depends on the locally available irradiance inside the canopy. Within the patch, the gradient of light attenuation downwards in the canopy is computed with regard to absorption by higher located crown layers. The calculation of the biomass losses considers the respiration of woody tree organs and leaves, litter fall and the losses due to the renewal of roots.

The increment calculated for the representative tree of a given collective changes the size of all trees belonging to this collective and therefore determines the transition of trees from lower to higher canopy layers. Subsequent to the transition from one crown layer to another, stem number and average size of each tree collective (i.e. of each species group in any of the height layers and patches) is recalculated. In the course of the simulation process this recalculation is performed on a monthly basis.

Competition

Two types of growth competition are reflected in the model: the competition for light and the competition for space. Trees in lower crown layers are shaded by larger trees of upper canopy layers and thus receive less radiation. This affects the carbon balance of these trees as they produce less biomass per leaf area. Regarding space competition, the model increases the mortality rate if a forest stand is very densely stocked, since this reduces the available growing space per tree.

Regeneration

FORMIX3 not only simulates the individual tree growth, but also accounts for the process of seedling establishment on patch level. The establishment of seedlings requires suitable micro-climatic conditions at the forest floor. Particularly the availability of sufficient irradiance is an important factor. For this reason, FORMIX3 uses the light intensity at the forest floor in order to simulate seedling establishment. For non-pioneer species only a minimum light requirement is assumed, whereas pioneer seed germination (e.g. *Macaranga spp.*) needs a considerably higher irradiance level. If the light intensity at ground level is too low, the model assumes that no new seedlings establish within the 20 x 20 m patch.

Mortality

Tree mortality is included in the model as a random event, its rate depending on the actual diameter increment and the species group. Unfavourable growing conditions are reflected in low increments and lead to increased mortality rates. Additionally, the crowding of trees of similar size, i.e. of trees in one height layer, is causing an increased rate of mortality. Typical figures for average mortality rates of tropical forests range between 1 and 2 % per annum (Milton et al. 1994, Swaine et al. 1987a, b). However, this only refers to trees with diameters > 10 cm, since seedlings are subject to a considerably higher mortality rate (Kennedy & Swaine 1992).

Growth of the forest

Individual tree growth, regeneration and mortality are the driving processes for simulating the forest growth in each patch. Total stand dynamic is synthesised from the development of the single patches by adding their interaction. Large dying trees have a certain probability to break and fall and then cause damages in a neighbouring patch (Putz & Milton 1982, Brokaw 1985). This leads to gap formation as the driving force of the shifting stand mosaic (Whitmore 1990, Swaine & Whitmore 1988). In order to realistically simulate the gap dynamics and the related natural stand disturbances of climax-state forests, the model was calibrated by using empirical data obtained from nearly undisturbed Dipterocarp forests at Deramakot.

3 Testing the model

3.1 Introduction

Since growth models are applied to predict the future forest conditions, it is essential to conduct a comprehensive model evaluation and to assess its accuracy. Model errors and weaknesses have to be eliminated to increase the reliability of the simulations, making it an operational tool for forest management planning. For this reason, the quality of the FORMIX3 model was tested by comparing the simulation results with actual field data obtained from recurrent measurements of PSPs. In this way, the model and its behaviour was analysed in relation to the growth dynamics of real forest stands.

Various approaches have been applied to test the quality of FORMIX3. Two of them are presented in the following Chapters 3.2 and 3.3. Additional information related to the validation of the model can be found under Chapter 4.3 (Simulation of forest stands).

3.2 Comparing the climax-state of simulated forest with field data of primary forests

According to the theory of succession the regeneration of a heavily disturbed forest stand can be described in the following way: in the early successional phase fast-growing trees dominate the forest stand and the standing biomass increases very quickly (Krebs 1994, Whitmore 1990). As succession continues, the species composition changes from light demanding species to more shade tolerant species. In the final successional phase, called climax stage, the forest is dominated by shade tolerant tree species. The forest has reached its maximum height and the standing biomass has stabilised. In the climax phase the forest is in a relatively steady state and in the long run stand characteristics as standing volume, stem number and species composition vary only little within certain thresholds. A forest in this state corresponds to an undisturbed forest, called primary forest.

There is common agreement about the stability and dynamics of primary forests under constant environmental conditions (Whitmore 1988, Weidelt 1986). Falling big trees create gaps in which a new succession proceeds. These gap building events are part of the internal dynamics of the forest. It follows that the species composition at a particular spot may differ, but on a large scale the species composition is more of less stable.

To test the model quality the structure of the simulated forest in its climax state was compared with the structure of existing primary forests. The comparison was carried out on basis of key-variables which quantify the stand structure, e.g. total stem volume, stem number and species composition. The results of the simulation reveal that a **heavily disturbed forest** reaches a climax stage structure after approximately 150 years, indicating that the model outputs are reasonable (see Figure 2).

A similar form of validation test was carried out by simulating the development of a **primary forest**. It is assumed that the model produces realistic results, when the simulated structure of the primary forest remains stable in the long run (e.g. over a period of 400 years). On the other hand, the quality of the computer model is insufficient and has to be enhanced in case the simulated primary forest does not show these steady features, e.g. if the

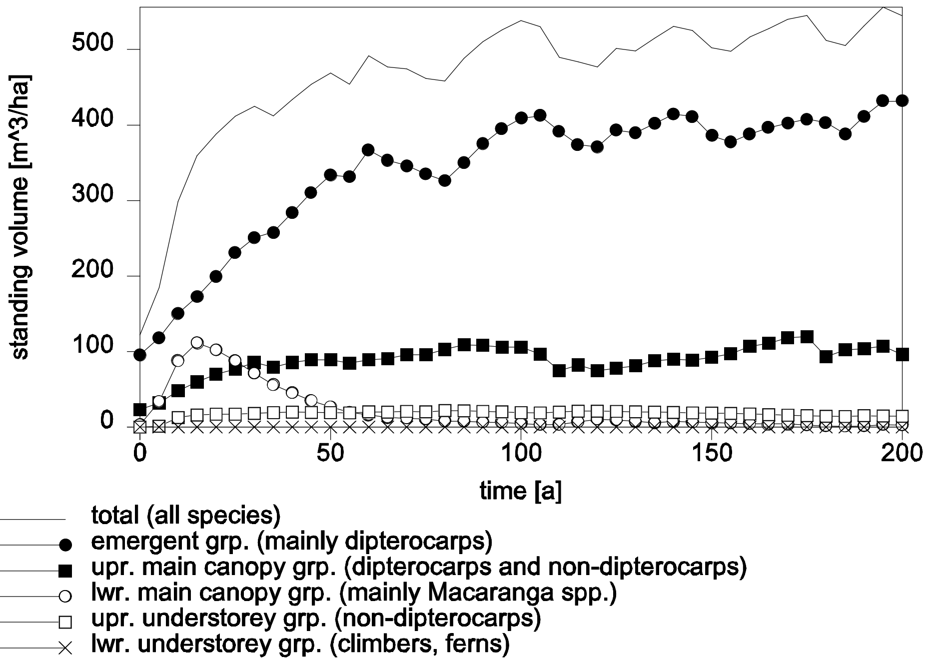


Figure 2: Simulation of a heavily disturbed forest at Deramakot. Total standing volume and volume of the different species groups over time for trees with diameter > 10 cm (stand L3 described in Chap. 4.1, definition of standing volume see Chap. 2.4.6).

total standing volume decreases or increases, or the species composition permanently changes into one direction. Figure 3 shows the simulated development of a primary forest at Deramakot. Except for some fluctuations caused by dying trees, both the total standing volume and standing volume of the different species groups is rather stable, indicating that the model produces realistic results. A comparison of the simulation results with data derived from literature, which can be found in Appendix C, also proves that the model performance is satisfactory and realistically predicts the future stand conditions.

Calculating the so-called **stability indices** is another efficient method to check the accuracy of a model. Stability indices can be computed for a number of parameters describing the structure of a forest, e.g. the stem number, the gross biomass production and the standing volume. In the

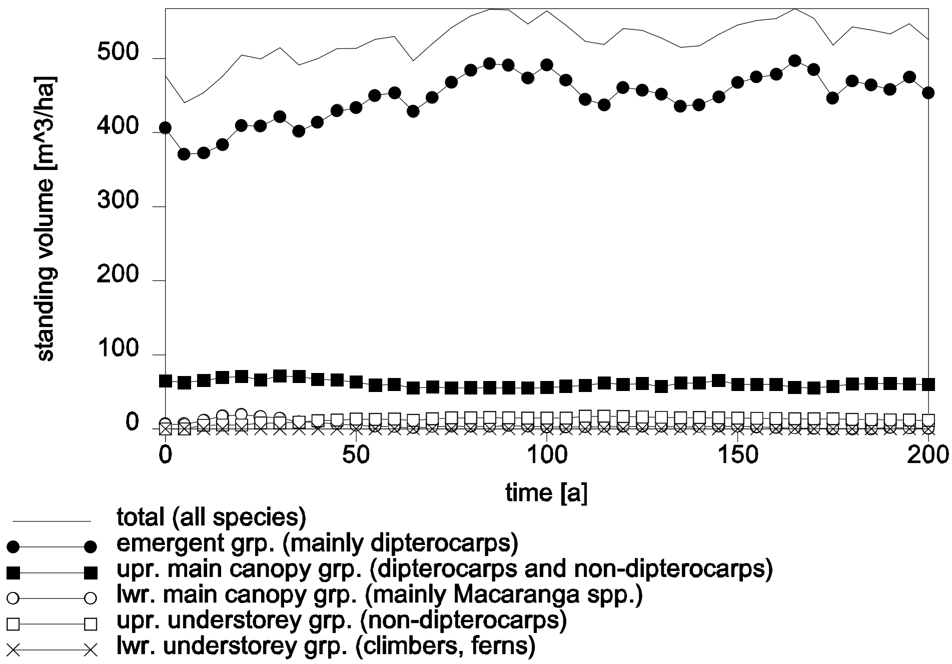


Figure 3: Simulation of a primary forest at Deramakot. Total standing volume and volume of different tree species groups over time for trees with diameter > 10 cm (stand P1 described in Chap. 4.1).

following the methodology is exemplified by calculating the stability index of the standing volume. The stability index STI of the standing volume is defined as the average standing volume at the end of a simulation period divided by the standing volume at the beginning of the simulation, which is equal to the standing volume measured in the field:

$$STI = \frac{standing\,volume_{simulated}}{standing\,volume_{measured}}$$

The stability index STI is equal to 1 in case the simulated values correspond exactly to the field data, whereas an STI value of 2 indicates that the predicted standing volume of the simulated forest is twice as high as measured in the field. To assess the reliability of the FORMIX3 model, various stability indices were computed by using field data obtained from primary forests at Deramakot. A simulation period of 200 years was chosen. The results of the simulation show that the model in general realistically reflects the growth of lowland Dipterocarp forests, as the STI values provided by the model only slightly deviate from the optimal value of 1. Only in case the STI values are calculated for very small groups (e.g. the stem number of a certain diameter class within a specific species group) the model produces some deviations, pointing to the limits for the application of the model.

3.3 Comparing the growth dynamics of the simulated forest with field data

Growth rates are an important factor to determine the time period which a logged forest needs for regeneration and thus strongly influence the results of simulated logging scenarios. For this reason, it is important that the model shows a satisfactory performance regarding the estimated growth rates. The growth dynamics of a forest can be described by diameter increment and gross biomass production.

3.3.1 Diameter increment

The results of the diameter increment simulations are presented in Figure 4. The Figure shows the simulated diameter increments of the emergent species group (group 1, see Chapter 2.2) depending on the diameter of the tree and the individual light conditions. The light conditions are expressed by the "overtopping basal area" (OBA), which is defined as the aggregated basal area of all trees higher than the regarded tree. A low OBA value indicates that a tree receives nearly full sunlight, a high value describes that the tree is standing in the shade of bigger trees.

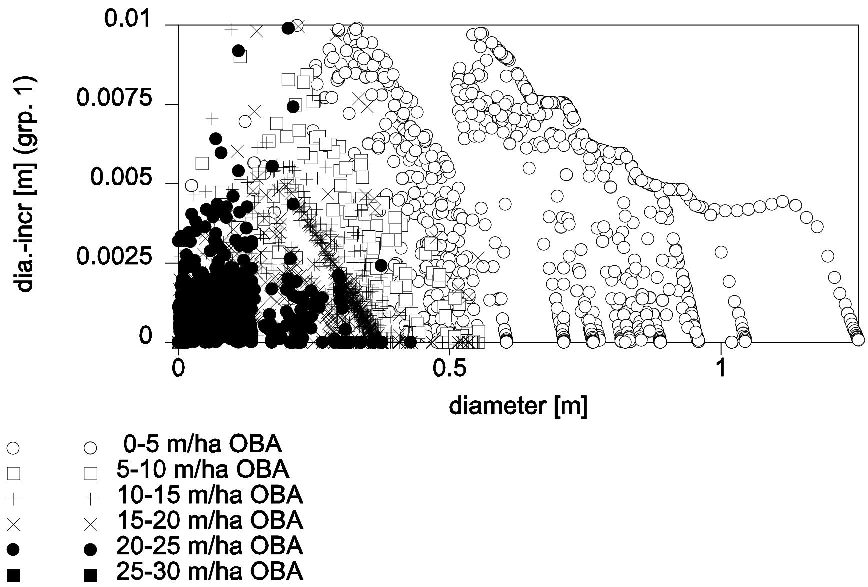


Figure 4: Simulation of primary forest at Deramakot. Annual diameter increment of the emergent species group (group 1) over actual diameter for different overtopping basal areas (OBA) as an indicator of the light conditions. Every point represents the increment of a certain tree at a certain time.

Typical values for average annual diameter increments of Dipterocarp species range between 0.4 and 0.8 cm/a (Manokaran & Kochummen 1987, Whitmore 1984). The simulation results depicted in Figure 4 coincide with these observations, proving that the estimated growth rates of the model adequately reflect the behaviour of existing lowland Dipterocarp forests.

3.3.2 Gross biomass production

Various approaches are suitable for measuring the gross photo production of a forest. For primary forest stands in Malaysia values ranging from 67 to 86 tons/ha/a were measured (Table 1). These figures correspond well with data measured in tropical forests in Africa or America (Medina & Klinge 1983, Kira 1975).

Table 1: Gross photo production of primary forest stands in Malaysia (Dipterocarp lowland rain forest). The gross photo production equals the gross primary production minus the leaf respiration at daytime.

location	**gross photo production**	**reference**	**method**
Pasoh	86 t/(ha a)	Kira 1978	light response curve
Pasoh	67 t/(ha a)	Kato et al. 1978, Kira 1978	biomass balance
Pasoh	81 t/(ha a)[a]	Aoki et al. 1975	CO2 fluxes in different heights
Deramakot	70 t/(ha a)	Eschenbach 1994, Ditzer & Huth 1995	own calculations based on light response curve

a Including the respiration of leaves at daytime.

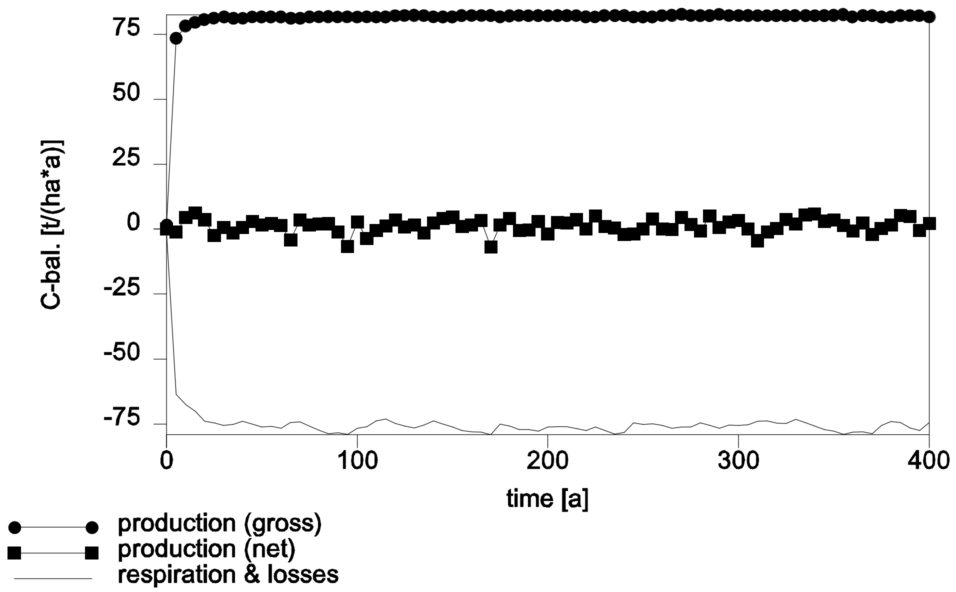


Figure 5: Annual gross photosynthesis production, net photosynthesis production and biomass losses (respiration & litter fall) over time for the simulation of a primary forest at Deramakot.

Figure 5 shows simulation results regarding the gross photo production of a primary forest at Deramakot. The production rate is stable and has an average value of about 80 tons/ha/a, which coincides with the figures given in Table 1.

Summarised, it can be concluded that the FORMIX3 model was extensively tested. The results of the various test runs indicate that the model produces realistic results and adequately reflects the growth behaviour of lowland Dipterocarp forests.

4 Simulation of typical forest stands in Deramakot Forest Reserve

Structural heterogeneity is a basic property of natural tropical forests. A small scale structural pattern due to dying and falling large trees that form gaps in the canopy is superimposed by large scale disturbances as for instance timber harvesting operations. The current forest structure is the result of the preceding disturbances and the forest-specific growth dynamics. Since the present structure determines future stand development for decades, a detailed knowledge of the stand characteristics is essential for the development of reliable growth projections. For this purpose, comprehensive forest inventories were carried out in several typical stand types. The inventory results were later on used as the basic data set for the initialisation of the model (see Chapter 4.2).

The simulations covered eight typical stands representing different structural types of natural Dipterocarp forest, all of them located in the Deramakot Forest Reserve:

- three stands of primary forest
- two stands of secondary forest with few pioneers (i.e. moderately logged forest)
- two stands of a pioneer-dominated secondary forest (i.e. heavily logged forest)
- one secondary forest stand that was logged for a second time with air-borne yarding equipment.

Each stand was recorded in a sample plot with a size of 8.100 m². The following two Chapters contain a brief description of the investigated stands and present their projected development as simulated by FORMIX3.

4.1 Short description of investigated forest stands

In the following the investigated stands are referred to by specific abbreviations (P1, P2 etc.) which are listed in Table 2.

To represent the variety of **primary forest stands**, a very dense stand on a slope (P1), a sparsely stocked stand on a ridge (P2), and a stand with a natural gap (P3) were selected. The gap in stand P3 was caused by the decaying crown of a dead emergent tree and has an extension of approximately 15 m x 20 m. The primary forests were not logged due to the steep slopes and the high abundance of heavy hardwoods which do not float (e.g. *Shorea atrinervosa*). The logs could therefore not be transported via the river, which was the usual means of transport in the early seventies, the time when the forest at Deramakot was logged. Besides, at the time of logging the heavy hardwoods were not marketable.

The **secondary forest stands with few pioneers** were selectively logged between 1970 and 1972. The logging intensity was rather low. Similar to the primary forest, a dense stand stocking on a slope (S1) and a rather sparsely stocked stand on a ridge (S2) were selected.

The **secondary forest stands dominated by pioneers** developed on plots heavily disturbed by commercial logging. The stands are characterised by a dominance of the pioneer species *Macaranga hypoleuca* and *Anthocephalus*

Table 2: List of inventoried stands as referenced in this report.

stand abbreviation	**short description**
	primary forest
P1	dense primary forest stand on slope
P2	sparsely stocked primary forest stand on ridge
P3	primary forest stand with natural gap
	secondary forest with few pioneers
S1	secondary forest stand with few pioneers on slope
S2	secondary forest stand with few pioneers on ridge
	secondary forest dominated by pioneers
M1	secondary forest stand dominated by pioneers with climber undergrowth
M2	secondary forest stand dominated by pioneers with climbing bamboo
	relogged secondary forest
L1	recently relogged secondary forest stand

chinensis. Two stands were selected, one with undergrowth dominated by climbers (M1) and one with climbing bamboo invading from the sides (M2).

The structure of the **relogged forest stand** (L1) was similar to the secondary forest with few pioneers, until it was logged for a second time by a Long Distance Cable Crane System in 1993. The logging operations in 1993 followed the principles of reduced impact logging (RIL) and on the average only three trees per hectare were harvested. However, even this rather moderate logging operation with low harvesting intensity caused some damages to the residual stand.

4.2 Initialisation data for simulation of investigated forest stands

To project the development of the selected stands, the initial model stands have to be derived from the collected field data. The initial model stands serve as the starting point for the subsequent stand simulations. Three steps are necessary to prepare the inventory data for the initialisation of the model. First of all, the inventory data have to be aggregated according to the five species groups (compare Chapter 2.2) and the corresponding **stem-diameter distributions** have to be calculated. Secondly, the trees have to be distributed to individual patches of the stand (note: in the model a 1 ha stand is composed of 25 patches, see Chapter 2.2 for further explanations), reflecting the **spatial heterogeneity** of the stand structure. Thirdly, the **site quality** of the forest stand has to be considered.

4.2.1 Stem-diameter distribution

The total number of stems has been grouped into certain diameter classes, each with a width of 10 cm (class 1: 10-20 cm, class 2: 20-30 cm, etc.). An overview on the stem-diameter distributions of the eight selected stands is given in Figure 6. A more detailed picture is presented in Figure 7 which illustrates the stem-diameter distributions of the individual species groups within the primary forest stand P1 and the relogged secondary forest L1. The corresponding Figures of the other six stands are given in Appendix D.

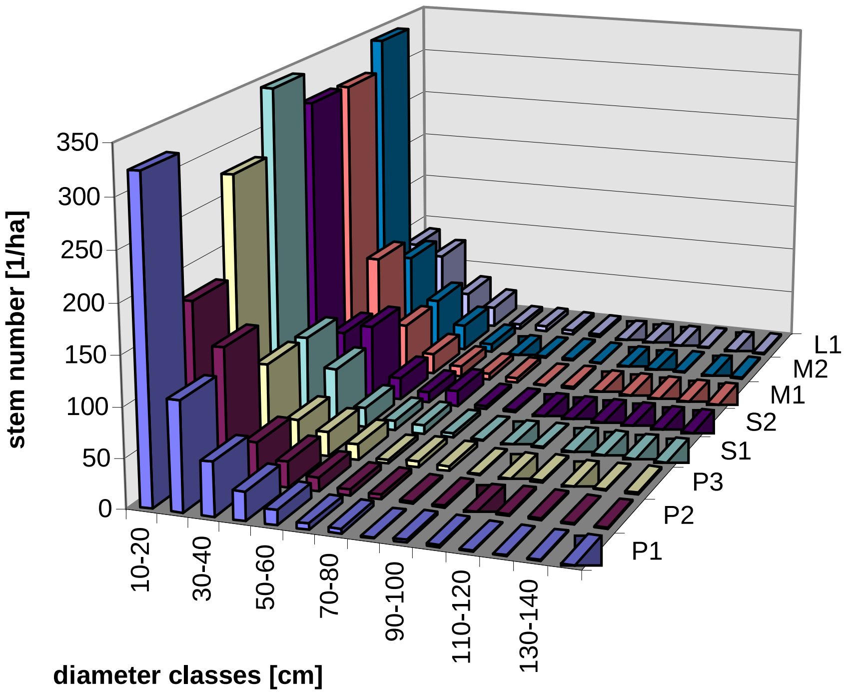


Figure 6: Overview of distribution of stem numbers to 10 cm diameter classes in the eight inventoried stands (description in the text) for diameters > 10 cm.

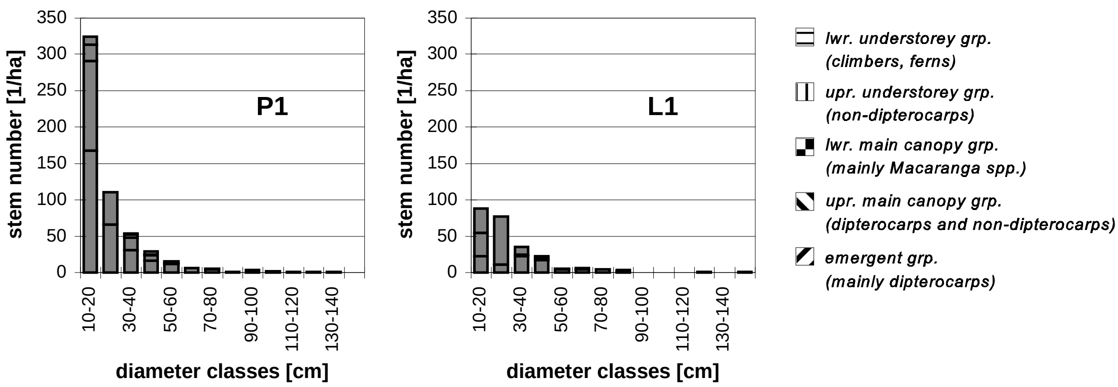


Figure 7: Detailed diameter distribution for the primary forest stand on slope (P1): distribution of stem numbers of single species groups to 10 cm diameter classes for diameters > 10 cm.

The Figures show a distribution pattern which is typical for natural forests. The highest stem numbers can be found in the lowest diameter class, while the highest diameter classes are characterised by very low stem numbers. Regarding the secondary forest stands (S1, S2, M1, M2, L1), only few trees with diameters exceeding 70 cm can be found. This lack of large trees as well as the high abundance of juvenile trees with diameters below 40 cm are the consequences of the previous logging operations and typical for the structure of secondary forests. The analysis of the data describing the relogged secondary forest stand (L1) illustrates the impact of the re-entry. The diameter classes below 40 cm feature considerably reduced stem numbers, probably caused by the recent logging operations which particularly damaged the saplings and poles. Besides, it is obvious that the number of large trees with diameters of more than 70 cm has been further diminished due to the second harvest.

4.2.2 Spatial heterogeneity

The inventory results do not provide sufficient information about the spatial heterogeneity of the stands. For this reason, the specific growth phases of a forest (gap phase, building phase, mature phase) were used to derive a hypothetical spatial distribution of trees.

According to a generally accepted definition by Whitmore (1984), forest patches belonging to the gap phase are characterised by the absence of any trees with diameters of more than 10 cm. Patches ranking among the building phase comprise trees above 10 cm, however, trees with diameters above 30 cm are lacking. Only the patches in the mature phase include large trees above 30 cm diameter.

The characteristics given by Whitmore have been adapted to the height layer structure of FORMIX3. **Gaps** are defined as patches without any trees above 25 m height, **building** patches include such trees but no trees above 36 m height, whereas **mature** patches also contain trees of more than 36 m height.

The model describes the spatial heterogeneity of the eight investigated stands in the following way:

- the stands without gaps (P1, P2, S1, S2, M1, M2) show a homogeneous structure, hence it is assumed that all patches of these stands come under the mature phase.
- the primary forest stand with a natural gap (P3) is characterised by one 20 m x 20 m patch belonging to the building phase. The rest of the stand area is homogeneously structured and therefore assumed to be in the mature phase.
- the relogged secondary forest stand (L1) features six logging gaps with an average size of 20 m x 20 m. The rest of the stand area is supposed to be in the mature phase.

4.2.3 Site quality

Site quality is considered in terms of the mature height of the stand. The mature height of a stand is defined as the height of the largest trees, i.e. the emergents, at maturity. For the stands at Deramakot the model assumes a mature height of 50 m and a corresponding diameter of 120 cm.

4.2.4 Initial states of investigated stands

Based on the given stem-diameter distribution, the assumptions concerning spatial heterogeneity, and the individual site quality of the investigated stands, the model calculates the initial states of the eight stands. The results of the calculations were visualised and assessed in comparison with stand profiles observed in the field. Figures 8 - 15 display profile views of all stands and compare them with stand profiles drawn in the field (Schlensog 1994, 1995, 1997). The profiles recorded in the field as well as profiles provided by the model display all trees of more than 4 m height in a transect of 10 m width. Top views giving additional information about the spatial structure of the stands can be calculated and visualised by the model as well (see Huth et al. 1996 for more details).

The analysis of the stand profiles reveals that the model representations show a strong similarity to the profiles drawn in the field. It is a fact that every model is a simplification of reality, however, it can be concluded that the simplifications used by FORMIX3 are not too strong and sufficient to adequately depict the variety of stand structures found in natural Dipterocarp forests. The initial states of the eight stand depicted in the Figures 8 - 15 mark the starting points for the ensuing simulations which are presented in the following Chapters.

P1: primary forest stand on slope

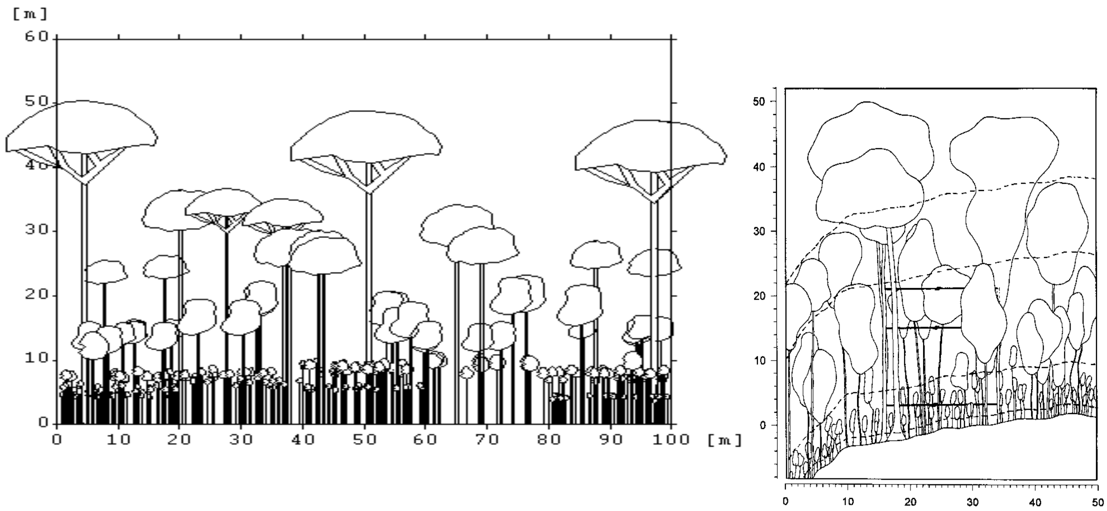


Figure 8: Profile of primary forest stand on slope (P1) as represented in the model (left) and as observed (right); the profile shows all trees of more than 4 m height in a transect of 10 m width.

P2: primary forest stand on ridge

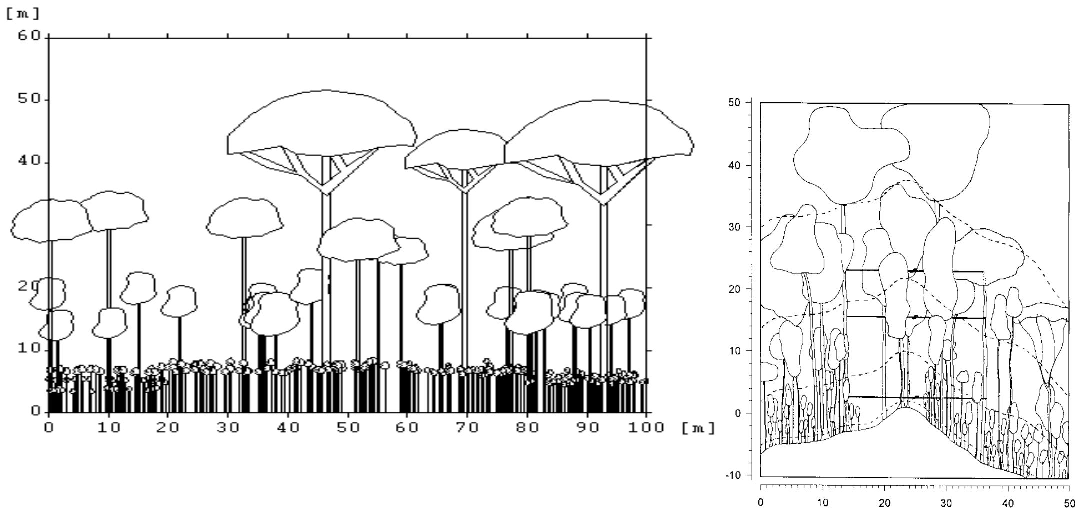


Figure 9: Profile of primary forest stand on ridge (P2) as represented in the model (left) and as observed (right); the profile shows all trees of more than 4 m height in a transect of 10 m width.

P3: primary forest stand with natural gap

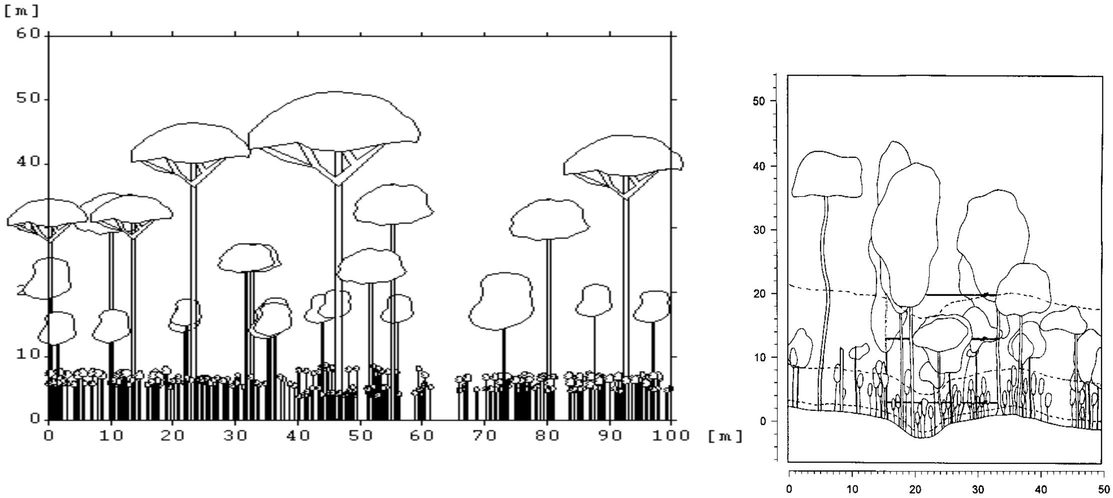


Figure 10: Profile of primary forest stand with natural gap (P3) as represented in the model (left) and as observed (right); the profile shows all trees of more than 4 m height in a transect of 10 m width.

S1: secondary forest stand with few pioneers on slope

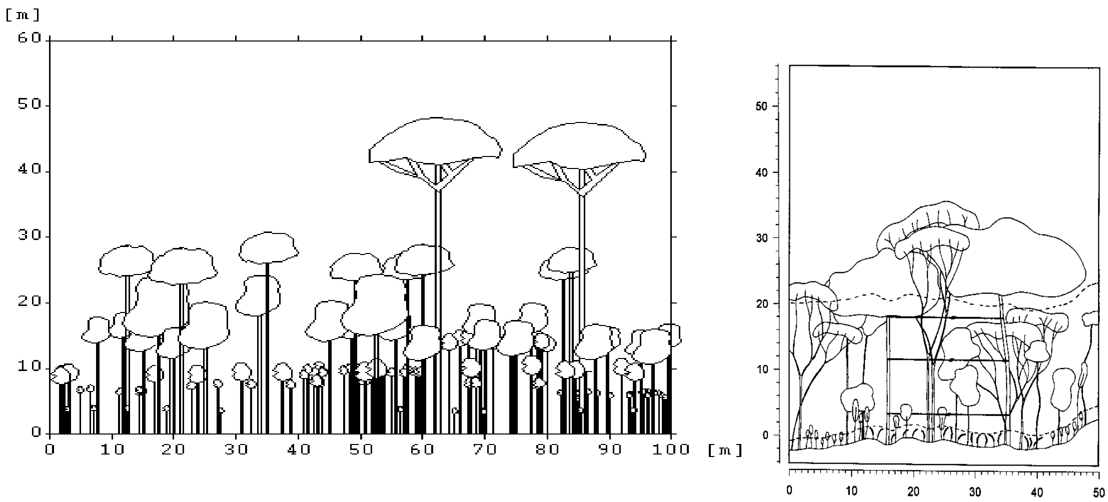


Figure 11: Profile of secondary forest stand with few pioneers on slope (S1) as represented in the model (left) and as observed (right); the profile shows all trees of more than 4 m height in a transect of 10 m width.

S2: secondary forest stand with few pioneers on ridge

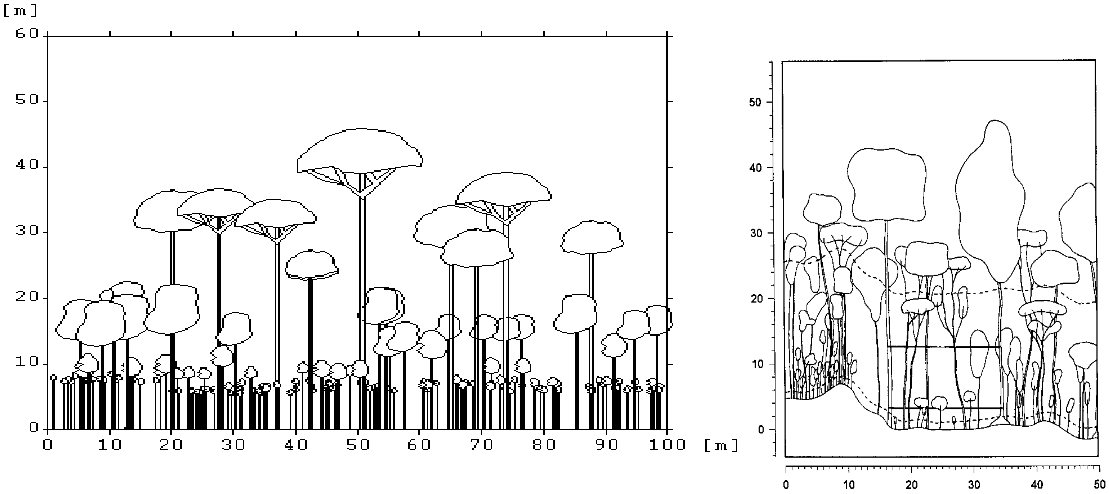


Figure 12: Profile of secondary forest stand with few pioneers on ridge (S2) as represented in the model (left) and as observed (right); the profile shows all trees of more than 4 m height in a transect of 10 m width.

M1: secondary forest stand dominated by pioneers with climber undergrowth

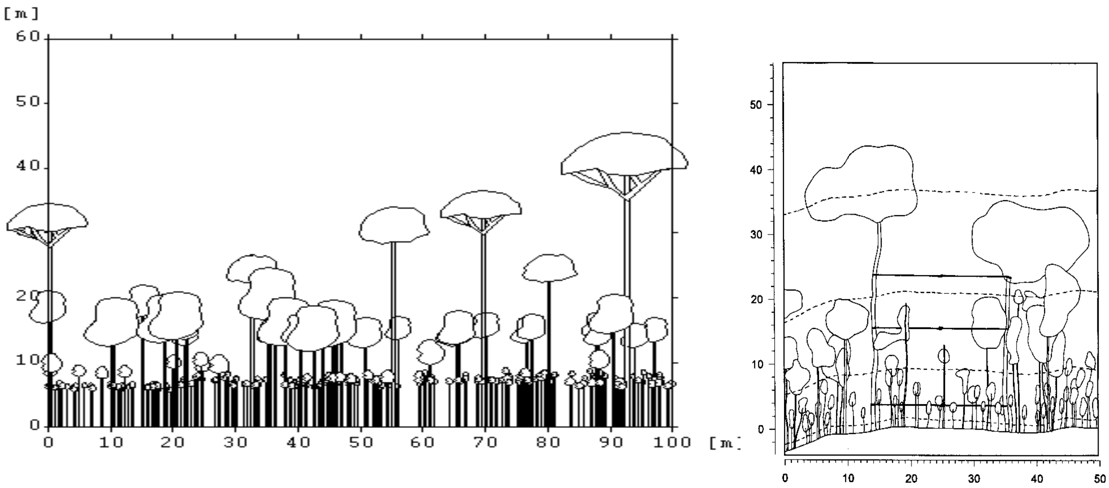


Figure 13: Profile of secondary forest stand dominated by pioneers with climber undergrowth (M1) as represented in the model (left) and as observed (right); the profile shows all trees of more than 4 m height in a transect of 10 m width.

M2: secondary forest stand dominated by pioneers with climbing bamboo

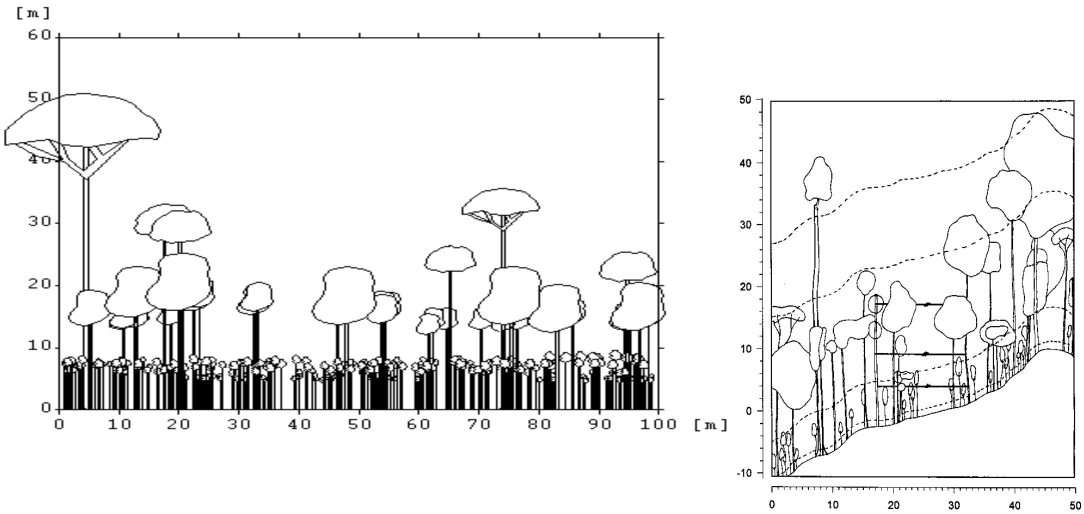


Figure 14: Profile of secondary forest stand dominated by pioneers with climbing bamboo (M2) as represented in the model (left) and as observed (right); the profile shows all trees of more than 4 m height in a transect of 10 m width.

L1: relogged secondary forest stand

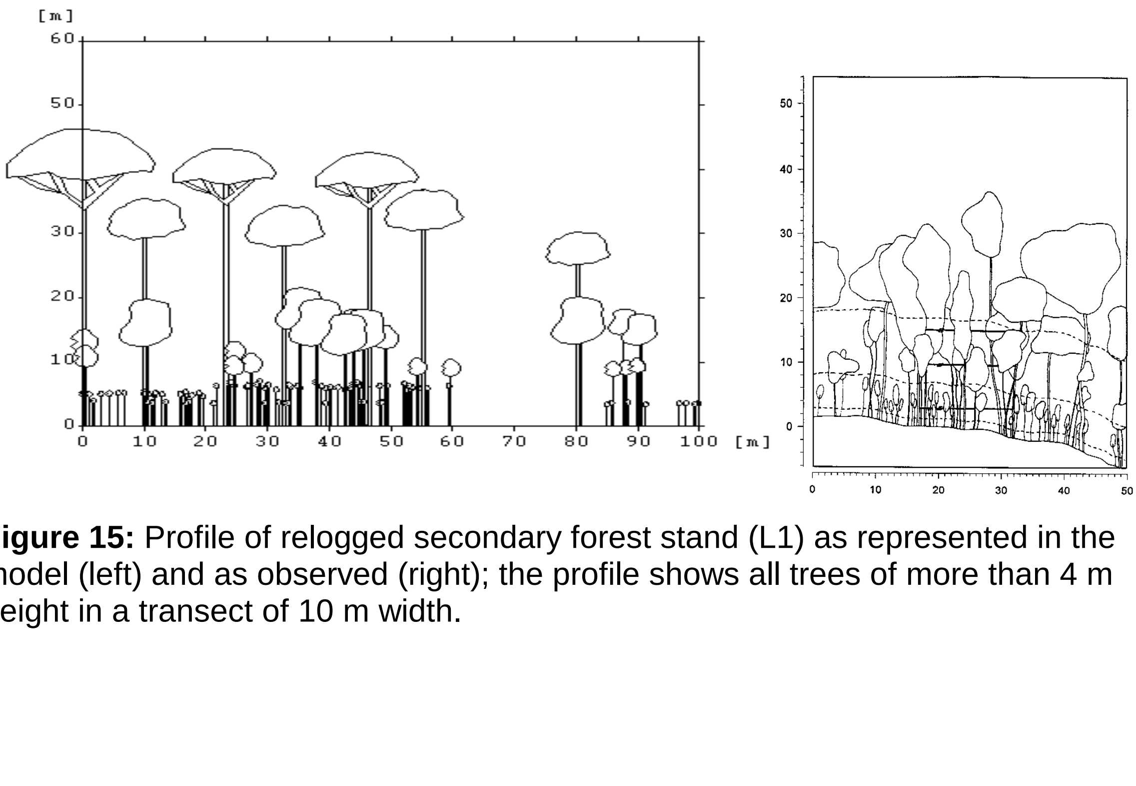


Figure 15: Profile of relogged secondary forest stand (L1) as represented in the model (left) and as observed (right); the profile shows all trees of more than 4 m height in a transect of 10 m width.

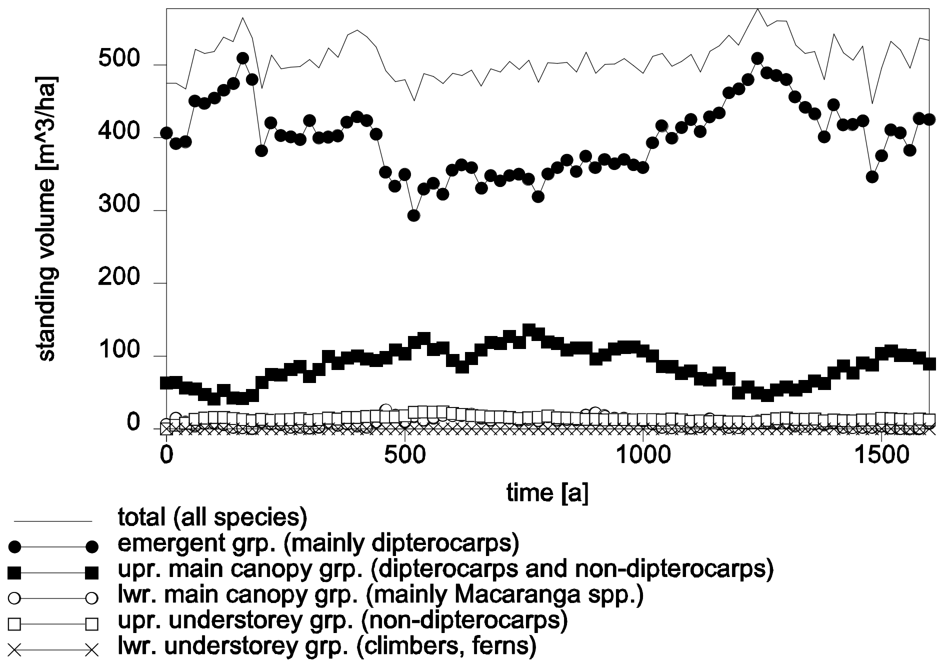


Figure 16: Simulated standing volume in the primary forest stand on slope (P1): development of standing volume (stem volume including one main branch in the crown, cf. Chap. 2.4.6) of trees > 10 cm diameter in the whole stand (total) and in the different species groups.

4.3 Simulation of forest stands

4.3.1 Simulation of primary forest stands

The characteristic long-term stability of primary forest structure should be reflected in the simulation results, hence the following simulations demonstrate the model forecasts for a very long period of 1600 years. The results of the simulations are discussed with respect to some key characteristics describing forest stands, as for instance total standing volume, number of trees and spatial heterogeneity.

In the simulation, the **total standing volume** (defined as the stem volume including the volume of the main crown branch) of the primary forest P1 fluctuates around a constant level of 490 m^3/ha. Species group composition remains fairly constant (Figure 16). The distribution of volume to the

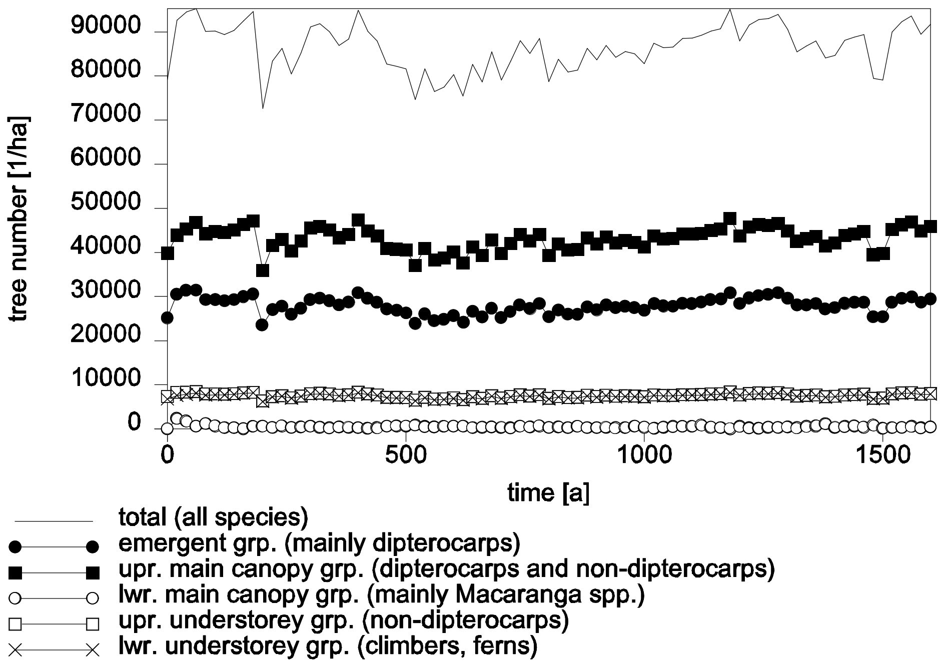


Figure 17: Simulated tree number in the primary forest stand on slope (P1): development of tree number of all trees in the whole stand (total) and in the different species groups.

different height layers has been calculated as well. The results are encouraging as they show that the volumes of the individual crown layer classes remain rather stable, regularly occurring short-term fluctuations are balanced in the long run.

The **number of trees** is the second key variable to characterise forest structure. Therefore, the stability of primary forest structure can also be described by analysing the predicted stem numbers. The projected stem numbers of stand P1 show long-term stability, irregular one-sided oscillations do not appear (see Figure 17). The distribution of the total stem number to the various species groups and height layers, which has been simulated as well, also provides figures which only slightly fluctuate within acceptable limits.

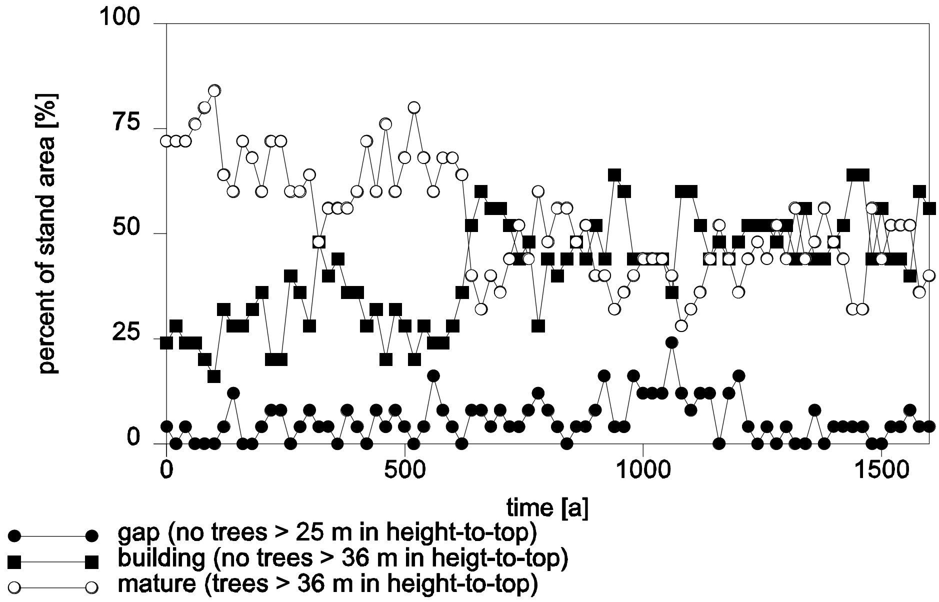


Figure 18: Simulated portion of stand area in gap (no trees larger than 25 m in height) and building phase (no trees larger than 36 m in height) in the primary forest stand on slope (P1).

Regarding **spatial heterogeneity**, primary forests should only show little variation over the years. The natural gap dynamics and the inherent growth cycle phases should result in small parts of the stand area being in the gap and building phase, respectively, while the majority of the stand should come under the mature phase. Figure 18 shows these dynamic properties of spatial heterogeneity as simulated for the primary forest stand P1. The predicted values oscillate around values of 10 % for gaps and 45 % for building patches, respectively, while a stable fraction of total stand area (fluctuating around 45 %) remains with the mature phase.

Figure 19 shows the **stem-diameter distribution** simulated for the long term development of stand P1. The simulated data were averaged over a period of 1500 years beginning with year 100 of the simulation. The analysis of the

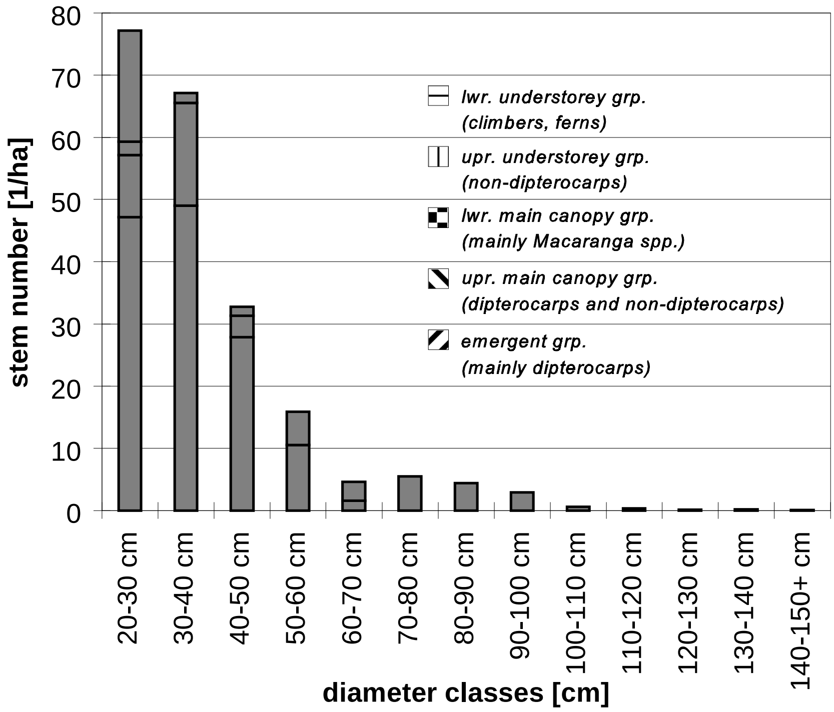


Figure 19: Distribution of stem number to 10 cm diameter classes > 20 cm diameter in the steady state of simulation of the primary forest stand on slope (P1). Simulation results were averaged over a period of 1500 years following to 100 years of simulation.

data shows the typical J-shaped decrease of stem numbers when moving from smaller to bigger diameter classes, which is characteristic for primary forests.

The above-described simulation results all refer to the primary forest stand P1. For the other two primary stands P2 and P3 the same simulations were performed. The results indicate that in the long view, independently of the respective initial stand conditions, all stands approach almost exactly the same steady state of stand development. The average total standing volume for instance constantly fluctuates around 490 m³/ha.

As a final step, the simulated primary forest structure (averaged over a period of 1500 years) was compared to field data collected in the three primary forest stands P1-P3. Summarising the analysis of this comparison, it can be concluded that the simulated primary forest structure matches the structure observed in the field quite well in all investigated aspects (e.g. distribution of volume and stem number to species groups and height layers). It is obvious that a number of three simulated stands is still a rather weak basis for any statistical analyses. However, as the stands were selected to represent the variability of primary forest structure, it can be assumed that applying the FORMIX3 model to other lowland Dipterocarp primary forest stands will also lead to accurate growth forecasts.

4.3.2 Simulation of secondary forest stands

A secondary forest stand significantly differs from a primary forest. However, past experience has shown that after a long period of time a logged-over forest finally develops a structure quite similar or even identical to the one of primary forest. This qualitative change in forest structure can be simulated by FORMIX3. This Chapter mainly focuses on the relogged forest stand L1, since its structure features the strongest deviations from primary forest and therefore most clearly reflects the typical patterns of regrowth. The growth characteristics of the other investigated secondary stands are only briefly discussed, as their growth patterns in general coincide with the development of stand L1.

Having been logged for a second time about 22 years after the first harvest, the **relogged secondary forest stand** L1 is heavily disturbed. Its initial standing volume of 270 m^3/ha reaches only 55 % of the standing volume of primary forest. Accordingly, the stand has a very open canopy. Figure 20 shows the simulated standing volume of the relogged stand L1 over the next 400 years. Characteristic of growth dynamics in a heavily disturbed stand is an initial predominance of pioneer species such as *Macaranga spp.* and

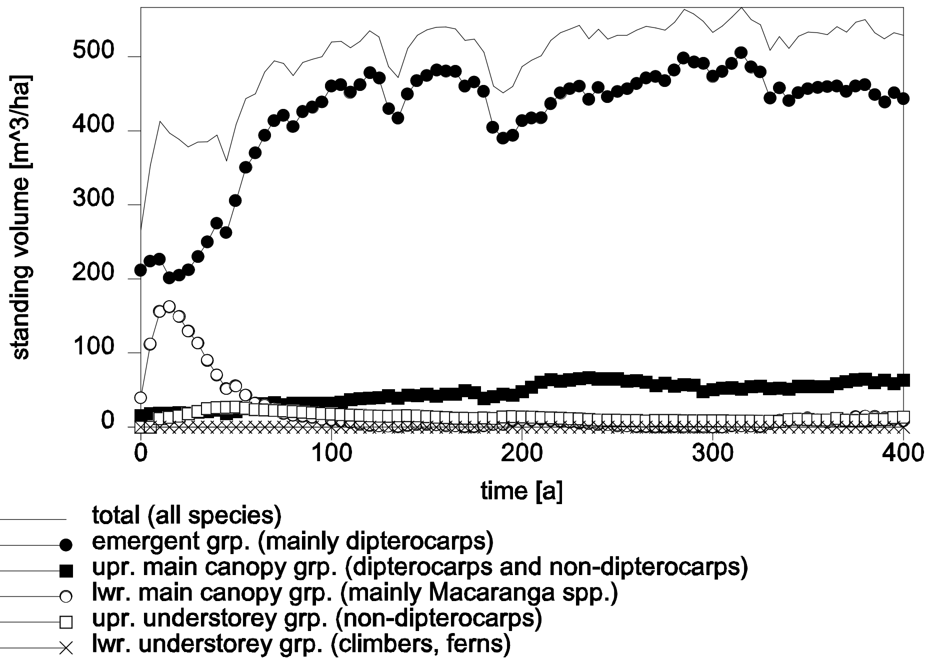


Figure 20: Simulated standing volume in the relogged secondary forest stand (L1): development of standing volume (stem volume including one main branch in the crown) of trees > 10 cm diameter in the whole stand (total) and in the different species groups.

Antocephalus chinensis. In the course of succession, the pioneers gradually disappear and the population of climax species establishes again. Step by step the standing volume is increasing and after a period of about 80 years the total volume of the simulated primary forest (490 m^3/ha, see chapter 4.3.1) is reached.

Since it is not sufficient to take the volume as the sole indicator for describing the forest growth dynamics, other parameters have to be analysed as well. It is equally important to consider the development of the species composition. The gradual change of species composition is reflected in Figure 20, which illustrates the distribution of the simulated standing volume to the different species groups. The Figure reveals that the volume of the pioneer species culminates 15 years after logging and then rapidly decreases.

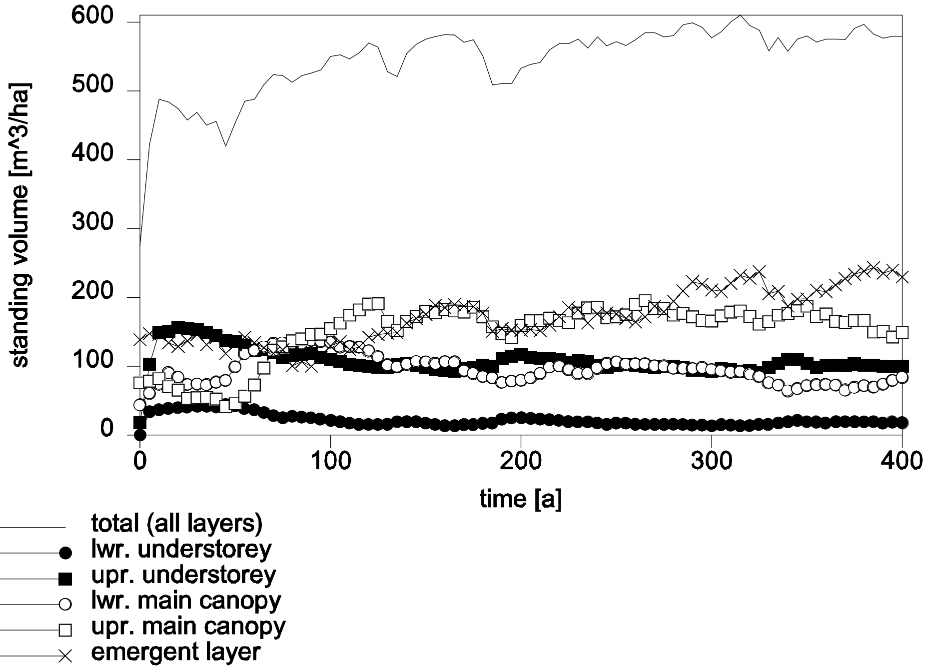


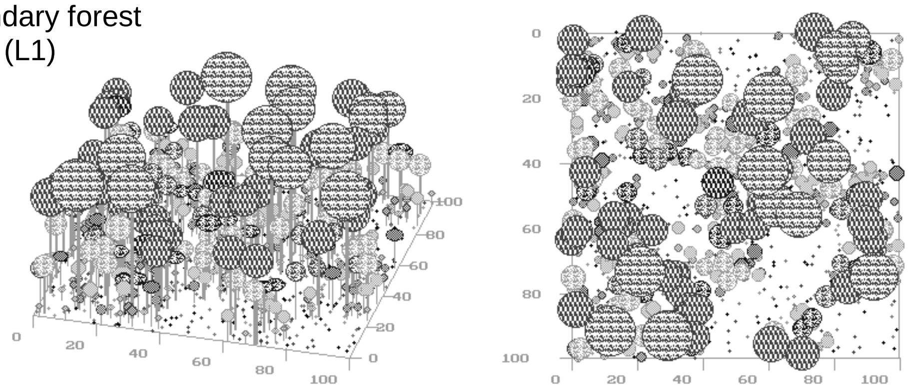
Figure 21: Simulated standing volume in the relogged secondary forest stand (L1): development of standing volume (stem volume including one main branch in the crown) of all trees in the whole stand (total) and in the different species groups.

About 100 years after logging, the pioneer species are again suppressed by the shade tolerant species groups (emergent and upper main canopy group).

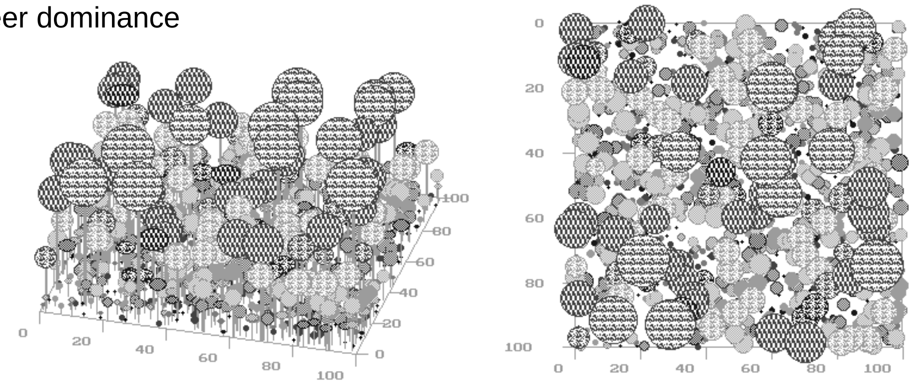
Figure 21 shows the total standing volume distributed to the different height layers. Over the years, the upper layers are successively populated. The increase of volume in the emergent layer is completed only after about 300 years. This simulation result indicates that the restoration of the approximate original primary forest structure takes about three centuries.

Figure 22 visualises the characteristic stages of stand development in a series of pictures showing the stand in a 3D-view and from above. The picture at the top illustrates the condition of the stand immediately after logging (year 0 of simulation). The opened canopy and the gaps caused by the previous logging operations can be recognised. Some pioneers are already established.

year 0: relogged secondary forest stand (L1)



year 15: maximum pioneer dominance



year 300: recovered primary forest structure

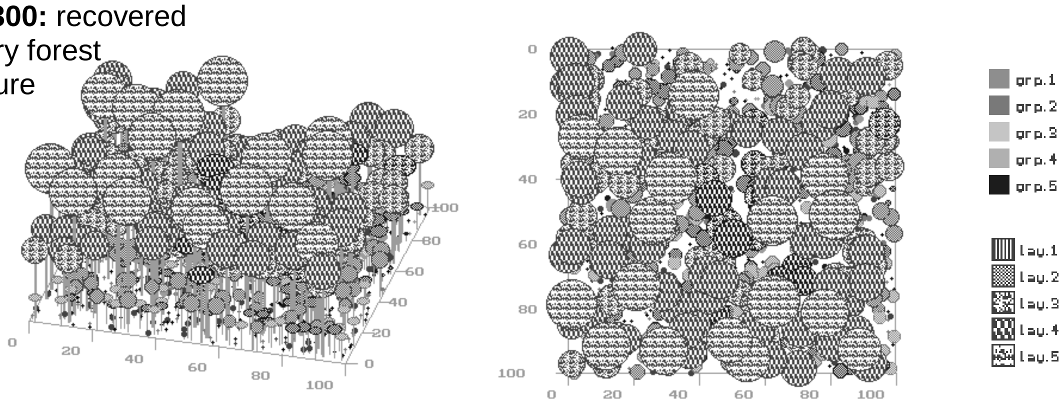


Figure 22: Simulated stand structure in the relogged secondary forest stand (L1) at the beginning of the simulation (year 0, top), at the stage of maximum pioneer dominance (year 15, middle) and after recovery of primary forest structure (year 300, bottom). 3D-views (left) and top views (right) of the stand; the gray tones indicate the species group of the tree and the patterns indicate to which height layer the tree belongs.

The illustration in the middle of Figure 22 shows the stand in its early successional phase at the time of maximum pioneer predominance (year 15 of simulation). In the following years, the number of pioneers decreases and Dipterocarp species of the emergent layer and upper main canopy take over. Finally, after a period of about 300 years (Figure 22, bottom), the primary forest structure has approximately recovered.

The simulation of **secondary forest stands with few pioneers** (stands S1 and S2) gives similar results, although the recovery period is considerably shorter due to the fact that the stands were less disturbed by logging operations. Stand S1 (secondary forest on slope) for instance needs a period of only 170 years to approximately recover to the initial species composition, compared to 300 years for the relogged stand L1. The simulated standing volume of primary forest (490 m^3/ha) is reached 100 years after the end of logging.

The simulated growth behaviour of **secondary forest stands dominated by pioneer species** (stands M1 and M2) results in a resembling growth pattern. Both stands are characterised by an initial predominance of pioneers and a severe infestation with climbers, particularly by climbing bamboo (*Dinochloa trichogona*). The severely disturbed stand structure was caused by intensive conventional tractor logging. A high amount of timber volume was extracted in a rather destructive way, which led to an extensive opening of the stand coinciding with strong exposure of the top soil.

Concerning the heavy infestation by climbers it should be mentioned that the collapse of mechanically instable pioneer trees under the load of climbers, especially climbing bamboo, and its damaging effects on smaller plants is not reflected in the simulation. Despite this simplification, the model produces realistic results, showing that the dominance of the pioneer species lasts for about 50 years, followed by a predominance of Dipterocarp species. In the case of stand M2 the simulation results indicate that the complete recovery of the original primary forest structure will take more than 200 years.

All simulations concerning secondary forest stands resulted in similar growth patterns. It can be concluded that the complete recovery of secondary stands takes at least 150 years, sometimes even more depending on the degree of damage caused by the harvesting operations. However, current forest management practices usually apply cutting cycles which are considerably shorter than the minimum recovery period projected by the model. Only by reducing the harvesting intensity and introducing improved logging techniques it will be possible to shorten the recovery period. For this reason, the next chapter analyses the impact of different logging scenarios by simulating various cutting cycles and harvesting intensities.

5 Simulation of logging scenarios

For the simulation of logging operations assumptions about the occurring harvesting damages have to be made. The figures cited in the literature vary widely depending on the felling intensity and the applied logging technique. In case only one or two trees are extracted per hectare and felling and yarding work is done as carefully as possible (e.g. by skyline yarding) only a small fraction of the forest is demaged. On the other hand, intensive felling and destructive harvesting techniques (e.g. logging with tractors on steep slopes) can destroy large parts of the forest. Detailed studies suggest that 20 % to 80 % of the residual trees are destroyed or damaged during the logging operations (Whitmore 1990, Hendrison 1990).

In the following the impact of two different logging methods is analysed: conventional logging with high damages and reduced impact logging with low damages. The damage percentages used in the simulation were estimated based on figures given in the literature (see Table 3).

The following logging scenarios are based on the structure of stand P1 (dense primary forest on slope). All trees above 60 cm diameter belonging to the Dipterocarp species groups are supposed to be of commercial interest. Depending on the harvesting intensity, the model assumes that the number of felled trees in one logging operation ranges between 5 and 30 trees.

Table 3: Assumptions used in the simulation for two different logging methods: fraction of damaged trees in the residual stand after logging. The damage percentages depend on the size of the damaged trees.

	Diameter class			
	< 20 cm	**20-35 cm**	**35-50 cm**	**> 50 cm**
Conventional logging	40 %	50 %	60 %	70 %
Reduced impact logging	20 %	25 %	30 %	40 %

5.1 Results for selected logging scenarios

Figure 23 shows the simulation results of **conventional logging with a cutting cycle of 20 years**. Each logging operation can be recognised in the diagram by a sudden decrease of total standing volume (Figure 23a). The simulation shows that 20 years after the first logging there are not enough harvestable trees to perform a second harvest. Thus, the next logging can only be carried out after a period of 40 years. The same situation occurs in the years 80, 100, 120, 160, 200, 220, 300, 320 and 380, a strong evidence that the forest is over-exploited (Figure 23d). The logged volumes per cut range between 40 and 150 m^3/ha. After each logging operation the forest growth is mainly constituted by accelerated increment of pioneer species (open circles in Figure 23c). Besides, the species composition of the Dipterocarp species (groups 1 & 2) gradually shifts to smaller Dipterocarps (group 2).

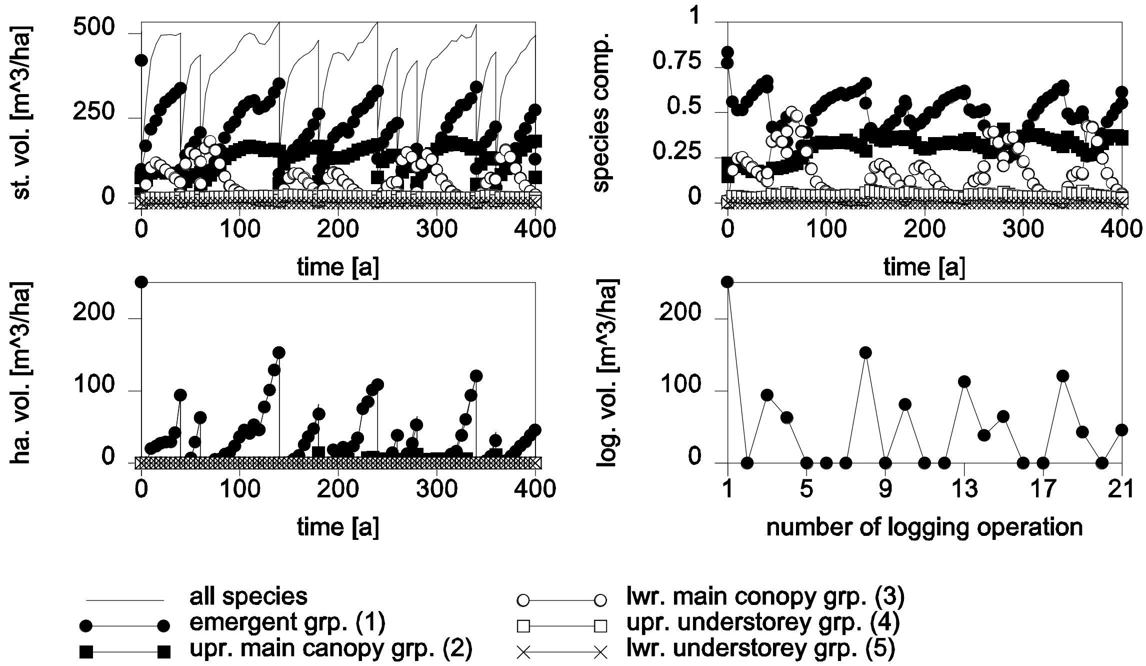


Figure 23: Scenario results for a conventional logging method and a cutting cycle of 20 years. (a) Standing volume (all trees above 10 cm diameter), (b) harvestable volume (standing volume of harvestable trees) and (c) species composition (as fraction of total stem volume) over time for different species groups. (d) Logged volume over the number of the current logging operation (logged volume = volume of the whole stems and the main branches of the logged trees). To calculate from the logged volume the merchantable yield a reduction factor of 0.4 has to be applied (see Chap. 5.2). Discussion see text.

The scenario for **conventional logging with a cutting cycle of 60 years** shows the same trend, although the logged volumes per cut are higher than for the short cycle and fluctuate between 100 and 250 m^3/ha. Considering the volume of Dipterocarp species, the simulation results reveal that even by an extended cutting cycle of 60 years the Dipterocarp trees are not able to reach the pre-harvest value (i.e. the volume at the beginning of the simulation).

The simulation results obtained for **low impact logging with a logging cycle of 20 years** also feature strong fluctuations in the logged volume per cut, including cycles without any logging. The harvestable volume remains very low during the whole simulation and varies between 30 and 100 m^3/ha. In contrast to conventional logging, the growth of Macaranga is moderate.

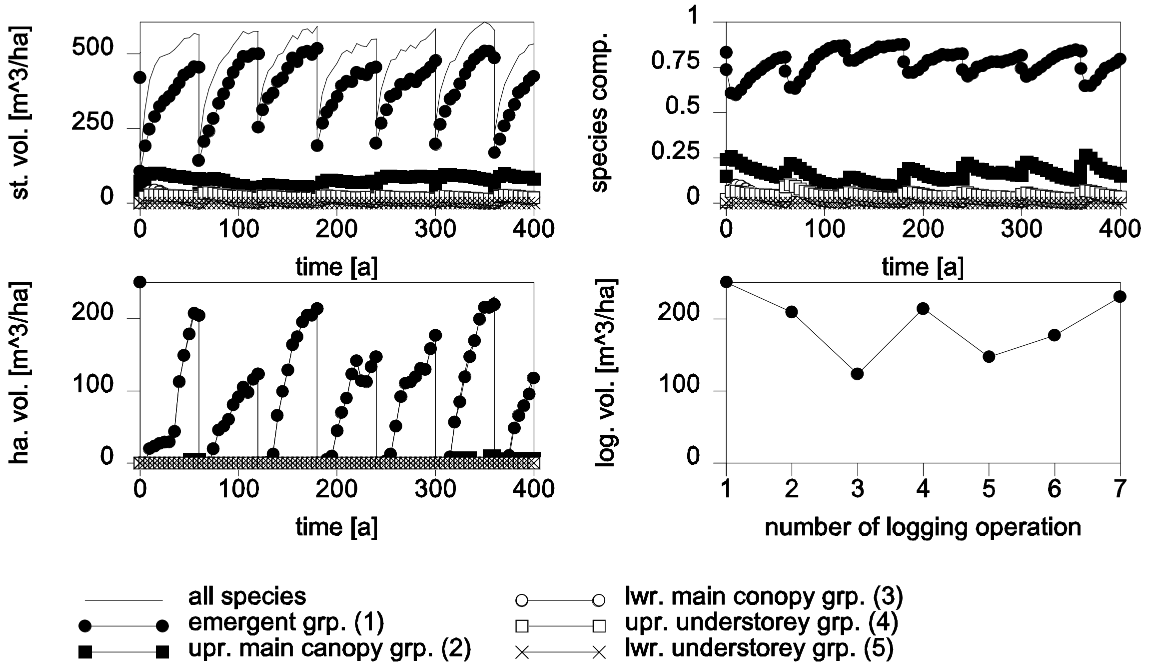


Figure 24: Scenario results for a reduced impact logging method and a cutting cycle of 60 years. For a description of the single graphics see caption of Figure 23. To calculate from the logged volume the merchantable yield a reduction factor of 0.4 has to be applied (see Chap. 5.2). Discussion see text.

Regarding the Dipterocarp trees, species composition changes to smaller Dipterocarps (species group 2).

Figure 24 displays the scenario for **reduced impact logging with a cutting cycle of 60 years**. In the 60 years after the individual logging operations, both the volume of all trees and the volume of harvestable trees almost reach the same value as in non-logged forests (Figure 24a). Although the logged volumes per cut still show some fluctuations (Figure 24d), the species composition in general remains rather stable (Figure 24b).

Comparing the four investigated scenarios, the low impact logging with a cutting cycle of 60 years seems to be best adapted to the growth dynamics and regeneration capabilities of Dipterocarp forests.

5.2 Sustainability of logging scenarios

Two main aspects of sustainable forest management are analysed in the following chapter:

a. the development of an adequate yield regulation, i.e. the sustainability of timber yields

b. the preservation of the forest ecology and its protective functions (soil, water)

For the comparison of the different logging scenarios (conventional logging and low impact logging) regarding their long-term sustainability four indicators are used: (i) total logged volume, (ii) logged volume per cut, (iii) species composition and (iv) opening of the canopy. The first two indicators refer more to the economic interest of obtaining a continuous timber flow from the forest. The other two indicators are related to the ecological status of the forest. A change in composition of tree species has a strong influence on animals living in the forest and thus on the faunal diversity, while the opening of the canopy can be used as an indicator for the erosion hazard. For a comprehensive assessment of the long-term sustainability of logging scenarios further indicators have to be considered as for instance bio-diversity, compaction of the soil and nutrient balance. However, these parameters are currently not taken into consideration by the model.

Figure 25 illustrates the **total logged volume** accumulated over a period of 400 years, pointing to the significant differences between the two logging practices. With conventional logging, a cutting cycle of 60 years shows the highest logged volumes with about 1400 m^3/ha in 400 years (~ 3.5 m^3 ha^{-1} a^{-1}). A cutting cycle of 20 years has the lowest gross timber output (950 m^3/ha

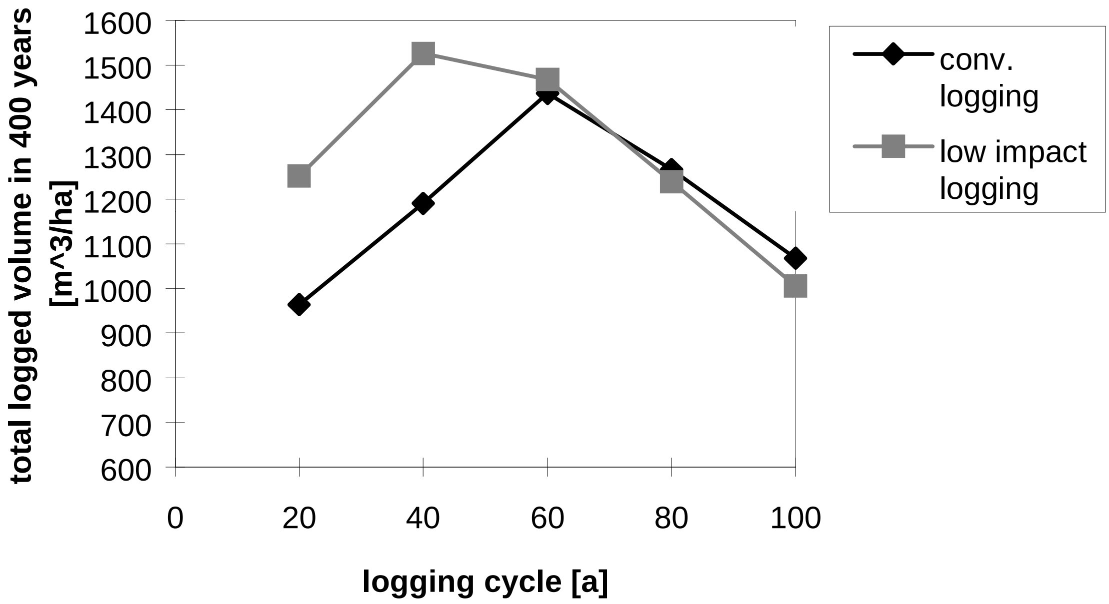
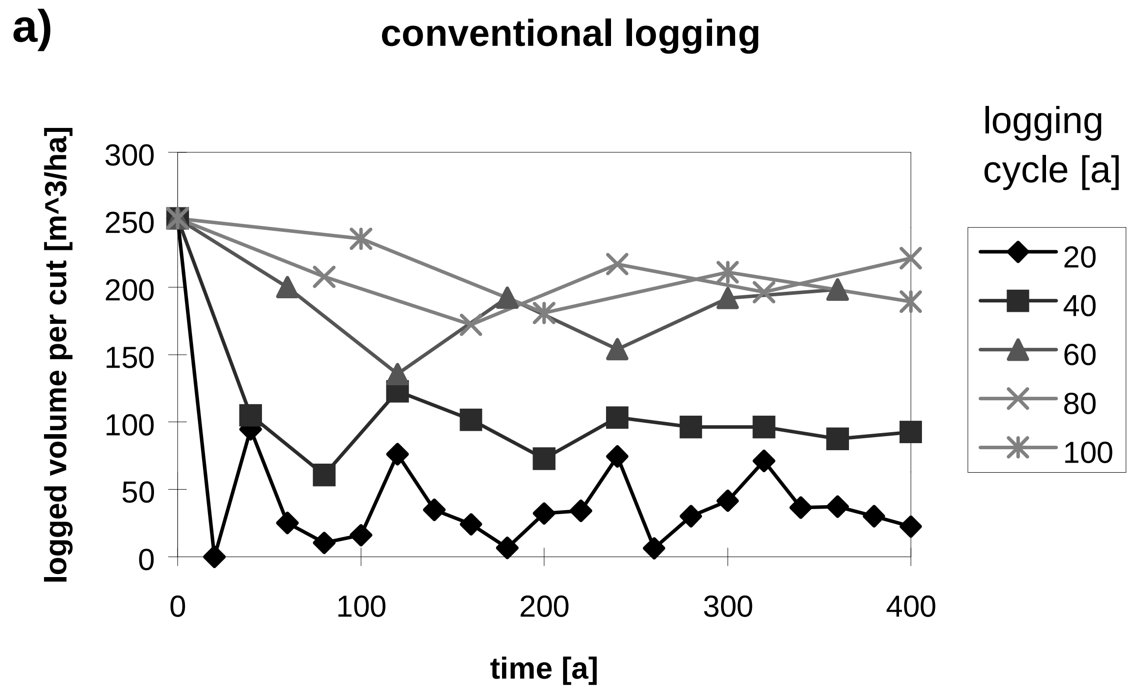


Figure 25: Results for the simulation of different logging scenarios. Total logged volume obtained in 400 years for different cutting cycles and logging methods. Total logged volume is defined as accumulated logged volume in 400 .To calculate from the total yield (volume of stem and main branch of all harvested trees) the merchantable wood volume we have to multiply the total yields by 0.4. (Each value is an average of 5 simulations.)

in 400 years, i.e. 2.4 m^3 ha^{-1} a^{-1}). This result proves that short cycles overuse the forest and are disadvantageous from the economic point of view. For the reduced impact logging the highest logged volumes are obtained for a logging cycle of 40 years. This cycle produces an aggregated gross harvest of 1500 m^3/ha in 400 years. Due to the reduced logging damages, on the average the logged volume is higher than for conventional logging.

Figure 26 shows the **logged volume for each cut**. For both logging methods the cycle of 20 years produces the highest fluctuations. Very stable harvests are achieved for cutting cycles of 80 and 100 years, since the forest always has sufficient time to regenerate its original structure.



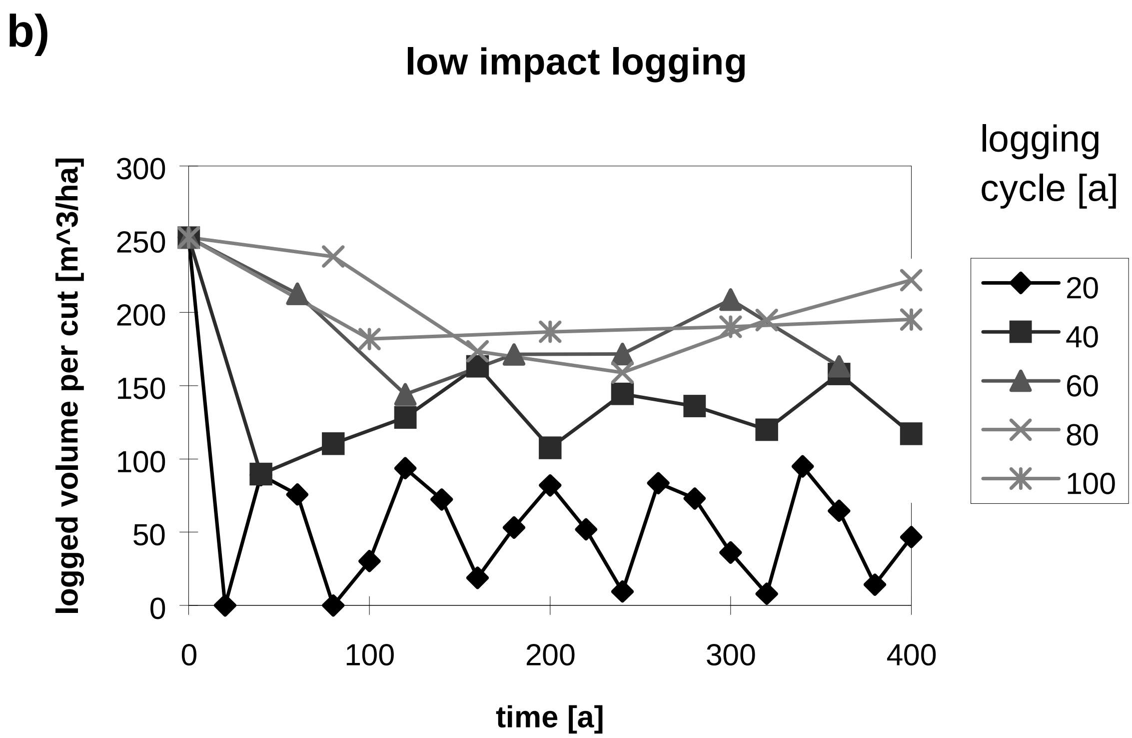
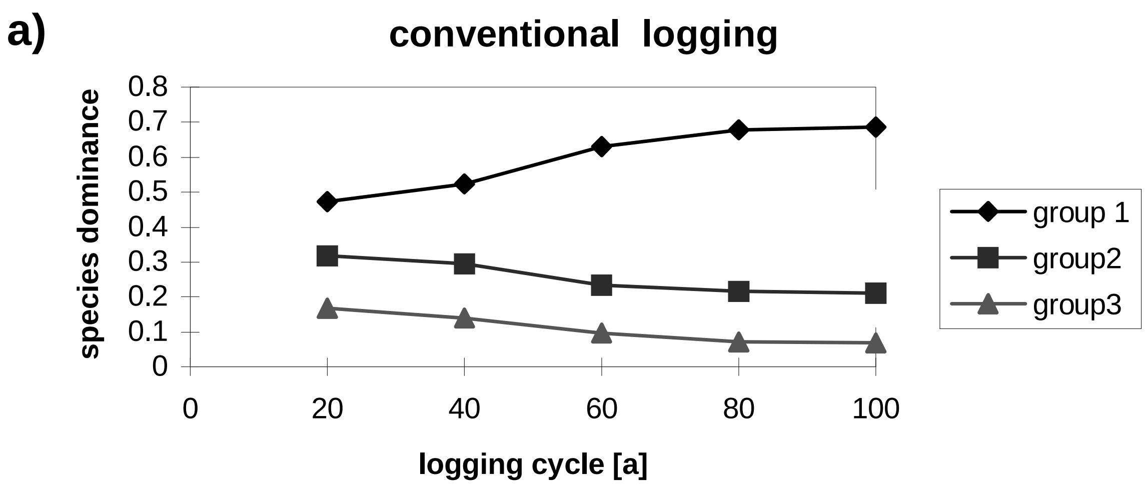


Figure 26: Simulation results for different logging scenarios. Logged volume obtained per cut over time for different cutting cycles and logging methods. The total logged volume over a period of 400 years are shown in Figure 59. (Each value calculated is the mean of 5 simulation runs.)



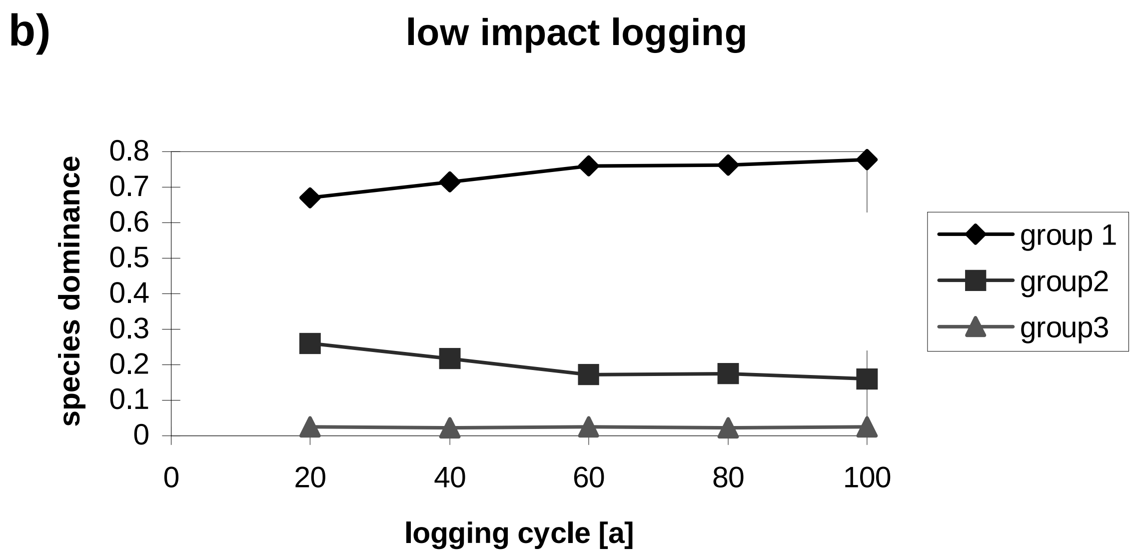


Figure 27: Results for the simulation of different logging scenarios. Mean species composition for different cutting cycles and logging methods. The mean species fraction was calculated by averaging the species fraction over 400 years. The species fraction represent the fraction of stem volume of a certain species group at the total stem volume.

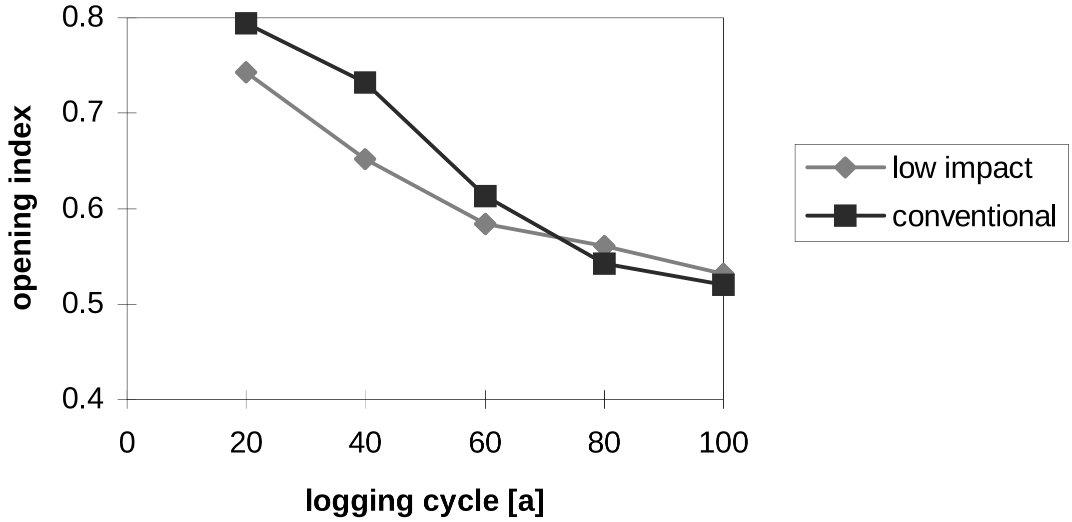


Figure 28: Simulation results for different logging scenarios. Opening of the forest for different cutting cycles and logging methods. The opening index is defined as the fraction of the stand area without big trees (no trees higher than 36 m). The opening of the forest is an indicator for the risk of soil erosion.(Each value is an average of 5 simulation over 400 years).

From the changes in **species composition**, more details about the impact of logging on the ecology of forest stands can be obtained. Figure 27 shows the development of the tree species groups 1, 2, and 3. There is a clear trend that very short logging cycles and conventional logging methods promote the growth of *Macaranga* and other pioneers (group 3). Accordingly, the volume of Dipterocarp species (group 1 & 2) is reduced. Regarding the low impact logging scenario, the percentage of pioneers remains fairly stable at a very low level and seems to be independent from the length of the cutting cycle.

Figure 28 illustrates the **opening of the stand** (i.e. the opening index) for different logging methods and cutting cycles. The opening index is defined as the portion of the stand area without any big trees higher than 36 m. Logging scenarios with short cycles increase the gap portion and thus the danger that erosion affects the soil. Due to the additional soil compaction and surface disturbance caused by heavy tractors, the erosion risk is much higher for conventional logging methods.

According to the long-term effects of the simulated logging scenarios, it can be concluded that short logging cycles < 40 years have negative impacts on the forest stands, even if reduced impact logging methods are applied. Only long cutting cycles of 80 and 100 years in combination with careful logging methods ensure that the main characteristics of stand structure can be maintained. Logging cycles of 60 years seem to be an acceptable compromise between economic and ecological interests. This cycle produces higher harvestable volumes than short cycles, while causing comparatively low impacts on species composition and soil.

6 Discussion

In contrast to some other models developed for the growth simulation of tropical rain forest, the quality and reliability of the FORMIX3 model was tested over a huge range of situations. The combination of model development and comprehensive collection of field data is rare and an exceptional feature of this research project. The results of the simulations indicate that the model shows a realistic behaviour for a wide range of different forest stands. Particularly the future development of logged-over forests can be predicted with an adequate precision. However, as any other growth model, FORMIX3 has its limitations and weaknesses.

At present, the structure of the model restricts its application to evergreen tropical rain forest at sites where climatic conditions remain fairly constant throughout the year. Contingent implications of severe droughts or other unusual climatic conditions are not incorporated into the model. Moreover, the present version of FORMIX3 assumes that the availability of nutrients does not limit the forest growth and that logging operations only marginally change the nutrient pool of the forest. Erosion processes, which are likely to occur on steep slopes with erosion-prone soil types, are not included in the model.

Concerning the different components of the model (see Chapter 2.2), adequate field data are available for most of the parameters. Nevertheless, for a few parameters some uncertainties remain due to the small number of measurements. In some cases it was unavoidable to use data from other forest types, assuming that these values are also typical for the lowland Dipterocarp rain forest. Thus, more measurements are needed for some of the parameters. Additional field work is particularly required with regard to respiration of stem- and branchwood, seedling recruitment rates, and damages caused by logging.

The described shortcomings of FORMIX3 point to the limitations of the model. It has to be kept in mind that models are always simplifications of reality and therefore have a specific range of application. To extend the model´s range of application and to further improve its accuracy and reliability, additional refinements of FORMIX3 are recommended. The future development of the model should focus on the following topics:

- ***Logging damages***: At the moment, the model does not distinguish between damages caused by the construction of skid trails and logging roads and those caused by the felling of merchantable trees. To obtain more detailed information about the impact of logging operations these damages should be calculated separately. Besides, the damaged trees should be classified into two different groups: (a) partially damaged trees with reduced growth rate and higher mortality and (b) totally damaged trees which die immediately. The impact of climbers should also be taken into account.

- ***Site quality***: In the present model the site quality is included in a rather simple way. For more detailed simulations it would be necessary to develop some new approaches for integrating site quality, particularly taking into consideration topography, soil fertility and hydrology. For a comprehensive assessment of the sustainability of logging scenarios some additional parameters such as soil compaction and nutrient balance should be integrated into the model.

- ***Regeneration***: It is recommended to refine the regeneration model. The regeneration of a certain species should not only be dependent on the intensity of the incoming light, but also on the available number of mature trees belonging to this species. This is currently not reflected in the model. The development of the regeneration is quite negligible for short-term growth forecasts as the small trees contribute little to the total growing stock. However, for realistic long-term predictions it is important that this aspect is adequately considered.

- ***Species composition and biodiversity***: The simulation results prove that FORMIX3 is able to provide rough estimates of modifications in the species composition of a forest. By increasing the number of simulated species groups it would be possible to get more detailed information about changes in the species composition caused by logging operations. Needless to say, the development of a concept for estimating the whole stand biodiversity (i.e. flora and fauna) is a comprehensive task. However, some investigations for temperate forest have shown that abundance of certain animal groups and forest structure are correlated (Smith et al. 1981, Shugart and Smith 1992). These linkages between the various parts of the ecosystem indicate that it might be feasible to develop appropriate concepts for simulating the biodiversity of tropical rain forests.

- ***Yield regulation***: The simulated logging operations with fixed cutting cycles (see Chapter 5) are rather simple, but useful for investigating the principal trends. At present, forest management experts discuss more flexible logging strategies. These new strategies link the execution of a logging operation to the actual condition of the forest and not to certain pre-fixed cutting cycles. Furthermore, some foresters propose that a certain number of mature trees should not be harvested, assuming that this would promote the natural regeneration of the stand. Such modified yield regulations and logging strategies could easily be included in the model and as well be investigated by simulations.

Several of the topics discussed above are subject to a currently ongoing research project supported by the Deutsche Forschungsgemeinschaft (DFG). This project in particular aims at utilizing the FORMIX3 model in a GIS-framework (Geographic Information System) to analyse management options for the whole management unit at Deramakot (55.000 ha).

7 Recommendations

This study detected recovery periods of more than 150 years for the present stands at Deramakot Forest Reserve. This result shows that a continued logging must be expected to alter forest structure and thus stresses the importance of carefull evaluation of logging policies. The long recovery periods clearly demand reducing the harvesting intensity and introducing new improved logging techniques. The investigation of the long-term effects of different logging strategies lead to the conclusion that only long cutting cycles of more than 80 years in combination with careful logging methods ensure that the main characteristics of stand structure can be maintained. Preliminarily, logging cycles of 60 years are recommended as a practicable compromise between the needs of adequate yields on the one hand and the preservation of the forest ecology and its protective functions on the other hand.

The development and application of detailed growth models is a relatively new approach to decision making in forest managment planning. The results obtained in this study indicate that an ecophysiological model like FORMIX3 may produce valuable information on stand level growth dynamics, impacts of disturbance and forest recovery periods, and that it can support the analysis of overall logging policies. Such information can only be gained using modelling techniques. It is thus recommended to continue the development of growth models as support tools for professional judgement in forest management planning.

The FORMIX3 software represents a powerful tool for forest management planning. The model is currently under development aiming at the application to whole management units (compare Chapter 6). Having been developed for Sabah, FORMIX3 can now relatively easily be adapted to other tropical forests. FORMIX3 is presently used in cooperation with a GTZ-project in Sarawak, Malaysia (FOMISS, Kuching). The network of South-East Asian forestry management projects of GTZ and its counterparts in different countries of the region shows a continued interest in the development of the model and will in future jointly coordinate the application and further development of FORMIX3. The transfer of the model to African tropical forest is discussed with another GTZ-project in Kenia. A continuation of the ongoing cooperation in South-East Asia and furthermore the application of FORMIX3 in tropical regions in Africa and America is recommended.

8 References

Aiken, S.R. and Leigh, C.H., 1993. Vanishing Rainforests: The Ecological Transition in Malaysia. Clarendon, Oxford.

Aoki, M., Yabuki, K. and Koyama, H., 1975. Micrometeorology and assessment of primary production of a tropical rain forest in West Malaysia. Journal of Agriculture and Meteorology, 31: 115-124.

Appanah, S., Weinland, G., Bossel, H. and Krieger, H., 1990. Are tropical rain forests non-renewable? An enquiry through modelling. Journal of Tropical Forest Science, 2: 331-348.

Bazzaz, F.A. and Pickett, S.T.A., 1980. Physiological ecology of tropical succession: a comparative review. Annual Review of Ecology and Systematics, 11: 287-310.

Bernard, A., Ong, R.C. and Titin., J., 1993. Crown and stem diameter relationships of dipterocarp and non-dipterocarp trees in Deramakot Forest Reserve. In: Sabah Forestry Department Malaysian-German Sustainable Forest Management Project (Editors), Research methods for silviculture and forest ecology (Report 172), Sabah Forestry Department, Sandakan, pp. 53-55.

Bossel, H. and Krieger, H., 1991. Simulation model of natural tropical forest dynamics. Ecological Modelling, 59: 37-71.

Bossel, H. and Krieger, H., 1994. Simulation of multi-species tropical forest dynamics using a vertically and horizontally structured model. Forest Ecology and Management, 69: 123-144.

Botkin, D.B., 1993. Forest Dynamics: An Ecological Model. Oxford University Press, Oxford, 309 pp.

Botkin, D.B., Janak, J.F. and Wallis, J.R., 1972. Some ecological consequences of a computer model of forest growth. Journal of Ecology, 60: 849-872.

Brokaw, N.V.L, 1982. Treefalls: frequency, timing, and consequences. In: E.G.jr. Leigh, S.A. Rand & D.M. Windsor (Editors), The ecology of a tropical forest, Smithsonian Institution Press, Washington, D.C, pp. 101-108.

Brokaw, N.V.L., 1985. Treefalls, regrowth, and community structure in tropical forests. In: S.T.A. Pickett & P.S. White (Editors), The Ecology of Natural Disturbance and Patch Dynamics, Academic Press, Orlando, pp. 53-69.

Burgess, P.F., 1966. Timbers of Sabah. Sabah Forest Record No. 6. Sabah Forestry Department, Sandakan, 501 pp.

Cannell, M.G.R., 1982. World forest biomass and primary production data. Academic Press, London, 391 pp.

Chai F. and Sia, P., 1988. Standtable projections for a mixed swamp forest of Sarawak. Forest Department Sarawak, Kuching.

Clark, D.A. and Clark, D.B., 1992. Life history diversity of canopy and emergent trees in a neotropical rain forest. Ecological Monographs, 62: 315-344.

Cockburn, P. F., 1980. Trees of Sabah I and II. Sabah Forest Record No. 10. Sabah Forestry Department, Sandakan, 385 pp.

Crome, F.H.J., Moore, L.A. and Richards, G.C., 1992. A study of logging damage in upland rainforest in North Queensland. Forest Ecology and Management, 49: 1-29.

Devoe, D.N., 1992. Regeneration from seed under a range of canopy conditions in tropical wet forest, Puerto Rico. In: M.J. Kelty, B.C. Larson & C.D. Oliver (Editors), The Ecology and Silviculture of Mixed-Species Forests, Kluwer Academic Publishers, Dodrecht, Boston, London, pp. 81-100.

Ditzer, T. and Huth, A., 1995. Simulation of structural dynamics in dipterocarp rain forest. Report to Malaysian-German Sustainable Forest Management Project (Report 193), Sabah forestry Department, Sandakan. Center for Environmental Systems Research, University of Kassel, Kassel.

Ditzer, T., Huth, A. and Bossel, H., 1996. Simulation des Wachstums von Dipterocarpaceen-Regenwald in Malaysia zur Bewertung von Nutzungsverfahren. Verhandlungen der Gesellschaft für Ökologie, 26: 425-434.

Ditzer, T., Huth, A. and Bossel, H., 1997. Modelling growth dynamics of tropical rain forest and its disturbance based on functional groups of tree species. Ecology: submitted.

Doyle, T.W., 1981. The role of disturbance in the gap dynamics of montane rain forest: an application of a tropical forest succession model. In: D.C. West, H.H. Shugart & D.B. Botkin (Editors), Forest Succession: Concepts and Application, Springer, New York, pp. 56-73.

Eschenbach, C., 1994. Photosynthesis rates of selected tree species. Sabah Forestry Department, Malaysian-German Sustainable Forest Management Project, Nr.:189, Sandakan.

Fox, J.E.D., 1973. A Handbook to Kabili-Sepilok Forest Reserve. Sabah Forest Records No. 9. Sabah Forestry Department, Sandakan, 102 pp.

German Bundestag (eds.), 1990. Schutz der Tropenwälder- 2. Bericht der Enquete-Kommission "Vorsorge zum Schutz der Erdatmosphäre".. C.F.Müller, Karlsruhe.

Hendrison, J., 1990. Damage-controlled logging in managed rain forest in Suriname. Agricultural University Wageningen, Netherlands.

Howard, A.F. and Valerio, J., 1992. A diameter class growth model for assessing the sustainability. Commonwealth Forestry Review, 71: 171-177.

Hubbell, S.P. and Foster, R.B., 1986. Canopy gaps and the dynamics of a tropical forest. In: M.J. Crawley (Editors), Plant Ecology, Blackwell Scientific Publications, Oxford, pp. 77-96.

Huth, A.,Ditzer, T. and Bossel, H., 1996. Simulation of the growth of tropical rain forest. Final report to GTZ. Center for Environmental Systems Research, University of Kassel, Nr.:P9602, Kassel.

Huth, A., Ditzer, T. and Bossel, H., 1997. Simulation of the growth of tropcial rain forests - FORMIX3. Ecological Modelling: submitted.

Huth, A., Ditzer, T. and Bossel, H., 1997. Long-term impacts of logging in a tropical rain forest - a simulation study. Ecological Applications: submitted.

Huth, A., Hahn-Schilling, B. and Bossel, H., 1994. Untersuchung der Auswirkungen von verschiedenen Nutzungsstrategien auf das Wachstum von Moorregenwald - Simulationen mit FORMIX. Zeitschrift für Ökologie und Naturschutz, 3: 217-225.

Jonkers, W.B.J., 1987. Vegetation structure, logging damage and silviculture in tropical rain forest in Suriname. Agricultural University Wageningen, Netherlands.

Juin, E., Malim, P., Glauner, R. and Uebelhör, K., 1994. Log supply scenarios for Sabah: A fifty years perspective to 2044. Sabah Forestry Department, Malaysia.

Kato, R., Tadaki, Y. and Ogawa, H., 1978. Plant biomass and growth increment studies in Pasoh Forest. Malaysian National Journal, 30: 211-224.

Kennedy, D.N. and Swaine, M.D., 1992. Germination and growth of colonizing species in artificial gaps of different sizes in Dipterocarp Rain Forest. In: A.G. Marshall & M.D. Swaine (Editors), Tropical Rain Forest: Disturbance and Recovery. Philosophical Transactions of the Royal

Society of London B 335, Royal Society, London, Great Britain, pp. 357-367.

Kira, T., 1975. Primary production in forests. In: J.P. Cooper (Editors), Photosynthesis and productivity in Different Environments, Cambridge University Press, Cambridge, pp. 5-40.

Kira, T., 1978. Community architecture and organic matter dynamics in tropical lowland rain forests of Southeast Asia with special reference to Pasoh Forest, West-Malaysia. In: P.B. Tomlinson & M.H. Zimmermann (Editors), Tropical Trees as Living Systems, Cambridge University Press, Cambridge, pp. 26-30.

Kira, T. and Shidei, T., 1967. Primary production and turnover of organic matter in different forest ecosystems of the Western Pacific. Japanese Journal of Ecology, 17: 70-87.

Kira, T. and Yoda, K., 1989. Vertical stratification in microclimate. In: H. Lieth & M.J.A. Werger (Editors), Tropical Rain Forest Ecosystems, Elsevier, Amsterdam, Netherlands, pp. 55-71.

Kleine, M., 1994. Voraussetzungen und Strategien für eine umweltverträgliche, nachhaltige Nutzung tropischer Regenwälder in Sabah, Malaysia. Journal für Entwicklungspolitik, X/3: 375-403.

Kofod, E.O., 1982. Standable Projections for the Mixed Dipterocarp Forest of Sarawak. Forest Department Kuching, Kuching.

Kohyama, T., 1993. Size-structured tree populations in gap-dynamic forest.The forest architecture hypothesis for the stable coexistance of species. Journal of Ecology , 81: 131-143.

Koyama, H., 1981. Photosynthetic rates in lowland rain forest trees of Peninsular Malaysia. Japanese Journal of Ecology, 31: 361-369.

Krebs, C.J., 1994. Ecology. Harper Collins, New York, 801 pp.

Kürpick, P., Kürpick, U. and Huth, A., 1997. The influence of logging on a Malaysian Dipterocarp rain forest: a study using a forest gap model. Journal of theoretical Biology, 185.

Lang, G.E. and Knight, D.H., 1983. Tree growth, mortality, recruitment, and canopy gap formation during a 10-year period in a tropical moist forest. Ecology, 64: 1075-1080.

Manokaran, N. and Kochummen, K.M., 1987. Recruitment, growth and mortality of tree species in a lowland Dipterocarp forest in Peninsular Malaysia. Journal of Tropical Ecology, 3/4: 315-330.

Medina, E. and Klinge, H., 1983. Productivity of tropical forests and tropical woodlands. In: O.L. Lange, P.W. Nobel, C.B. Osmond & H. Ziegler

(Editors), Physiological Plant Ecology IV, Encyclopedia of Plant Physiology, Springer, Berlin, Heidelberg, New York, pp. 281-303.

Meijer, W. and Wood, G.H.S., 1964. Dipterocarps of Sabah. Sabah Forest Record No. 5. Sabah Forestry Department, Sandakan, 344 pp.

Milton, K., Laca, E.A. and Demment, M.W., 1994. Successional patterns of mortality and growth of large trees in a Panamanian lowland forest. Journal of Ecology, 82: 79-87.

Newbery, D.M., Campbell, E.J.F., Lee, Y.F., Risdale, C.E. and Still, M.J., 1992. Primary lowland Dipterocarp forest at Danum Valley, Sabah, Malaysia: structure, relative abundance and family composition. In: A.G. Marshall & M.D. Swaine (Editors), Tropical Rain Forest: Disturbance and Recovery, Royal Society, London, Great Britain, pp. 341-356.

Oikawa, T., 1985. Simulation of Forest Carbon Dynamics Based on a Dry-Matter Production Model I.Fundamental Model Structure of a Tropical Rainforest Ecosystem. The Botanical Magazine, 98: 225-238.

Ong, R.C. and Kleine, M., 1996. DIPSIM: Dipterocarp Forest Growth Simulation Model - A tool for forest-level management planning. In: A. Schulte & D. Schöne (Editors), Dipterocarp Forest Ecosystems - Towards Sustainable Management, World Scientific, Singapore, pp. 228-246.

Phillips, O.L. and Gentry, A.H., 1994. Increasing turnover through time in tropical forests. Science, 263: 954-958.

Poker, J., 1993. Struktur und Dynamik des Bestandesmosaiks tropischer Regenwälder. Mitteilungen der Bundesanstalt für Forst- und Holzwirtschaft, Nr.:174, Wiedebusch, Hamburg.

Putz, F.E. and Milton, K., 1982. Tree mortality rates on Barro Colorado Island. In: E.G.jr. Leigh, A.S. Rand & D.M. Windsor (Editors), The ecology of a tropical forest, Smithsonian Institution Press, Washington, D.C., pp. 95-100.

Ruhiyat, D., 1989. Die Entwicklung der standörtlichen Nährstoffvorräte bei naturnaher Waldbewirtschaftung und im Plantagenbetrieb, Ostkalimantan, Indonesien. Göttinger Beiträge zur Land- und Forstwirtschaft in den Tropen und Subtropen, 35. Goltze, Göttingen, Germany.

Sabah Forest Department, Forestal International Limited, 1973. Sabah forest inventory 1969-1972. Sabah Forestry Department, Sandakan.

Schlensog, M., 1994. Light profiles in different stand types in Deramakot Forest Reserve. Sabah Forestry Department, Malaysian-German Sustainable Forest Management Project, Nr.:190, Sandakan.

Schlensog, M., 1995. Experimentelle Untersuchung des Lichtklimas in Urwaldparzellen Nordborneos. Diploma thesis, Universität Kiel, Kiel.

Schlensog, M., 1997. Experimentelle Untersuchung des Lichtklimas in Urwaldparzellen Nordborneos. Göttinger Beiträge zur Land- und Forstwirtschaft in den Tropen und Subtropen: in press.

Schuhmacher, J., 1995. INSEL 5.0: Reference Manual. Renewable Energy Group, University Oldenburg, Oldenburg.

Shugart, H.H., 1984. A theory of forest dynamics. Springer Verlag, New York, 278 pp.

Shugart, H.H., Hopkins, M.S., Burgess, I.P. and Mortlock, A.T., 1980. The development of a succession model for subtropical rain forest and its application to assess the effects of timber harvest at Wiangarree State Forest, New South Wales. Journal of Environmental Management, 11: 234-256.

Shugart, H.H. and Smith, T.M., 1992. Using computer models to project ecosystem Response, habitat change and wildlife diversity. In: R.L. Peters & T.E. Lovejoy (Editors), Global Warming and Biological Diversity, Yale University Press, New Haven + London, pp. 147-157.

Smith, T.M., Shugart, H.H. and West, D.C., 1981. Use of Forest Simulation Models to Integrate Timber Harvest and Nongame Bird Management. 46th Northa American Wildlife and Natural Resource Conference, Nr.:Wildlife Management Institute, Washington, D.C., U.S.A.

Swaine, M.D., 1989. Population dynamics of tree species in tropical forests. In: L.B. Holm-Nielsen, I.B. Nielsen & H. Balslev (Editors), Tropical Forests: Botanical Dynamics, Speciation and Diversity, Academic Press, London, pp. 101-110.

Swaine, M.D., Hall, J.B. and Alexander, I.J., 1987. Tree population dynamics at Kade, Ghana (1986-1982). Journal of Tropical Ecology, 3: 331-345.

Swaine, M.D., Lieberman, D. and Putz, F.E., 1987. The dynamics of tree populations in tropical forest: a review. Journal of Tropical Ecology, 3: 359-366.

Swaine, M.D. and Whitmore, T.C., 1988. On the definition of ecological species groups in tropical rain forests. Vegetatio, 75: 81-86.

UNESCO, UNEP and FAO, 1978. Tropical Forest Ecosystems. A State-Of-Knowledge Report. UNESCO-UNEP, Paris, 683 pp.

Valentine, H.T., 1990. A carbon-balance model of tree growth with a pipe-model framework. In: R.K. Dixon & et al. (Editors), Process-Modeling of

Forest Growth Responses to Environmental Stress, Timber Press, Oregon, pp. 33-40.

Vanclay, J.K., 1989. A growth model for North Queensland rainforests. Forest Ecology and Management, 27: 245-271.

Vanclay, J.K., 1994. Modelling forest growth and yield: Applications to Mixed Tropical Forests. CAB International, Wallingford, 312 pp.

Weidelt, H.J., 1986. Die Auswirkungen waldbaulicher Pflegemaßnahmen auf die Entwicklung exploitierter Dipterocarpaceen-Wälder. Institut für Waldbau, Universität Göttingen, Göttingen.

Whitmore, T.C., 1984. Tropical Rain Forests of the Far East. Oxford Science Publications, Oxford, 352 pp.

Whitmore, T.C., 1988. The influence of tree population dynamics on forest species composition. In: A.J. Davis, M.J. Hutchings & A.R. Watkinson (Editors), Population biology of plants, Blackwell, Oxford, pp. 271-291.

Whitmore, T.C., 1990. Tropical Rain Forest. Clarendon Press, Oxford, 226 pp.

Yamakura, T., Hagihara, A., Sukardjo, S. and Ogawa, H., 1986. Aboveground biomass of tropical rain forest stands in Indonesian Borneo. Vegetatio, 68: 71-82.

Yoda, K., 1974. Three-dimensional distribution of light intensity in a tropical rain forest in West Malaysia. Japanese Journal of Ecology, 24: 247-254.

Yoda, K., 1983. Community respiration in a lowland rain forest in Pasoh, Peninsular Malaysia. Japanese Journal of Ecology, 33: 183-197.

9 Acknowledgments

For their contributions to this study we would like to thank R. Glauner, C. Eschenbach, B. Hahn-Schilling, B. von der Heyde, L. Kappen, M. Kleine, and M. Schlensog. The Forestry Department of Sabah, the Forest Research Center and the Malaysian-German Sustainable Forest Management Project kindly accompanied our work.

Appendix

A Species grouping for Deramakot

Table 4: Species grouping derived for the Dipterocarp lowland forest of Deramakot Forest Reserve. The species groups described in the following table are parametrised (see Appendix B) for simulation with the model (for further details see Huth et al. 1996).

species group	maximum height of mature tree	response of growth to light	species composition
1	emerging (> 36 m)	non-pioneer canopy species	mainly Dipterocarps
2	upper main canopy (25-36 m)	non-pioneer canopy species	Dipterocarps and non-Dipterocarps
3	lower main canopy (15-25 m)	pioneer	mainly *Macaranga spp.* and *Antocephalus chinensis*
4	upper understorey (1.3 -15 m)	non-pioneer understorey species	non-Dipterocarps
5	lower understorey (0 - 1.3 m)		climbers, shrubs, ferns

B Parametrisation for Deramakot

Table 5: Parametrisation for the Dipterocarp lowland forest of Deramakot Forest Reserve. The parameter values listed in the following table were used for the simulation of Dipterocarp forest at Deramakot, Malaysia, with the FORMIX3 model. The values were determined by a comprehensive literature review and additional specific field measurements. References are given in the table (for further details see Huth et al. 1996).

name	description	parameter value					reference
	parameters for species groups	*grp. 1*	*grp. 2*	*grp. 3*	*grp. 4*	*grp. 5*	
PMAX	maximum photosynthetic production in light response curve [mg CO_2/(dm^2 h)]	10.9	11.6	29.1	18.8	10.9	Eschenbach 1994, Koyama 1981, Bazzaz & Pickett 1980, Whitmore 1984
M	initial slope of light response curve (quantum efficiency) [mg CO_2 m^2/(dm^2 h W)]	0.36	0.20	0.20	0.30	0.36	see PMAX
G	wood density [t_{ODM}/m^3]	0.62	0.57	0.37	0.78	0.62	Cockburn 1980, Burgess 1966, Meijer & Wood 1994
SR	biomass loss rate (respiration, litter fall and root renewal) [1/a]	0.16	0.16	0.16	0.16	0.16	Yoda 1983, Kira 1978
TR	stemwood fraction (ratio of stem biomass to total above-ground biomass) []	0.7	0.7	0.7	0.7	0.7	Kato et al. 1978, Kira & Shidei 1967, Kira 1978, Yamakura et al. 1986, Ruhiyat 1989
CD	crown-stem-diameter ratio []	25	25	25	25	25	Poker 1993, Whitmore 1984, UNESCO 1978, Bernard et al. 1993

NS	potential seedling establishment rate [1/(a 400 m²)]	2500	4000	6000	700	700	Poker 1993, Phillips & Gentry 1994, Milton et al. 1994, Swaine et al. 1987, Lang & Knight 1983
BS	biomass of establishing seedlings [g_{ODM}]	10	10	10	10	10	technical parameter
ISEED	minimum insolation required for seedling establishment [W/m^2]	1	1	10	1	1	Whitmore 1990, Devoe 1992, Bazzaz & Picket 1980, Kennedy & Swaine 1992
MNF	scaling factor for normal mortality rate []	1	1	8	1	1	Poker 1993, Swaine 1989
MNL	specific mortality rate for layer 1 [1/a]	0.08	0.08	0.08	0.08	0.08	Swaine 1989, Clark & Clark 1992, Kennedy & Swaine 1992
MC	specific mortality in case of crowding [1/a] lyr. 1 lyr. 2 lyr. 3 lyr. 4 lyr. 5	0.32 0.04 0.04 0.04 0.04	0.32 0.04 0.04 0.04	0.32 0.08 0.08	0.32 0.04	0.32	estimated
a_1	parameter for height-diameter-relation [a] [m]	2.94	2.30	1.97	3.11	3.11	Sabah Forest Department 1973
a_2	parameter for height-diameter-relation [a] [m/cm]	0.42	0.42	0.39	0.30	0.30	Sabah Forest Department 1973
a_3	parameter for height-diameter-relation [a] [m/cm²]	-0.002	-0.002	-0.002	-0.001	-0.001	Sabah Forest Department 1973
	parameters for height layers	*lyr. 1*	*lyr. 2*	*lyr. 3*	*lyr. 4*	*lyr. 5*	
HM	upper height limit of layers [m]	1.3	15	25	36	50	technical parameter
LAI	maximum leaf area index in a layer []	2	2	2	2	2	technical parameter
K	light extinction coefficient []	0.7	0.7	0.7	0.7	0.7	Kira & Yoda 1989

TN	specific transition rate to next layer [1/a]	0.1	0.1	0.1	0.1	0.1	technical parameter
FALLP	probability for a dying tree to fall []	0.2	0.2				Putz and Milton 1982, Brokaw 1982, 1985
FDAM	fraction of damaged trees due to a falling tree []	0.05	0.3	0.6	0.8	0.4	Whitmore 1990, Jonkers 1987, Hendrison 1990, Crome et al. 1992
	general parameters						
IS	solar radiation above canopy [W/m^2]	335					Aoki et al. 1975, Kira 1978, Kira & Yoda 1989, Schuhmacher 1995, Yoda 1974
i_{max}	number of layers	5					technical parameter
j_{max}	number of species groups	5					technical parameter
AP	spatial size of a patch [m^2]	400					technical parameter
PN	number of patches	25					technical parameter

a A parabolic functions is used for the height-diameter-relationship: $h = a_1 + a_2 d + a_3 d^2$ with h height-to-top and d diameter at breast height.

C Simulated data compared with field data for Dipterocarp forest

Table 6: Simulated data for Dipterocarp forest in climax-state at Deramakot Forest Reserve compared with field data reported for other mature Dipterocarp lowland evergreen rain forests in South-East Asia (mostly Malaysia).

variable	description	value simulated for Deramakot [i]	field data recorded for comparable forests	reference
B	aboveground biomass [t_{ODM}/ha]	460 [a]	294-420	UNESCO (1978, Malaysia)[b]
			400	UNESCO (1978, Malaysia)
			475	Kato et al. (1978, Pasoh, H=57 m)[k]
			664	Kato et al. (1978, Pasoh, H=46 m)
			650	Proctor et al. in Whitmore (1984, Mulu)
			364	Bullock in Cannell (1982, H=40 m)
			421	Kira (1978, Pasoh, H=61 m)
			431	Kira (1978, Pasoh, H=61 m)
			508	Yamakura et al. (1986, H=71 m)[c]
BA	basal area [m²/ha]	40	37	Appanah et al. (1990, Pasoh, d > 9.6 cm)[k]
			26-38	Newbery et al. (1992, Danum Valley, d > 10 cm)
			36.8	Yamakura et al. (1986, d >4.5 cm)[c]
LAI	leaf area index [ ]	7	6.8- 4.7	Schlensog (1995, Deramakot)
			7.1-8	Kato et al. (1978, Pasoh), Kira & Yoda (1989)
			6.8-6.9	Kira (1978)
			8-10	Bullock in Cannell (1982)
			7.3	Yamakura et al. (1986) [c]
GAP	gap area fraction [%] [j]	8	0.5	Newbery et al. (1992, Danum Valley)
			13-8	Brokaw (1995, Malaysia)
			10	Poore in Whitmore (1984, Malaysia, 23 ha)
			9	Yamakura et al. (1986, h < 10 m, 0.5 ha)
			3-25	Brokaw (1995) [e]
			30	Hubbell & Foster (1986, h < 20 m, 50 ha) [f]

SDS	slope of the stem number-diameter-distribution [] [g]	2.9	2.9 2.6 ~2.9	Appanah et al. (1990, Pasoh) Newbery et al. (1992, Danum Valley) Fox (1973, Sepilok)[h]

a In FORMIX3 the standing volume (= volume of all stems and main branch) is calculated from the aboveground biomass as follows: standing volume = aboveground biomass * TR * G, with TR stem wood fraction (0.7 in the standard parameter set) and G wood density.
b The biomass is calculated from the standing volume by multiplying with the wood density. 0.6 g/cm³ is a reasonable mean density for primary lowland tropical rain forest (Whitmore 1984).
c Dipterocarp evergreen rain forest (primary forest) in Indonesian Borneo.
e Gaps in tropical lowland rain forest all over the world with different definitions of gap. Whether all of these forests are mature forests is not reported.
f Tropical rain forest in Panama.
g Calculation on the basis of 10 cm classes for the diameters and stem number per hectare.
h The value of SDS for this field data was estimated in Bossel & Krieger (1994).
i The values for the aboveground biomass and the basal area are for all trees with diameter > 10 cm. The values for the leaf area index include all trees (no dimeter threshold).
j In the simulation an area of 20 x 20 m size is called gap, if all trees in this area are smaller than 25 m in height to top. The indicated literature values are based on different gap definitions. For details see references.
k H is the maximum height of the forest stand. d diameter, h height.

D Diameter distributions of inventoried stands

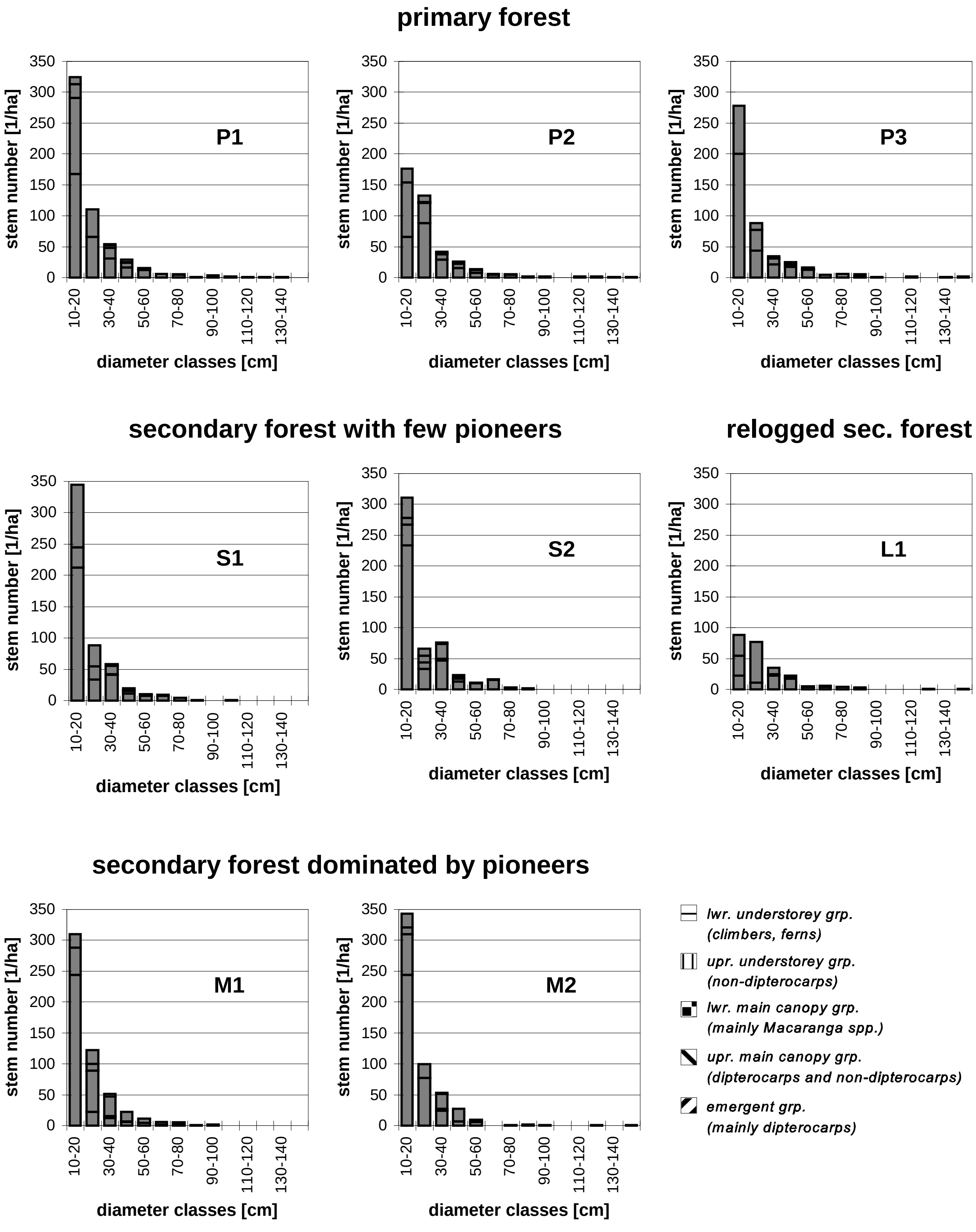


Figure 29: Detailed diameter distribution for eight inventoried stands representing four types of forest structure in Deramakot Forest Reserve: distribution of stem numbers of single species groups to 10 cm diameter classes for diameters > 10 cm. The recorded inventory data were used to initialise simulations of stand development.

E Contact address

Dr. Andreas Huth

Thomas Ditzer

Center for Environmental Systems Research

University of Kassel

Kurt-Wolters-Str. 3

D-34119 Kassel

Germany

Tel +49.561.804.2496 (office +49.561.804.2231)

Fax +49.561.804.3176

Email huth@usf.uni-kassel.de

URL http://www.usf.uni-kassel.de

Deutsche Gesellschaft für
Technische Zusammenarbeit (GTZ) GmbH

Tropenökologisches Begleitprogramm (TÖB)
Tropical Ecology Support Program
Postfach 5180
D-65726 Eschborn
Federal Republic of Germany

Fax +49-(0)6196-79-7413
E-Mail (Internet): GTZ-TOEB@GEOD.GeoNet.de
World Wide Web: http://www.gtz.de

Im Auftrag des Bunmdesministeriums für
wirtschaftliche Zusammenarbeit und Entwicklung (BMZ)