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# TROPICAL RAINFOREST SILVICULTURE: A RESEARCH PROJECT REPORT

by

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# FOREWORD

This is the final report on a research project financed by the Ministry of Overseas Development from 1974-77, and carried out by Dr. T.J. Synnott at the Commonwealth Forestry Institute, University of Oxford. An essential part of the Project was the preparation of a Manual of Permanent Plot Procedures for Tropical Rainforests, which has been published as Tropical Forestry Papers No. 14.

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## SUMMARY

This report describes the results of a research project concerned with silviculture and management of tropical rainforest. Data from silvicultural treatment experiments were analysed to examine the effects of logging and treatments on growth rates and yields. It waw shown that diameter increments, and basal area and volume production, were strongly affected by reductions in stocking resulting from logging and treatment.

Various computer programs were developed and adapted for processing data from recurrent measurements of rainforest plots, including versions suitable for small computers. New programs were developed to find ways of using such data for making more reliable forecasts of future stocking and yields in rainforest, and were shown to be feasible and very promising for management and research purposes.

The results of the project, and their practical implications for management and research, are presented and discussed.

## INTRODUCTION

In 1974, a research project was initiated in the Unit of Tropical Silviculture at the Commonwealth Forestry Institute entitled 'The Management of Tropical High Forests'. The aims of this project included:-

1) developing guidelines for management, by analysing data from silviculture experiments involving various treatments or cutting systems; determining, with improved statistical reliability, the effects of treatments on growth rates; and interpreting these effects in terms of different management systems;

2) developing new computer programs for forecasting stocking, composition and size frequencies from recurrent measurements of permanent plots, by projecting the observed growth, mortality and recruitment into the future;

3) developing programs for essential data-processing and calculations, suitable for small computers in interested tropical countries.

In addition, an ongoing program of training and routine data-processing for various countries was continued.

The project came to an end in 1977, but work on some aspects of the research has continued with the Unit. The results and conclusions reported here should be considered as part of a continuing search for methods of analysing and interpreting measurement data and methods of managing rainforest for their long-term productive and protective benefits. In particular, much more work is required to develop the existing stand-projection program into a system for reliable forecasts and management planning.

The experience gained with rainforest plots and data of different kinds has been used to prepare a manual of methods and techniques for establishing and measuring permanent plots for continuous forest inventory and silviculture research. This manual is intended to give practical guidance to researchers and forest managers who are concerned with establishing or measuring permanent plots. It has been published separately as Tropical Forestry Paper No. 14, A Manual of Permanent Plot Procedures for Tropical Rainforests.

ACKNOWLEDGEMENTS

This projected was financed by Research Scheme R.2878 of the United Kingdom Ministry of Overseas Development, through the Department of Forestry of Oxford University, and it was made possible by the help of the staff and resources at the Commonwealth Forestry Institute, particularly in the Unit of Tropical Silviculture, the Library, and the Computing Section.

The project has been carried out at Oxford because it was possible to arrange collaboration between tropical silviculturists, computer operators and biometricians with the facilities and accumulated data at the Institute. Thus, almost all the work reported here has been carried out by two or more people working together. I particularly want to note with much gratitude the major contribution of Julie Smith in writing, developing and applying computer programs and in manipulating and analysing quantities of complex rainforest data, the valuable help of Philip Adlard, Denis Alder (particularly for programe GROPE), Ian Andrew (particularly for program GROWTH), Colyear Dawkins, John Palmer, Linda Roberts, Howard Wright and other members of the UTS, the unfailing clerical help of Pam Taylor, Coral Taylor and Sue Lygo and the stimulus and comments from many other professional colleagues.

I also wish to acknowledge the great debt owed to Colyear Dawkins, since much of the work reported here is founded on his reports of field methods developed in Uganda and on his statistical and computing work, and to Barbara Dawkins who wrote the first versions of several of the computer programs in regular use for handling rainforest data.

The final Project Report was produced at the end of 1977, and copies were distributed for comments. My thanks are due to all those who wrote to me, sending many valuable suggestions.

Data have been received from many tropical regions for analysis at Oxford, either at the request of the country concerned or at our request for particular research purposes. Data from the following countries have been used for this project, supplied by the individuals or organizations named; they are gratefully thanked, since the project depended entirely on outside sources of measurement data:-

Australia: from C.S.I.R.O. Queensland Regional Station, Atherton.

Ghana: from Planning Branch, Dept. of Forestry, Kumasi.

Malayan Peninsula: from Tang Hon Tat, Forest Research Institute, Kepong, and the FAO Forestry and Forest Industries Development Project.

Nigeria: from P.R.O. Kio, Dept. of Forest Resources Management, Ibadan.

Sabah: from Forest Research Centre, Sandakan.

Sarawak: from Forest Dept., Kuching.

Solomon Islands: from Forestry Division, Honiara.

Uganda: from Forest Dept., Entebbe.

Venezuela: from M.A.B. Project, San Carlos.

# REPORT ON A TROPICAL RAINFOREST RESEARCH PROJECT

## 1. STAND FORECASTING

### 1.1 Background to problems of forecasting

Production forecasts for many tropical plantations can now be made reasonably confidently, based on site classification, accurate volume tables, and yield tables. This is because it is not difficult to correlate growth-rates, size, site and competitive status (crowding) in stands of one species and known ages grown together. Further, the performance of each individual tree is closer to the average performance in an even-aged monoculture, where sizes, spacing or thinning are relatively uniform, than in a mixed indigenous forest.

In Tropical Rain Forest (TRF) a variable mixture of numerous species, each with much genetic diversity, grows in a wide variety of combinations of ages, sizes and relative competitive statuses. In order to obtain a reasonably precise estimate of average growth rates, many measurements are required for each category of size and species and preferably for several categories of competitive status; the large sizes and less common species will inevitably be less well represented in any fixed-area sample, and their growth rates and their correlations with status can be less accurately estimated. Thus large samples are needed for accurate estimates of their average growth rates, and hence "times of passage" (the term coined by Biolley for the average time required by trees to grow from one diameter class to the next higher one). However, such large samples increase the problems caused by the variability of site, stocking and composition, since they usually embrace much variation in genetic potential, age and status in each category. Therefore in TRF the tree-by-tree variation around the average growth rates in each category is much larger than is found in a managed plantation monoculture. The variability of growth rates within a size class of one species is generally greater than the differences between size classes or even between species.

Average growth rates have often been used in the past for estimating times of passage, rotation lengths and felling cycles, and sometimes for production forecasts in TRF. (cf 17; 32, p. 218; 38; for ways of calculating increments and times of passage for rotations, felling cycles and yields.) However, these methods could take little account of the variability between trees and the fact that most trees are growing faster or slower than the average. Therefore they cannot reliably predict the range of sizes expected within each species or the numbers of trees which will reach any particular size. It is biologically unreasonable to base detailed management plans or forecasts on the assumption that each tree will grow at just the average rate calculated from other trees of the same size-class in the past. Such forecasts may become more reasonable if they include confidence limits calculated from the observed variability of growth rates, and better still if they relate growth rates to other measured variables in addition to size.

## 1.2 Computer programs for stand table projections

Several stand forecasting models have been developed for mixed hardwood forests in North America (7, 21, 36, 41, 56). These appear to be very useful and effective in certain circumstances but not all suitable for the data collected in TRF sample plots. In several of the studies reported, data were obtained from recurrent measurements of stands, spanning up to 40 years, and the predictions involved a Markov approach, based on a transition probability matrix for calculating the probability for each tree of growing from its current size class to the next larger. These transition probabilities for each tree are calculated from the actual observed growth of all trees between size classes during the preceding measurement period, and are not affected by the growth rates of the tree earlier in its life.

In TRF Sample Plot data, the diversity is so great that many size-classes of many species would contain few or no trees, so the transition matrix contains discontinuities, and the probabilities cannot be accurately estimated. Many more transition matrices are required if it is desired to relate increments to other variables such as crown scores or competition indices. This would result in a very clumsy model, and in TRF it would be almost impossible to obtain enough data to calculate probabilities reliably.

The stand table projections by this method are based on movements between size classes, so much of the precision obtained in TRF plots by careful measurements of individual trees is lost in the forecast.

A number of other models of tree growth, mortality, regeneration and stand development have been developed for long term forecasts (6, 22, 48). These methods are not necessarily based on several recurrent measurements of the stand, but require information about individual species characteristics such as maxima for age, height and diameter, and relationships between photosynthesis and light regimes, climate and soil moisture, and also about the environment (regimes of seed-eaters and seedling-browsers, and topographic and climatic data). In TRF, such detailed information is seldom available, so we are limited to methods which involve projection of existing trends in the measured variables such as size and stocking.

We need a model which can make the best use of careful measurements of, often, few trees covering a wide range of sizes, and will project these measurements, often only a few variables, allowing for correlations between increment, size, status and the tree-by-tree variation, over the whole period of measurement.

## 1.3 Current approach

The approach adopted in this project has been to use recurrent measurements of permanent plots in TRF to correlate growth rates with sizes and other measured variables for each tree, for any species or group of species. A regression model is derived from all the trees and is then applied to each tree individually to predict its increment from its size and status. Inevitably, the competitive status of each tree changes with time and its growth is influenced by different factors which cannot always be measured so the model cannot be used deterministically. A random element is included in the model to allow for the apparently random elements of growth, i.e. the often poor correlation between growth rate and size, species, and available measurements of status. If there is little correlation between growth and the other variables, then the model will predict nearly random increments for successive periods for each tree.

The computer program GROWTH is a first working version, while program GROPE is a more complex version not yet fully developed (2).

1.4 Program GROWTH

In GROWTH, a regression is calculated relating diameter increment to diameter only, thus using the same variables as in time of passage calculations. Usually, observed increments are very variable and not strongly correlated with initial diameter, i.e. the diameters account for only a small part of the observed variation. This model incorporates a random element (see below) to ensure that predicted increments show a variability comparable to that of observed increments; this feature distinguishes GROWTH from deterministic models, based on smoothed graphs and times of passage, in which predicted increments conform to the mean of the observed increments with no variability.

The growth model is in the form of a regression

$i_d$ from $t_1$ to $t_2$ = a + b (d at $t_1$) + e

where d = diameter
i = individual tree increment
e = a random element, generated by the program, with a mean of zero and a variance defined for each species by the standard deviation (S.D.) of the regression $i_d$ on d
$t_1$, $t_2$ = times of measurement
a, b = constants

Program GROWTH also constructs models of ingrowth (recruitment) and loss (mortality) for each species-group. The program calculates the average size of the ingrowing or lost trees, and the S.Ds., and the average rates of ingrowth or loss (i.e. the numbers of ingrowing or lost trees as a proportion of the population) and the S.Ds. of the rates in successive intervals. The predicted numbers and sizes of all ingrowing and lost trees are then calculated, based on the observed averages modified by random elements based on the S.Ds.; thus the numbers and sizes of trees lost or gained in each predicted interval continue to be as variable as in the observed data. Ingrowth trees predicted by the program will usually be close to the lower size-limit of measurement, whereas lost trees will usually have a wider, more random distribution through all sizes.

Separate regression models are calculated for each species or for any chosen group of species. In addition, several different types of model have been developed and tested, incorporating transformations of the independent variable d using reciprocals, logarithms, etc.

Program GROWTH can derive the models of increment, ingrowth and mortality from two or more sets of measurements, and operates by applying the models to the last measurements to forecast future sets of trees and sizes in the form of a full stand composition. Each tree is projected forward, with successive increments, unless the mortality model predicts its death; simultaneously, new ingrowth trees are introduced and each is grown through successive intervals. The program can list the complete predicted stand and also a stand table of numbers and total basal area for each species-group, each size-class and each predicted date.

The program includes several ways of assessing the reliability of 1.
the predictions. The program calculates the stand table for each date of measurement using the data provided, derives a regression model from the same data, and then calculates a "predicted" stand table for the same dates by applying the regression model to the first measurements. The calculated "predicted" stand table is then printed beside the true, "observed" stand table and any major faults or discrepancies will show up as differences. So far, these differences have been assessed subjectively, while testing the usefulness of different types of model.

A more useful check is possible if several years of measurements are available; the regression model is then constructed from only the earlier years of data and then used for predicting the later years. If there are no important differences between the predicted and observed stand tables for the later years, then longer predictions into the future may be made more confidently using models based on all the data.

The accuracy of this model is inevitably limited since it correlates only size and increment, and takes no account of other information on tree status and stand competition. This was appreciated when the program was first written, and it was anticipated that the model would be developed to include crown form, crown position and some measure of competing basal area. We have gained considerable experience of the problems and techniques of this kind of modelling approach, particularly in:-

a) the use of several different regression models using transformations of the diameters;

b) methods of manipulating the data and results so that numerous options could be calculated and tabulated clearly, including any chosen grouping of species and converted units of measurement;

c) methods of calculating recruitment and mortality in terms that are biologically and statistically acceptable;

d) developing ideas of what other factors are required for improved models.

During 1976, GROWTH was developed and tested sufficiently to eliminate problems of handling various types of data and of printing the results in the formats and options required. Predictions using various conversions of diameter were compared, and it was found that the equation using (log d) gave results which were usually the closest to the observed stands. Differences could usually be attributed to observed discrepancies or anomalies in the data (such as those caused by the Kolombangara cyclone (58)).

The results confirmed the feasibility of this approach for making reliable forecasts without the inadequacies of earlier deterministic methods. We did not make an exhaustive attempt to develop the most reliable version of GROWTH, and the program is not being further developed, because it was clear that we needed a more complete model incorporating other variables. (Thus, although the Kolombangara cyclone drastically changed competitive statuses, a more complete model should incorporate the responses to these changes and still make reliable projections from the final measurement.)

1.5 Program GROPE

We have now developed a second prediction program called GROPE (written by Denis Alder and Julie Smith (2)) which incorporates additional tree variables such as crown position and tree height. It also calculates some measures of the local growing stock and of each tree's competitive status which may be correlated with individual tree increments: these measures include numbers of stems, basal areas and volumes of all trees and of those in certain categories (e.g. emergent crown status), within the subplot or quadrat (called quadrat variables).

GROPE uses a generalised multivariate model which projects rates of change of any of the commonly measured tree or quadrat variables available, not only the sizes, numbers, ingrowth or losses used and modelled by GROWTH. In effect the model will reflect the basic patterns of response to competition variables characteristic of each species more sensitively than the GROWTH models.

For example, a test run of GROPE may be used to project data for sizes, heights and crown positions. The program constructs models of changes in total basal area, stocking, ingrowth and mortality per quadrat, and in diameters, heights and crown positions per tree and it then predicts the stand composition for a date in the future showing every tree, each with perhaps a changed diameter, height and crown position. The program then recalculates the new quadrat variables (basal area, etc.) and applies the model to the new predicted values of tree variables (diameter, etc.) to predict values for the next date.

Since GROPE is a stochastic model, incorporating random elements, repeated runs of the same program with the same data will produce slightly different forecasts of the stand tables for any future dates. The differences will be related to the natural variability of the rainforest. In this way, it will be possible to attach some form of confidence limits to the yield predictions for purposes of management planning. It should again be noted that GROPE is for tree growth projection and cannot make prophecies about events which do not depend on the relation between tree increment (or yield) and status (or competition).

It must be stressed that GROPE and its current developments are not yet operational as management tools. They require further development and testing, including comparative tests between the results of these regression models and of stand table projections based on mean times of passage, before they can be shown to be reliable, accurate and suitable for management planning. This objective can be pursued by any organization with adequate computing facilities and suitable data, and all existing programs are available for all who wish to use them.

## 1.6 Summary of forecasting methods

Forecasts by "time-of-passage" calculations:-

i. Calculate average annual increments for each species and size class

ii. Determine growth of each tree through successive classes using average growth rates to predict sizes for a future date

Forecasts by Markov Chain transition probabilities:-

i. Calculate rates of growth from each size class to the next larger

ii. Calculate probability of any tree moving from one class to the next in a given time

iii. Apply these probabilities to each tree for successive intervals to predict size class distribution

Forecasts by regression models GROWTH and GROPE:-

i. Calculate regression of increments on size and various measures of competitive status, plus variance

ii. Apply regression model with random element to each tree to predict its next increment and status from its current size and status

## 1.7 Future developments

### 1.71 Growing space; competition indices; basal area tallies

Using new programs (1), it is possible to characterise the competitive status of each tree, using the relative diameters, heights and crown sizes of neighbouring trees and their distances apart (from their co-ordinates). These measurements indicate the "growing space" or ground area occupied by each tree. Further, the actual space occupied by each tree may be compared to a measure of the average growing space occupied by trees of the same size and species, or the "ideal" space occupied by fast-growing exposed individuals, to give an index of competitive stress or crowding for each tree. In addition, simulated relascope sweeps may be calculated, to give the local basal area, centred on each individual tree, as a better measure of local competition than basal area per quadrat.

It may be possible to develop a competition index or a measure of growing space which will be better correlated with individual tree growth than the size, crown status or quadrat variables, thus improving the accuracy of predictions. Suitable data should define individual tree positions as well as heights and crown measurements which are not usually measured in Sample Plot programs. Data from several countries (Malaysia, Australia, Uganda, Venezuela, Annex 1) have all or some of this [illegible] information; most of the very detailed measurements have been in untreated forest, but the same methods apply when appropriate measurements are available from treated forests.

1.72 Simulated felling or treatment regimes

The stand projection program may be developed into a management model by artificially applying various cutting regimes or stand treatments during runs of the program. This may be done by eliminating certain categories of trees on certain dates, such as unwanted species or valuable species down to various sizes, thus producing changes in crown status, competition and growth-responses among the remaining trees.

If sufficient data are available (e.g. from treatment experiments or any area logged or treated to variable intensities) for calculating regression models of the growth and behaviour of different species in different competitive situations, it should then be possible to simulate the long term production effects of different cutting cycles, different girth limits for different species, or of eliminating certain categories of trees determined by species, size or status.

For accurate predictions, sensitive measures of individual tree competitive status will be required, based at least on quadrat variables defining the whole local stocking, and preferably on tree-by-tree indices of growing space.

1.73 Simulated tending or enrichment treatments

A further development of the management model may be achieved by simulating various weeding, thinning and enrichment planting treatments. This may be achieved by altering the ingrowth and mortality models so that certain categories (species, sizes or statuses) of small trees have higher mortality or less recruitment (simulating weeding or thinning) while others have increased recruitment (successful natural or artificial regeneration) or lower mortality (through tending or liberation).

1.8 Practical applications

GROWTH has demonstrated the feasibility of using conventional permanent plots as the basis for models to predict yields from TRF, and GROPE will allow a significant advance in yield predictions. There is no technical limit to the period of time over which forecasts can be made, but the accuracy of the forecasts will depend upon the reliability of the data and on the long-term uniformity of the patterns of growth, mortality and recruitment.

1.81 Management and planning

Using the GROPE model, it will be possible to make forecasts of the growing stock and potential yield from a management unit, broken down into species and sizes, allowing land use planners and forest managers better scope for selecting options between quantified alternatives. This may be done in two ways:-

1.811 Sample plot projections

If permanent sample plots are measured for some years, each plot may be projected to the future date, and the future composition of the whole forest may be estimated with confidence limits. The accuracy of the forecast will depend on the number of years of measurements, the size of the sample and the variability of the forest.

1.812 Inventory projections

Appropriate models for each species may be constructed from sample plot data and then applied to data from an inventory of the same (or even a different) forest, to forecast its future composition.

Clearly the accuracy of this approach will depend on the extent to which a model of growth rate and size, status and competition can characterise the behaviour of any one species growing in a broad range of sites and communities. If this is feasible, we may construct species models from a small sample (e.g. 1-2%) in repeatedly measured plots and then apply them to a larger inventory sample (e.g. 5-20%) for a more precise estimate of future production.

1.82 Research plot studies

In order to make a reliable interpretation of forest dynamics from short term results (single or a few repeated measurements) in plot-based studies, it is often essential to obtain some information about the past status of the plot, particularly of the past relative stocking of different species. Equally, it would often be extremely valuable to have reliable estimates of the future stocking and composition of plots in terms of projections of observed trends. Two among many possible research applications are:-

1.821 Comparison of treatment effects

Different treatments (logging intensities, poisoning, enrichment) have a variety of simultaneous effects on numbers, basal area, volume, growth rates, recruitment and mortality of different species. Even when it is possible to distinguish these effects, it may be impossible to evaluate them in terms of the management objectives.

For example, after treatment one species may have more stems and faster growth but higher mortality than another species; and comparable differences from any other species; and different effects under different treatments. What will be the net results after 40 years?

The treatment effects can be evaluated directly if the treated stands are projected to the end of a potential felling cycle and the forecast stand compositions compared.

1.822 Studies of succession and stability; ecological studies

A number of plots in relatively undisturbed forest have been regularly measured over many years, particularly in Africa and Malaysia. Projections of their measurements will demonstrate tendencies towards fluctuations or trends in standing basal area or volume, changes in species composition through succession, invasion, failure of some species to maintain their population, and other aspects of rainforest dynamics.

These forecasts could be very valuable in ecological studies. If some successive measurements are projected into the future, the potential effects of any current changes in the stand are clearly displayed. The trends may make it clear that the existing stand composition and size-structure are inherently unstable, or the projected stand may appear so unlikely, in the light of local ecological experience, that it may be clear that current trends cannot continue indefinitely and that a change or reversal of current trends may be anticipated.

Clearly, the program cannot predict events which may be triggered by extraneous stimuli such as droughts and hurricanes, including mast years. (Such events may nevertheless be essential for the long-term maintenance of the system; species with too few seedlings to maintain the population, if projected unaltered into the future, may rely on occasional catastrophes or mast years when regeneration becomes established.)

# 2. EFFECTS OF SILVICULTURAL TREATMENTS

## 2.1 Background to analysing treatment effects

Silvicultural treatment experiments have been established in many tropical countries, often with rather general objectives such as "to determine the effect of the individual operations employed" (34) or to provide "basic information on growth ...... to be able to prescribe cutting limits and decide on rotations" (12). In particular, the aims are usually either to compare the effects of various felling or poisoning regimes in naturally regenerating forest, or to compare the production from variously treated natural forest with that from enriched or replanted forest.

A fundamental feature of scientific method is that experimental treatments should be reproducible so that the results can also be reproduced and checked. However, rainforest can never provide exactly reproducible experimental material either for controls or after treatment. Treatments and treated plots may be slightly "more reproducible" than controls or nil treatments, but it has become clear that untreated and preferably undisturbed plots are extremely valuable for interpreting treatment effects, especially if replicated.

Almost invariably, treatment effects are assessed by comparisons between treated and untreated plots, not by comparisons of growth before and after treatment. Therefore instead of directly measuring the effects of a treatment, the analyst is faced with the statistical problems of making inferences about treatment effects from different plots treated in different ways. These statistical problems are often inadequately settled, with inadequate replication or no controls, so that many experiments are incapable of demonstrating cause-and-effect relationships.

Further, the analyses of such treatment experiments have sometimes been based on a very limited characterisation of treatment-intensities and growth effects. For example, RP 273 (Annex 2) was analysed mainly in terms of assessments of milliacre stocking: no data on crop or tree increments were collected until 11-13 years after the first treatments and 5 years after a felling operation had further affected tree statuses to an unknown extent. Not surprisingly, Lowe (34) recorded simply that he "tried to show effect of treatment on increment of trees but could not find any significant results".

Similarly, Kemp and Lowe (28), analysing data for Khaya grandifoliola, concluded that they could not "distinguish any considerable influence of measures of competition on the increment of subject trees"; however, in 5 of their 7 multiple regressions, size plus the other measures of competition accounted for >60% of the variability in increment. The competition variables were measured 11 years after treatments, and were therefore rather inexact measures of the treatment intensity, so an $R^2$ of more than 0.6 appears to be very encouraging. Here also, it was impossible to quantify treatment intensities (interference including logging was spread over 5 years), basal areas removed or changes in competitive status, so no comparison between cause and effect is possible. The growth rates in "untreated" and "treated" plots were unfortunately not directly compared, although earlier data (27) had shown higher increments in treated plots.

In another experiment (33) with four treatments and three replications, 3 control plots received no treatments while 9 plots received a complete poisoning of all except Mitragyna at various times. Some of these residual Mitragyna >5 cm d were measured over a span of 3 years; the mean annual diameter increment of 51 trees in treated plots was 1.05 cm, that of 33 trees in the untreated plots was 0.5 cm. No statistical analysis of this striking effect was mentioned. Surprisingly, Lowe wrote elsewhere (35) that "in Nigeria nobody has succeeded in demonstrating that canopy opening can actually accelerate the growth of potentially exploitable trees".

Lowe and other workers have, in my opinion, demonstrated cases where increments have had an important degree of correlation with competition (although the measures of competition sometimes appear arbitrary and only crudely related to the effects of earlier treatments) and also where increments were higher in more intensively disturbed stands in the few cases where interference intensity could be realistically compared or quantified. In other cases, however, treatment effects remain uncertain, because of inadequate experimental design, measurement or analysis.

Treatment experiments in other regions have also often produced inconclusive results, often through an inadequate characterisation of "treatments" (e.g. ignoring the variable impact of logging) or "effects" (e.g. only the average diameter increment of leading desirables or only the milliacre stocking). Some experiments have been left without full analysis when it was seen that a defined objective, such as enhancing the regeneration of a few chosen species, was not achieved, after which the tested system was rejected as ineffective.

Any work with treatment experiments and permanent plots in TRF is very costly, in establishment and remeasurement, and is capable of providing much important information about the growth of the stand and of each species and about responses to local competition. It is a waste of money if such experiments are used only for assessing effects on regeneration with no regard to effects on increments and production. No research worker should be satisfied with using such large bodies of data purely for elementary tests for significant differences in one factor. Palmer (40) has shown how responses may appear in quite different forms, depending on the choice of measurements.

Many investigators (Lowe, Dawkins, Wadsworth, Palmer) have shown that individual-tree growth rates often have only a weak correlation with the usual, or easily measured, indices of status or local competition, such as crown form and position. This has led some workers to conclude that silvicultural treatments have no important effect on tree or crop increments. However, these measured indices of status and competition are probably not the best indicators of the competitive stress actually felt by the trees. The weakness of the systems of data collection and analysis, and the weakness of the correlations found for the measured indices, account for the inconclusive results obtained from many treatment experiments.

Studies of rainforest ecology and silviculture have been carried out in Surinam for many years and have confirmed some of the more positive conclusions of the investigators mentioned above. For example, de Graaf and Geerts (24) found that mean diameter increments in all size classes in logged treated forest tended to be consistently greater the more intensive the treatment and the lower the surrounding competing basal area per unit area.

Some foresters may, at first sight, agree with Leslie (30) that "all the effort in tropical forestry has yielded very few reliable and reproducible methods for natural regeneration of moist tropical forests". However, what is usually lacking is actually a method for regenerating the few "desirable" species up to some predetermined level of "full" stocking. There may be abundant regeneration of other species, but experiments seldom characterise responses of all species in terms of a broad range of production - and growth-rate variables.

## 2.2 Current investigations of treatment effects

### 2.21 Problems of definition

In the Sarawak experiments analysed (Annex 3), the stands were selectively logged and subjected to various poisoning treatments. In all plots, the basal area removed by poisoning was much less than that removed by logging; even in some of the untreated 'control' plots, logging reduced basal area by up to 70%. Clearly, the overall response of trees and stands is influenced by a combination of the logging and poisoning intensities; an evaluation of the responses to poisoning must take account of the simultaneous responses to logging and the effect of the intial status or stocking of the stand.

The difficulties, described earlier, of quantifying the treatments and responses, apply even more to partitioning the response components between poisoning effects and logging effects.

To tackle these problems, we have defined and calculated "treatment effects" in many ways. This involves first defining what is the treatment and then what is the response of the trees or stand.

### 2.22 What is the treatment?

Forest managers can define their treatments in terms of field instructions, and in experiments these may be a set of clearly defined alternatives such as:-

1. poison non-desirables to 20 cm dbh
2. " " " " 10 cm dbh
3. no poisoning

Experiments may involve many defined "treatments" including controlled logging, poisoning, thinning, climber cutting, etc., defined in terms of the operations to be carried out. In an evaluation of such experiments, the managers would like to know whether the "effect" of treatment No. 1 differs from that of treatment No. 2 etc., and in what way.

However, initially any TRF plots must inevitably have carried variable species compositions, sizes and stockings. During logging, the initial variability is confounded by a variable reduction in numbers and basal area for each size and species, producing variable responses even if the logging is partially controlled by sizes and species. During poisoning, a further variable number of stems in each size and species is removed, adding more variability to the responses. Thus, ultimately, no two plots have the same stocking or have been subject to identical forms of interference, so it is only to be expected that all plots will respond differently. In a rainforest, with its inevitable variability, this situation cannot be entirely overcome by more replication or by more careful field instructions.

Thus it is inevitable that most replicated treatment experiments have resulted in a broad range of treatment intensities as measured by their impact on composition of species and sizes, or competitive status of trees. If more replicates are added, the range will tend towards a continuum of impacts or treatment-intensities.

If this is the case, a broad range of treatment intensities will result in a broad range of responses, however defined. Moreover, the intensities and responses may not be proportional to the original simple field instructions: a light poisoning in one plot , where logging was by chance heavy, may be followed by a greater response than a heavier poisoning in another plot which was lightly logged. It is therefore no surprise that a simple analysis of "treatment effects" may show no significant differences between treatments "Nos. 1-2".

When analysing the results to distinguish differences between treatments, the influences of the initial stand basal area (G) and the logging intensities (all highly variable) can be separated out by a covariance analysis. If the impacts of each numbered treatment are clearly distinct in terms of basal area removed, etc., then a covariance analysis could distinguish differences in responses to treatments even when imposed on a variably logged stand. However, if the real impact of each treatment is itself variable, and overlaps the impacts of other treatments, because of its variability in distribution and sizes of the poisoned and unpoisoned trees for example, then covariance analyses are less likely to distinguish clear differences between the artificially defined treatment numbers.

Note that this is not due to a lack of response to interference but to the statistical and experimental difficulties of demonstrating the real effects with such variable materials and methods.

To sum up, treatment instructions are not always closely correlated with the impacts or treatment intensities felt by the trees and stands; they are especially inadequate indicators if the stand is integrating the effects of treatment and logging. The physical impact, nature or intensity of treatments or interference on the stand at any one time may be characterised more realistically in many ways, some of which are shown in Table 1.

Table 1. Measures of the intensity or impact of treatments or interference in a stand, in terms of basal area (G)

1. Total G removed by logging
2. " " " " treatment
3. " " " " " as a proportion of total removals
4. " " " " logging and treatment
5. Proportion of initial G removed by logging
6. " " " " " " treatment
7. " " " " " " logging and treatment
8. " " post-felling G removed by treatment
9. G of desirable trees in specified year
10. As above, as a proportion of total stand G in that year
11. " " " " " " " initial G (indicating proportion of maximum potential G for that site)
12. G of Leading Desirables in specified year
13. As above, as a proportion of total stand G in that year
14. " " " " " " " initial G
15. G of undesirable trees remaining in specified year
16. As above, as a proportion of total stand G in that year
17. " " " " " " " initial G

Each of the measures in Table 1 can be expressed as numbers or volumes rather than basal areas (G), per plot or per unit area and can be calculated to relate only to one species or species group, and to particular sizes in particular years. These are all different ways of quantifying any one intervention in the stand, and analyses based on different measures will demonstrate different results, each relating to one part of the whole system.

2.23 What is the response?

In actively managed forest, the managers often have a broadly defined silvicultural objective such as to increase the stocking of currently-valuable species, either at once (in numbers) or by the end of the felling cycle (in volumes). Current numbers and diameter increments give a simple indication of these objectives, and it is useful to use these variables for comparing "treatment effects".

It is clear that the stocking of a species after interference must in a general way depend on the numbers present before interference and the effects of the interference; the numbers of new seedlings will also be affected by a wide range of environmental and biological factors including current rainfall, the local animals which eat seeds and seedlings, the periodicity of flowering and fruiting in the different species, the numbers of seed trees available, the survival of shaded seedlings and also by a broad range of induced changes in local status and competition. Similarly, if the interference affects increments, then the broad range of interference intensities will produce a broad range of responses, superimposed on the initial variability of growth rates.

However, interference affects not only numbers and growth rates but also rates of mortality and ingrowth, and hence it affects many stand variables such as future basal areas and volumes of survivors or of the whole stand in all sizes and species.

Thus responses and effects can usually be compared most effectively by assessing those factors which are directly changed by or which respond directly to the treatment, such as current stocking and increments of surviving trees. Responses will inevitably be less clear if, like seedling regeneration rates, they result from many integrated factors in addition to the impact of the treatments.

The term 'response' suggests a change induced by interference; in general we can seldom measure changes but we can compare differences in growth and production characterised in various ways, as in Table 2.

Table 2. Measures of growth or production after logging, treatment or release, as indicators of responses

Net changes in numbers (N), volumes (V) or basal areas (G) of

- standing crop (all trees/desirables/L.Ds./undesirables) or
- survivors only, excluding losses or ingrowth, expressed as:
    - net change in N, G or V from $t_1$ to $t_2$
    - ditto, as a proportion of initial N, G or V at $t_1$
    - net increase in G or V of measured survivors, i.e. the sum of all the increments of surviving individuals measured at $t_1$ and $t_2$

Mean annual increment per tree per year, for all surviving trees/desirables/L.Ds. in each plot, $i_g$, $i_v$, $i_d$ or $i_c$

Each of these measures may be calculated to relate only to one species or group, and to particular sizes or other categories such as crown position, crown form, etc.

2.24 Correlations between treatment and response

Responses to treatment may be characterised or analysed by the relation of "growth or production" to "treatment intensity" as follows:-

1. A comparison of each measure of growth and production between sets of plots defined by treatment-numbers or ranges of treatment intensities, e.g. by analysis of variance.

   If the experimental design is suitable, this approach may give good results and it may be the only possible approach if the treatment intensities are defined by field instructions but cannot easily be described quantitatively. If treatments are confounded with unknown logging intensities, a finite number of 'treatments' will result in a wide range of 'responses', and this approach may not demonstrate any differences between the treatments; a covariance analysis may be possible.

2. A correlation (graphically or algebraically) of each measure of growth per plot with each measure of treatment intensity, [illegible] to avoi[illegible] e.g. mean diameter increment of surviving desirables against basal area removed, or [illegible] physical impact. total volume increment per plot against volume after treatment. [illegible] This is particularly [illegible] trial of a fixed number of treatments where [illegible] clearly be[illegible]

This is appropriate when several measures of growth, competition and treatment intensities can be quantified as plot totals or averages, instead of a few arbitrary 'treatment specifications'. Then, growth effects can be related to stand and stocking variables and to some direct physical measures of treatments, and hence to some more valid definition of treatment specifications.

Dawkins suggested (17) and later used (18) multiple regressions for correlating tree increments with variables describing each tree's status, to investigate the effects of treatment and liberation on tree-by-tree growth rates. It is only recently that larger computers and new programs have enabled us to calculate and analyse crop increments, stocking, competition and impacts in the same way, thus demonstrating effects which could not be adequately analysed in the past.

3. A model of tree growth, mortality and recruitment in relation to species, size (d, h, etc.) and competition (crown size and status, growing space, local basal area, etc.), derived from recurrent plot measurements.

   Such a model of the performance of all components of the stand can be used to extrapolate the observed trends and to forecast the stand composition for future dates. Data from treatment experiments will allow the model to incorporate a wide range of individual tree statuses and responses, and the forecast stands can be used for a direct comparison of treatment effects.

   This approach is appropriate if the data allow individual tree competitive statuses, and their changes, to be characterised, since it takes account of variations in competition at the single tree level. It thus avoids the deficiencies of using plot means derived from diverse species and sizes, as used in the second level of analyses from Tutus Forest, Sarawak (Annex 3).

During this project we devised ways of examining various measures of stocking and growth which are likely to be affected by silvicultural treatment and logging, and used them for comparing and quantifying treatment effects. In order to make a convincing demonstration of the effects of treatments based on comparisons between plots, it is necessary to be sure of comparing like with like, i.e. of comparing effects on sufficient trees of each species or group from each size, site and competitive or silvicultural category. Inevitably, in diverse rainforest, there are few trees per plot in each precisely-defined category. The comparisons made here have been based largely on plot means and totals, and some individual analyses are open to objection, although the effect of all analyses combined is convincing. The possible statistical methods of coping with the problem of valid comparisons in greater detail remain to be tackled, and the stand simulation models such as GROPE appear to be the most promising solution.

# 3. IMPLICATIONS FOR DESIGN AND ANALYSIS OF RAINFOREST STUDIES

## 3.1 General

The inadequacies in the data and design of some existing treatment experiments have been mentioned above. Our attempts to analyse and interpret these experiments have clearly indicated improvements and extra requirements which can greatly increase the chances of obtaining useful and positive results. These recommendations are for all plot-based trials for testing the effects of various intensities of logging or treatment or other silvicultural operations; a methodology for individual tree treatments and comparisons in rainforest is now being developed (1) but plot-based experiments have not yet been superseded.

If these recommendations are not followed, it may prove impossible to demonstrate any correlation between treatment intensity and growth rate even in cases where basal area reduction is genuinely correlated with growth rates. The recommendations are described and discussed in the Manual of Permanent Plot Procedures (TFP 14) and some important points are stressed here.

## 3.2 Objectives of experiment

The main objectives must be clearly defined, stating, for example, the growth parameters which are to be tested or compared. The objectives vary in different situations but it will always be most important to measure the sizes and increments of the larger trees.

The design, measurements and analysis may be organised in many different ways; all will be affected by the choice of parameters tested, but not all will be carried out by the same people, so objectives must be recorded. Comparisons of stocking of valuable regeneration may require quite different layout and measurements from comparisons of leading-tree increment. The objectives should take account of the fact that any interference affects the stem numbers, species composition, growth rates, volume production, recruitment and mortality simultaneously, so a simple inquiry into one variable will be inadequate and may be misleading. However, it may be possible to design an experiment to allow for a transition from early measurements of regeneration and stocking to later measurements of sizes, growth and competition.

## 3.3 Definition of treatments

In most treatment experiments it is necessary to define the treatments in terms of field instructions or prescriptions. Before defining these prescriptions, it is essential to consider or assess their probable impacts on structure, stocking and composition. A pre-experiment survey and inventory is a great help when deciding on treatment definitions. The choice of instructions should ensure that the impacts are likely to be sufficiently and consistently different from each other. The aim should be to apply a number of genuinely different impacts and to avoid the danger of applying treatments which look very different in the prescriptions but which overlap broadly in their physical impact. [illegible]

[illegible] or relevant and [illegible]

This is particularly important in a replicated trial of a fixed number of treatments where the aim is to distinguish clearly between treatments; the treatments then must be clearly different in their impacts, or it will be hard to show differences in response. This has been the main design deficiency in many tests of treatments defined mainly by different minimum girths for poisoning; this is most serious if the stand measurements do not allow the impact of treatments (e.g. on standing basal area) to be quantified in any other way.

This point is less important if the aim is to correlate responses and impacts over a broad range; then the treatments may be 'defined' or prescribed in any way, so long as the impacts can be quantified, and the most useful results will come from comparing growth responses over the resulting range of treatment intensities.

3.4 Plot sizes

The plots must be large enough to integrate both the local variability of the forest (single tree gaps, etc.)(17, pp. 48, 118) and the local variability in the impact of a treatment.

This may be illustrated by considering tree responses in two small plots of say 10 x 10 m subjected to apparently identical treatments. Mean growth rates will be greatly affected by the different stocking and status of the plots before the treatment in relation to nearby gaps or dominants, and such differences may be much greater for such small plots than for plots of say 100 x 100 m. In addition, the responses within each small plot will be greatly affected by changes just outside the plot boundaries; edge-effects are much more important on small plots than on large plots, and, more seriously, they cannot be quantified solely by measurements within the plot.

These considerations apply in all trials where a) the treatments are potentially large scale field operations which need areas of many hundreds of square metres or many hectares for a realistic test, and b) some of the growth rate comparisons will involve means (e.g. of increments), totals (e.g. basal area growth per plot) or proportional changes in various categories of numbers, basal areas or volumes.

The most efficient size will depend on the local structure and variability of the forest and treatment effects and on the objects of study. In practice this is difficult to determine and there are great advantages in some standardisation.

Dawkins and other workers have recommended plots of 1 ha or 2.5 acres to cope with small scale variability, and this is often the largest size which can be consistently and accurately laid out in moderately rough terrain.

The theoretical and practical advantages of 10 x 10 m subplots built into 100 x 100 m plots, and the wider advantages of standardisation for comparative purposes, lead to a choice of 1 ha as the most suitable standard plot size (see Manual, Tropical Forestry Paper 14, Section 3).

3.5 Replications

An experiment which is designed to detect differences between treatment responses should usually include replications of the treatments in order to work out the likelihood of such results arising by chance, to attach statistical significance to the results and to allow the conclusions to be extrapolated over wider areas. Replication is essential for analyses of variance, and is a valuable insurance against the accidental loss or destruction of some plots.

When correlations between growth effects and treatment intensities are to be examined by linear regression analyses over a range of treatments, the closeness of the regression line to reality will usually depend on the number of observations independently of any replication, and a systematic clinal design may be more economical than a randomised replicated design. However, a replicated design is recommended so that the results will be suitable for analyses of variance as well as regression analysis, so that more observations are available overall and, in some cases, so that duplicate observations are available at each level of treatment intensity.

3.6 Measurements of forest before treatment

In order to quantify the treatment intensity or impact, and the changes in stocking, ingrowth or mortality induced by treatment, it is essential to obtain some data on the total removals and deaths caused by logging, treatment, and other interference, in order to characterise the original stand and to quantify the disturbances, even if the data are collected after the application of the interference. It will usually be impossible to demonstrate significant differences in growth rates, and frequently difficult to demonstrate correlations with treatment intensity, unless all recent major disturbances (logging, etc.) can be quantified as well as the treatments.

At the least, all trees felled or poisoned should be measured, so that pre-treatment basal areas, and proportional reductions, can be calculated. The intensity of interference may then be characterised in several ways, by numbers, basal areas or volumes, in size- and species-categories.

Ideally, it would be very valuable to measure the plots 2-3 times over a period of 1-5 years before the start of treatments to indicate pre-treatment growth-rates, production and population turn-over, allowing a direct comparison of the effects of treatments as well as an indirect comparison with untreated plots. In practice, this will often be impossible either because of lack of roads for access before logging or because of uncertainties about where logging will next take place. Fortunately, the most important data on pre-logging stocking and the impact of logging and/or treatment can be collected when the plots are established after logging.

The potential value of undisturbed plots is also strongly indicated. A genuine nil-treatment (i.e. no interference by logging or silviculture) is seldom included in treatment-experiments because

a) it is difficult to control the activities of loggers,
b) silviculture is usually now applied only to logged stands so only post-logging treatments appear possible or relevant and
c) the uncontrolled variation of an unlogged forest is not exactly reproducible in another experiment so that according to strict theory the

3.8 What to do with existing treatment experiments?

In many countries there are silviculture experiments and accumulated data awaiting analysis and interpretation. It is pointless to delay the analyses until several measurements have been made: by then it will to too late to check discrepancies and errors, or to correct any deficiencies. Hard experience has often shown that cumulative errors can render the data valueless by the time analyses eventually start and that it is always worth starting the data-processing as soon as the data are collected. The first priority in any existing treatment experiment is therefore to proceed with analysing the data, and this often means seeking assistance in the form of statisticians, computers or programs from outside the Department directly involved.

Many existing treatment experiments have obvious deficiencies such as the absence of information about the impact of treatments in each assessed plot or the lack of individual tree measurements for calculating increments. Further, the treatments tested in some experiments involve complex and expensive sequences of operations which may never be feasible on a management scale.

These deficiencies certainly do not mean that the experiments have no further use, but research officers should regularly review their experiments in progress to determine whether they are still yielding, or capable of yielding, results which are of present or future value. If an experiment is still valuable, it is important that silviculturists should collaborate with statisticians in analysing and interpreting the results and perhaps in finding ways of improving their value; if it is not considered valuable, it may be appropriate to do nothing more than maintain and protect the plot for possible future assessments at long intervals, or to close it completely, rather than to continue with costly regular measurements without analysing the data or using the results.

Even if the treatments applied are no longer relevant, the value of treatment experiments may still be very great

(a) if the impact or intensity of logging or treatments can be quantified;

(b) if the individual trees are numbered and measured for calculations of stand and tree increments and for comparisons between, or correlations with treatment intensities;

(c) if tree increments, competitive statuses, survival, mortality, recruitment and stand density are measured in plots with a range of stockings and histories, for constructing competition models and growth regressions like the program GROPE; this would make it possible to assess the responses of various species to competition and to draw conclusions about silvicultural practices;

(d) if small stems and young regeneration are regularly assessed in sub-plots or strips (using techniques such as Diagnostic Sampling and Linear Regeneration Sampling), to relate the regeneration to past treatments or present stocking.

If none of these aspects have been or can effectively be assessed, and if the experiment was originally designed to provide a quick answer to a problem which is now of little interest, then it may be better to divert funds to collecting and analysing information about more urgent problems.

3.9 What to do with existing Sample Plot programs?

Existing PSP programs do not usually have serious deficiencies in design, so the work involved has seldom been without value although often it is not put to good use and its value could be greatly increased by modifying the methods of assessment.

Some existing systems attempt to measure the tree and crop increments and also the regeneration of different species simply by assessing 40-100 Leading Desirables per plot. More valuable information for assessing the current stocking and competition, calculating production and forecasting future stand tables can be obtained if all or most of the trees are measured, above a chosen size. Assessments of seedling and sapling regeneration are more revealing if carried out separately in plots or strips.

It needs to be stressed again that it is extremely important,

(a) to survey and demarcate the plots permanently, to avoid the very real danger of losing them;

(b) to check and process the data as soon as possible after collection, to eliminate measurement errors, to ensure that the correct procedures are being followed and to determine the trends in increments and production.

## IMPLICATIONS FOR MANAGEMENT AND SILVICULTURE

- including general conclusions about the response of TRF to treatment and logging, from the results of experiments analysed here (particularly the Sarawak Tutus experiment (Annex 3)).

### 1 Silvicultural treatment effects

This project has led to the clear conclusion that reductions in stocking and basal area by felling and/or poisoning normally result in faster mean increments of remaining trees, not only overall but also for 'Leading Desirables' (L.D.s) and individual species groups.

Such reductions also affect the net production of the survivors and of the total crop, by reducing the numbers of trees available as well as by affecting diameter increments. In Tutus (Annex 3) the larger increments more than balanced the effects of reduced basal areas, so that faster net basal area growth rates per unit area, of surviving L.D.s, of all desirables and of the whole stand, were correlated with greater basal area reductions. However, this will not always be so for a particular species or group if the reductions are too severe or are concentrated on the larger stems with no selective treatment to reduce basal areas of other species. The preliminary evidence from Trengganu (55) (Annex 2) was that greater reductions in plot basal area resulted in lower net basal area growth of the measured survivors, because the higher increments did not compensate for the reduced stock produced by felling, logging damage and mortality.

These analyses have not examined whether silvicultural treatments affect total dry-matter production or gross yield, or the growth rates of those of the remaining crops which are physiologically old or which had been suppressed, but they clearly demonstrated that treatments can affect net yields in certain categories.

It is important to appreciate the management implications of the different kinds of responses. The basal area production per hectare, measured plot by plot, may be affected quite differently from diameter increments measured tree by tree. All such effects should be examined; for some purposes, the objective may be to maximise volume production in certain categories, irrespective of sizes, whereas for other purposes maximum tree increments may be required, with less concern for total production, in order to reduce felling cycles. Any two treatments may have quite different effects, either favourable or unfavourable, on tree numbers, size distribution, increments and crop production, and it is essential to examine and interpret these effects before drawing conclusions and making decisions about silvicultural practices (as discussed by Palmer (40)).

Most logged forests contain some established trees of valuable species, too small to be used by loggers, ranging in size from seedlings up to 30-50 cm d. These trees are often very valuable as part of the next crop, and as a source of seeds for future crops. The intensity of logging determines the damage inflicted on these trees and the number of survivors. Logging damage is often so severe that very few larger trees survive to form usable logs in future, and those that remain may be so damaged that they cannot respond quickly with faster growth after release;

the future crop must then be formed from seedlings, a slow and uncertain process. In these cases, treatments immediately after logging may have little effect on production or increments, and other methods of improving production may be tested, such as treatments 5, 10 or 20 years after logging, or some control over logging methods and intensities.

If a heavy logging, followed immediately by silvicultural treatment, is likely to lead to an invasion of unwanted pioneer species, it may be more effective to delay silvicultural treatment for some years to avoid excessive canopy opening, to allow the post-logging regeneration of valuable trees to become established and to favour these young trees as well as pre-existing trees by the treatment.

The net growth of a stand, or of particular species groups, is affected by rates of ingrowth and mortality as well as by the stocking and the tree increments; it is therefore impossible to generalise about all the short-term effects of basal area reductions. In the longer term, after the initial effects on mortality and recruitment have subsided, but before a "limiting basal area" with minimum net growth is approached, the evidence remains compatible with Dawkins' conclusion that "silvicultural treatment would not in most cases have greatly affected total yield", i.e. that the net annual total above-ground production of woody material including branches on one site will be similar over a fairly wide range of basal area stocking (and reduction in stocking). However, this will not be so if the species composition is changed to one with a different relationship between basal area stocking and production. Further, the net production in particular species and sizes, thus the utilisable yield, may be greatly changed even if the yield of all species combined is relatively constant.

In spite of the greater diameter increments which may result from basal area reductions, a normal logging selectively and immediately reduces the stocking of only the most valuable categories (species, form) of trees and may permanently reduce their stocking and production if regularly repeated. This problem may be reduced if reductions are made less selective against the valuable groups, by more complete stand utilisation, e.g. for timber, fuel, poles, etc., or if some reductions selectively favour the valuable categories, e.g. by utilising or killing some non-timber trees after exploiting the timber.

The Tutua experiment (Annex 3) showed that treatment intensity had a weaker correlation with growth rates than the intensity of logging and poisoning combined. This was simply because the poisoning amounted to only a small part of the total basal area reduction in each plot (the experimental area had been particularly heavily logged). However, the poisoning had the expected effect of increasing the proportion of desirable species in the stand as well as influencing tree and stand increments of desirables. This probably applies almost universally, except that stand increments, especially in species categories, will respond more variably depending on species characteristics, and recruitment and mortality rates.

Note that most of the effects of poisoning, especially the increased average girth increments of remaining undamaged trees, can be obtained by applying appropriate logging intensities. The responses to disturbance may be assessed from experiments involving logging and/or treatment, the required effect can be chosen, and then the corresponding logging (or treatment) intensity devised to produce the required results. The need for some silvicultural operations may remain, but many of the silvicultural problems could be solved by controlling the methods and intensities of logging and utilisation.

In conclusion, it is clear that the production from logged forest and the possibilities for increasing the usable production by silvicultural treatments are too important to be ignored. However, it is not usually feasible to control the precise species mix in the regenerating forest.

The problems of silvicultural systems based on natural regeneration (N.R.) can be better tackled by utilising what N.R. provides instead of trying to induce the N.R. to provide only what is currently utilised. Many of the silvicultural problems of TRF management should be and can more easily be solved by sawmilling and marketing more species rather than by poisoning.

Some of the conclusions reached during this project, concerning the biological and environmental consequences of logging and silvicultural treatments have been described elsewhere, as have methods of monitoring these effects (49-54). It is important to be aware of the consequences of increased logging for soil conservation and hydrology and the consequences of major changes of composition for conservation of genetic and wildlife resources. Forest Departments which are concerned with satisfying future requirements have a responsibility to monitor the production of remaining areas of TRF and to test the costs and benefits of methods of improving the value of the production.

## 4.2 Recommendations for silvicultural treatments

### 4.21 Justification and aims

Silvicultural treatments, such as eliminating unwanted trees by poisoning or by extracting them for firewood or charcoal may sometimes be justified through

(a) the higher tree increments which result from local basal area reductions, by logging or treatment, over a broad range. The increases resulting from treatment may be slight if the logging intensity has been high or if the treatment itself has been light, but the increases may be larger in lightly logged forest left with many large residual dominants; careful regulation of logging, and cutting climbers in the canopy or cutting undergrowth shrubs (especially if they suppress smaller valuable trees) may also be effective in certain conditions for promoting increments or survival.

(b) their selective (eugenic) effect on the residual stand; the proportion of the favoured species is immediately increased by selective treatment leading to an increased proportion of the net stand increment and, through normal biological processes, to changes in the composition of the regeneration (although not always exactly as required or expected).

When the growth rates and the numbers of valuable trees can be increased by treatments, then the saleable production from the forest is increased and the cutting cycles may be shorter. Clearly, to achieve the effects, it will be more constructive and profitable to find some use for previously useless species than to waste them.

The increased growth rates after treatment are less important if smaller trees can be utilised; the selective effect on forest composition is less important as more species become utilisable. Since the total dry-matter production from closed forest on one site is likely to be similar over a wide range of basal area stocking, silvicultural treatments become less important as more of the stand can be used, but most managed TRF still contains many large unwanted trees and climbers which depress the growth rates and production of valuable trees.

4.22 Decision making

It is now possible to draw general conclusions from the effects of some silvicultural treatments about the value of applying them in TRF. The treatments considered here are only those which involve some thinning, poisoning or refining after logging. Enrichment, line planting or fertilising experiments have not been examined in this project.

It is clear that reductions in stocking by many methods will result in faster average increments in the remaining trees, and hence often higher production in those categories of species, sizes or qualities thus partially relieved of competition.

If the remaining trees do not fully occupy the site, the total production of the stand may be reduced, at least temporarily, although the long-term value production may be increased if the most valuable trees reach larger sizes more quickly. Selective treatments can improve the value of the species-mixture by reducing the diversity of species in favour of the most valuable, as an immediate impact and also in the long term by eliminating the seed-bearing unwanted trees and by increasing the seed supply of valued species. However, there may be an increase in pioneer species; heavy interference by intensive logging with or without treatment, combined with short ("polycyclic") felling cycles, will increase the likelihood that pioneer species will form an increasing proportion of the standing crop.

Many of these effects are desired by foresters but great care must be taken to choose the appropriate intensity and timing for any kind of treatment. If any system is wrongly applied it may fail to achieve its objectives, or may waste money,

(a) by achieving an improvement which is too small to justify the expenditure;

(b) by achieving a change in stocking or composition which, after subsequent changes in sawmilling and marketing, may be seen as no improvement at all;

(c) by achieving a beneficial effect by one method, e.g. poisoning, which could equally have been achieved by a cheap or cost-free method such as charcoal burning or improved utilisation.

The highest priority for rainforest management is to increase the scope for selling the existing growing stock by developing new markets for the smaller sizes and the lesser known species for fuel, chipboard, timber and other purposes. The aim is not necessarily to achieve high intensities of removals, leading eventually to complete clear felling, which may result in the destruction of the forest environment and of the ability of the forest to regenerate itself; the aim is rather to increase the options of the forest manager so that he can be sure of selling what is most easily and cheaply grown, allowing him, if necessary, to reduce expenditure on silvicultural operations which may not be justified by their long term benefits.

In most rainforest areas, the investment of time and money on increasing the utilisation of more species, sizes and qualities will probably achieve a far greater return than expenditure on attempts to manipulate the regeneration and composition of the forest. Many countries already have the technical information needed for grouping their TRF species according to similarities in properties or potential end uses, and to organise marketing on a basis of end use groups instead of individual species.

The current market trends, especially in domestic markets, for tropical timbers and wood products of all kinds strongly suggest that in future a far wider range of species will be saleable, in smaller sizes and including stems of poorer quality. It is therefore sensible that any species should be considered usable if it produces wood which is at present used anywhere in its range or which can reasonably be believed to be potentially marketable.

In any forest there will be some species with difficult properties and many individual trees with sizes, forms or defects such that it is unlikely that they can ever be sold for timber. The forest manager must decide whether it will be a good investment to eliminate such trees; if they may be saleable in future, it is hard to justify expensive poisoning treatments to eliminate them, unless the potential benefits can be shown to outweigh the costs (e.g. if a full stocking of only the most valuable species can be regenerated reliably and cheaply).

In all such cases, there may be great benefits from using the least valuable trees for fuel or other purposes, since this can often be done at little or no cost and can supply important sources of energy or materials.

Some forests contain many large and small trees of the most highly valued species, many of which are destroyed during felling and logging. Several workers have stressed the importance of reducing this damage by:-

(a) cutting large climbers before logging, preferably at least a year in advance, so that they break more easily and do not lock several trees together when one tree is felled;

(b) directional felling;

(c) conspicuously marking the young valuable trees which should be left undamaged;

(d) controlling log-dragging;

(e) fines for careless damage by loggers.

In many countries these controls are not possible, and forest services often have little or no authority to control the intensity of logging or to limit the incidental damage and wastage by logging organizations. All those concerned with long-term forest management should aim to improve this situation.

Burgess (10) in Malaysia has shown that cutting undergrowth before seedfall can reduce the subsequent rates of seedling mortality of some dipterocarp species. This is particularly important with the stemless palm Eugeissona tristis and some non-self-supporting bamboo species. There are probably many cases where cutting undergrowth shrubs, palms and bamboos would increase tree seedling survival when this is limited by low light intensities and competition for moisture.

4.23 Recommendations

The following features of silviculture and management are confidently recommended for implementation, research or statutory regulation where appropriate, since the scale and reliability of the benefits, in terms of survival, increments and production, will in many cases justify the costs. Some of these operations, such as climber cutting, may be relatively cheap, especially when combined with routine inventory work or supervision of logging; others may even be profitable, such as the development of new outlets.

(a) Control of felling and extraction techniques to minimise damage to the stand, especially to remaining trees of the most valuable species.

(b) Control of road works and log transport to minimise damage to soils and drainage systems which may lead to erosion, waterlogging and reduced productivity.

(c) Climber cutting, preferably 1-3 years before logging, to reduce damage caused by intertwined tree crowns, to reduce regeneration of climbers, and perhaps to allow more light to young regeneration.

(d) Climber cutting during or after logging to reduce the competition affecting young trees from climbers in the canopy and in the regeneration.

(e) Control of certain plants such as Eugeissona and some understorey shrubs if they can be killed relatively cheaply and have an important effect on valuable regeneration.

(f) The removal and sale, as poles, firewood or charcoal, of trees which have no potential value for timber or less potential value than other trees which are available.

(g) The development of markets for all lesser used timber species.

The last two recommendations are the key factors for increasing the production and revenue and decreasing the cost of TRF silviculture and management. The first two are the keys to avoiding environmental degradation.

It is not possible to make a general recommendation about removal by poisoning or other costly methods the large or defective trees which have little or no present use for man, because circumstances vary so widely. Their removal will probably increase increments on the remaining valuable trees and may increase the total production of usable wood, but the increased value of the production may not justify the cost. If the unwanted trees are left to grow and die, some useful production may be lost to man, but the land is not wasted since such trees contribute (often greatly) to nutrient cycling, seedling regeneration, conservation of wildlife and genetic resources and the yield of other forest products such as fruits and meat. The decision must be based on local markets, costs and resources, on the stocking of such unwanted trees and on the responses and benefits anticipated from removing them.

Major decisions about extensive programs of silvicultural treatment and management should not be taken until quantitative information is available about the effects of the interventions. In rainforest, this requires sample plots and experimental plots, and adequate analyses of the data for yields and costs. Some countries have some information about stocking and rates of diameter and basal area increment (or they have raw data which could supply this information), but in most cases much basic information is needed about rates of production, especially of utilisable sizes of timber, and costs, before final decisions about lengths of cutting cycles can be formulated. Thus PSP programs, yield controls and forecasts, and management plans should be implemented as a regular, routine operation by management staff, and not simply as a research exercise.

Annex 1. Data available for development of forecasting programs

All the data detailed below have some feature which made them particularly suitable for stand modelling; large quantities of less useful data from Ghana, Nigeria, Uganda, etc. were also available but are not included here:-

Australia: Atherton, Queensland, Plot No. 3, one undisturbed plot of 0.5 ha measured 1971, '73, '75. Heights measured once; co-ordinates from plot map.

Malaysian Peninsular: Selangor, S.P.1, one plot established in 1915 in regenerating Kapur, *Dryobalanops aromatica*, remeasured almost every year. Initially 101 trees, finally 16 survivors after mortality and some silvicultural operations.

Sabah: Many sample plots in harvested forest with up to 10 measurements since 1966; only leading desirables are individually numbered, no heights or co-ordinates.

Sarawak: Undisturbed forest: Bukit Mersing, Lambir and Bako forests, 13 plots totalling 19.5 ha, all measured 3 times over 10 years, including c. 5,000 trees.

Treated forest: several treatment experiments, with up to 5 measurements since 1970.

Solomon Islands: Kolombangara Island, 22 plots of 0.625 ha, established 1964. 10 measurements of all trees ≫6 ins girth of 12 commonest species, 1964-1975. Cyclone destroyed one plot and damaged others in 1967.

Vanikolo Kauri stands, 9 areas established in 1957, measured 6 (-7) times for girth and once for crown status. 5 plots logged and 4 unlogged.

Uganda: Budongo Forest Nature Reserve, R.P.7. One plot of 1.418 ha established in 1939. All trees of all 75 species >10 (sometimes only >20) cm d measured 16 times, 1939-1976. Initially 539 trees >20 cm d, now 1124 trees >10 cm d. Crown status recorded at all measurements; co-ordinates from plot maps. Unlogged, untreated.

Venezuela: San Carlos de Rio Negro, MAB project: one block of undisturbed forest, 10 ha, in which all trees >13 cm d (in some sub-plots, all >5 or >1 cm d) measured in 1975. Data include co-ordinates, total heights, crown depth and crown diameter. This block is part of a larger plot (>28 ha) in which many other soil and environmental variables are measured. Some plots of disturbed forest and cultivation are also being tested. The data provide the most complete characterisation of tree and stand status available.

Annex 2. Data used for analyses of silviculture treatment effects, and the conclusions drawn from the experiments

1. NIGERIA

R.P. 273, Sapoba Forest. 13 treatments, 4 replicates. Treatments were applied in 1956-60, harvesting in 1962. Regeneration surveys were carried out in 1956, '57, '60, '65 and '75; some individual tree measurements were made in 1967, '69, '72 and '75.

Surveys and measurements were carried out in strips in the treated areas. Some data are available for total basal areas poisoned and the number of trees felled per treatments, but unfortunately there is no way of quantifying the interference (basal areas removed by poisoning or treatment) or the changes in the competition within the measured areas or the damage from felling and extraction.

The available data, including individual tree increments, were analysed at Oxford by P.R.O. Kio, working with project and UTS' colleagues (29). Earlier analyses by Lowe and Jeffers had indicated that the stocking of young regeneration of selected valuable species was lowest in the least treated area, but they gave no indication of current crop production The main value of the data for this project has been in drawing attention to the problems caused by inadequacies in the data, in the available analyses and in the experimental design (including the uncontrolled, inadequately recorded logging confounded with the carefully planned but unquantified treatments).

2. PENINSULAR MALAYSIA

Cutting and Growth Trial, Trengganu
6 Logging intensities, 3 replicated and 3 unreplicated; 2 measurements, 1973 and '74.

Tang Hon Tat worked with project and UTS staff and with new and adapted programs to process these data which he brought to Oxford; he analysed the results for an Oxford M.Sc. thesis (55).

The data are particularly valuable in including details of the quantities felled in each plot, and there was no poisoning superimposed. Several individual tree variables were measured, so that correlations between treatment intensities and growth can be examined in several ways.

Tang examined variation in stocking by species groups and sizes before and after logging, and variation in growth rates and logging damage after logging. The effects of treatments on growth rates were studied by linear regression analysis, rather than by analysis of variance between the 6 prescribed treatments, because the prescriptions were not reflected consistently by the actual or proportional residual basal areas or logging intensities.

Tang found a significant linear correlation between residual plot basal area and diameter increment for three of his four species-groups (light hardwoods, medium hardwoods, and heavy + miscellaneous) but not for dipterocarps only (present in smaller numbers); mean increments tended to increase as plot basal area decreased. On the other hand he found that the total basal area increment of all survivors ($m^2$/an/unit area) was higher in plots with higher basal area, indicating that in this case the large numbers of survivors in heavily stocked plots counter-balanced the faster individual growth rates in the lightly stocked plots.

In further data from Selangor sample plots, Tang found significant positive correlations between plot basal areas and total basal area increment of survivors, presumably because more heavily stocked plots had more survivors, but no significant correlation between plot basal areas and diameter increments.

3. SARAWAK

3.1 INV. 13, R.P. 52, Tutus Forest
6 treatments, 2 desirable lists, 5 replicates (see Annex 3).

3.2 INV. 52, R.P. 43-44, Naman and Pulau Bruit Forests. 4 Old treatments, 2 new treatments, 2 sites, 2 replicates.

3.3 INV. 47, R.P. 68, Niah Forest
8 treatments, 2 desirable lists, 6 replicates.

In all these Sarawak experiments, the data enable us to calculate basal areas in the initial stand, as well as the basal areas felled and poisoned, fairly accurately. The Tutus experiment covers a longer period, and has a simpler design than the others and has received our main attention, but the results of INV. 47 may be more valuable when 3 or more measurements are available.

Annex 3. Results and conclusions from analysis of available data from Sarawak Investigation 13, RP 52, Sg. Tutus Forest

1. Objective of experiment

To examine the "effect on the regeneration of desirable species of 6 poisoning treatments in heavily felled Mixed Swamp Forest immediately after exploitation" (39).

The data available in Oxford consist of tree measurements, not regeneration counts, so the objective of the analyses has been to examine the effects of the treatments on tree and crop increments and production.

2. Layout

Established in 1969-1970 in a 900 acre plot containing 60 logging blocks. Assessments were carried out in a systematic 5% sample, arranged as one line of 30 quadrats in each logging block. Each quadrat was ½ chain square (c. 10 x 10 m) and each strip was 0.75 acres (0.3035 ha). The area was logged in 1969-70 and treated in 1970.

3. Treatments

6 treatments were applied to 5 blocks selected at random with 2 species-lists, making a total of 60 plots. The treatment instructions consisted of poisoning trees down to various diameters in various categories of species and form, as follows:-

| Treatments | Poison sound and well shaped trees of | | Poison undesirables plus unsound, damaged and badly shaped trees of any species |
|---|---|---|---|
| | Ramin and Jongkong | other desirables and acceptables | |
| 1 (1 & 7) | over 24" dbh | over 16" dbh | over 12" dbh |
| 2 (2 & 8) | - | - | over 12" " |
| 3 (3 & 9) | - | - | over 8" " |
| 4 (4 & 10) | - | - | over 4" " |
| 5 (5 & 11) | - | - | over 10' tall |
| 6 (6 & 12) | - | - | - |

The list of "desirable and acceptable" species used during poisoning contained 16 species in treatments 1-5, and 25 species in treatments 7-11. This difference affected the severity of poisoning and the basal area remaining after treatment, and was apparent in the results; however, in most of the discussion below the effects of the desirables lists have been ignored in order to concentrate attention on the difference between treatment prescriptions.

The instructions suggest a sequence of treatment intensities of 5 4 3 1 2 6, arranged in order of decreasing intensity. The actual intensity in any one plot, and the order of intensity in any one replication inevitably depended on the distribution and sizes of undesirables due for poisoning and of residual desirables.

4. Assessment

The strips and quadrats were laid out and first measured in mid-1970 after the treatments and remeasured in 1971, 1972, 1974 and 1975. At each assessment, the four best trees in each quadrat, from a list of nearly 60 desirables species, were measured for girth (or height, for seedlings and saplings) and scored for crown position and crown form. These trees, the Leading Desirables and any subsequent replacements, were individually numbered, identified and recorded so that their individual progress could be followed. In addition, all other trees in the stand were measured and tabulated in 1 ft girth classes in categories of desirables, undesirables, poisoned and felled (stumps or broken trees).

These data, all collected at one time, made it possible to calculate the original, prelogging stocking of the forest and the intensities of logging and poisoning in terms of numbers, basal areas and proportions removed. Many of the analyses are based on the fully checked data for 1970-74.

5. Data processing

The data for Leading Desirables were processed through the program UPDATE to provide information about their basal area production and average increments, including several of the items listed in Table 2 (section 2.23), particularly mean annual $i_c$, $i_g$ and $I_g$ for each plot over different intervals (e.g. 1970-72, 1972-74). Sapling heights were converted to estimated girths.

The data for the full stand in each plot were processed through the program BASALAREAS to provide the following kinds of information:-

(1) a measure of the stand at any one time, e.g.

| | | | |
|---|---|---|---|
| TOTALG | 1970 | : | total stand basal area before logging or treatment |
| FELLG | 1970 | : | basal area of logged trees |
| POSTFG | 1970 | : | basal area remaining after logging |
| DESRG | 1970 | : | basal area of desirable trees |
| UNDSRG | 1970 | : | basal area of undesirable trees |
| POISG | 1970 | : | basal area of poisoned trees |
| TOTALG | 1974 | : | total stand basal area alive in 1974 |

and similarly for each year

(2) a measure of the impact of treatments, shown by the 1970 data:
e.g. TOTALG – FELLG – POISG : basal area remaining after logging and treatment;
DESRG 1970 ÷ TOTALG 1970 : proportion of the unlogged stand remaining as surviving desirables;
and other measures listed in Table 1 (section 2.22).

(3) a measure of the production and development of the stand in the years following interference, e.g.

DESRG 1974 – DESRG 1970 = net basal area production per plot of all desirable trees, equivalent to the sum of the tree increments plus the b.a. of new recruits from 1970-74.

## 6. Analysis of results

### 6.1 Analyses of variance

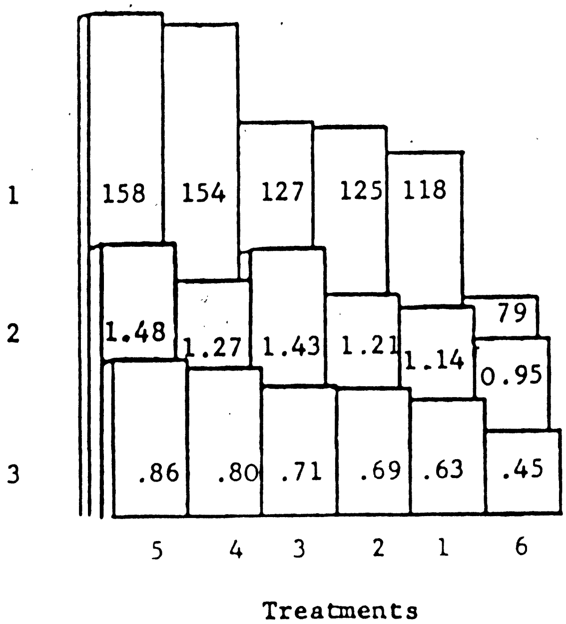
First, the differences in the impacts and responses between the 6 treatments were assessed by analyses of variance. Several covariance analyses were tried, to separate the effects of different pre-logging stockings and logging intensities.

Several of the analyses showed highly significant differences between treatments (at the 1% or 0.1% level of significance). The following list shows some of the factors which showed highly significant differences and the treatment numbers arranged in decreasing order of their mean values.

| | | |
|---|---|---|
| 1. | Basal area removed by logging and treatment | 543216 |
| 2. | % of initial b.a. removed | 543216 |
| 3. | B.a. production per acre of all desirables 1970-74 | 452316 |
| 4. | Mean $i_c$ of leading desirables (several intervals) | 534216 |
| 5. | % of total 1974 b.a. consisting of desirables | 542613 |
| 6. | Basal area of all desirables after treatment, 1970 (range 34-16 $ft^3$/acre) | 612453 |
| 7. | Total basal area 1974 (range 101-43 $ft^3$/acre) | 612345 |

These and other results confirmed that the total removals and the basal area remaining after logging and poisoning corresponded approximately to the expected severities of the treatments, and also that the heavier the b.a. removals, the faster the survivors grew (e.g. item 4 above). All this was expected and some examples of differences between treatments are shown in Figure 1, but the significant differences were almost all between the extremes. Thus the responses (measured in various ways) in treatment 5 were often significantly different from those in the control treatment 6 and perhaps the lightly treated 1 and 2; likewise the response in the control (logged but not poisoned) was often significantly different from that in 5 and perhaps 4 and 3; but it was usually impossible to show a significant different between treatments 5 and 4, 4 and 3, etc.

There were no significant differences between the treatments in the initial or felled or post-logging basal areas, but it was clear that these were highly variable both in the stocking and in the proportion felled or remaining in each plot (logging intensities ranged from 10.4 to 190 $ft^2$ b.a./acre).




1. Average basal area removed by felling and treatment, $ft^2$/acre
2. Mean girth increment of L.D.s, 1971-74, ins/an
3. Proportion of initial basal area removed by felling and treatment

Figure 1. Some examples of measures of treatments and response, Inv. 13, Tutus Forest

The treatments were designed to remove defective desirables and in fact the total b.a. of desirables, as well as of undesirables, after treatment was approximately in the same sequence as the intended treatment intensities. This effect was still clear in 1974 but by then the sequence was changed, indicating that changes had been induced in the development of the stand as well as in the initial stocking.

The total basal area growth per acre of the whole stand, of the desirables and of surviving Leading Desirables, and the mean $i$ and $i_c$ per tree, were almost invariably lowest in the untreated control, which contained the highest stocking of all categories, and highest in the more heavily treated plots.

## 6.2 Regression analyses

The effects of silvicultural treatments were not fully displayed by analyses of variance between numbered treatments, so some simple linear regressions were calculated.

Three groups of regressions were examined for correlations between increments and

(1) reductions in basal area caused by logging + treatment
(2) reductions in basal area caused by treatment alone or logging alone
(3) basal area stocking

**Table 3. Some examples of statistically significant correlations between increments and various measures of treatment-impacts**

(1) Correlations between increments and b.a. logged and poisoned:

(1.1) $\bar{i}_c$ of Leading Desirables (L.D.s) 1972-4, and the proportion of initial b.a. removed.
$y = 0.38 + 1.32x$ $R^2 = 0.65$

(1.2) $\bar{i}_c$ of L.D.s 1972-74, and the total b.a. removed
$y = 0.62 + 0.0053\ x$ $R^2 = 0.56$

(1.3) $\bar{i}_c$ of Meranti L.D.s 1972-74, and the proportion of initial b.a. removed
$y = 0.38 + 1.78\ x$ $R^2 = 0.66$

(1.4) $\bar{i}_c$ of Meranti L.D.s 1972-74, and the total b.a. removed
$y = 0.72 + 0.007\ x$ $R^2 = 0.54$

(1.5) Net b.a. production of all stand 1970-74 as a proportion of the total 1974 b.a., and the proportion of initial b.a. removed
$y = -0.29 + 0.85\ x$ $R^2 = 0.68$

(1.6) Net b.a. production of all stand 1970-74, and the proportion of initial b.a. removed
$y = -3.23 + 30.9\ x$ $R^2 = 0.38$

(1.7) Net b.a. production of all desirables 1970-74 as a proportion of the 1970 desirable b.a., and the proportion of initial b.a. removed
$y = -1.05 + 2.49\ x$ $R^2 = 0.40$

(1.8) Net b.a. production of all desirables 1970-74, and the proportion of initial b.a. removed
$y = -7.6 + 24.4\ x$ $R^2 = 0.47$

(1.9) Net b.a. production of all desirables 1970-74, and the total b.a. removed
$y = -3.9 + 0.10\ x$ $R^2 = 0.46$

(2) Correlations between increments and reduction in b.a. caused by treatment alone or logging alone

(2.1) $\bar{i}_c$ of L.D.s 1972-74, and b.a. poisoned as a proportion of POSTFG 1970 (b.a. remaining after logging)
$y = 1.05 + 0.66\ x$ $R^2 = 0.35$

(2.2) Total b.a. growth of residual stand 1970-74 as a proportion of the total 1974 b.a., and the b.a. poisoned as a proportion of POSTFG 1970
$y = 0.094 + 0.55\ x$ $R^2 = 0.61$

(2.3) $\bar{i}_c$ of L.D.s 1972-74, and b.a. logged as a proportion of initial b.a. (i.e. ignoring the proportion poisoned)
$y = 0.72 + 1.13\ x$ $R^2 = 0.34$

(3) Correlations between increments and b.a. stocking

(3.1) $\bar{i}_c$ of surviving Meranti L.D.s 1972-74, and total 1974 b.a.
$y = 2.56 - 0.013\ x$ $R^2 = 0.65$

(3.2) $\bar{i}_c$ of all L.D.s 1972-74, and total 1974 b.a.
$y = 2.02 - 0.010\ x$ $R^2 = 0.68$

The evidence from analyses of variance that heavier treatments resulted in faster growth rates was confirmed by the fact that almost all the measures of basal area reduction or stocking were significantly correlated with measures of tree and crop increments by linear regression (often at the 1% or 0.1% level). In Table 3, some examples are listed where the variation in basal area (b.a.) reduction or stocking accounted for at least 35% of the variation in increments, showing the co-efficient of determination ($R^2$) value and the regression equation.

After plotting many measures of increment and production against many measures of treatment and logging intensities, it is clear that with increasing basal area removals in any plot there was a strong correlation with increasing tree-increments and a good but more variable correlation with increasing b.a. production in various categories. Table 4 below demonstrates the intensities of logging and treatment and the $R^2$ shown by the linear regression of these removals with the $i_c$ of L.D.s in 1972-74.

Table 4. The average logging and treatment intensities and their correlation with L.D. increments

| | Average removals $ft^2$/acre | $R^2$ | Removals as proportion of initial stand | $R^2$ |
|---|---|---|---|---|
| Logging | 95.3 | 0.30 | 51.5% | 0.34 |
| Treatments | 31.4 | 0.22 | 17.7% | 0.16 |
| Total | 126.7 | 0.58 | 69.2% | 0.67 |

## 7. Interpretation

The analyses of variance provided clear evidence that average increments in the heavily treated plots were higher than in untreated plots, after logging. The sequences of increasing average growth rates strongly suggested that the differences in response between the numbered treatments were real, and not simply a random effect, and that each numbered treatment could be expected to produce, on average, a slightly larger or smaller response than the next treatment. However, it was clear that each numbered treatment included much variation in its impact on the stand. Thus there was apparently a real response of growth rates to treatment intensities, but the comparison between treatment numbers does not distinguish it very clearly.

It appears that there is an interaction between logging and treatment effects, and that the impact of poisoning is strongly dependent on the previous impact of logging. It has not been possible to devote enough time to analysing these data by multiple regression, using logging and treatment intensities as independent variables: this would be particularly useful if there were more data for the two extremes of (a) unlogged or lightly logged plots and (b) plots affected so heavily that basal area production was reduced and girth increments showed no further increase.

On average, the basal area removals by logging were three times larger than the removals by poisoning (Table 4) but the values of $R^2$ in the regressions suggest that the logging intensity accounted for only about twice as much of the variability in L.D. increments as the treatment intensity. This suggests that the extra opening applied to already partially opened forest had at least as much effect as, and perhaps more effect than, an equivalent opening applied to undisturbed forest. There is scarcely any suggestion from the plotted data used for regressions that the response to treatments has reached a maximum at less than the maximum intensities. Indeed it appears in this case and others that only extreme treatments allow all or most of the established L.D.s sufficient space to grow at their maximum possible rates. If the apparent extra effectiveness of the treatments is real, a possible explanation may be that b.a. removal by poisoning of, say, 30 $ft^2$/acre has a proportionately larger impact on residual b.a. in logged forest with, say, 100 $ft^2$/acre (30% reduction) than in unlogged forest with 200 $ft^2$/acre (15% reduction), and hence perhaps more effect on growth responses. In this respect the effect of poisoning on average increments was probably similar to the effect of any basal area reduction by logging or thinning.

In addition, treatments had a selective impact on the residual stand which was clearly apparent but less consistent, shown by several regressions of poisoning intensity on the proportion of desirables in the residual stand. For example, treatment intensity was measured as the proportion of the post-logging basal area which was poisoned; the selective response was measured as (a) the proportional increase in the desirable basal area 1970-74 and (b) the proportion of desirables in the whole 1974 stand (range 20-80%). Both regressions had an $R^2$ of 0.29; similarly the selective effects of treatment intensities on annual basal area production per acre of desirables also produced significant regressions with $R^2$ of less than 0.3.

This is a real affect of poisoning, and is likely to have an important effect on the composition of the final crop, so it is most important to understand why the selective effect is not as clearly displayed in these analyses as the overall effect on average girth increments. This does not mean that poisoning must have had only a minor selective impact on the stand.

The selective impact of poisoning in any one plot depended on the stocking and size distribution of both desirables and undesirables with respect to the size limits for logging and poisoning. These varied considerably from plot to plot: the basal area of undesirables in one plot may have been high, resulting in a heavy treatment-intensity, while the basal area of unlogged desirables may have been either high or low irrespective of the poisoning intensity. Thus simple comparisons between plots have only a limited ability to distinguish changes in composition and selective responses within plots and may easily underestimate them.

We may also examine the selective effects of poisoning on the present and future production of desirable species. These will depend on even more factors which can vary more or less independently and are difficult to quantify in an experiment: not only
(a) the tree increments, affected by the basal area reduction and by the characteristics of individual species, and
(b) the stand composition, the chance factors of size- and species-composition before logging, but also
(c) the composition and abundance of the regeneration and recruitment.

All these factors show a natural range of local variation and of responses to features outside the plot (e.g. nearby seed-trees) or outside experimental control (soil and site factors). In these regressions of basal area growth of desirables and poisoning-intensity, the correlation is almost inevitably rather weak, because of all these sources of variation; it is therefore reasonable to attach more importance to the fact that the correlation is clearly evident in the scatter diagrams and in the statistical significance of the regressions. More detailed analyses are required to separate the relative importance of treatment intensity, initial stocking and subsequent recruitment.

## 8. Conclusions

The Tutus experiment shows clearly that basal area reductions led to increased increments, and the extra reductions in treated plots enhanced increments still more. Within the range of treatments applied, the lower the final basal area (and the greater the total or proportional reduction) the greater were the average girth increments of the whole stand, the desirables and the Meranti and, to a more variable extent, the greater was the measured basal area production per plot.

It was clear that the trees responded at least proportionately to basal area reductions by poisoning even in heavily logged plots, and that poisoning produced persistent effects on basal area production of desirables and on species composition.

The plots with reduced basal area had a higher basal area production because of their enhanced girth increments, in spite of having fewer and usually smaller trees available. Further reductions in basal area would have reached a stage where total measured basal area production would also have dropped, when the increased girth increments could no longer compensate for the fewer measured trees, cf. Figure 2. The "break-even" point, with the highest increments and production per unit area from the fewest trees, will depend on the characteristics of the species and the forest; a stand of species which respond only slightly to heavy basal area reductions would show a drop in overall production at a higher stocking than a stand of sensitive, large crowned species such as *Maesopsis*, *Terminalia* or Meranti.

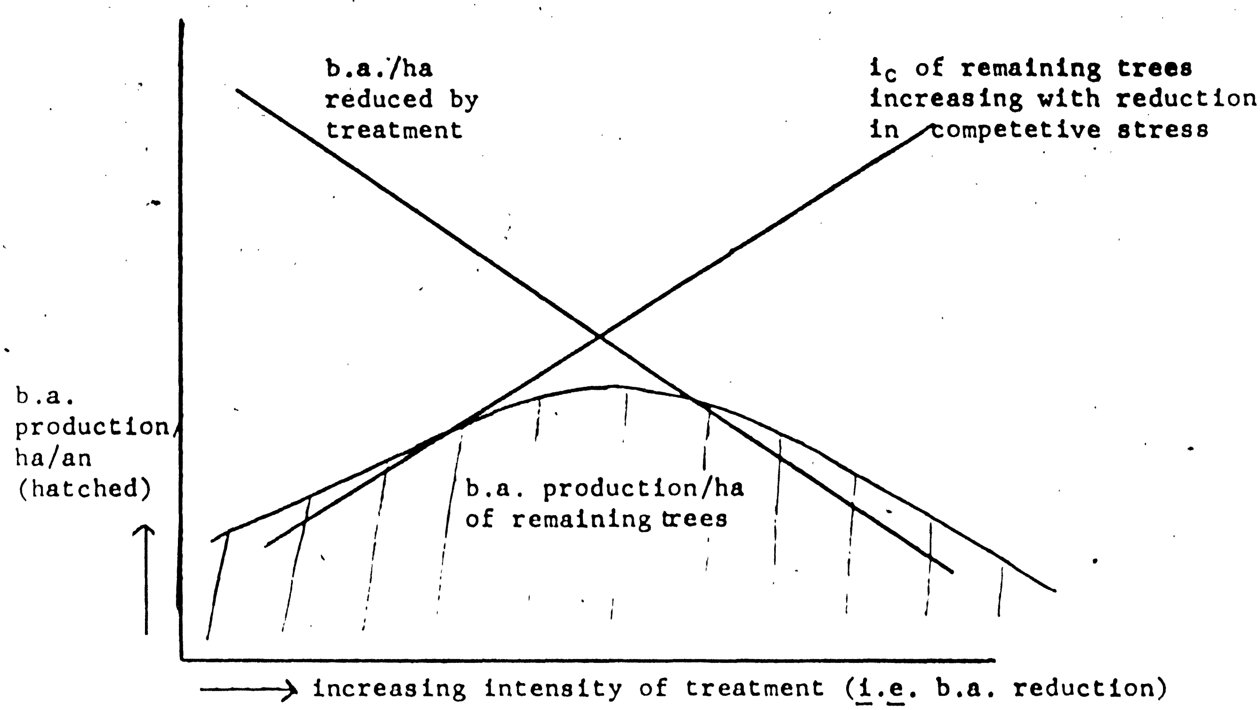



Figure 2. Diagrammatic representation of relation between the reduction in basal area (and numbers) per ha by treatment, the girth (or diameter) increment of remaining liberated trees, and the basal area production per ha of remaining trees, of measured categories

There is much scope for examining these effects in more detail, both in this experiment and in others where some other variables are measured. In this case, it was not possible to examine volume increments. If logging or silviculture affect the average sizes of residual desirables trees, then effects on volume production may not be the same as effects on diameter increments. However, it is possible that net volume production of all woody material per unit area in regenerating rain forest (the "building phase" of Whitmore) remains roughly similar over a broad range of stocking provided that the canopy is closed and the stocking is below the Limiting Basal Area (Dawkins (17)). Therefore the most important criteria for judging the use of treatments are likely to be their effects on diameter or girth increments and on the proportion of the developing stand which consists of usable trees. Through these factors, the treatments affect the net annual production of usable wood as a proportion of the total yield of the site, and the rate at which that annual production is developing into trees of usable sizes.

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