A GROWTH AND MANAGEMENT MODEL FOR CONIFEROUS PLANTATIONS IN EAST AFRICA

by

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A thesis submitted for the degree of
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ABSTRACT

A mathematical model is presented for growth and yield of Cupressus lusitanica, Pinus radiata and Pinus patula growing in the highlands of Kenya, Uganda, Tanzania, and Malawi, based on permanent sample plot data. Stand dominant height is predicted by a log/reciprocal function of age and site index. Initial diameter distributions are predicted by spacing at a dominant height of 7 metres and generated by a Weibull function. The diameter distribution of stems is simulated by a vector of 10 cumulative percentiles which are incremented over each growth period by a function based on relative basal area, dominant height, and tree dominance. Relative basal area is defined in terms of maximum basal area, which itself is modelled by a Chapman-Richards function in terms of dominant height. Dominance is defined as the ratio of tree diameter to stand dominant diameter. Thinnings are simulated by a novel and efficient algorithm that takes some trees from all size classes but is biassed to the smaller stems, although the degree of bias varies with thinning intensity. Tree volumes are determined by a new tree taper function using a quadratic/cosine model of relative height and relative sectional area. An algorithm is presented based on the taper function for subdividing stand volume into classes determined by log diameter and length. Validation of the model showed that diameter increment and height prediction, as well as the thinning routine were very accurate over a wide range of stand conditions; but the taper function was biassed towards underestimation of larger sizes and required re-fitting by a suitable method of weighting, whilst the initial distribution estimation required an additional variable to account for some of the variation occurring in practice. Two computer programs and a subroutine library are presented in the Appendix. VYTL-2 is a program to produce variable yield tables; whilst PYMOD is a forecasting program for multicompartment forests.

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1. INTRODUCTION

The highland conifer plantations of Eastern and Central Africa form a significant resource whose actual area is difficult to estimate, but certainly exceeds 200,000 hectares in Kenya, Tanzania, Uganda and Malawi. On the basis of this resource, a number of development projects have been planned, including a pulp mill financed by private capital which is already operational in Kenya, and proposed mills in Tanzania and Malawi (FAO 1970,1971, Adlard et al. 1974). The major species, which between them comprise perhaps 90% of the resource, are Pinus patula Schlect. & Cham., Pinus radiata D. Don., and Cypresses of the Cupressus lusitanica group, notably C.lusitanica, C.lindleyi and C.benthamii and some hybrids. For management purposes this latter group is generally treated as a single species.

Planning of the resource use, both for long-term project evaluation, and short term operational purposes, clearly requires yield tables that can predict growth and size assortments under a variety of stocking conditions. A number of such tables exist, either derived locally for specific inventories (e.g. Adlard et al., 1974, Smith, 1967) or more generally based for a whole region or country (e.g. Kingston, 1970, Wanene 1975a,b). Three principle difficulties exist with regard to the use of these existing yield prediction tools:-

1) Being based upon graphical or simple regression methods, they represent very poorly the dynamic processes in the stand, and can at best only provide estimates of average stand parameters under normal growing conditions.
2) The graphical or tabular form is not well suited to computer-based planning systems. Evaluation of alternative policies is at least partially a manual process which is relatively slow. Time becomes a major limiting factor on the number of alternative options that can be considered.

3) The currently available data base of permanent plot records now includes a significant number of plots entering the asymptotic phase of growth, as against the earlier linear phase. Much more realistic estimates of maximum volume and height growth are now possible than could be achieved by earlier investigators with a more limited set of data.

These three factors give rise to the three major objectives of the present study:-

1) To re-evaluate growth trends for P.patula, P.radiata, and Cupressus species using the latest available permanent plot data.

2) To develop modelling techniques that represent adequately dynamic stand processes; but which at the same time are computationally efficient and practicable for small computer systems.

3) To develop a planning and scheduling system, utilizing the stand model for the three species in question, that can be used by forest managers for operational and long-term planning.

2. SELECTION OF MODELLING STRATEGY

2.1 Background

The first work specifically aimed at constructing a computer model of forest growth appears to be attributable to Newnham (1964a,b). This model was based upon the assumption that height and diameter increment of trees growing free of competitive stress could be progressively reduced by a multiplier derived from crown area overlap between adjacent competing trees, assuming certain crown diameter/tree diameter relationships. The model characterises a generation of what Munro (1974) has called "distance-dependent" models which have evolved from and elaborated on Newnham's approach. The actual technique for calculating competitive stress between trees has varied widely. Opie (1968) developed and compared a number of methods based upon Bitterlich's angle count system. Bella (1971) produced a variation of the competitive overlap technique involving differential weighting for tree size.

Arney (1972) extended the individual tree position dependent approach to provide a stand model in which competition was determined at a series of sectional heights up the stem by a number of competitive zones. It is an interesting model in that tree form was a result of differential growth rates at different section heights, rather than being simply implicit in a functional equation. It is also theoretically capable of demonstrating pruning effects on ring width and the dimensions of the juvenile core.

Mitchell (1969,1975) has been responsible for developing a rather different approach utilizing individual branch growth up the stem. Branch growth is inhibited by the presence of other foliage from adjacent trees. Increment is proportional to the net production of photosynthates which is a weighted function of the volume of each whorl of foliage. The weights are determined by the photosynthetic efficiency of the needles and depend on age, nutrient content, and so on.

These models provide extremely detailed information on the local environment of each tree and are most suited to the simulation of heterogeneous stands containing varied species, tree ages, and irregular spacings. On the other hand they are computationally very complex and are essentially limited to the simulation of small plots. These difficulties are discussed by Ek and Monserud(1974) in relation to the FOREST program, which is another model of this type. They state that their model is too expensive to be used directly for updating large numbers of forest inventory records, but can be used indirectly through the production of appropriate yield tables, which can be applied automatically in an updating system for mass forest data.

Another factor which mitigates against the use of distance-dependent models as a direct planning tool is the fact that they require tree position data as a basis for simulation. This would be a very expensive item of information to collect with normal ground-based forest inventory procedures. It is possible that current developments in low-level aerial photography, combined with electronic photo-interpretation may in future permit the mass gathering of this type of data, in which case the situation will change(Rhody, 1977). For the time being however, the distance-dependent model must be regarded as a tool for investigating the silviculture and economics of single stands, rather than as a potential sub-module for a forest planning system.

The alternative approach to the distance-dependent models involves treating the stand, with more or less justification, as the case may be, as a homogeneous entity with regard to spacing and tree age. The oldest and simplest sub-class of this approach includes the mean and dominant tree methods. In this group of models, growth functions are derived for a representative class of trees whose characteristics are then used, by the application of suitable weights, to obtain descriptive parameters for the whole stand. These models can be further sub-divided into two groups:-

1) Static models: The dependent variables such as mean diameter and volume are defined as functions of independent variables such as age, stocking, and site index.

2) Dynamic models: The dependent variables are rates of change of diameter or volume defined in terms of various independent factors. Where one or more independent variables are integrals of dependent variables, positive or negative feedback effects are incorporated in the model.

Static models can be expressed entirely in graphical or tabular form, as in the older types of forest yield tables (Meyer 1968). Such models may also be expressed as functional equations, either derived directly from data, or fitted to hand-drawn graphs (e.g. Hamilton & Christie, 1974). Dynamic models on the other hand require integration before they can be used. This may be possible analytically,, if a single function of relatively simple form is involved, as in the case of Clutter's work on Loblolly Pine (Clutter, 1963). More normally with this type of model, a system of difference equations constitute the model which is coded as a computer program. The precursor to this type of work in forestry appears to be the model developed by Lemmon & Schumacher (1963), although their model appears in fact to have been hand computed.

The above remarks apply to models of homogeneous stands that determine only mean production for the stand as a whole. Munro (1974) in his classification of yield models calls these "whole stand/distance independent" models. By the mid nineteen-sixties, with the wider availability of computers, it became apparent that the dynamic model approach could also be applied to class means of the stand diameter distribution, or even to the individual tree diameters themselves. These models are called by Munro "individual tree/distance independent models". Two general strategies appear to have been

adopted:-

1) Prediction of stand basal area increment, which is then partitioned by some algorithm among the individual diameters or diameter classes comprising the stand.

2) Prediction of diameter increment for each class directly as a function of other relevant state variables in the model, including at least one variable that is tree diameter or class dependent (to give differential growth rates between the classes).

It is interesting that the major published examples of such models appear to originate from Australia and New Zealand. Indeed, there appears to be a distinct regional bias amongst the industrialized nations as to the preferred type of model. In North America, the distance-dependent tree models have received greatest attention; in Europe and Japan the mean tree models are more important; whilst only in Australasia does the major interest lie with the individual tree distance independent models. The author is inclined to think that this is the outcome of historical factors in forest management, as follows:-

1) In Europe, low growth rates and relatively conservative management practices, together with increment data from long established permanent plots have led to mean tree models being adequate for forest planning purposes.

2) In North America, there are much more diverse and heterogeneous forest types; with at the same time relatively much less data about forest growth. Computer-based modelling techniques were available and acceptable at an earlier stage, leading to the rapid development and diversification of individual

tree models, both distance-dependent and distance-independent.

3) In Australasia, management of fast-growing exotic plantations is an extensive form of investment, financed by private capital or State loan funds at more or less commercial rates of interest. Maugé (1974) has emphasised the importance of the optimal intensity and timing of operations under these circumstances. It is perhaps this fact, combined with the homogeneity of the resource in question that has led to the elaboration of modelling techniques intermediate in complexity between crown-competition models, and whole stand models.

2.2 Distance-independent models

A preliminary assessment of the existing forest growth modelling technology suggested that on the one hand, mean tree models would underutilize the data currently available from growth plots in East Africa and Malawi; whilst on the other hand crown-competition models would be too complex to represent a viable planning tool. The intermediate level provided by the distance-independent tree models appeared to provide the most appropriate basis for a modelling strategy. Having made this decision, some operational examples were examined in more detail.

The FORSIM model has been used for operational planning in the Victorian Forestry Commission, Australia. Two basic growth functions are used. One defines height in terms of age and site index. Another defines basal area increment per unit area as functions of age and stocking, with a proportional correction factor for understocked stands. Trees are grouped into classes, with class mean basal area being incremented in each time cycle by allocation to the class of a proportion of the stand basal area increment. The initial stand condition is either supplied as inventory data, or generated as a fixed diameter distribution for stands

at a fixed initial stocking. FORSIM simulates the growth of many stands, comprising a total forest estate, at one time, and summarizes yields by various size classes from all compartments. There is an option which permits scheduling of cutting operations either strictly by silviculture, or according to a regulated yield algorithm. The main user options involve varying the specified thinning intensities and timing, the clearfelling age, the planting dates for new stands, or, with the regulated yield option the volume requirement. (Gibson et al, 1969,1970)

Whereas FORSIM was intended to facilitate the management of exotic Radiata Pine plantations in Victoria, STANDSIM was developed to predict yields for Mountain Ash (Eucalyptus regnans) forests which are indigenous to the wetter areas of Victoria and form a substantial resource. STANDSIM is a silvicultural rather than a planning model, in that it simulates the growth of a single stand only, but does so in more detail than FORSIM. The basic functions are similar, i.e. stand dominant height from site index and age, and basal area increment for the stand from age and stocking. However, additional functions permit variable initial stocking, self thinning of over-stocked stands, which is a frequent occurrence with natural regeneration following a forest fire; and mortality. As with FORSIM, basal area increment is distributed proportionally through the stand, although in this case individual tree diameters rather than class means are grown. The model is used to develop preferred silvicultural treatments by simulation, which are then used in a linear programming based scheduling system to actually define the location and timing of cutting operations. (Opie,1970, Weir, 1972)

Both the above models have the common feature of computing stand basal area increment and distributing it among the components, whether classes or individual trees. The alternative approach of predicting individual tree or class increment directly, is exemplified by the PREDICT model. In

this case, both tree diameter and tree height are predicted directly from complex multivariate models utilizing class and stand variables selected by combinatorial screening from the previous history of the stand. The system differs from many stand models in that growth functions are implicit in the model only as general relationships, and are determined specifically for each situation to which the model is applied. It is geared to a system for the acquisition of plantation growth information from systematic permanent plots (Rudra, 1970, Hall, 1974, Dargavel et al., 1975).

2.3 Stochastic versus deterministic models

Before turning to the specification of the modelling strategy finally selected for the current work, it is necessary to discuss the relative merits of stochastic and deterministic models. Deterministic models are those which, given an initial state, generate only a single outcome; whilst for stochastic models, a theoretically infinite variety of outcomes exists for continuous variables, defined by some probability distribution which may be determined by repeated runs of the model from the same initial state. This is achieved by inserting into some of the functions of the model random number generators, designed to simulate the probability distribution of the unexplained variation associated with any particular function.

The dichotomy might be characterised this way: a deterministic model gives a single answer in a given situation; the stochastic model can give many answers, which must be analysed statistically before any conclusions can be drawn. However, more than this is involved in choosing between the two approaches. In complex systems, with many feedbacks and interactions, threshold events may trigger a major change of state in the system. Such events would be eliminated from a deterministic model because only average results are possible for a given function; whilst they can occur as rare events in stochastic models. An example is given by Conway (1971) of such a

model for insect pest populations, in which pesticide application can occasionally trigger an increase in insect population due to differential effects on different life stages combined with predation/cannibalism mechanisms.

However, forest models are generally concerned with very few feedback effects (if one excepts the semi-physiological models of Mitchell, 1975). Threshold processes do of course occur with regard to climatic factors and their interaction with direct mortality due to frost or water stress, or indirectly via fungal or insect pests; and there is a case therefore for a stochastic approach in modelling these situations. For a simple mensurational model however, the limits of variability can be defined during the validation phase of model construction. A stochastic approach is therefore rather redundant, as well as greatly increasing the computational burden of the model, possibly to the point of rendering it impracticable as a management tool.

2.4 Definition of the modelling strategy

Having considered the various existing models described here, it was possible to define a strategy for modelling the growth of the three species that are the subject of the study (i.e. Pinus patula, P.radiata, and Cupressus lusitanica group species). Two basic growth functions were defined: Height as dependent on site index and age; and diameter increment as a function of height, relative tree dominance, and stand density. Initial stem diameter distribution, and limiting stand basal area functions were also necessary; the former to initialise the diameter vector of a stand in cases where inventory data is unavailable; and the latter to ensure that increment on stands at high stockings did not lead to excessive basal areas.

The model also required functions to simulate thinning operations, and to predict merchantable volumes from stem diameter and stand dominant height. After some consideration

of the data, it was decided that mortality would not be included in the model as described in this work; principally because simple density-dependent mortality appears to be negligible in all three species at the stockings at which they are planted at present, with future trends likely to be to lower rather than higher stockings. Mortality from local biological factors, such as Dothistroma pini needle blight of Radiata Pine; and mortality arising from water stress or storm damage are subjects that require extensive investigation in their own right before patterns can be delineated. They were therefore treated as exogenous to the present model.

Much of the experience required to define the type of model to be produced was obtained from work by the author on a number of precursor models; the most significant of these was the VYTL* model, which was designed to produce simple yield tables using growth functions similar to those described in Clutter & Allison (1974). The model was implemented on computers in Uganda and Tanzania, and demonstrated the feasibility of the approach as a practical planning method for forest departments in developing countries. However, VYTL was not well validated, and a number of the functions proved to be inadequate. The programme was also large and slow, and would not easily have been adaptable for use as a sub-module of a planning system. In the present work therefore this earlier approach was abandoned, and functions and algorithms were developed which as far as the author is aware are unique to the growth model described here.

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* This work is described in a mimeographed report. See Alder, 1975.

3. THE DATA ANALYSIS SYSTEM

3.1 The permanent plot network

The data used in the present study is derived from permanent growth plots set up in the exotic plantations of Uganda, Kenya, Tanzania, and Malawi. The original specifications and raison d'être of these plots are described by Wright (1967, 1969). They are in all cases circular 1/10th acre plots (i.e. approximately 0.04 hectares) whose location is determined by the responsible department in the country in question usually on the basis of a general stratification by plantation units, species, and site type, with final location being determined subjectively. The plots are usually clearly marked, and hence may not be subject to typical treatment by forest workers and contractors. Remeasurement intervals vary from three to four years in Uganda to annually in Kenya. The main parameters measured are tree diameters at 1.3 metres, using a fixed marker point to ensure strict relocation of the reference height, and the heights of dominant trees and in some cases a systematic subsample of trees for mean height estimation. The dominant trees are defined as a sample whose size corresponds to 100 trees per hectare, selecting only the largest diameter trees on the plot. For a significant subsample of plots tree positions have been recorded by measuring distance and bearing from the plot centre.

For several years, data recorded from these plots has been sent to the Commonwealth Forestry Institute, Oxford University, where a large data base and processing system has been established by H.L.Wright for storing, retrieving, summarizing and printing the plot measurements and major derived variables such as tree volumes, basal area, mean diameters, stocking, and so forth. The summaries are then returned to the countries providing the data to be used in developing management guides.

The actual extent of the data base is now considerable, with some 2000 plots altogether for the three species and four

countries considered here, in addition to data from other softwood and hardwood species in other tropical areas not included in this work.

3.2 Requirements for data analysis

The principle tools used in analysing data to develop functions, look-up tables, and transition matrices for simulation models are linear and non-linear regression, multiway tabulation, and graphical displays. On the basis of these requirements, the author decided that much time would be saved later in the study if packages could be developed at the outset to provide the services in a form that integrated directly with the pre-existing permanent sample plot (PSP) system, with a minimum of interfacing and data manipulation being needed to proceed from one type of analysis to another.

The resulting system is shown in figure 1. Input data from recent plot measurements are added to the existing data base as and when the measuremnts are received. These activities are carried out under the direction of H.L.Wright. The data base is maintained on magnetic tape, with all plots for a species group on a single tape (of which there may be several editions for security purposes). This tape contains full information on plot identification, measurement dates, individual tree diameters, and stand heights and derived variables (i.e. stand volume,basal area, stocking, etc.). The PSP system also updates a summary tape, which contains pooled information for all species and plots in a single location, but has only plot identification and the derived stand variables for each plot and remeasurement.

The CSPSP program (Control System for Permanent Sample Plots) combines a variety of data manipulation and analysis features. It can extract data from the summary tape, selecting only the specified variables required. Conditional elements can be used to restrict the plot records selected or analysed at any phase. Graphs of two variables may be

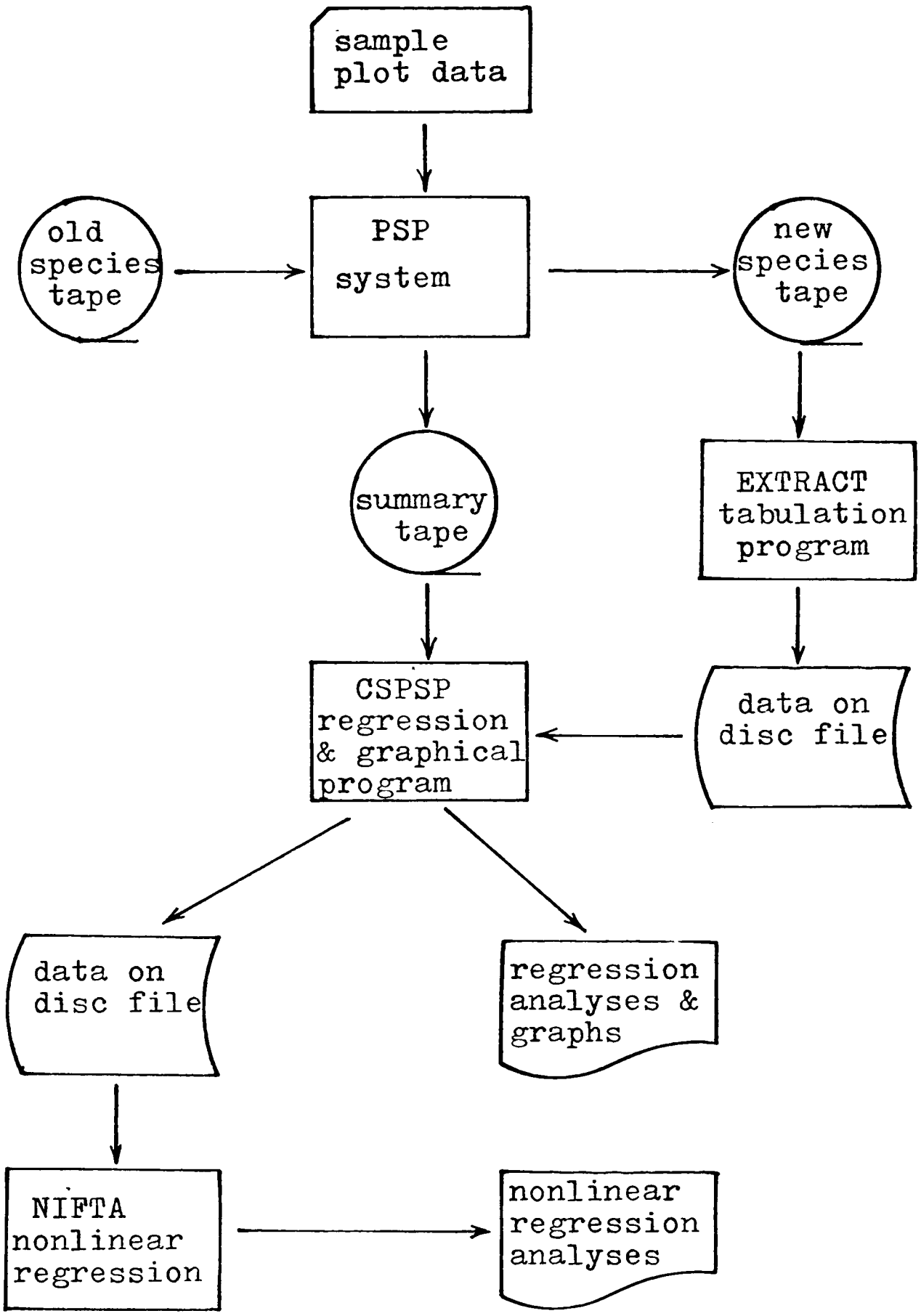


Figure 1 : Data analysis system for growth model functions

plotted, optionally classified by a third and fourth variable, to allow visual assessment of inter-relations between upto three independent and one dependent variable. Data may be subject to a variety of arithmetic transformations; and multiple linear regressions can be calculated. Predicted values from a regression can be computed and plotted against selected independent variables.

The data read from tape can be output to a magnetic disc file by the program (having been subjected if desired to transformations and conditional selection), whence it may be analysed by the NIFTA program. NIFTA (Nonlinear Fitting Algorithm) fits a general regression using a function provided to the program as steering data. It is based upon Hartley's (1961) modified Gauss-Newton algorithm. Apart from the normal regression statistics, NIFTA also provides a graphical deviation analysis which is useful in assessing lack of fit due to an inappropriate model structure.

The EXTRACT program was the last to be developed, and is a multidimensional tabulation package whose specific purpose is to summarise individual diameter measurements and diameter increments in cells defined according to classes of any of the tree or derived stand variables on the data base. The output from EXTRACT is suitable for direct input to CSPSP for graphical analysis and linear regression, and to NIFTA for nonlinear regression.

All three statistical programs (CSPSP, NIFTA, and EXTRACT) were written in their entirety by the author, except for system graphical and utility routines, and a linear regression library routine used in CSPSP.

3.3 Regression analysis assumptions

Since regression analysis is extensively used in this work for fitting the functions of the model, it is appropriate at this point to indicate the assumptions implicit in the method, and to consider to what extent these assumptions

may be violated in practice.

A linear regression model may be expressed in matrix notation as:

$$Y = \underline{b}.\underline{X} + N(e) \qquad (3.3.1)$$

and the nonlinear model as:

$$Y = f(\underline{b},\underline{X}) + N(e) \qquad (3.3.2)$$

where $\underline{b}$ is the n-vector of coefficients to be determined by regression; $\underline{X}$ is an n-vector of independent, known, factors. N(e) is a normally distributed random error with standard deviation e; and Y is the scalar dependent variable. The most crucial assumption in the fitting process concerns the normality and independence of the random errors. In practice, when fitting to data from permanent plots, one is dealing with a nested regression situation in which errors within each plot will be correlated and cannot truly be regarded as independent. Also when constructing linear models which involve transformations of the dependent variable the error distribution will be effected; the effect of any such transformation is not only to alter the shape of the resultant function, but to weight the data on the basis of a different error distribution.

These difficulties can be corrected after due investigation of each situation; Draper & Smith, for example, describe how the variance-covariance matrix can be corrected to allow for auto-correlation with nested data (Draper & Smith,1966). In practice however, provided the problem is not gross, the estimated coefficients will be good approximations to the true maximum liklihood estimators; although the weighting effects of Y-transformations may make a considerable difference in some cases.

In the present work, time did not permit detailed statistical investigation of each case; instead the view was taken that regression methods were to be regarded as aids in coefficient estimation which were not to be followed blindly, but were

rather to be judged according to the performance of the resultant functions. Furthermore, a good statistical fit could not be assumed to lead to the inference that the resultant function was a particularly stable or accurate component of the system model as a whole. For this reason great stress is laid in this work upon the importance of extensive validation at all stages during model development. It was found necessary to plot fitted functions individually and in groups and subsystems and compare them carefully with similar graphs derived from raw or tabulated data before a function could be considered to be performing in an unbiassed and realistic manner.

Similarly, non-statistical methods of coefficient adjustment such as the conditioning of site index equations or the ad hoc modification of coefficients to eliminate bias were found to be necessary in some cases and were used as appropriate. In some cases where data was lacking, e.g. the delineation of maximum basal area trends, hand-drawn curves were tabulated and converted to equations by regression.

Such cases were however reduced to a minimum, as the whole emphasis in the data analysis work was to automate as far as possible the processes involved, in order to allow a large number of alternative model hyptheses to be tested. At the same time, no use whatsoever was made of stepwise regression procedures; these tend to lead to the blind and unconsidered construction of very complex models that have no very logical basis. Rather, the author sought to proceed from an initially simple model, through a gradual process of complexification in the light of trends detected in the residuals of simpler models, until no useful improvement could be obtained.

4. THE MATHEMATICAL MODEL OF STAND GROWTH AND YIELD

4.1 Introduction

The main stages or groups of activities required to simulate stand growth according to the selected strategy are shown in figure 2. The initial condition of the stand can either be generated internally, or it may be supplied as a summary of inventory measurements. The model then enters an annual cycle of activities, the first of which is the determination of stand dominant height at the current age. The model then tests for thinning according to criteria based upon either dominant height, or age. If thinning is required, its effects are simulated, resulting in the modification of the vector of standing tree diameters as a result of removals, and the generation of a diameter vector representing thinned trees. The thinned tree vector then forms the basis for volume calculations designed to estimate merchantable volumes according to length and diameter assortments specified to the program.

Whether thinning is required or not, the diameter vector of the stand is then modified to incorporate one year's increment; the resulting standing basal area after the addition is compared with the permissable limiting basal area for that height and stocking, and if necessary, a proportional adjustment is made. Finally, age is incremented and the cycle is repeated for the following year, until either the stand is clear felled (an operation which is treated in the same way as thinning) or until some limiting age is reached to terminate the simulation.

The external factors that control the direction of simulation are the initial stand condition if inventory data is supplied, or if it is not, site index, initial stocking and the timing and intensity of thinning treatments.

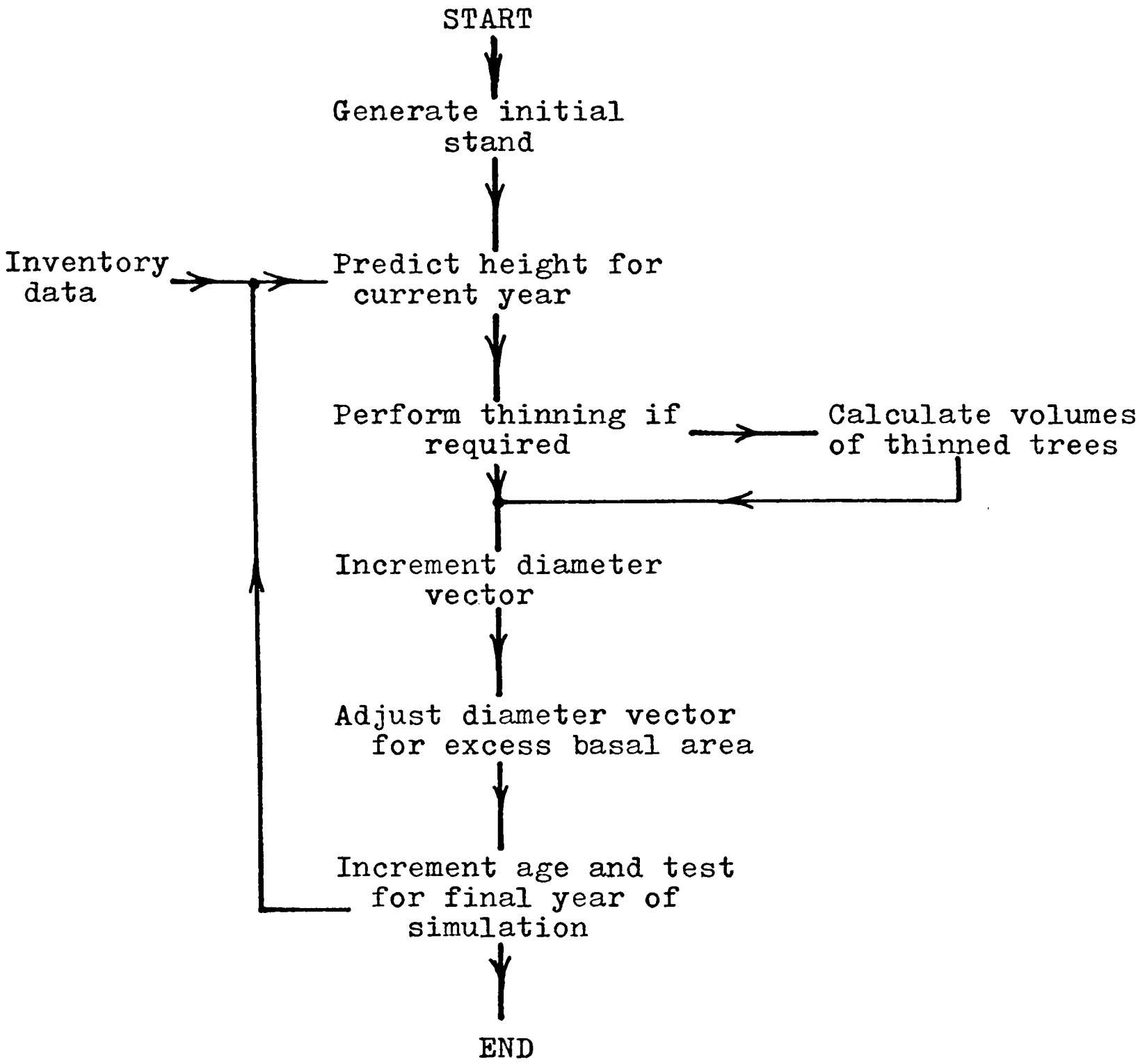


Figure 2: Outline of stages in stand simulation model

In the following sections, the mathematical models and the empirical species-dependent coefficients are developed and presented in order to describe the system in exact quantitative terms.

4.2 The representation and generation of diameter distributions

It is possible to apply diameter increment functions and volume equations to individual tree diameters as in the case of the STANDSIM model (Opie, 1970), or Goulding's (1973) model of Douglas Fir. However, considerable economies in computer time are realised if the diameter distribution is grouped into classes, and only the class mean values are incremented. This is the method employed by Gibson (1970) and Clutter and Allison (1974), among others, and adopted here, although with some alteration of technique from previously published methods. In the usual approach, both diameter medians d_i and class frequencies n_i are stored for the k classes in the stand. In the present model, storage requirements are reduced by storing only the d_i, which are diameters representing the 5%, 15%,....95% percentiles of a cumulative distribution function. Growth occurs, as with the frequency distribution method, by incrementing the diameters, although this approach is only valid with the cumulative distribution if increment is a monotonically increasing function of diameter, so that the ranking of diameters is unchanged by application of the function. The use of the cumulative form simplifies algorithms for thinning, and the calculation of stand parameters such as basal area and volume per hectare derived from summation processes. It also halves computer storage requirements when compared with methods that require the maintaining of class frequencies as well as diameters.

The following definitions are relevant to the later discussion:

(1) The model uses ten diameter percentiles, which are collectively represented by the vector $\underline{D}$. The elements of this vector are referred to as d_i .

(2) If the total stocking of the stand is N stems per hectare, then the number of stems less than d_i is :

$$n_i = N.\ 0.1(i-1) + 0.05 \qquad (4.2.1)$$

and the proportion of the stand less than d_i is similarly:

$$p_i = 0.1(i-1) + 0.05 \qquad (4.2.2)$$

As noted in section 4.1, the cumulative distribution must be defined initially prior to the simulation of stand growth. This may be done either by the provision of a distribution determined from measurements on plots in the stand to be simulated; or, alternatively, a distribution may be generated internally from a probability distribution function. The actual choice of the distribution function is governed mainly by the fact that it must be capable of assuming the requisite variety of distribution shapes to be adequately descriptive of the stands in question. For plantation conifers, Clutter & Allison (1974) use a Weibull distribution defined in terms of mean diameter, diameter variance, and minimum diameter; whilst Burkhart & Strub (1974) have used a Beta distribution whose parameters depended upon age, dominant height, and stocking. The Weibull distribution, described by Bailey & Dell (1973) was chosen for the present model on the empirical grounds that its parameters are simple to estimate; percentile diameters for the vector $\underline{D}$ can be generated very efficiently; and for the essential reason that it provides an adequate description of observed diameter distributions.

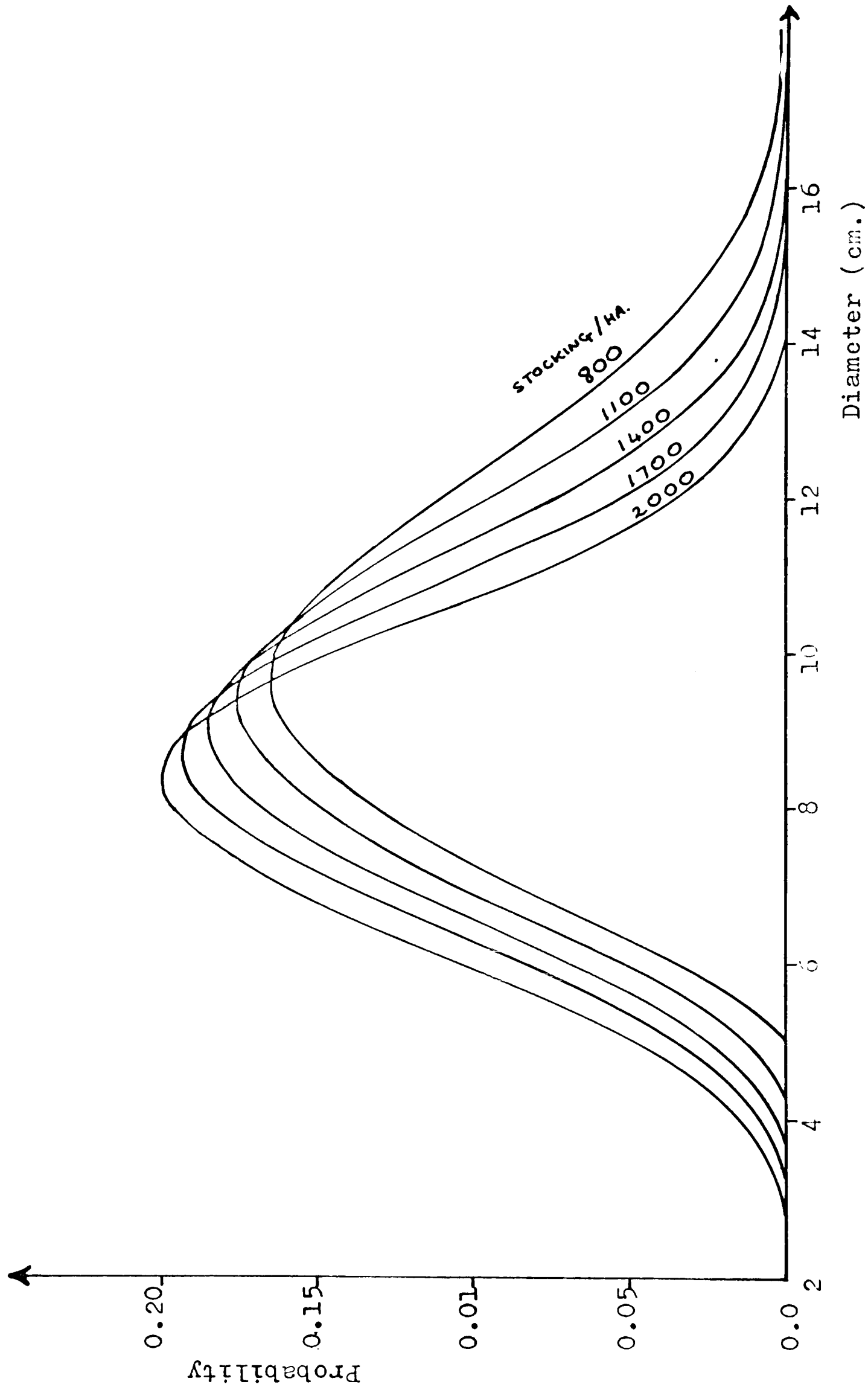
The cumulative form of the Weibull distribution can be written as:-

Table 1 : Coefficients for equations predicting Weibull parameters

	P.patula	P.radiata	Cupressus spp.
b_0	9.167	13.82	-0.6272
b_1	-14.63	-27.74	12.90
b_2	14.00	26.52	3.150
b_3	-11.16	-44.47	20.16
b_4	0.1260	-0.6550	-0.8880
b_5	4.343	5.067	4.540
b_6	-0.0563	-0.0047	-0.0076
b_7	0.2211	0.2304	0.3249
N	96	24	37
R^2 (1)	0.12	0.18	0.09
R^2 (2)	0.05	0.31	0.17
R^2 (3)	0.52	0.54	0.48

Note: (1) refers to equation (4.2.4), (2) to (4.2.5), and (3) to equation (4.2.6).

Figure 3 : Diameter distributions predicted for P.patula at various stockings



$$p_i = 1 - \exp(-((d_i - a)/b)^c) \qquad (4.2.3)$$

where p_i and d_i are as defined above, and a,b, and c are coefficients controlling distribution shape. This distribution was fitted using D'Agostino's method (1971) , to diameter distributions for the three species in the study, using stands with heights of 6-8m. only. The parameters obtained were graphed against spacing. Very wide variation was found to be present which may be partly the result of the small size of the permanent sample plots (0.04 ha.). However, simple regression models were formulated based on a reciprocal function in order to give an asymptotic effect with spacing. This might logically be expected in that the diameter distribution shape should be unchanged once the stand becomes sufficiently open for the trees to be effectively growing free of competition at the height selected. Three regression models were used, one for each of the Weibull parameters:-

$$W_a = b_0 + b_1/E \qquad (4.2.4)$$

$$W_b = b_2 + b_3/E - W_a \qquad (4.2.5)$$

$$W_c = b_4 + b_5/E + b_6 W_a + b_7 W_b \qquad (4.2.6)$$

In these equations, W_a,W_b, and W_c are the a,b, and c parameters of the Weibull distribution; the b_i are regression coefficients; and E is mean spacing, defined as:

$$E = \sqrt{10000/N}$$

where N is stocking in stems per hectare. In equation (4.2.5) the actual left-hand side fitted is $W_b + W_a$, which parameter combination represents approximately the 63% cumulative diameter in the stand (c.f. Bailey & Dell,1973), and shows better relationships with other parameters than W_b alone. Similarly, in equation (4.2.6) the two parameters W_a and W_b are introduced as independent variables for the

prediction of W_c to allow for some measure of interaction among the coefficients. The fitted values for the three species are shown in Table 1. The coefficients of multiple determination (R^2) are quoted on the table, and were of the order of 0.3; indicating that the relationships were very poorly defined. Nonetheless, the resultant predicted diameter distributions appear to change in a reasonable manner, as illustrated for five different levels of stocking for Pinus patula in figure 3.

In practice, initial distributions are very variable, and not strongly determined by mensurational factors such as height, spacing, et cetera. It is probable that the variability is largely a result of heterogenous spatial patterns of survival following planting and mortality in early growth. These patterns are themselves strongly influenced by microtopography and local edaphic variation. However, the model does not appear to be very sensitive to the initial distribution shape (see section 5); and in many cases for which the model is used, a measured diameter distribution from inventory data will provide the basis for the simulation.

In the computer program, the stand is generated during the year in which it reaches a height of 7 metres, this being the median of the range 6m to 8m from which the stands used in estimation of the parameters were obtained. The probabilities p_i corresponding to the elements in the vector $\underline{D}$ are known, and equation (4.2.3) is transformed to give the equivalent d_i, viz:-

$$d_i = a + b(-\ln(1 - p_i))^{1/c} \qquad (4.2.7)$$

where a,b, and c are the Weibull parameters derived from equations (4.2.4) to (4.2.6).

The diameters are stored in the vector $\underline{D}$ as they are calculated and are incremented in the subsequent annual growth cycles by the diameter growth model. The major limitation in this

approach is that thinning operations prior to the time at which the stand is first simulated cannot be modelled. However, the dominant height chosen (7m) is such that this is not likely to greatly restrict the use of the model; whilst the additional data needed can be gathered from temporary plots if the case for such work appears to be strong.

4.3 The prediction of stand dominant height

Stand dominant height is defined for the purposes of the present study according to the usage in the four countries to which this work relates. Denoted by the symbol H, it is the mean height of the 100 largest diameter trees per hectare. It is to a large extent independent of stand density except for tree grown for most of their life at very wide spacings, and depends primarily upon the age of the stand and the environmental variables effecting growth; the latter are principally climate, soil factors, and nutrient availability. A widely accepted assumption in forest research is that these varied factors can be integrated and quantified in their influence on stand growth by using the trees themselves as phytometers. The height of the stand at a fixed index age is assumed to provide a single measure, usually termed site index, of the potential productivity of the stand (Stage,1963). In some cases, the fixed index age is replaced by a measure of slope in the height/age function (Bailey & Clutter, 1974).

Because of their primary importance in classifying forest productivity, a considerable body of literature has developed concerning methods for the development of height/age/site index functions. Three principal groups of methods are widely used:-

1) The use of curves drawn by hand through a scatter of height/age observations. This is the oldest method, predating developments in mathematical statistics in the 1920's and 1930's, and described in most forest mensuration textbooks (e.g. Carron,1968). In spite of their non-statistical nature, such methods remain

perhaps the most satisfactory approach where data is limited.

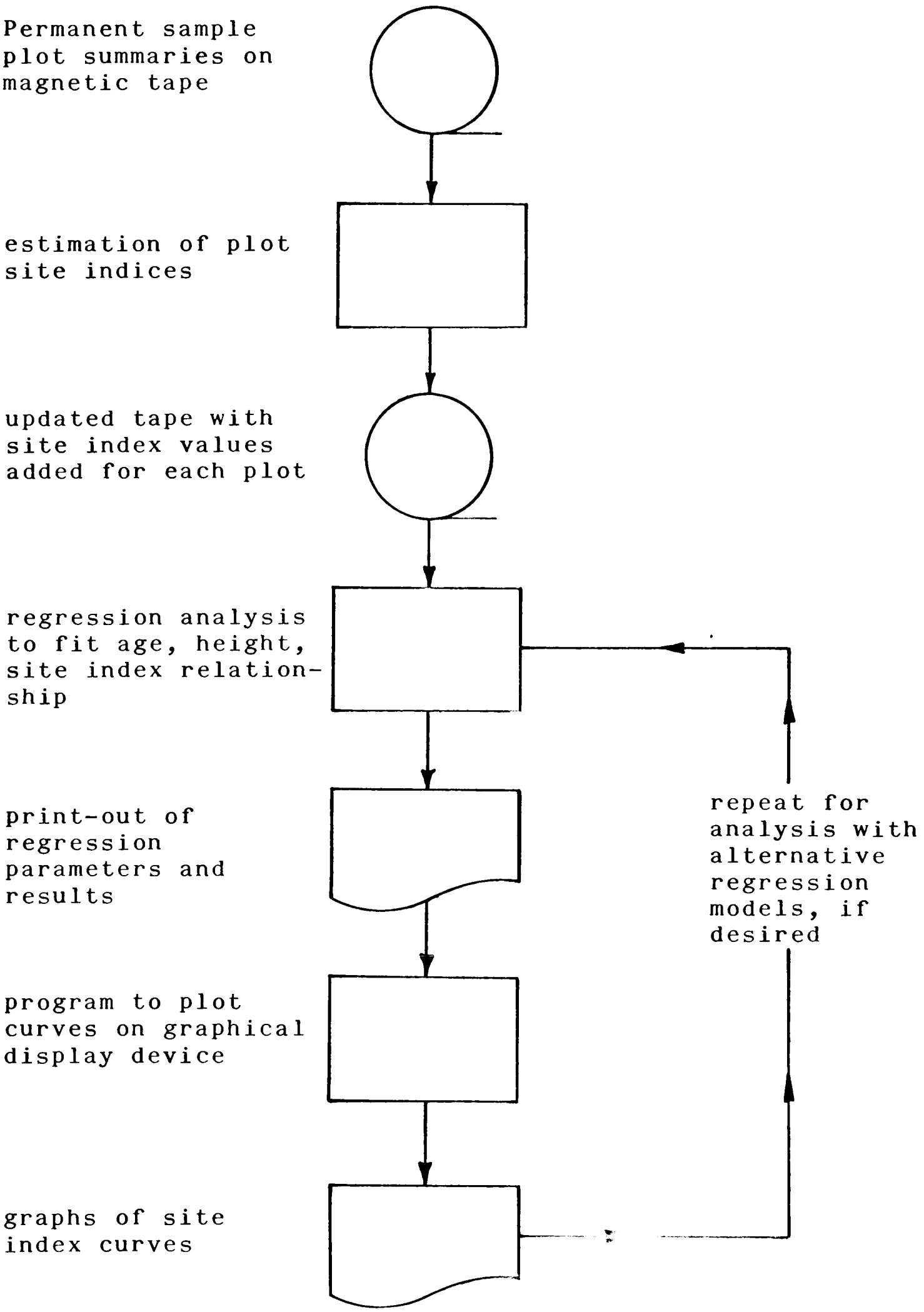
2) A mathematical approach based upon the assumption that all site indices are represented in each age class with the same relative probabilities. In this case, observations are grouped by joining equivalent confidence levels from a mean height/age line at each age to stratify the observations into a given number of site index classes (eg Tveite, 1969). A simplification of this approach uses only the mean, maximum and minimum observations (e.g. Wanene & Wachiori, 1975). Once the observations are grouped, discrete regression lines are fitted to each class.

3) Direct determination of site index independently for each plot. This may be done by (a) the use of a height measurement taken at the index age (e.g. Alder, 1973) or (b) retroactive estimation by stem analysis (e.g. Kirby, 1975), which is particularly useful for older stands, or (c) by extrapolation or interpolation of permanent plot growth trends.

For the present work ,the author selected the extrapolation method as most appropriate. This approach is closely related to and implicit in the methods of Bailey & Clutter (1974), but is somewhat more flexible in that once the basic data processing routines have been set up, a large number of functions can be tested with facility. This system is shown in figure 4. The stages in processing are as follows:

1) Each permanent sample plot has a site index assigned to it by extrapolation. The basic data is taken from the plot summary tape (see figure 1), and copied, together with site index, to a new tape in similar format, except that for each year of measurement, site index is now added as an additional stand variable. It is constant for all measurements of one plot, but varies between plots.

Figure 4 : System for developing height/site index models



2) A regression model is chosen, and fitted to the data. It is a three variable model, with age and the interpolated site index as independents, and height as dependent variable.

3) The resultant equation is "conditioned" as described below, and plotted graphically as a series of height/age lines, which are then compared visually with actual sample plot data drawn on the same scales by overlaying on a light table. When lack of fit is apparent, steps 2 and 3 can be repeated with an alternative function.

This brief description raises a number of points which must be considered in more detail. These are the technique of plot site index estimation, the choice of index age and regression dependent and independent variables, the method and criteria for function design, and the nature of the conditioning process.

The extrapolation method is illustrated diagramatically in figure 5, where the points represent height/age observations from a single sample plot. The line is a simple two variable linear regression model based on Schumacher's (1939) log/reciprocal model:-

$$\ln H = a - b/t \qquad (4.3.1)$$

where H is stand dominant height, t is stand age in years, and a and b are regression coefficients. Site index S is determined for the plot by solving:

$$S = \exp(a - b/15) \qquad (4.3.2)$$

where 15 is the index age used. In practice, both the degree of fit and the shape of the curve are influenced by the choice of index age (Heger, 1973). In this case three factors influenced the choice. Firstly, in young stands, current

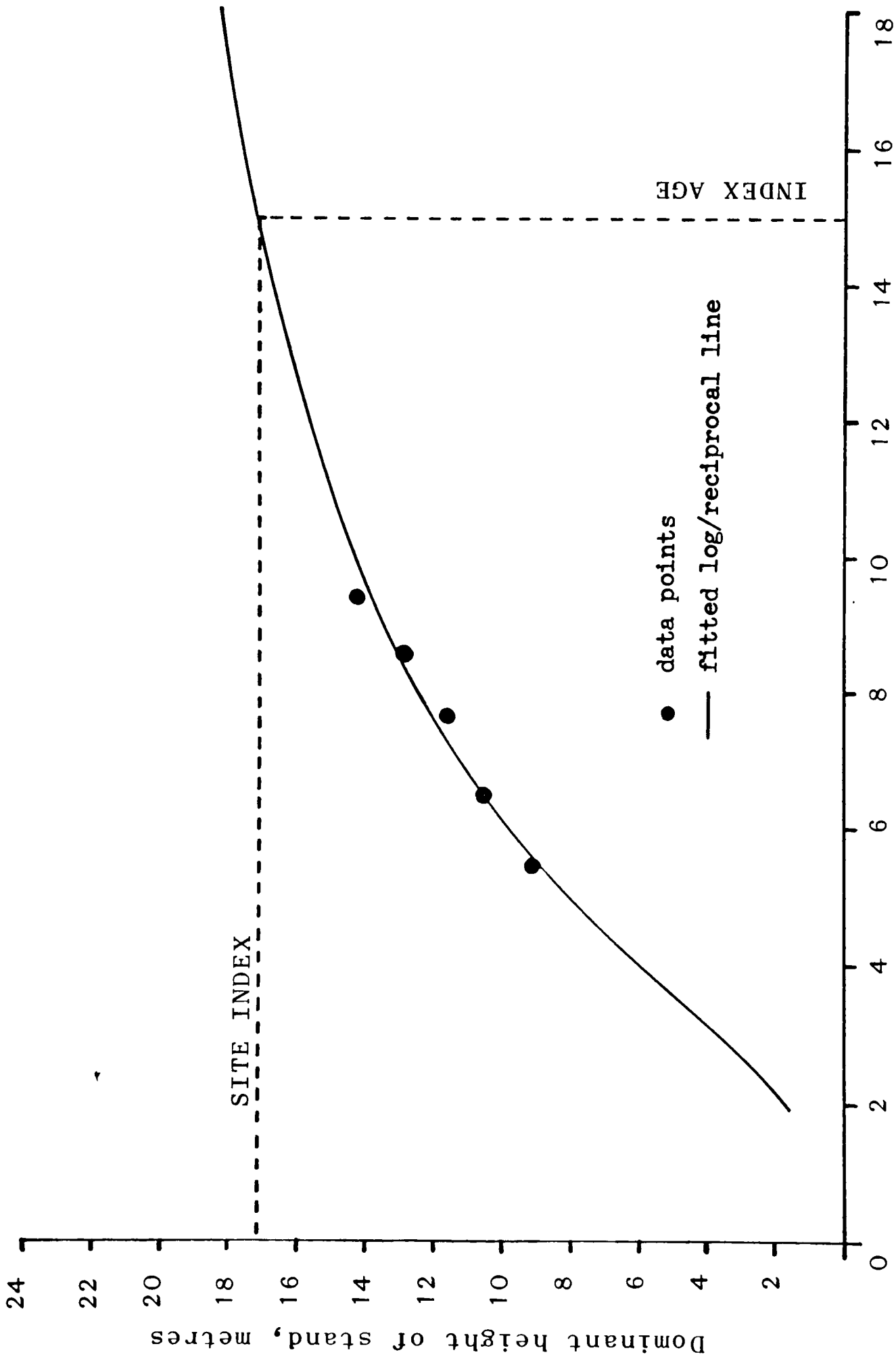


Figure 5 : Method of interpolating site index for a plot
Dominant height of stand, metres
24
22
20
18
16
14
12
10
8
6
4
2
SITE INDEX
INDEX AGE
data points
fitted log/reciprocal line
0
2
4
6
8
10
12
14
16
18
Age of stand from planting, years

height correlates poorly with subsequent productivity; it is not until the stand is approaching maturity that ranking of plots stabilises. This is probably a combined effect of high variability due to the great length of leaders in fast-growing tropical species; and the small sample that is taken for dominant height when using plots of only 0.04 ha. Secondly,too high an index age will lead to most of the site index estimates being extrapolations rather than interpolations. This would again induce variability, but would tend also towards severe bias. Thirdly, it was desirable to produce curves which conform to past precedents in the countries concerned. Fifteen years is the reference age used by Tanzania (Tanzania Forest Division, 1971); falls within the range of most of the sample plot measurements; and corresponds to approximate maturity for Pinus patula on the better sites, as assessed by maximum mean annual volume increment; and was accordingly chosen for these reasons. Other index ages were tested, however, but were found to be less precise as estimators of an unbiassed and stable site index.

The choice of regression model is determined by consideration of the shapes which the model must assume. A height growth model should be curvilinear, passing through the origin at age zero and tending towards an asymptote as age tends towards some maximal value. Suitable models are given by Schumacher's equation (see 4.3.1) and the Chapman-Richard's model (Richards, 1959). The latter equation has the form:-

$$H = a(1 - \exp(-bt))^{c} \qquad (4.3.3)$$

where H and t are as defined earlier, and a, b, and c are parameters to be fitted. This equation has certain attractions in that it is derived from logically explicable arguments concerning relative rates of anabolic and catabolic growth processes (Pienaar & Turnbull, 1973), and the function has been used as the basis for site index curves by a number of authors (e.g. Brickell, 1968; Payandeh, 1974; Alder, 1975b)..

Equation (4.3.3) is extended from a 2 variable function in Height and age to a 3 variable model by describing one or more of the coefficients as dependent functions of site index. In the author's work cited above, this approach was taken for the species in the study, and a number of complex equations developed. However, the Chapman-Richards model has a number of disadvantages. It is impossible to solve extensions in terms of site index except in the simplest forms; and it cannot in general be easily manipulated algebraically. For these reasons, alternative functions were sought that possessed similar shape characteristics but were easier to use. The final choice was an extension of the Schumacher equation, as follows:-

$$\ln H = b_0 + b_1/t + b_2 S + b_3 S/t \qquad (4.3.4)$$

where H, t, and S are as previously defined, and the b_i are regression coefficients fitted for each species. In this equation, both the asymptote and the slope are linear functions of site index, as can be seen by re-writing the model as shown:-

$$\ln H = (b_0 + b_2 S) + (b_1 + b_3 S)/t \qquad (4.3.5)$$

and comparing this with equation (4.3.1). The terms in the first bracket correspond to the a parameter in the latter function; and the second bracket to the b. The a parameter represents the natural logarithm of the ultimate asymptote as t tends to infinity; the b parameter governs the rate at which this asymptote is attained.

The coefficient values obtained when this equation was fitted by multiple linear regression are shown in table 2, together with some relevant statistics. The values shown relate only to a subset of the full data base, containing permanent sample plots from Kenya only. A further subset was formed from these in the case of P.patula to eliminate a number of plots which had changed their ranking with respect to other plots at an early age. When these plots were left

Table 2 : Site Index equation (4.3.4) coefficients for Kenya

	P.patula[1]	P.patula[2]	Cypress	P.radiata
b_0	2.5739	3.6068	3.4800	3.5438
b_1	-4.2269	-17.513	-11.716	-14.311
b_2	0.04793	0.008057	0.008467	0.01664
b_3	-0.1872	0.3308	0.1337	0.1474
N	1103	492	1096	1229
R^2	0.91	0.95	0.93	0.95
s_y	0.1201	0.0998	0.1069	0.0839
$\bar{S}$	22.3	23.6	18.2	27.4

Notes

(1) P.patula data from all permanent plots in Kenya.

(2) A subset of P.patula plots eliminating many young stands with anomalous early growth.

(3) N is the total number of observations.

(4) s_y is the standard error of the residuals from the regression.

(5) $\bar{S}$ is the mean site index for the data set used.

in, the b_3 coefficient was negative, giving rise to a singularity in equation (4.3.4) at the point where b_2S was equal to b_3S/t at which all site index lines passed through the same point; and below the age of this singularity, the ranking of site index lines was reversed.

Having fitted the equations, it was necessary to condition them so that the height predicted at the index age corresponded to the site index value used. There is no inherent statistical constraint in the least-squares fitting method to ensure that this will be so; on the contrary, it is an assumption of the method that the independent variables have no extrinsic relationship either with each other, or with the dependent variable apart from that stated in the model and determined by the coefficient values. The conditioning process can be avoided by constructing models using dependent and independent variables derived as heights and ages relative to the site index and index age; but the author's experience of fitting such models to the present data was that the resultant curves were much less satisfactory than with any unconstrained model i.e. one without inherent conditioning.

Conditioning the site index model is accomplished as follows:-

Defining S* as the height at the index age (15), we have from equation (4.3.4):-

$$\ln S^* = b_0 + b_1/15 + b_2S + b_3S/15 \qquad (4.3.6)$$

Solving for S, which is an unknown site index required to give a curve passing through S*, we obtain:-

$$S = (\ln S^* - b_0 - b_1/15) / (b_2 + b_3/15) \qquad (4.3.7)$$

and defining two new coefficients to simplify the expression:-

Figure 6 : Site index curves for P.patula in Kenya

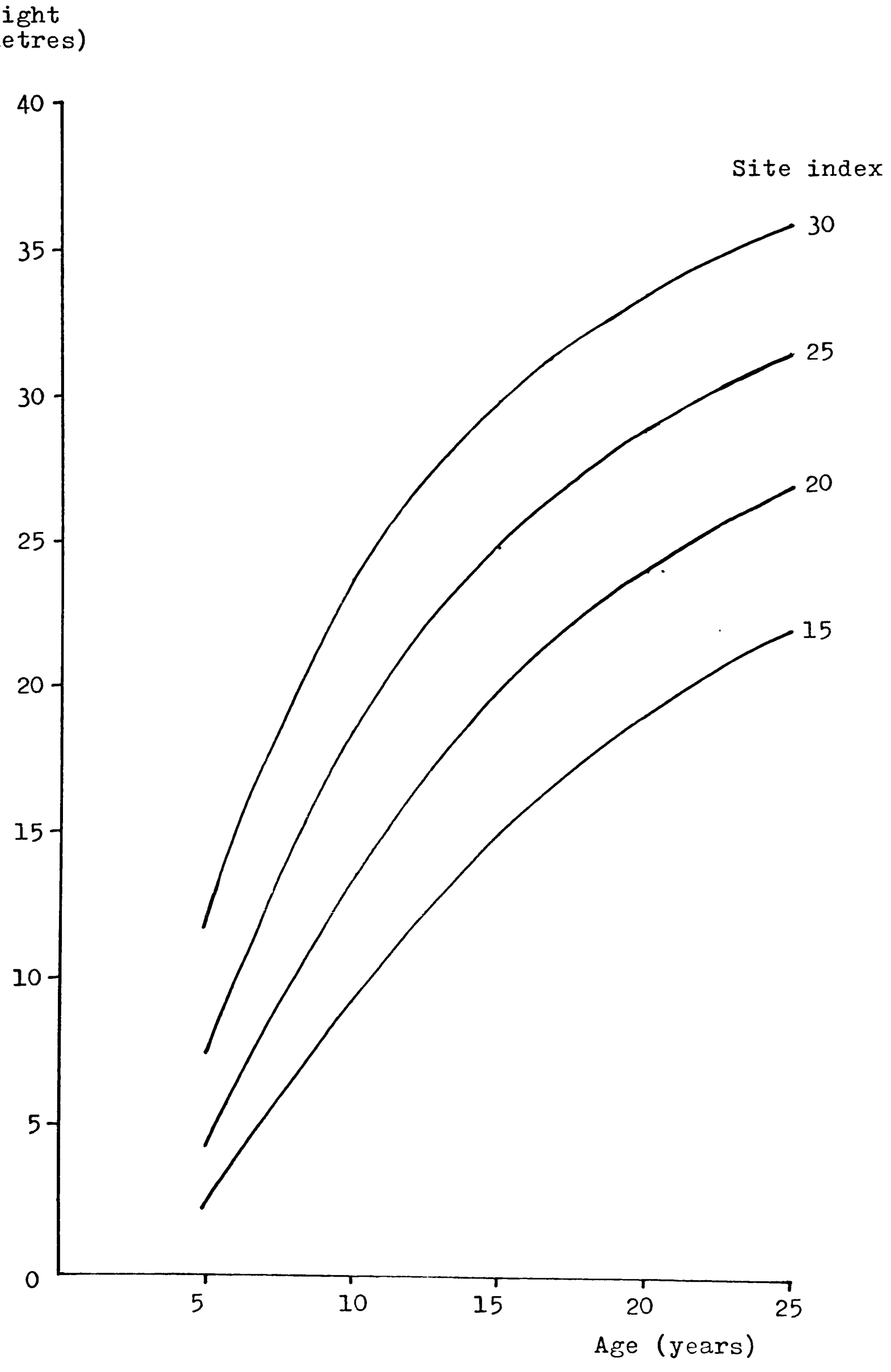


Figure 7 : Site index curves for P.radiata in Kenya

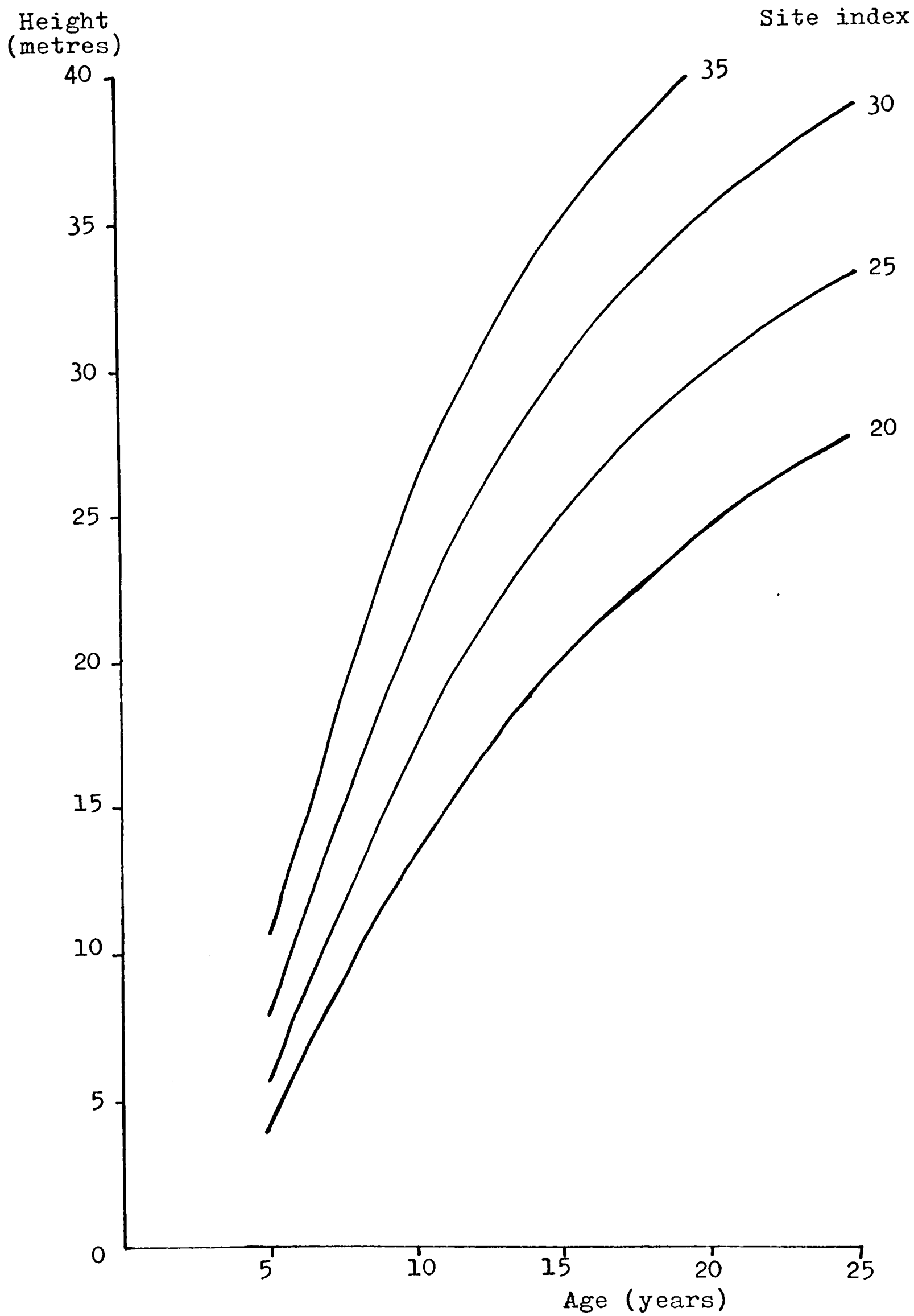
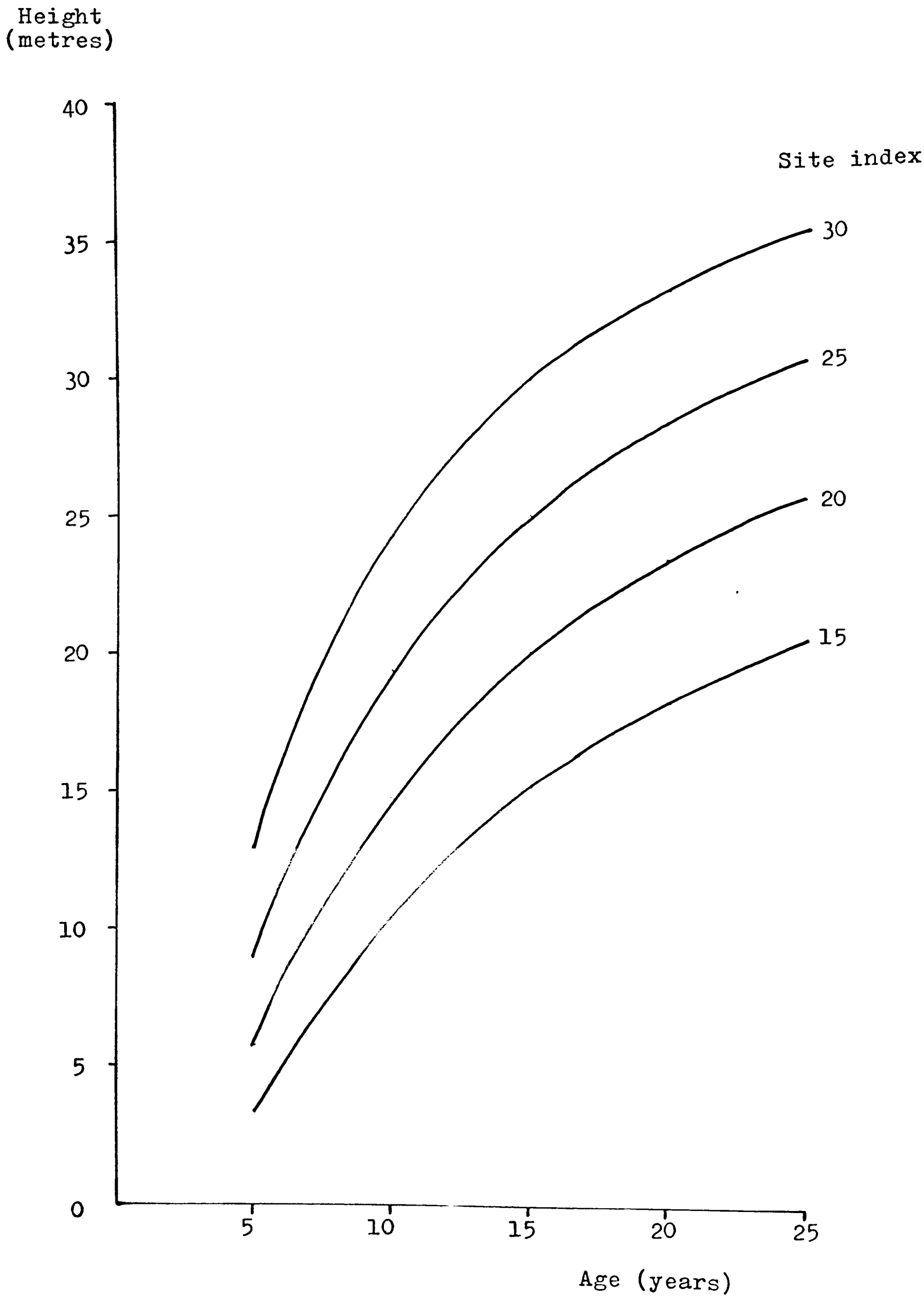


Figure 8 : Site index curves for Cupressus spp. in Kenya



$$c_1 = b_0 + b_1/15 \qquad (4.3.8)$$

$$c_2 = b_2 + b_3/15 \qquad (4.3.9)$$

we have:

$$S = (\ln S^* - c_1) / c_2 \qquad (4.3.10)$$

which is substituted into equation (4.3.4), giving:-

$$\ln H = b_0 + b_1/t + ((\ln S^* - c_1)/c_2).(b_2 + b_3/t) \qquad (4.3.11)$$

which is the conditioned site index model. This model can be readily solved for t, which is necessary to define the age at which stands reach 7 m., in order to initialise the diameter distribution; and for site index S*, which is necessary when inventory data is input to the model.

For the sake of simplicity of symbolism, site index as used in the balance of this work is defined as the value S* obtained from the application of equation (4.3.11) given height and age, and is symbolised simply by S. The site index curves obtained from the conditioned model, based on Kenya data, are shown for the three species in figures 6,7, and 8.

4.4 The simulation of thinning operations

The simulation of thinnings is an essential part of any stand growth model. Following thinning, the vector of stand diameters will be modified, as will stand density, and subsequent growth will follow an altered course. Thinnings themselves are controlled by a number of parameters:-

1) Timing.

2) Intensity.

3) Distribution of stem removals.

The timing for thinnings is a matter of management decisions, and is an exogenous variable in the stand model, although it becomes endogenous when the latter is incorporated in the PYMOD management model described in section 6. It is normally specified in one of three ways: by age, by dominant height, or by basal area. Only the first two methods are used in the areas to which this model relates for normal management; but basal area control is used in some thinning and spacing experiments. In the model, once the specified threshold value for age, height, or basal area is reached, then the thinning routines are executed. Apart from this simple decision, the timing of thinnings does not effect any other aspect of their simulation.

The intensity of thinnings is most often considered in terms of the number of stems to be removed, or the proportion of the existing stand to be removed or left. It may also be specified in terms of basal area, but again this only applies in the study zone to experimental sites. This factor is again exogenous to the model; i.e. supplied from outside or determined by the user. Internally, the method of specification is converted to a leave fraction L, defined as the ratio of the stocking after thinning to the stocking before thinning.

The distribution of thinnings is determined endogenously. Other workers have used distributions based upon an examination of observed thinning patterns, usually from stands managed under fairly uniform regimes (e.g. Clutter & Allison 1974). Attempts to characterise thinning distributions with the present data failed to produce any strong or consistent patterns, presumably because of the following interacting factors:-

1) The permanent sample plots are, as mentioned in section 4.2, too small to give reliable estimates of diameter distributions.

2) The plots are clearly marked in the forest

and are unlikely to receive typical treatment.

3) Factors other than thinning, notably windthrow, lead to removals which are not distinguished from thinnings in the data base, and which can be expected to follow a quite different distribution.

4) The varieties of stand treatment are quite heterogeneous as a result of the many different projects, thinning regimes, and variations in local management.

In the author's earlier model, VYTL (Alder, 1975a), these difficulties lead to the adoption of an "ideal" low thinning in the simulation, in which only the smallest trees were removed. This assumption appears in practice to be most unrealistic, since such evidence as is available suggests a tendency to fairly uniform distributions, although slightly biassed to the smaller stems.

Accordingly, in the present case, a different type of model was assumed, based upon a simple power function of percentiles of the cumulative diameter distribution , and the proportion of a class to be removed. Considering this as a continuous probability function, thinning distribution is defined by the basic equation :-

$$r = p^c \qquad (4.4.1)$$

where r is the probability that a stem will be left whose diameter corresponds to p in the cumulative diameter distribution. c is a constant which is dependent on thinning intensity. The cumulative probability of removal corresponds to the leave fraction L, i.e. it is the integral of (4.4.1) for values of p from 0 to 1 :-

$$L = \int_0^1 r.dp \qquad (4.4.2)$$

which is expanded as follows:-

$$L = \int_0^1 \left[1/(c + 1).\ p^{c+1} \right] \qquad (4.4.3)$$

$$= 1/(c + 1)$$

and hence the constant c can be defined as:

$$c = 1/L - 1 \qquad (4.4.4)$$

From these relationships, a finite algorithm can be developed for application of a thinning treatment of a given intensity to the stand diameter vector $\underline{D}_b$ before thinning to generate a new vector descriptive of the stand after thinning, symbolised by $\underline{D}_a$. At the same time, the number and distribution of removed stem diameters is evaluated. The proposed algorithm proceeds in the following steps:-

1) For each class i, an after thinning percentile p_a is obtained from the before thinning value p_b. It can be seen that this will be given by:-

$$p_a = 1/L.\int_0^{p_i} r.dp \qquad (4.4.5)$$

which from equations (4.4.3) and (4.4.4) reduces to:-

$$p_a = p_i^{1/L} \qquad (4.4.6)$$

2) A new diameter vector $\underline{D}_a$ is then computed from the before thinning vector $\underline{D}_b$ by interpolation between the p_a to the equivalent percentile points p_i. It should be noted that during step 1 above, the thinning has been simulated by adjustment of the percentile values, but leaving the corresponding diameters unchanged. The interpolation method used in the model is linear, since it is doubtful whether the assumed nature of the model justifies

anything more sophisticated (e.g. quadratic or cubic splines). The new after thinning diameter elements d_i of the vector $\underline{D}_a$ are therefore given by:-

$$d_i = (p_i - p_j)/(p_k - p_j).(d_k - d_j) + d_j \qquad (4.4.7)$$

where p_j, p_k are the percentile values from the vector $\underline{P}_a$ (i.e. the vector formed from the elements p_a in (4.4.6)) which enclose the standard percentile value p_i of the current class. d_j and d_k are the corresponding elements of the old diameter vector $\underline{D}_b$. d_i is the new diameter for the after thinning stand vector $\underline{D}_a$.

In cases where p_i is 0.95, i.e. for the tenth class in the vector, then p_k is taken as 1, and d_k is estimated, on the assumption that the interval:

$$d_{max} - d_{.95} = d_{.95} - d_{.85}$$

where d_{max} is the limiting diameter, hence given by:

$$d_{max} = 2.d_{.95} - d_{.85} \qquad (4.4.8)$$

d_k is taken as d_{max}.

3) Thinning frequencies are calculated by the following logic:-

a) 11 diameter classes are constructed, with mid-points given by :-

$$d_j^* = (d_j - d_i)/2 \qquad (4.4.9)$$

where j is i+1 and i varies from 1 to 10. The d_j^* are the mid-points of the diameter classes for the thinnings. d_2 to d_{10} are taken from the vector $\underline{D}_b$. d_1 and d_{11} are diameters corresponding to the terminal elements of the distribution and are obtained by similar assumptions to (4.4.8), viz:-

$$d_1^* = 2d_1 - d_2 \qquad (4.4.10)$$

$$d_{11}^* = 2d_{10} - d_9 \qquad (4.4.11)$$

b) The before thinning frequencies corresponding to the d_j^* diameter classes are :-

$$f_{bj} = 0.1N_b \qquad (4.4.12)$$

for j from 2 to 10. For j=1 and j=11, they are:

$$f_{bj} = 0.05N_b \qquad (4.4.13)$$

which definitions are implicit in the class bounds set up (4.4.9 to 4.4.11) and the original definition of the cumulative vector $\underline{D}$ (section 4.2). N_b is the stocking per hectare prior to thinning.

c) After thinning frequencies are derived from the vector $\underline{P}_a$ of cumulative percentiles corresponding to $\underline{D}_b$ and hence the d_j^*.

$$f_{aj} = N_a\,(p_{aj} - p_{ai}) \qquad (4.4.14)$$

where j is from 1 to 11 and i is j-1. N_a is stocking after thinning:-

$$N_a = L.N_b \qquad (4.4.15)$$

d) The frequencies of the thinnings are simply the differences between the before and after thinning frequencies from (4.4.12 to 4.4.13) and (4.4.14):-

$$f_j^* = f_{bj} - f_{aj} \qquad (4.4.16)$$

We thus have a definition of thinning in terms of a simple power model of thinning frequency distribution. It is based

upon purely hypothetical assumptions but gives a distribution of removals that is spread through all diameter classes in the stand, although strongly biassed to the smaller stems for light thinnings, with the degree of bias becoming less as the intensity of thinning increases.

A similar analysis can be applied to any thinning distribution defined in terms of cumulative diameter percentiles and and the probability or proportion of stems of that percentile being left untouched; only equation (4.4.6) in the algorithm would be affected. Ideally such a function should be integrable, but if this were not the case (e.g. a Beta distribution) then a numerical integration could be employed based on equation (4.4.5). Empirical functions derived from large temporary plots could be used in this way to render the model more accurate when applied to specific management areas.

In the present model, apart from the thinning from below simulated by equation (4.4.1) with a positive c coefficient, another type of thinning, non-selective or mechanical thinning, has been included. This is simulated by simple adjustment of stocking N, since the actual distribution of diameters D will be unaffected by the thinning, which is assumed by definition to affect equally all diameter classes.

4.5 Tree taper and volume determination

In East Africa and Malawi at the present time, tree volume equations developed by Wright (private communication) in the mid and late nineteen-sixties are in use for predicting tree total volume from tree diameter and either tree total height or stand dominant height. These volume equations are widely used in management practice, and have been subjected to a number of field tests that have confirmed their validity.

At the same time, it should be noted that tree taper systems have major advantages over whole tree volume equations in

that they include information relating to any diameter limit, as well as section lengths to a given limit or between limits. Extensive recent studies have been made of taper functions by Demaerschalk (e.g. 1973), Kozak et al.(e.g. 1966,1969), and Ormerod (1973,1976). The general principle involves fitting a regression of the type:-

$$d_k = f(h_k) \qquad (4.5.1)$$

where d_k is a sectional diameter at height h_k from the ground. The data is derived either from felled and sectioned trees, or alternatively by direct or optical measurement of standing trees (Arney & Paine, 1972).

To derive volume over a given interval, equation (4.5.1) is integrated as a solid of revolution to the required limit:-

$$v_k = \pi/4 \int_0^{h_k} f(h)^2 . \partial d \qquad (4.5.2)$$

where v_k is volume from the ground to a height h_k. ∂ is used as the symbol for the differential function to avoid confusion with the symbol d for diameter at height h. If h_k is the total height of the tree, then v_k is tree total volume.

In order to use this approach, the function f(h) should be integrable with respect to diameter d. If it is not, numerical integration can be used in some contexts; for example, when printing volume tables. But when used as a subsidiary part of a more complex model in which the volume estimation routine may be required many thousands of times, it is highly desirable to avoid the computational overheads associated with a numerical method, and have instead an analytically-derived integrand.

A common form of integrable function that has been used by other authors is the polynomial ofrelative diameters or

basal areas (e.g. Bruce et al., 1969). A curve of this type was fitted to tree taper data for Pinus patula collected during 1965 in Kenya and archived at the Commonwealth Forestry Institute, Oxford. It was this data that was used as the basis for the tree volume equations developed by Wright, referred to above. The polynomial function obtained was:-

$$Y = -0.9727X + 8.3178X^2 - 12.909X^3 + 6.6188X^4 \qquad (4.5.3)$$

where Y is the relative sectional basal area:-

$$Y = (d_k/D)^2 \qquad (4.5.4)$$

where D is tree diameter at breast height (1.3m). X is the relative height:-

$$X = (h_t - h_k)/(h_t - 1.3) \qquad (4.5.6)$$

where h_t is tree total height. This measure is zero at the tip of the tree, and unity at breast height D, and was taken from Ormerod (1973).

This polynomial is shown as a dotted line in figure 9, superimposed on stippled areas illustrating the spread of data; the denser stipple shows the region within which the majority of observations lay, with the balance between the outer dotted lines except for a few anomalies. The principal difficulty with this model lay in the poorly defined lower region of the curve, below relative heights of 0.125; here the polynomial runs almost parallel to the x-axis, resulting in great sensitivity when the function was used to estimate heights, as required in the algorithm described later in this section.

By visual examination of the data, a simplified alternative model was seen and developed, based upon the superimposed quadratic and periodic effects that are present. The model

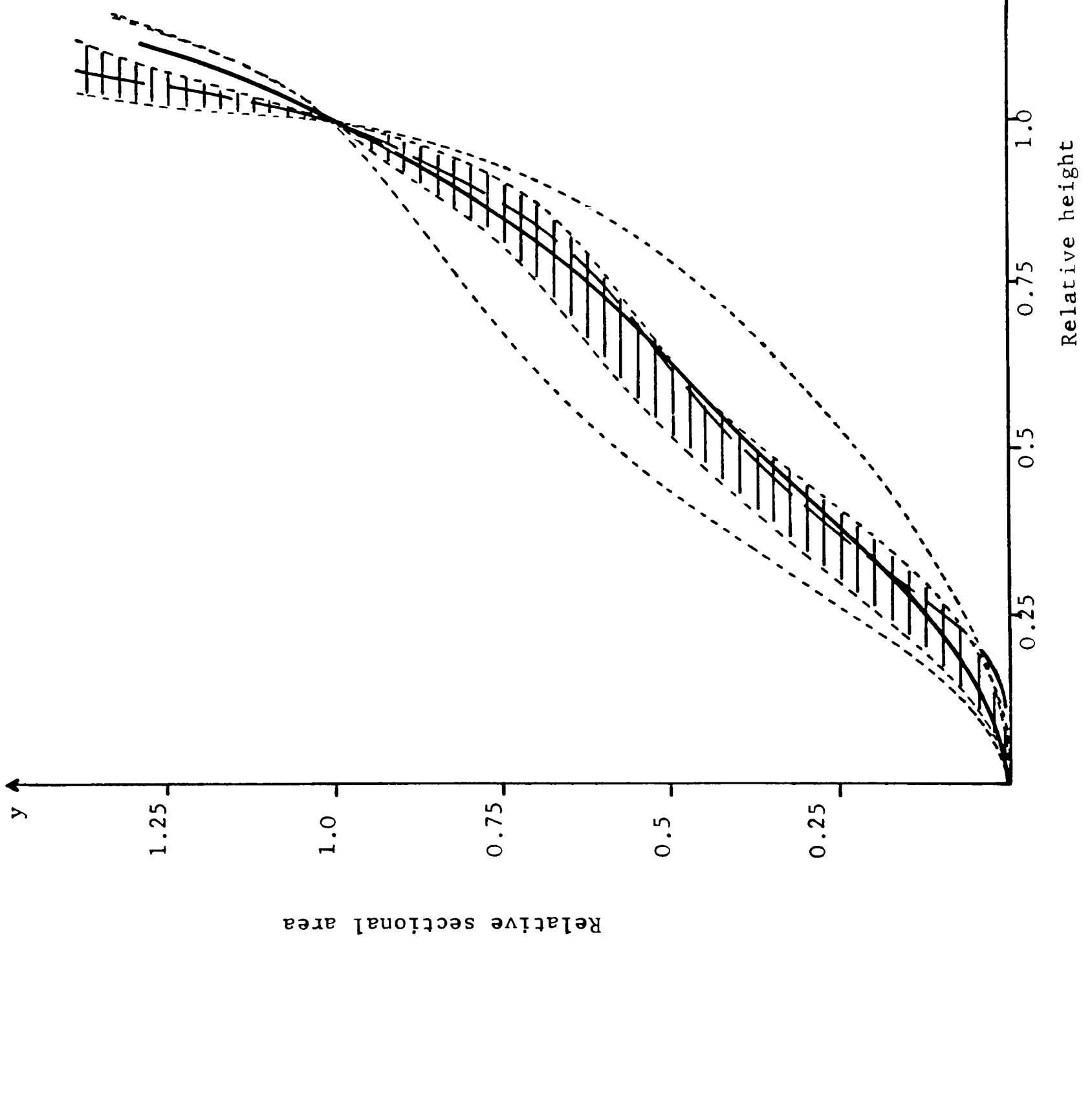


Figure 9: Quadratic/cosine and polynomial taper model compared, for P. patula

consisted of a basic quadratic curve of relative sectional area on height, with a superimposed sine wave scaled to reach its minima at X = 1. The version fitted graphically is:-

$$Y = X^2 - 0.0625(\cos 2\pi X - 1) \qquad (4.5.7)$$

where the argument of the cosine function is in radians. This function can be integrated to yield relative volume from the tip of the tree (Y=0) down to a relative height y quite simply :-

$$v_r = 0.00008745 \int_0^y Y.\partial X \qquad (4.5.8)$$

$$= 0.00008745 \left[\tfrac{1}{3}X^3 - 0.0625(\sin(2\pi X)/2\pi - X) \right]_0^y \qquad (4.5.9)$$

noting that the factor 0.00008745 is the conversion from sectional area in centimetre diameter squared to square metres. Actual volume is derived from relative volume by multiplying by true height, viz:-

$$v = v_r . h_t \qquad (4.5.10)$$

Equation (4.5.9) is used in the stand growth model as the basic taper equation for all species to determine the assortment of tree volume, as calculated by Wright's equations using tree diameter and stand dominant height, into merchantable classes defined by diameter and length restrictions. Undoubtedly there are in fact significant differences in the taper equations for Cypress species and the two Pinus species; but these differences will have only a minor effect on the gross allocation of volumes between classes; and none whatsoever on volume estimation as such since this is based on the species-specific Wright equations.

The harmonization of taper equation volume predictions with those from total volume equations is not a new idea (Demaerschalk, 1972), but the method used here has not apparently been reported before. It is achieved by calculating tree height indirectly from tree volume based on stand dominant height and tree diameter. Designating v_t as tree volume derived from Wright's equations:-

$$v_t = f_s(D,H) \qquad (4.5.11)$$

where D and H are, as previously defined, tree breast height diameter and stand dominant height, and the s subscript denotes that the function is species dependent, we note that:-

$$h_t = v_t/(0.00007845/D^2.F) \qquad (4.5.12)$$

where F is a form factor. This is taken as 0.5, which corresponds to a relative height of 1.0893, which can be seen by inspection to be a reasonable assumption (figure 9).

Given tree height from (4.5.12) and the taper equation (4.5.7) and its definite integral (4.5.9), an algorithm can be described to allocate tree total volume between m merchantable classes, with the i'th class defined by a minimum acceptable diameter d'_i and a minimum acceptable length l'_i. It is assumed that the subscript denotes their preferred order, i.e. class 1 is preferred to class 2, etc. However the actual values of the d' and l' need not be in any particular size relationship between classes. The stages in the algorithm are as follows, and are shown as a flowchart in figure 10:-

1) The m merchantable classes are defined initially, either as input data, or through some mathematical programming or simulation routine at the wood production scheduling level.

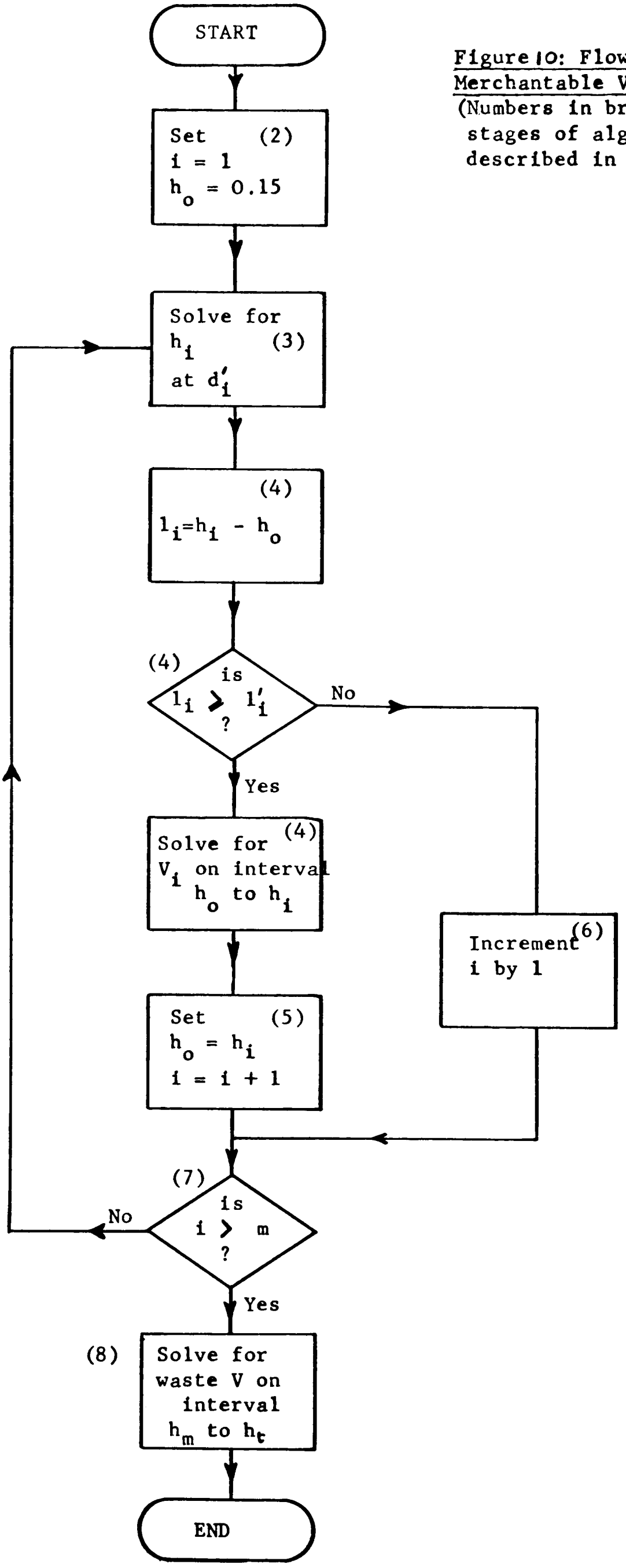


Figure 10: Flowchart of Merchantable Volume Algorithm (Numbers in brackets refer to stages of algorithm as described in the text).

2) For a given tree, the class index i is set to 1, and the base height h_0 is set to an assumed stump height of 0.15 metres.

3) The tree height h_i corresponding to d_i' is solved from equation (4.5.7). An analytical solution is not possible for h_i from this equation; but a numerical solution is evaluated by the bisection procedure (Stark,1970).

4) The actual length of the section h_0 to h_i, termed l_i, is compared with the minimum acceptable length l_i'. If l_i is less than l_i', then the algorithm branches directly to step (5). Otherwise, the volume is computed over the section h_0 to h_i using equations (4.5.9) and (4.5.10) and added to a volume accumulator v_i for the current class.

5) The section base h_0 is reset to the current value of h_i.

6) The class index i is incremented by 1.

7) If i is greater than m, the algorithm branches to step (6); otherwise it returns to step (3) for volume computations for the next class.

8) Waste volume, not assigned to any class, is calculated by applying equation (4.5.9) over the limits h_m to h_t, after which the algorithm terminates.

One additional logical phase, not included in the above description, involves checking the the diameter of the tree at h_0 for the first class against the merchantable diameter for that class d_i', during the initialization of i in step 2. If d_i' is less than d_0, then i is incremented by 1 and the test repeated until either d_i' is greater than

d_0 , or i exceeds m,in which case the algorithm branches directly to step (8).

This method gives a more realistic discrimination of merchantable volumes than is possible in systems based only on diameter limits, as for example in FORSIM (Gibson, 1970).. Short lengths of high diameter material normally occur in the lower bole, but cannot be allocated for use as for example, veneer logs, because their length is insufficient. Similarly, special classes of long material such as structural beams or transmission poles can be discriminated from shorter lengths of saw timber or pulp with the same diameter restrictions.

All these volumes are assumed to be over-bark. No account is taken in this work of bark thickness or underbark volumes, principally because discussions with forestry personnel in countries likely to be prime users of the model suggested that their current marketing and planning practices are based on over-bark volumes; but at a later stage, work will be needed on this factor and also on questions of defect.

The volume algorithm described above refers only to a single tree. The method is applied to the class values in the vector of thinning removals, whose diameters are obtained as described in section 4.4, equation (4.4.9). The merchantable volumes obtained for each class median tree are multiplied by the frequencies for that class as obtained from equation (4.4.16) and the preceding steps. The volume calculations are a relatively time consuming component of the whole model, and are therefore performed in the PYMOD program formulation only when thinnings are carried out (or clear felling operations). However, their is no reason why this volume calculation logic should not be applied in other ways, as for example to inventory data to determine alternative conversion options. This type of approach has been used by Burkhart et al (1971), with a

different method of volume calculation, as the basis for a "conversion alternative" simulator; and could in the author's opinion, be of great practical value in its own right.

4.6 Tree diameter increment

The prediction of tree diameter increment is the basis of any forest model that functions at the individual tree level. In the distance-dependent model, the general strategy is to define a growth rate equation by differentiating total diameter as a dependent of some age-related factor such as height, using observations from open-grown trees to obtain coefficients. This defines a maximum growth, which can then be successively reduced according to the competitive status of the tree. The latter, in this class of model, involves computations based upon the positions and sizes of neighbouring trees, as discussed in section 2.1 (e.g. Newnham, 1964). Most models of the distance-independent class have, as mentioned earlier, based tree increment estimates upon stand basal area increment which is then distributed among trees using a proportionality factor dependent on tree diameter.

In the present work, neither approach was used. The distance dependent tree modelling concept was too complex, computationally, to provide the basis of a feasible management model; whilst the algorithms based upon the distribution of basal area seemed too empirical and arbitrary.

As a starting point for the investigation, individual tree increment data for dominant trees was tabulated for classes of stand dominant height, using the EXTRACT program discussed in section 3.2; the results are shown in figure 11. Each point in this graph is the mean of several hundred or thousand individual tree observations, grouped by 5 metre height classes. A clear and well defined trend is indicated, whose

Figure 11. Mean diameter increment of dominant trees grouped into classes of dominant height - P.patula

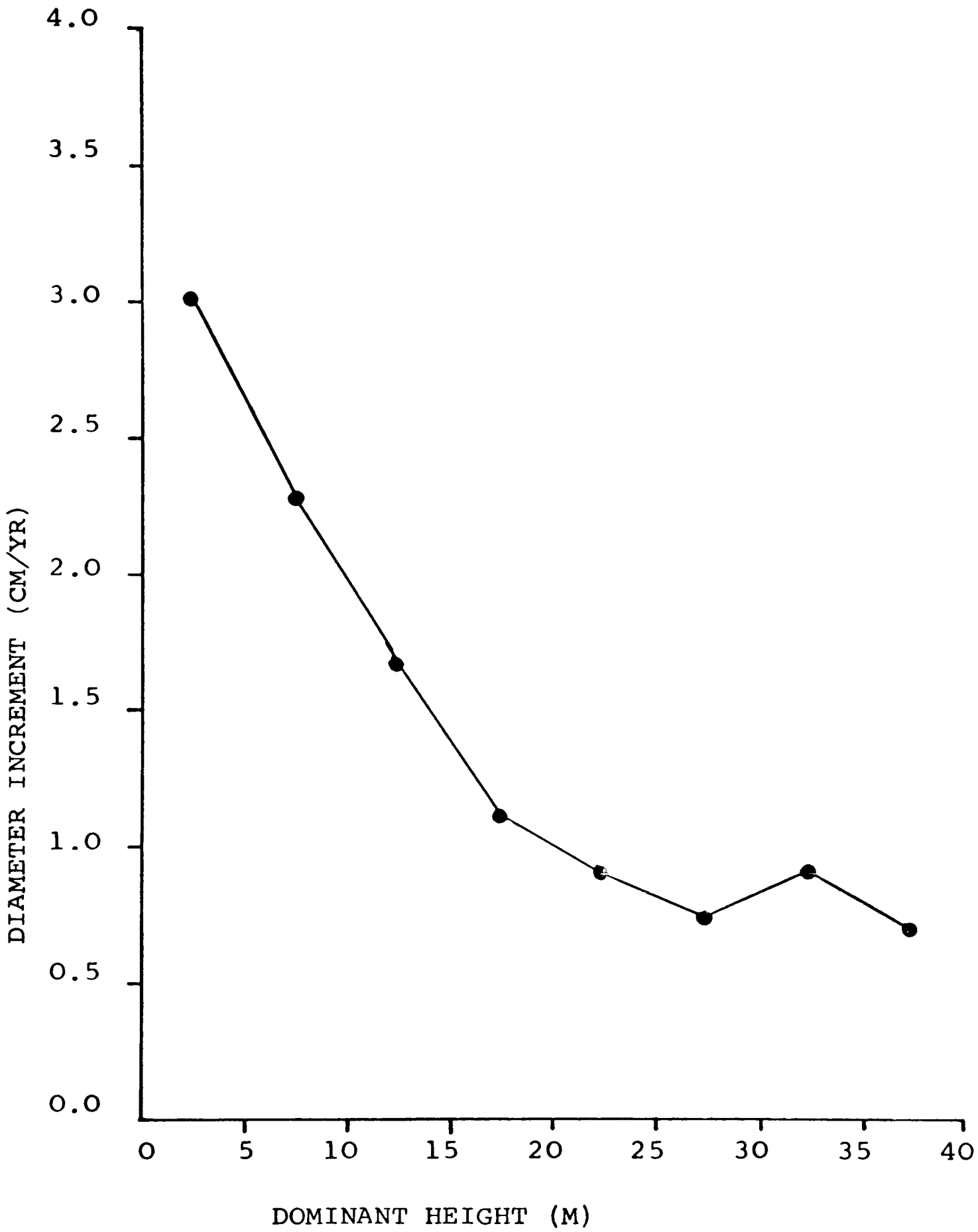
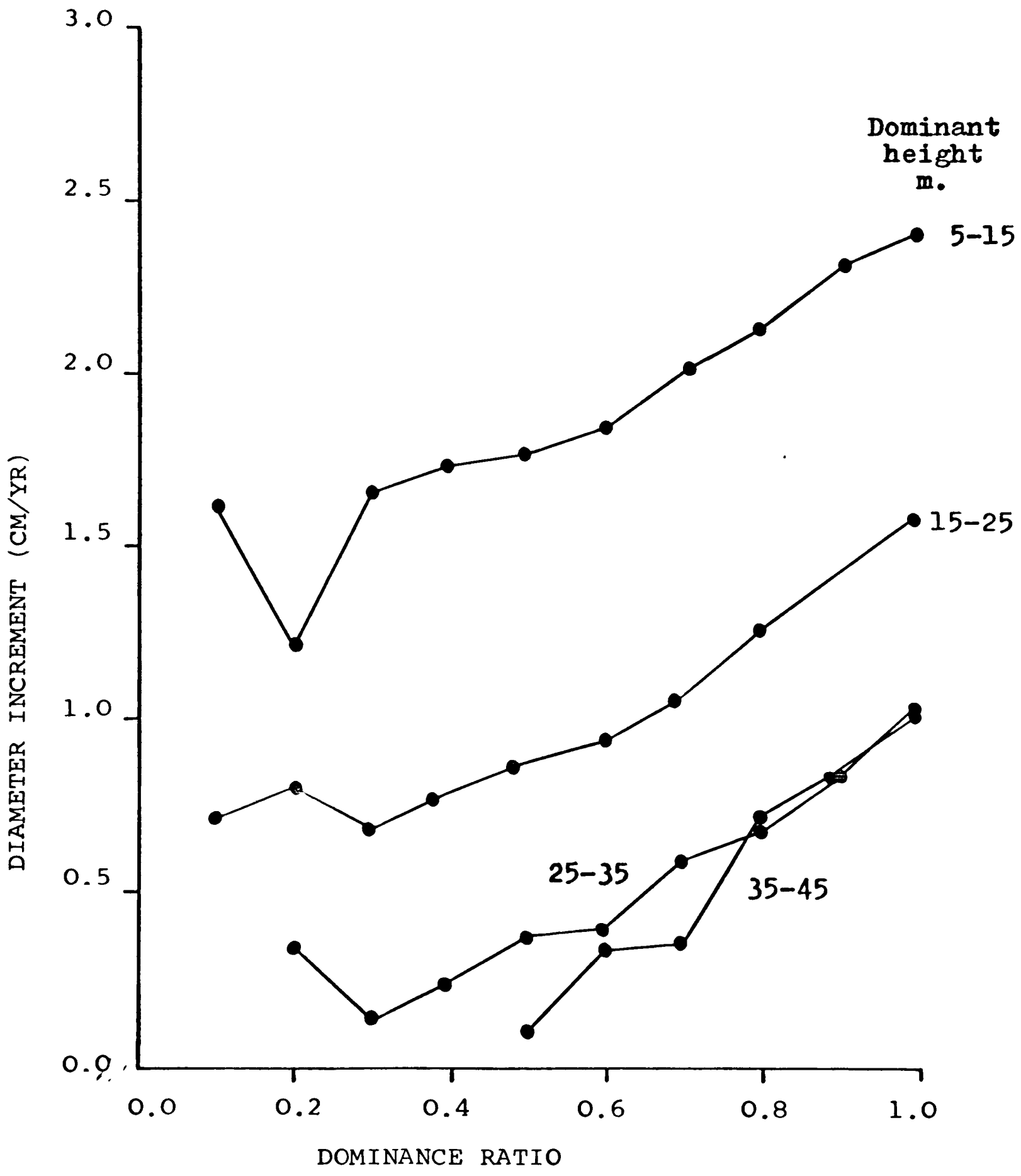


Figure 12 The influence of dominance ratio on diameter increment in P.patula at 4 dominant heights.



form approximates closely an exponential decay declining to an asymptotic minimum of about 0.6cm/yr diameter increment. The use of height as the dependent variable is a device to integrate the effects of site and age into a single variable.

An index of competitive stress experienced by the tree was defined as:

$$R = D/D_{dom} \qquad (4.6.1)$$

where R is termed dominance ratio, D is tree diameter at breast height, and D_{dom} is the mean diameter of the 100 largest diameter tree per hectare, called dominant diameter.

Figure 12 shows the results obtained with the tabulation of increment for classes of dominance and height. Increment tends to increase approximately linearly with dominance; the slope appears to be fairly constant at each height. Similar observations were made concerning the effect of spacing, which acts as a modifier to the influence of dominance ratio as a competition index. At wide spacings, large differences in dominance ratio are not indicative of relatively high equivalent differences in competitive stress. But at low spacings, even small differences in dominance ratio reflect sharply defined differences in competitive status.

A number of functions were tested that were basically in the form of exponential decays of increment with respect to height, but with modifier terms for dominance ratio and spacing. Most gave satisfactory fits of the data, but when incorporated into the stand model resulted in excessively high basal areas accumulating at high stockings (which are poorly represented by the sample plot distribution).

A test was made of routines to compensate for this effect through the introduction of mortality as the basal area approached the limiting values observed on the most densely

stocked permanent sample plots. For each species, a limiting basal area was defined by hand-drawn curves touching the maximum values for all permanent sample plots of standing basal area on dominant height. The resultant curves were tabulated and equations of the Chapman-Richards type:-

$$G_{max} = a(1-\exp(-bH))^{c} \qquad (4.6.2)$$

were fitted to them by nonlinear regression. G_{max} in the equation is maximum basal area; H is stand dominant height; a,b, and c are the regression coefficients. Dominant height was used as the dependent variable for the reason cited earlier - that it represented an inclusive index of age and site effects. Table 3 shows values of the coefficients obtained for the three species studied, using only data from permanent sample plots in Kenya.

An index of spacing was then defined as the basal area of the stand relative to the maximum basal area. Denoted by Q, it is defined so that it will take a value of zero when the stand is at the limiting basal area; negative values when exceeding it, and value tending towards a limit of 1 for an open grown tree:-

$$Q = 1 - G/G_{max} \qquad (4.6.3)$$

where G is the standing basal area per hectare.

Individual tree diameter measurements were tabulated for each species into classes giving mean increments for intervals of dominant height, dominance ratio, and standing basal area. The standing basal area class values were converted to the corresponding Q by application of equation (4.6.2) and (4.6.3) using the appropriate species coefficients from table 3.

Table 3 : Coefficients for the limiting basal area function for Kenya

	P.patula	P.radiata	Cupressus spp.
a	67.8	86.3	63.9
b	0.1292	0.03382	0.1219
c	2.597	1.198	2.551

Note

Criteria of goodness of fit are not quoted as the function is based upon a hand-drawn curve enveloping permanent plot standing basal area data (see text), and hence such criteria would be meaningless in this context.

A number of possible models were then tested involving the variables H, R and Q to predict diameter increment I. Each function was tested in the stand model, so that its system performance could be evaluated by comparison of maxima, minima, and means of simulated diameter distributions with observed distributions, as well as showing suitably stable characteristics in relation to stand basal area and mortality. The following model was finally selected as being among the most suitable:-

$$I = a + b_0.\exp(H(b_1 + b_2R + b_3Q + b_4RQ)) \qquad (4.6.4)$$

where a, b_i are the regression coefficients; H and Q are stand parameters, being dominant height and relative basal area as defined earlier; R is the dominance of an individual tree, as determined from equation (4.6.1); and I is the predicted increment in diameter for that tree.

For each species, equation (4.6.5) was tested in two forms:-

1) The linear form, which assumes proportional errors and an a coefficient of zero. This is obtained by rewriting (4.6.4) as:-

$$\ln I = b_0^* + b_1H + b_2HR + b_3 HQ + b_4HRQ \qquad (4.6.5)$$

where the terms are as defined above except that b_0^* is $\exp(b_0)$.

2) The nonlinear form, as in equation (4.6.4). In this case, nonlinear regression is used to fit the coefficients, with additive errors assumed. The a coefficient is determined from the data, as well as the b_i.

The results obtained are shown in table 4. The b_0 parameters

Table 4 : Coefficients for the diameter increment equations

	P.patula		P.radiata*	Cypress	
	Linear	Nonlinear	Linear	Linear	Nonlinear
a	0.0	0.1818	0.0	0.0	0.1812
b_0	2.799	3.499	1.008	2.256	2.936
b_1	-0.2125	-0.2306	-0.1532	-0.1682	-0.2054
b_2	0.1667	0.1492	0.1629	0.1365	0.1477
b_3	0.1307	0.1478	0.0948	0.0691	0.1100
b_4	-0.1115	-0.1112	-0.0854	-0.0561	-0.0894
N	1624	1663	1834	1438	1438
R^2	0.64	0.54	0.59	0.32	0.60
S_y	0.514	0.568	0.636	0.868	0.425

Notes: a is not fitted for the linear models, but is assumed to be zero.
b_0 is converted to a common scale by taking $\exp(b_0^*)$ from the actual fitted values in equation (4.6.5).
N is the number of cell means; not the number of raw observations, which was of the order 20,000 to 35,000.
S_y is the standard error of the residuals; this is not directly comparable between the linear and nonlinear models.
* The nonlinear model for P.radiata was not fitted.

are converted into the common form for equation (4.6.4) for the linear models for ease of comparison. For P.radiata the nonlinear model was not fitted. It appeared to be converging slowly to a large negative value of a, and was poorly defined with respect to the parameters. The linear model appeared more satisfactory in this case.

The coefficients of equation (4.6.4) can be interpreted to indicate the general behaviour of the curve, and it is perhaps valuable to do this. The basic function in the model is an exponential decay of increment in terms of height, considering the latter as a site-dependent measure of age:-

$$I = a + b_0 . \exp(b_1' H) \qquad (4.6.6)$$

When this is fitted to the data in figure 11, the following coefficients are obtained:-

$$I = 0.581 + 3.11 \exp(-0.0895 H) \qquad (4.6.7)$$

The negative coefficient b_1' indicates a decay function. The larger its absolute value, the steeper the curve. a is the asymptote, or value reached as H tends to infinity. $b_0 + a$ defines the intercept when H is zero. In equation (4.6.4), b_1' has been expanded so that it is a linear function of dominance R, stand density Q, and their interaction RQ. For an open-grown tree experiencing no competition, we may note that for P.patula, using the linear model coefficents from table 4, and assuming R=1 and Q=1, then:-

$$b_1' = -0.2125 + 0.1667 + 0.1307 - 0.1115$$

$$= -0.0266$$

This indicates a flatter rate of decline in increment than for (4.6.7) which, although referring only to dominant trees, is for stands grown at normal densities, i.e. Q less than 1.

Considering once again equation (4.6.4), and the fitted parameter values in table 4, we note that b_1 and b_4 are always negative, whilst b_2 and b_3 are always positive. This is as may be expected. b_1 is negative and relatively larger than b_2 and b_3 , which are in any case further reduced by multiplication with variables R and Q, which for most stands are between zero and one. This gives the overall negative value to the multiplier for H necessary to result in a falling curve of increment with height. The positve value for b_2 shows that the slope decreases as the dominance increases. A similar effect occurs with the relative growing space Q: as it increases, slope of the curve decreases. This suggests greater values of increment at a given height for either more dominant trees, or for more open spacing; it also suggests that increment decreases less rapidly with height at wider spacing. On the other hand, the negative b_4 in the interaction term RQ is also explicable in terms of stand characteristics. It suggests that the rate at which the curve grows less steep as dominance increases is reduced at wider spacings; or conversely, that in denser stands (lower Q) the increasing steepness of the curve will be further accentuated, because of the negative b_4, by a relatively lower dominance. In biological terms, this amounts to a statement that the mensurational dominance ratio R will be a less heavily weighted index of competition at low stand densities than at higher ones.

4.7 Adjustments for limiting basal area

Referring once more to figure 2, it will be seen that the final stage in the cycle over time involves the adjustment of the diameter increment in cases where the limiting basal area is exceeded. This tended to occur with the model when it was used to simulate unthinned stands at high stockings. In earlier versions, an attempt was made to introduce a density dependent mortality factor in these cases. This tended to produce approximately correct basal area and

volume estimates, but the stocking was forced to decline severely in order to compensate for the excess basal area generated. An alternative adjustment was found to be more satisfactory in these cases, involving a simple proportional reduction in the estimated increment in order to limit stand basal area to the predicted maximum. In matrix notation, the adjustment is simply:

$$\underline{D}^* = (G_{max}/G).\underline{D} \qquad (4.7.1)$$

where $\underline{D}^*$ represents the stand vector that is used as the basis of prediction of the next growth cycle; $\underline{D}$ is the stand vector predicted from the application of equation (4.6.4); and G_{max}/G is a scalar multiplier that reduces the diameter of each class by the requisite amount to bring stand basal area exactly to G_{max}.

This adjustment is only made in cases where excessive basal area develops, and is essentially a result of using the model for extrapolation to situations outside the data base used to develop the growth functions.

4.8 Integration of the individual routines into a unified model.

The previous sections describe the submodels developed to simulate aspects of stand growth. These have been coded as FORTRAN subroutines which can then be used in a variety of ways according to the exact configuration of a particular system. One such configuration is the PYMOD sustained yield planning model described and documented in Appendix A. This description also contains details of the subroutines, which are summarised here only briefly in order to synthesise the forgoing discussion. The subroutines are as follows:-

1) INDD - This routine initialises a vector SV of ten diameter percentiles, using the equations and parameters described in section 4.2.

2) HTF - A routine to apply equation (4.3.11) to calculate (a) height, given site index and age, or (b) site index, given height and age, or (c) age, given height and site index.

3) THIN - executes the algorithm described in section 4.4 in order to modify the stand vector for a simulated thinning, and to return a frequency distribution for thinned stem diameters.

4) TABVOL,TAPER, VOLINT and TREVOL carry out the calculations described in section 4.5. TREVOL contains Wright's tree volume equations. TAPER corresponds to equation (4.5.7) and VOLINT to equation (4.5.9). They are organized within the algorithm shown in figure 10 by TABVOL; this also accumulates the volumes for all classes.

5) GROW increments diameters and adjusts them as described in sections 4.6 and 4.7. It uses subroutine DDOM which calculates stand dominant diameter.

The only other subroutine in the PYMOD program is CUT, which serves as an interface between the two routines THIN and TABVOL,and returns merchantable harvested volumes to the main program. The logical aspects of the PYMOD program are discussed in section 6, together with other possible methods of using this family of subroutines, depending upon the particular managerial requirements in question.

5. MODEL VALIDATION

5.1 Introduction

Model testing tends to be a recursive process of adjustment between parameters of submodels and comparison of overall performance with test data. When this has proceeded to a satisfactory point then a final validation process may be undertaken to define the limits of model performance and accuracy. In the present case, two types of test results are presented:-

1) Some detailed studies of individual stands are shown to illustrate graphically features of model response over a wide range of growing conditions.

2) Results from a mass testing program are given, designed to illustrate probable limits to error in model performance.

In all these cases, the only parameter shown is total standing volume. This can be assumed to be proportional to the product of basal area and height, and was found in fact to be the most sensitive of all the variables that could have been tested. The percentile diameters were found to follow the volume errors, but to be relatively smaller in magnitude. Usually the proportional error in volume was approximately twice the proportional error in diameter statistics. The error in height was additive to diameter errors in estimating volume, but provided site index was accurately known, height error was generally less than 5% of true height, as might be evident from the high correlations in table 2 and the simple nature of the height function.

The accuracy of the stem taper method could not be determined absolutely as no appropriate test data existed. Instead, a

comparison was made with results obtained from Wright's merchantable volume equations to given diameter limits. Such a comparison can only indicate the compatiblity and consistency of the method, but is extremely useful in allowing errors of logic in the program formulation of the model to be detected and in highlighting areas of performance where the discrepancy between the two methods is large, indicating a need for further investigation.

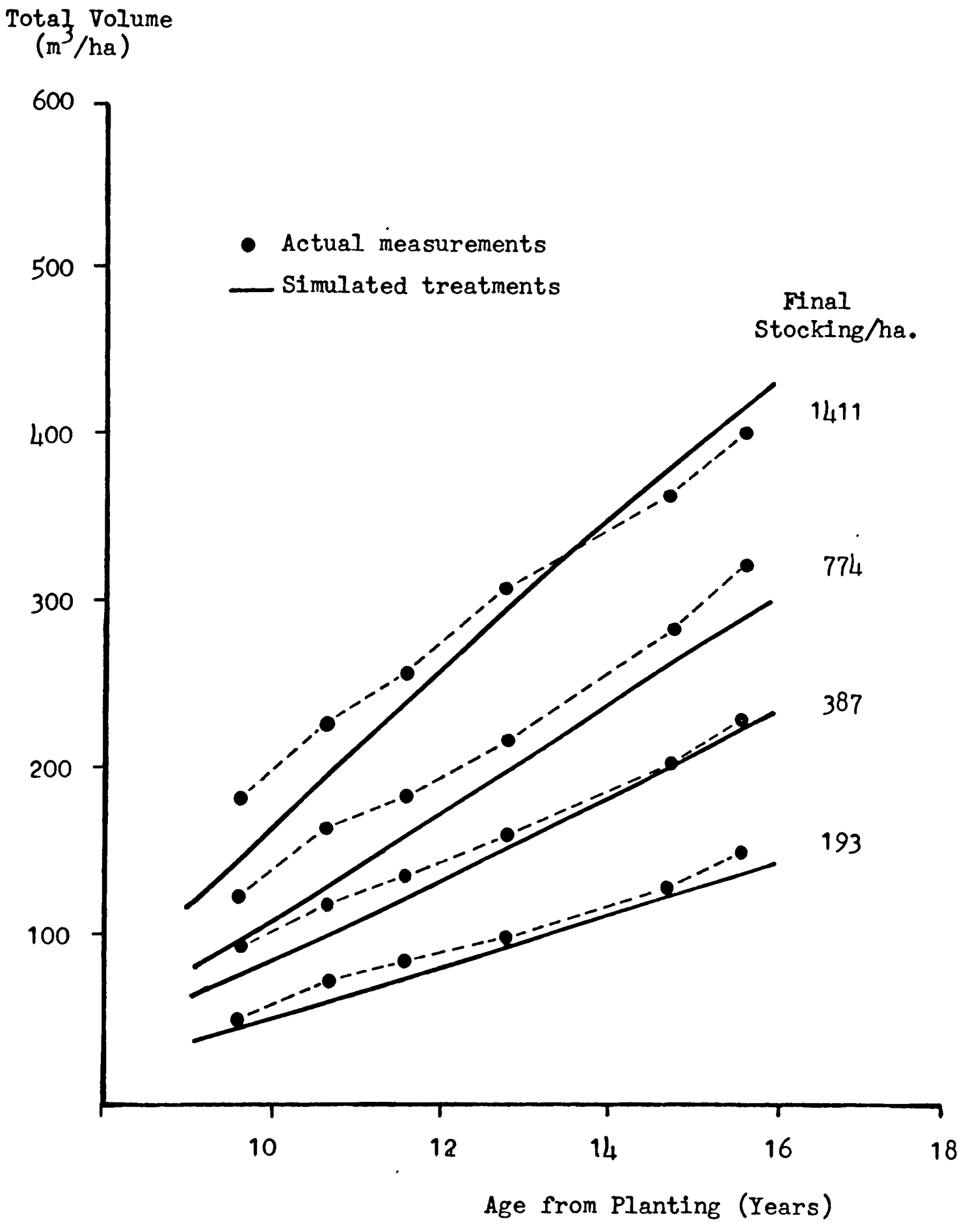
5.2 Simulation of Tanzania thinning experiments

Tanzania has a number of well laid-out thinning experiments in Pinus patula stands which provided excellent material for validation of the growth model. With this end in view, the data from the experiments was excluded from the analyses in which the growth functions were fitted, thus providing a completely independent test of the model. Two of the experiments, E345 at Kwira, and E661 at Sao Hill were particularly suitable. Some background information and results for these two experiments are given in Adlard & Alder (1976).

The treatment patterns of both experiments were based on similar principles, with the use of frequent early thinnings to achieve a specified stand density ahead of stand closure. The treatments were then allowed to grow at their selected stockings without further interference. This pattern of treatment has most of the features of a pure spacing experiment, except that the diameters achieved by the time final spacing is attained will be larger than would have been the case had the stand been planted at that spacing, as a result of the selection effect of the thinnings.

Several of the earliest thinnings (usually two or three) occurred before the trees had attained the 7m. threshold of dominant height at which the simulator initialized the stands. This implied that when simulating the treatments, it was not possible to imitate exactly the thinning pattern. Instead, an approximation was used of fewer, heavier thinnings.

Figure 13 : Simulation of Experiment 661 in Tanzania (P.patula)

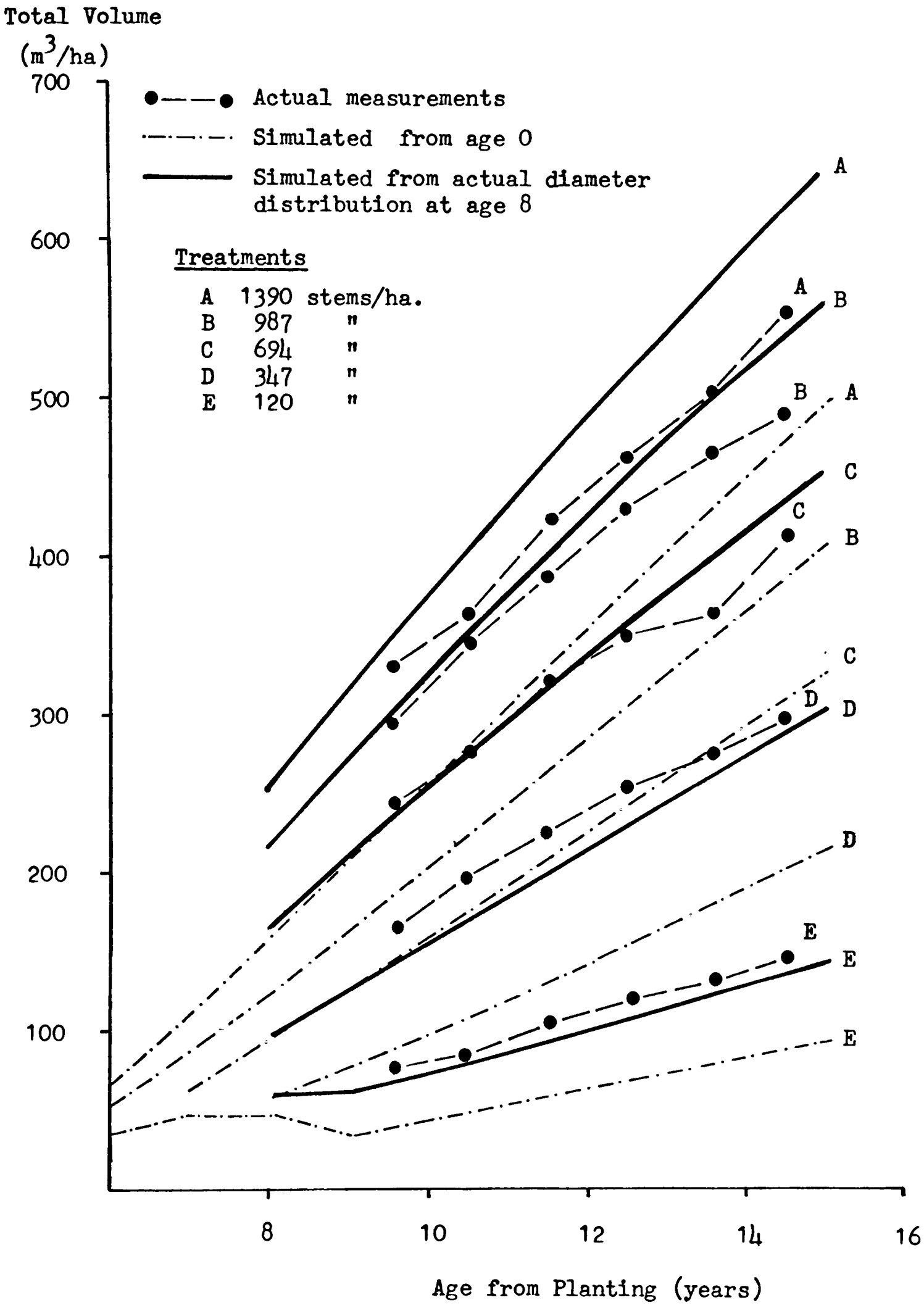


Tests with a variety of alternative sequences and initial stockings suggested that the error involved from this procedure was likely to be of the order of 5% of total volume on the most affected replicates, which were those with the lowest final stockings. This error was most marked at age 9, which was the first measurement at the final stocking, and tended to remain constant in absolute magnitude, and hence decrease relatively, with time.

Figure 13 shows the results from a simulation of four replicates from experiment 661 at Sao Hill. On the figure, actual measurement points are shown from the time at which each replicate reached its final stocking. The value of the latter is shown at the end of each line. The simulations are shown as solid lines. It can be seen that simulations and actual treatments are very similar both with regard to their slope and their vertical position on the graph . There is a suggestion that the model may underestimate the early volumes at the higher stockings. On the whole it is however quite apparent that the model provides in this case an extremely accurate reflection of stand behaviour over a very wide range of competitive intensity. It is also interesting to note the accuracy of the model at the lowest stocking level. This is quite contrary to the performance of the VYTL model under these conditions, as shown in Adlard & Alder (1976).

Thinning experiment 345 at Kwira is shown in figure 14. The simulation of the treatments using a similar, but not identical, sequence of early thinnings gave the results shown by the continuous dot and dash lines. It can be seen that in all cases these considerably underestimate yields. However, close examination and comparison of the simulated and actual treatments reveals that the slopes, or volume increments, of the total volume/age lines are similar; most of the error is in the vertical position of the lines. This suggests that the error is associated with the initialization and early growth in the simulator.

Figure 14 : Two Simulations of Thinning Experiment 345 in Tanzania (P.patula) from different starting conditions.



This hypothesis was confirmed by repeating the simulation using as starting point the actual cumulative frequency distribution at age 8. The results from this are shown as the solid black lines. It can be seen that these follow the observed values closely except on the densest stands, where there is a tendency to overestimation which appears to be increasing with age, leading at age 15, which is the last measurement, to an error of about 10%.

The results from these two thinning experiments show that the model is capable of simulating accurately a very wide range of competitive intensity. For both experiments, the range of stockings represented varies over an order of magnitude; the model faithfully mirrors total volume increment over the entire range. However, there is evidence that considerable error can result from incorrect determination of initial diameter distribution; and that this can vary widely in a manner not explicable in the present model framework. Nor do these experiments give any indication of what may happen if the stand is thinned at a later stage.

It is interesting to note how robust, geographically, the model appears to be. Both the thinning experiments are at least 1000 Km. distant from the nearest permanent sample plot data used in constructing the model. This does help to give considerable confidence in the potential utility of the model as a planning tool for new forest areas in the East African highlands.

5.3 Simulation of Kenya cypress permanent sample plots

As mentioned above, the simulations of the two Tanzania thinning experiments do not indicate in any way how the model might respond to thinning on older stands. To study this aspect, two series of permanent sample plot data were selected from cypress stands in Kenya, both of which represented a long series of measurements except for a single heavy thinning. They were also chosen so that the two series of measurements and the relative intensities and levels of thinnings

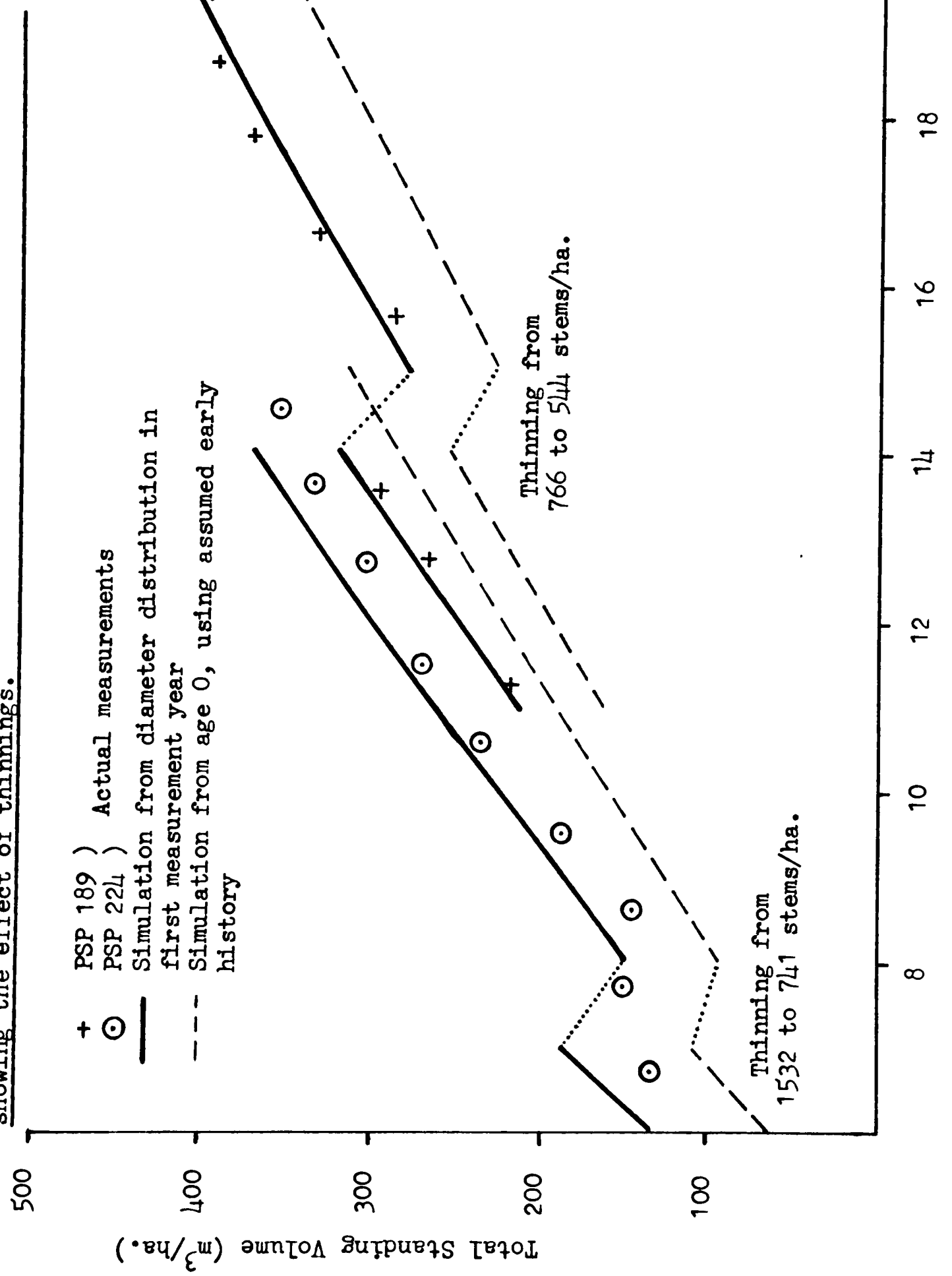


Figure 15 : Simulations of two permanent sample plots in Kenya Cypress stands, showing the effect of thinnings.

corresponded approximately to a sawlog thinning schedule. These plots were then simulated using a similar strategy to that adopted for the experiment 345 study discussed in section 5.2. That is to say, two forms of simulation were used: one starting from an assumed initial stocking and following a putative stand history to the point at which the plots were first measured; and another using the actual cumulative stand vector from the first measurement as starting point.

The two plots selected were PSP 189, and PSP 224. PSP 224 had a stocking of 1532 stems/ha. at 6½ years, which was reduced by a single thinning at age 8 to 741 stems/ha., after which it remained constant until the final measurement at 14½. PSP 189 was first measured at 11 years with a stocking of 766 stems/ha. This was reduced by a single thinning at age 14 to 544 stems/ha. The last measurement was at age 19½.

The results from the simulations are shown in figure 15. It can be seen that, as with experiment E345, the stands initialized by the model (the dashed lines) are too low for both plots; whilst the simulations commencing from the initial diameter distributions obtained from the first plot measurement are quite accurate. It may be noted that the version of the simulator used for these studies could only work with integral dates. This may account for the difference between observed and simulated values for PSP 224. If the solid line (the simulation) is shifted left by half a year, it can be seen that it will be closely coincident with the actual observations.

It is apparent from figure 15 that thinnings during the life of the stand are accurately portrayed by the simulator. It is important to note that the thinnings are specified in terms of stems/ha. removed, whereas the volume fraction removed is largely a reflection of basal area removed. The two will only

be equivalent if the distribution of removed stems is correct. Thus it can be deduced from figure 15 that for the PSP 189 simulation, the thinning distribution is relatively accurate. On the other hand, with plot 224 the simulated thinning appears to be somewhat heavier than the actual thinning, suggesting that in this case the proportion of small stems to be removed is under-represented in the model.

5.4 Sources of error in generating the initial stand

From both figures 14 and 15 it appears that when the initial condition of the stand is generated internally by the model, there is a persistent bias towards underestimation. A more detailed study of this problem was made in which stands were generated over a range of stockings for each of the species, and their standing basal areas calculated from this generated distribution. These were then overlaid on graphs of basal area versus stocking for stands between 6 and 8 metres dominant height (i.e. corresponding to the initialization point in the model) to allow comparison. The graph for P.patula is shown as figure 16. Similar results were obtained for the other species.

In figure 16, it is apparent that basal area varies widely independently of stocking, and clearly other significant factors are involved besides stand density in conditioning early diameter growth. When one considers that for most of the early growth period the competition between trees is slight, then this is not surprising. Some of these other factors may be, for example, weather conditions following planting, weed competition, disease and insect defoliation, soil fertility, moisture retention in the soil, and genetic variability.

The simulated stands appear to be biassed towards the lower margin of this variation. This is presumably a weighting effect due to the fitting of the predictor regressions to diameter distribution parameters which themselves tend to be strongly weighted to extreme values (and hence, especially, the

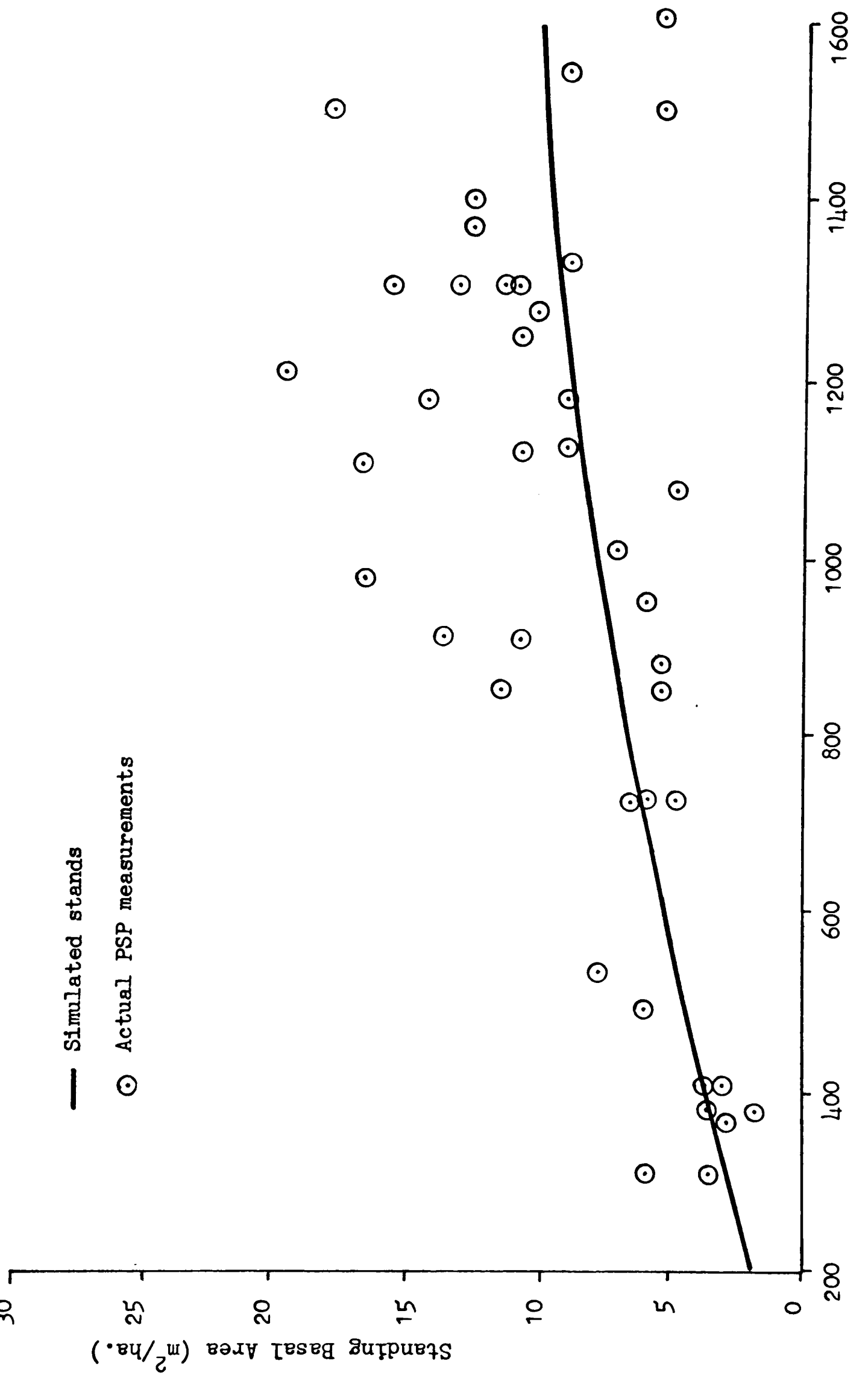


Figure 16 : Comparison of basal area/stocking relationship for actual and simulated stands of P.patula in Kenya at dominant heights between 6 and 8 metres.

smallest trees), whilst basal area and volume are estimators that are most strongly influenced by the largest trees. Although the bias does not appear, from figure 16, to be great, it is largest in the region that is most important to the model. This is the stocking range from 1100 to 1700 stems/ha. that covers most normal management practice. However, perhaps the greatest cause for concern is the failure of any variation of the present method, regardless of the system of differential weighting used, to take into account the wide natural variation present. It is clear that some method of site classification into production classes is necessary in order to break down the variation into limited groups; within these groups it appears probable that much more satisfactory relationships between stocking and the Weibull parameters of the early diameter distribution can be found than has been the case with the present unstratified system.

5.5 General limits of model reliability

The studies so far described are restricted to a limited number of stands and do not present a clear statistical picture of model reliability over the entire range of performance. To meet this latter requirement, a validation system was developed which simulated all permanent sample plots in the current data base, and calculated a residual for each measurement year, defined as:-

$$E = (V_o - V_s) / V_s \quad \%$$

where E is the residual, V_o is the actual standing volume at a given measurement, and V_s is the corresponding simulated volume.

The simulation for a given plot used the best estimate of site index derived as the mean site index of all measured dominant height/age pairs. It also used the actual diameter distribution as a basis for initializing the model stand vector. Thus the only sources of error are those arising

Table 5 : Bias and standard deviation of percentage differences in total volume between observed and simulated permanent plots.

Remeasurement no.	Cupressus spp.			Pinus radiata			Pinus patula		
	N	Bias %	s.d. %	N	Bias %	s.d. %	N	Bias %	s.d. %
1	160	3.3	12.6	169	-1.0	9.9	166	2.7	16.4
2	152	0.7	10.4	169	2.9	14.9	162	4.5	18.7
3	148	0.7	11.5	159	5.4	16.8	128	5.7	20.1
4	143	0.6	10.3	157	3.9	19.0	122	4.2	18.0
5	127	0.1	12.1	155	2.8	18.5	116	5.8	17.5
6	116	0.0	12.7	155	4.2	19.6	112	5.0	17.2
7	103	1.3	12.2	127	2.2	21.1	105	3.1	16.2
8	95	2.1	14.9	122	0.5	20.5	102	1.0	17.8
9	88	1.0	16.5	103	0.3	19.5	100	0.8	19.1
10	73	1.7	16.7	72	0.2	20.7	92	-0.8	19.1
11	35	-7.4	13.0	56	1.0	20.7	54	-4.4	21.1
12	17	-13.1	15.2	30	3.0	18.7	14	11.7	32.8

Notes: N is the number of plots contributing to a given estimate of bias and standard deviation. Bias % is the mean of the differences between observed and simulated volumes, expressed as a percentage of the simulated volume. S.d. is the standard deviation of these percentage differences.

from the pattern of diameter and height increments, and the distributions of thinnings.

The summarized statistical parameters for the residuals for Kenya permanent sample plots are shown in table 5. They are grouped according to the remeasurement number. The bias is the mean of the residuals; whilst the standard deviation of the residuals provides the basis for constructing confidence limits for model predictions of total volume.

It can be seen that for all species, bias is negligible, but may generally be said to tend to an underestimation of total volume by the model of 3 to 5%, except for Cypress, for which it is very close to zero. The standard deviations show that the range of variation of residuals is rather less for the Cypress model than for P.radiata or P.patula. The latter two are closely comparable.

There appears to be a slight tendency for error to increase with the number of remeasurements, but it is barely significant. This is important since it shows that the sources of error, whatever they may be, are factors that vary equally with time as with location. If the lack of fit by the model were principally locational in origin, then the results would be slightly different trends in height and diameter growth to those present in the model, with a consequent increasing deviation with each simulation cycle (equivalent to the number of remeasurements). Consequently a strong trend to increasing residual standard deviations with the number of remeasurements would be apparent. It is probable that there is a small component of spatial lack of fit; but the main source of error are factors which may vary year by year, and are probably largely accounted for by the following:-

1) Measurement errors.

2) Factors causing sudden change in dominant height, e.g. selection of different dominant trees following thinning or wind damage or tip dieback.

3) Variation in the distribution of stems removed for thinnings.

4) Climatic factors i.e. annual weather fluctuations and cumulative drought effects.

5) Biotic factors - notably Dothistroma pini in P.radiata stands.

The general conclusions from table 5 are that the model is unbiassed for all species; that the confidence limits at the 95% level are approximately plus or minus 25% of the predicted total volume for Cypress, and 35% for the two pine species; and that these limits are relatively independent of the length of the prediction, although there may be a slight tendency for the error to be initially less and ultimately slightly more.

5.6 Comparison of taper equation with Wright's merchantable volume equations.

Wright's system for determining mechantable volumes are currently in use in Uganda, Kenya, Tanzania, and Malawi. It is based upon a multiplier for total volume specific to each upper diameter limit and tree species. The multiplier is determined by the function:-

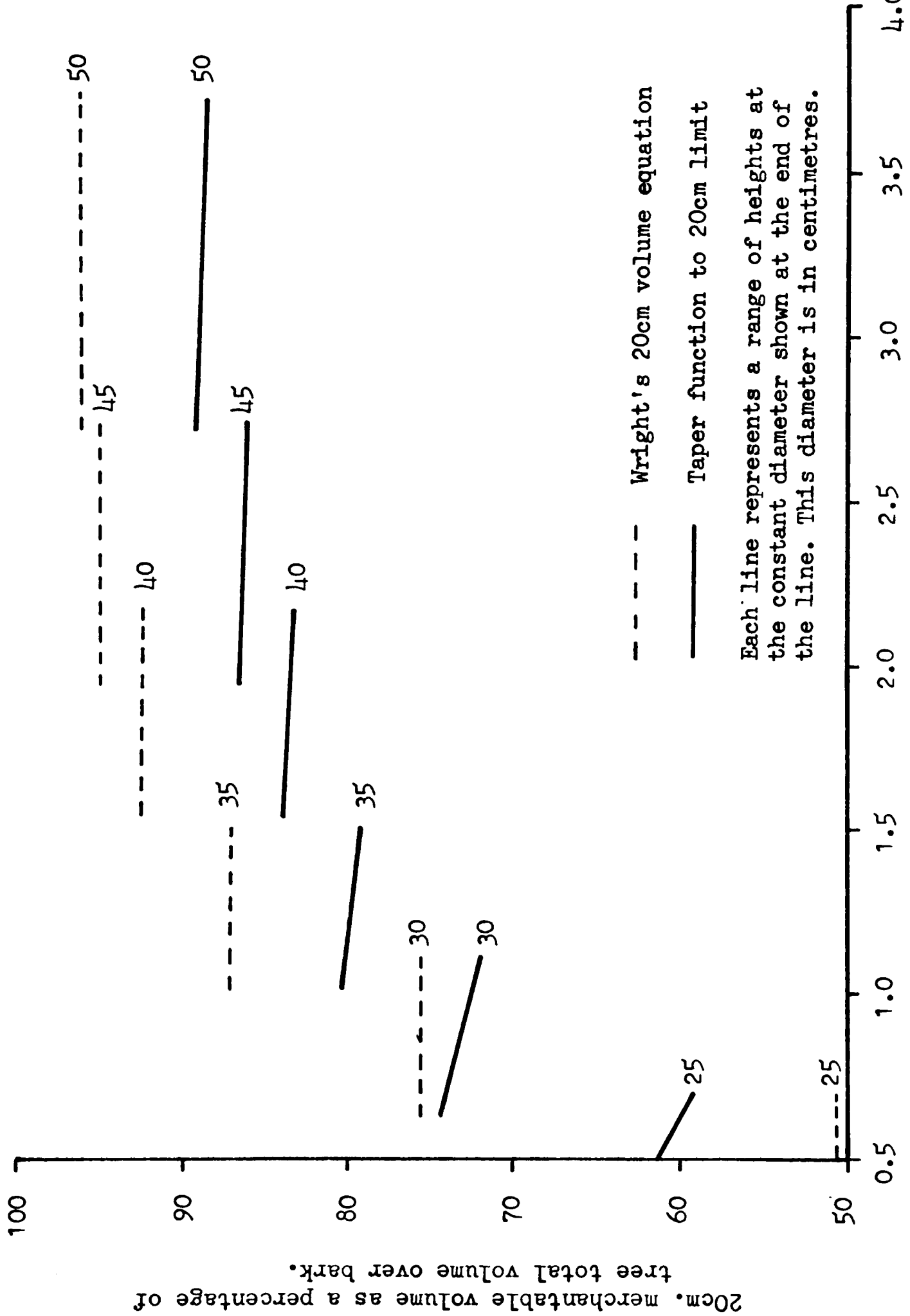
$$f = a + b.\exp(-c.D) \qquad -(5.6.1)$$

where D is tree diameter at breast height (1.3 m), and a, b, and c are coefficients fixed for a given diameter limit and species. Merchantable volume V_m is obtained from total volume V_t by the relation:-

$$V_m = f.V_t \qquad -(5.6.2)$$

This system is extensively used, and its accuracy generally considered high, although there are no published validation

Figure 17 : Comparison of predictions of 20cm merchantable volume by tree taper equation and by Wright's system of volume equations for Pinus patula.



studies of the system. However, it provided the only merchantable volume system available for testing the taper function developed in this work for the highland species of East Africa.

Figure 17 shows the result of the comparison of values obtained for tabulted diameters and heights by both methods. It gives the percentage of total volume in timber wider than the diameter limit of 20cm, plotted against tree volume at various diameter (breast height) levels. The predictions from the Wright equations are shown as broken lines, whilst those from the taper equation are shown as a solid line. It can be seen that the taper function predicts too low a merchantable volume by a factor of 5-10% of total volume. Although not shown on the graph, it was apparent that it predicted a correspondingly greater proportion of volume in the smaller diameter classes.

Clearly, a better fit for the taper function can be obtained than the present coefficient values, which were, as described earlier, obtained purely graphically by inspection. It may be noted also that for the other species, the values from the relevant versions of Wright's equations were very similar to those for P.patula shown here; whilst the taper function is at present a common one for all species. In spite of the relative lack of fit, the method is nonetheless sufficiently valid in its present form to be useful, especially when it is borne in mind that predicted volumes will in any case need to be adjusted by a margin for defect for planning purposes.

5.7 Conclusions regarding validation of the growth model

It is clear that the model is capable of accurately predicting stand growth for all the subject species. Several problem areas remain however, which must be investigated by further research. The two most important of these are a revision of the initialization procedure for the diameter distribution of young stands, to incorporate

some concept of productivity classes to account for the variability in early basal area; and the fitting of more accurate, correctly weighted, taper models for each species.

As an ad hoc approach to the problem of stratifying initial diameter distributions, a modification has been made to the VYTL-2 program shown in the appendix to permit the basal area of the young stand at 7 metres dominant height to be incorporated as an independent variable to the model in the same sense as site index. This is used as a multiplier in the INDD subroutine, where the stand is generated, to "stretch" or "squash" the diameter distribution values so that the initial simulated basal area is the same as the value given. This provides a temporary but practical solution to the problem of estimating early diameters under the control of a production class. It leaves, of course, the residual problem of determining the likely basal area for stands of given stockings in given locations.

Another research area to be considered is the possibility of stipulating thinnings in terms of basal area as well as stocking. The combination of two parameters should permit solution for parameter values controlling thinning distribution. This is likely to account for a significant proportion of the current error in residuals, and greatly improve the model.

Howver, apart from the error relating to early diameter distributions, it is clear that the model can be used both predictively, because of its accuracy, and as a research tool to investigate extreme silvicultural treatments. In particular, the model appears capable of simulating very low stocking levels without bias, and may be particularly valuable in deriving yield tables for low initial stockings and heavy thinning schedules.

It appears that various factors currently exogenous to the model, notably genetic variation, climatic fluctuations, edaphic and biotic conditions and interactions, and thinning

patterns can produce errors of upto 30% in predictions of total volume, in extreme cases. These errors appear unbiassed with respect to the present permanent plot data set, but may be expected to develop some bias when the model is extrapolated to other areas; although the results from Tanzania thinning experiments used in the validation studies suggest that this effect may be limited.

6. DISCUSSION : APPLICATIONS AND DEVELOPMENTS

6.1 Application of the model to plantation management

The principle aim of the present study was the development of practical yield forecasting techniques for the exotic softwood resource in the highlands of East Africa and Malawi. The model that has been described and tested in sections 4 and 5 of this work provides all the facilities necessary to achieve this aim. In the Appendix, two computer programs are listed and documented which are intended for two distinct managerial applications.

The first, VYTL-2, produces a yield table for a single stand. The necessary inputs are the site index and stand basal area and stocking at a dominant height of 7 metres, a schedule of thinning ages and residual stockings, and specifications for upto four merchantable volume classes. The model then prints out the main stand statistics (i.e. age, stocking, basal area, mean diameter, 5% diameter and 95% diameter, and standing total and merchantable volumes) and the statistics of any removals. The model is very fast and simple to operate, and has been written in a subset of FORTRAN compatible with existing computer equipment accessible to forestry personnel in the countries concerned.

It is envisaged that the VYTL-2 formulation of the model will be used to produce yield tables for distribution to regional offices and field management. It will also be extremely useful for silvicultural research, in investigating alternative thinning treatments to those currently used. The simplicity of the program and its high speed (and hence low computing cost) will encourage its use for this purpose. Such a model has an inevitable and almost subliminal side-effect; its users become forcefully aware of the dynamic and manipulable nature of the resource as a result of the time compression effect and the ease with which alternatives may be examined. This in turn leads to an attitude to the

management of the resource that is more flexible and more quantitative.

The second computer program is PYMOD. This is a data management and sequencing system for the simulation routines that allows a substantial number of even-aged compartments to be simulated at one time. This program is intended as a long-term forecasting and feasibility analysis system for entire forests. It is also capable of providing detailed outputs suitable for short-term operational planning.

As with VYTL-2, the user specifies the initial condition of the stands to be grown. These may either be done by a series of establishment option cards which instruct the computer to 'plant' compartments of a given species and site index at a given rate during a given time period; or it may be done by providing a data base of inventory summaries describing the current condition of existing forest areas. Both modes of forest initialization may also be mixed.

The thinning treatments and the description of the timber size classes must also be given to the program. Separate specifications are permitted for each species. The program is able to vary the thinning timing according to the requirements of the scheduling logic, as described below. The user must also specify for each species a cutting pattern, given in terms of the total volume to be harvested in each year.

The scheduling logic is extremely simple, in order to reduce running time for the program to a minimum. It consists of an attempt to satisfy the total volume quota for a given year by cutting all silviculturally 'available' compartments i.e. those which, on the basis of their age and stocking, are ready for either thinning or clearfelling. If the quota cannot be satisfied, then all available stands will be felled in a given year. If on the other hand the quota is satisfied,

then some stands are left uncut, and their treatment deferred. Internal indicators for each compartment show the next type of thinning operation due on a stand, and whether it has been deferred, and for how long. When selecting stands for cutting, the sequence of selection is based upon the length of time treatment has been deferred and the number of the thinning due. Priority is given firstly to the longest deferred treatments, and secondly, within deferment groups, to earlier rather than later thinnings.

Two modifications to this rather simple approach that naturally spring to mind are firstly the inclusion of some capacity for satisfying product-mixture constraints, and secondly, some method for incorporating the economies of scale that occur with spatial aggregation of harvesting operations. Satisficing (as opposed to optimizing) algorithms can in the author's opinion be developed within the framework of the existing PYMOD program by utilizing a recursive approach to the sorting of compartments, together with rather more complicated logic that would involve treating the product mixture from a compartment as a point in vector space. The problem then becomes one of determining a trajectory to an optimal mixture.

However, the author considers that for long-term planning, the present formulation of PYMOD will be found to be adequate, and its practical usefulness is more likely to be jeapordised than enhanced by further complications until forest managers have experienced the limitations of the present model, and have, through the process of using it, become more sophisticated in their appraisal of this type of planning tool.

On the other hand, the usefulness of PYMOD for short-term planning, which we may arbitrarily define as covering periods of one to seven years, will be very limited. Here, one may anticipate that a mathematical programming formulation may be found to be desirable and practically possible.

In such cases the model will have a role similar to the role of STANDSIM in the MASH allocation system for Mountain Ash (Eucalyptus regnans) in Victoria, Australia (Gibson et al., 1974); that is to say, the model will be used to define yields from thinnings and clearfellings for a number of fixed cutting strategies, whilst the actual area and time period are determined by the mathematical programming algorithm. An excellent discussion of the types of constraints required for a typical operational planning system is given by Rustagi (1976).

Another important planning application of a more general nature for which the model routines are well adapted is the maintenance of a current data base of forest compartments. In discussions with officers of the Kenya Forest Department in November 1976, this was stressed as being a major requirement. At present, there are some 6000 plantation compartments in the Kenya Forest Department's card index system, which has consequently reached saturation point for information retrieval and updating purposes. By converting this system to a data base on magnetic tape, it can be linked automatically to ongoing plantation inventory work, providing a record for each measured compartment of the last measured growing stock estimates. The role of the model routines in such a system is twofold. On the one hand, the model can update inventory records between measurements, which may be 5 - 10 years apart on a single compartment; on the other hand, for unmeasured compartments, the model can generate likely estimates of growing stock. The result is a current data base of administrative and yield data which can be accessed for a variety of short-term planning purposes.

We thus have four types of application for the models described here, all of which may to some degree be considered to overlap. The first is the VYTL-2 single stand simulator for silvicultural research purposes. The second is the PYMOD long-term planning model. Both of these have been tested, and current computer programmes are given in the

the appendix. The third and fourth applications both relate to short-term planning needs. The third mentioned, although possibly the last to be actually applied in practice, was the optimization of cutting location, timing, and strategy alternatives within a framework of budget, labour, physical resource, and yield product-mix constraints and/or goals. The fourth application is the fusion of the model routines within a system for maintaining a current compartment data base.

6.2 Further developments.

Most research is in reality a cyclic rather than linear process, in that the conclusion to any given area of investigation is determined extrinsically by administrative or related factors; the research work itself has no defined termination and leads naturally to revision and improvement of what has already been done, and expansion into new fields. This present work is no exception, in that several areas of improvement and extension can be seen as possibilities for future study. Five such extensions seem particularly relevant:-

1) More detailed studies of processes in young stands. The most important problems here concern early mortality factors, and patterns of spatial distribution of mortality; and the factors governing the great variation in early stand diameter distributions. Such studies cannot, in the author's opinion, be easily carried out using permanent sample plots, as they require larger areas, and a specifically designed site stratification to focus on different survival and weed control situations.

2) More detailed investigation of stem taper models; especially of appropriately weighted fitting methods to provide models that are unbiassed with respect to volume estimation.

3) Further studies of the limiting basal area concept, with a view to defining the biological basis of the function, and obtaining more satisfactory estimates than the rather ad hoc coefficients given here.

4) The inclusion of climatic variables in the diameter increment function. This appears to be quite possible with currently available data, but was deliberately excluded from the present work in order to draw realistic bounds to the project.

5) The generalization of the thinning algorithm to utilize empirical thinning distributions from large tempory plot studies laid down in recently thinned areas. The thinning algorithm could also be modified to allow thinnings to be defined by both stocking and basal area, which would give a much more accurate method of estimating thinning effects.

Another, and rather different way in which the present work may be continued and extended is through the use of the model as a reference point to define anomolous growing conditions. This would greatly assist site classification studies by selecting areas where growth cannot be explained in the purely mensurational terms of the model, and which therefore represent priority areas for special examination. The growth model could also be used for studying disease and pest epidemiology by providing a basic structure of habitat definition, onto which a insect population or disease transmission model could be welded. Stand models have been used for this type of work by Valentine & Campbell (1975), for example, in studying pest/forest interactions.

7. CONCLUSIONS

A model has been developed for the important tropical highland species of eastern and southern Africa (Cupressus lusitanica, Pinus radiata, and Pinus patula) which have been planted over an area of at least 200,000 ha., and for which previous yield tables were extremely limited. The model includes height/age/site index relationships; diameter increment functions based upon a distance-independant measure of dominance, and a new stand density index derived from the limiting basal area concept. Methods of generating diameter distributions for young stands are given, which are modified as a result of validation studies to allow stands of specific basal area to be generated. An algorithm is developed for thinning stands defined in terms of stocking and a cumulative diameter distribution. Volume taper functions are developed using a hitherto unused model, and an algorithm is described for breaking trees down into log classes defined in terms of size and length.

Testing of the model, using both independent results from thinning experiments in Tanzania, and by comparison with the actual permanent plot measurements used to fit the submodel functions, shows that the model is accurate with respect to the determination of total volume, with limits of variation at the 95% confidence level being about 30% of the predicted total volume. The error appears to be associated with a variety of exogenous factors of a genetic, biotic, edaphic, and climatic nature, and not with any structural flaw in the model, which is capable of mimicking very accurately the behaviour of stands over a very wide range of densities, and showing correct response to thinning treatments. The tests however show that the method of generating early diameter distributions can be improved, as can the fit of the stem taper function. For practical applications, an ad hoc adjustment is made to the model whereby specific basal areas for the initial stand may be given, and the diameter distribution that is generated is adjusted to corres-

pond to this basal area. The bias in the volume taper function tends towards underestimation of larger sized volumes. For practical purposes, the existing equation is probably adequate, since allowances must in any case be made for defect; but for the future a more accurate function is desirable.

Two main application areas are discussed, and relevant computer programs documented in the Appendix. These are VYTL-2, which is a single stand simulator that prints out detailed information on stand parameters, and is intended as a silvicultural research tool and for the production of yield tables; and PYMOD, which is a long term forecasting program for multicompartment forests composed of a mixture of the three species at a variety of ages. This program incorporates a logical scheduling algorithm for satisficing a total volume quota defined by the user. Its outputs include lists of compartments to be cut, and tables summarizing the yields in the merchantable classes, the areas subject to each type of thinning operation and for planting and replanting, and the numbers of seedlings required for planting operations.

Other application areas of importance, and future research priorities are also discussed. But the work as described is sufficient in itself, combined with the two application programs, to represent an important and necessary extension of planning capability in the plantation conifer resources of the East African and Malawi highlands.

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APPENDIX

Specifications, examples and listings of computer programs VYTL-2 and PYMOD.

part 1 - VYTL-2

part 2 - PYMOD

part 3 - Subroutine library

Part 1

VYTL-2 variable yield table program

Description

VYTL-2 produces yield tables for single even-aged monspecific stands. The variables controlled by the user that affect growth are the site index, the initial basal area, the initial stocking, and the thinning regime. There are built-in growth functions for three species: Cupressus lusitanica, Pinus patula, and Pinus radiata.

Volume production is calculated overbark, and is given as total volume and by four merchantable classes, which must be specified by the user in terms of a minimum diameter and minimum log length for each class.

Data specifications

card	description
1	title, upto 80 characters across the card.
2	nsp si stk ba7 nage nsp = species code. 1 = cypress, 2 = P.radiata 3 = P.patula. si = site index: dominant height in metres at age 15. stk = initial stocking at which stand is planted, in stems/ha. ba7 = the basal area of the stand, in m^2/ha., when it reaches a dominant height of 7m. If ba7 is zero, an internally generated estimate is used. nage = the number of specific ages for which output lines are to be printed. It may be zero, in which case card 3 may be omitted.

card	description
3	ages(i), i =1 to nage
	a list of ages at which specific output lines are required. This card is omitted if nage is zero. The maximum value for nage is 40.
4	nthin rage
	nthin is the number of thinnings required. It may be zero, and must not be more than 10. rage is the year in which the stand is to be clearfelled.
5	thage(i) thstk(i)
	card 5 is repeated for each thinning. It is omitted if nthin is zero. thage(i) is the year in which the i'th thinning is to be performed. thstk(i) is the residual stocking of the stand after the i'th thinning.
6	cname(i) dmin(i) hmin(i)
	card 6 is repeated for each of the four merchantable classes. The most valuable class is given first, followed by others in order of decreasing priority. cname(i) is an 8 character name for the class, which must be punched on the data card starting in column 1. dmin(i) must occur after column 8 on the card, and is the minimum diameter overbark acceptable for the i'th merchantable class. hmin(i) is the minimum log length acceptable for the i'th class.

Cards 1 to 6 may be repeated for several sets of tables in a single run. The run is terminated by an end-of-file card.

VYTL-2 example

As an example, the program was run for a hypothetical sawlog regime for Cypress. The data cards are shown below, which stipulate that site index is 20, initial stocking is 1600 stems/ha., and initial basal area is 17 m^2/ha at a dominant height of 7 m. Four thinnings are requested, at ages 8, 13, 18 and 23, down to stockings of, respectively, 1100,700,400,and 200 stems/ha. The four merchantable classes have diameter limits of 40,30,20, and 10 cm and length limits of 3m, 2.5m,2.5m, and 1m. The output produced by this regime is shown on the following two pages. The main table has been cut off after the 24'th year to permit it to fit onto the page.

Data cards for VYTL-2 example

```
EXPERIMENTAL SAWLOG THINNING SCHEDULE
1  20  1600  17  1
6.0
4  35
8  1100
13  700
18  400
23  200
PEELER   40  3
SAWLOG1   30  2.5
SAWLOG2  20  2.5
PULP      10  1
```

EXPERIMENTAL SAWLOG THINNING SCHEDULE

SPECIES: CYPRESS SITE INDEX: 20.0 STOCKING/HA : 1600. BA @ 7M HDOM : 17.00

NUMBER OF THINNINGS: 4 ROTATION AGE: 30.00

THINNING SCHEDULE :

AGE	STOCKING
8.00	1100.
13.00	700.
18.00	400.
23.00	200.

MERCHANTABLE O.B. VOLUME SPECIFICATIONS :

NAME	MIN O.B. DIAM	MIN. LOG LENGTH
PEELER	40.00	3.00
SAWLOG1	30.00	2.50
SAWLOG2	20.00	2.50
PULP	10.00	1.00

VYTL-2 example - output produced by program (continued)

AGE	HDOM M.	STK /HA	D(G) CM	B.A. SQ.M/HA	D 5% CM	D95% CM	STANDING TIMBER O.B. VOLUMES (CU.M/HA) PEELER	SAWLOG1	SAWLOG2	PULP	TOTAL
5.62	7.0	1600.	11.6	17.00	7.7	15.3	0.00	0.00	0.00	35.72	55.48
6.00	7.8	1600.	12.3	18.96	8.2	16.2	0.00	0.00	0.00	48.48	69.81
7.00	9.7	1600.	13.9	24.13	9.4	18.2	0.00	0.00	0.00	83.28	111.31
8.00	11.5	1600.	15.3	29.23	10.4	20.1	0.00	0.00	0.00	122.52	156.96
				THINNING YIELDS:-			0.00	0.00	0.00	24.63	34.92
9.00	13.2	1100.	17.5	26.49	12.5	22.5	0.00	0.00	14.78	117.91	160.80
10.00	14.6	1100.	18.7	30.33	13.3	24.2	0.00	0.00	35.22	133.36	200.27
11.00	15.9	1100.	19.8	34.03	14.1	25.8	0.00	0.00	61.09	144.63	240.55
12.00	17.1	1100.	20.9	37.60	14.7	27.3	0.00	0.00	92.07	151.57	281.10
13.00	18.2	1100.	21.8	41.02	15.3	28.7	0.00	0.00	127.28	158.23	321.54
				THINNING YIELDS:-			0.00	0.00	17.87	56.97	88.99
14.00	19.1	700.	24.3	32.38	18.0	31.1	0.00	17.23	129.97	93.89	264.95
15.00	20.0	700.	25.2	34.87	18.6	32.5	0.00	22.63	148.94	101.18	295.38
16.00	20.8	700.	26.0	37.29	19.1	33.8	0.00	44.69	160.00	98.04	325.54
17.00	21.5	700.	26.8	39.63	19.7	35.1	0.00	54.49	175.95	103.75	355.37
18.00	22.2	700.	27.6	41.91	20.1	36.3	0.00	64.30	191.64	107.67	384.79
				THINNING YIELDS:-			0.00	6.01	68.16	43.83	129.89
19.00	22.8	400.	30.8	29.72	23.2	39.2	0.00	90.59	118.00	62.96	278.75
20.00	23.4	400.	31.6	31.42	23.8	40.5	0.00	104.29	124.33	64.86	300.37
21.00	23.9	400.	32.5	33.10	24.3	41.8	20.57	107.09	120.94	67.74	321.89
22.00	24.4	400.	33.3	34.76	24.8	43.1	24.97	118.08	125.46	69.52	343.28
23.00	24.9	400.	34.0	36.39	25.3	44.4	29.39	138.80	120.15	72.32	364.53
				THINNING YIELDS:-			2.73	37.55	69.61	33.73	147.65
24.00	25.3	200.	38.3	23.05	29.4	47.8	46.70	93.77	54.01	39.25	233.73

VYTL-2 program listing

The program listing for VYTL-2 is shown on the following pages. It is written in a version of FORTRAN compatible with ICL 1900 computers. It is also largely compatible with IBM 370 DOS FORTRAN, except that the format statement 30 referred to in several READ's should be replaced by an asterisk (*) for free-formatted input.

One input channel or device is used, and one output device. These will normally be a card reader and line printer. The channel numbers are set to 1 and 2 for input and output early in the program. Resetting variables CR and LP allows different channel numbers to be adopted as system defaults.

The subroutines called by the main program are identical to those for PYMOD and are shown in part 3 of this document.

VYTL-2 main program listing

```
      MASTER VARIABLE YIELD TABLE PROGRAM
C
      REAL SV(10),TF(11),TD(11),VOLUME(6)
      REAL AGES(50),THAGE(10),THSTK(10),SPP(2,3),CNAME(2,4),TITLE(20)
      INTEGER CR,LP
      COMMON/VLIM/DMIN(3,4),HMIN(3,4)
      DATA SPP/'CYPR','ESS','RADI','ATA','PATU','LA'/
      CR=1
      LP=2
C INPUT RUN SPECIFICATIONS
    1 READ(CR,10,END=99)TITLE
   10 FORMAT(20A4)
      WRITE(LP,20)TITLE
   20 FORMAT(1H1,20X,20A4)
      READ(CR,30)NSP,SI,STK,BA7,NAGE
   30 FORMAT(100G0.0)
      WRITE(LP,40)(SPP(I,NSP),I=1,2),SI,STK,BA7
   40 FORMAT(//5X,'SPECIES: ',2A4,5X,'SITE INDEX: ',F6.1,5X,
     1   'STOCKING/HA.:',F8.0,5X,'BA @ 7M HDOM : ',F7.2)
      IF(NAGE.GT.0)READ(CR,30)(AGES(I),I=1,NAGE)
      READ(CR,30)NTHIN,RAGE
      WRITE(LP,50)NTHIN,RAGE
   50 FORMAT(//5X,'NUMBER OF THINNINGS: ',I4,5X,'ROTATION AGE:',F7.2)
      IF(NTHIN.EQ.0)GOTO2
      WRITE(LP,60)
   60 FORMAT(/5X,'THINNING SCHEDULE :      AGE     STOCKING')
      DO 3 I=1,NTHIN
      READ(CR,30)THAGE(I),THSTK(I)
    3 WRITE(LP,70)THAGE(I),THSTK(I)
   70 FORMAT(27X,F6.2,4X,F8.0)
    2 CONTINUE
      READ(CR,80)((CNAME(I,J),I=1,2),DMIN(NSP,J),HMIN(NSP,J),J=1,4)
   80 FORMAT(2A4,2F0.0)
      WRITE(LP,90)  ((CNAME(I,J),I=1,2),DMIN(NSP,J),HMIN(NSP,J),J=1,4)
   90 FORMAT(//5X,'MERCHANTABLE O.B. VOLUME SPECIFICATIONS :',5X,
     1 'NAME',6X,'MIN O.B. DIAM',5X,'MIN. LOG LENGTH',
     2   4(/51X,2A4,F14.2,F18.2))
C MAIN TABLE HEADINGS
      WRITE(LP,100)((CNAME(I,J),I=1,2),J=1,4)
  100 FORMAT(////54X,'STANDING TIMBER O.B. VOLUMES (CU.M/HA)'/11X,'AGE',
     1   2X,'HDOM  STK  D(G)    B.A.   D 5%  D95%  ',4(2A4,1X),2X,
     2   'TOTAL'/17X,'M.',3X,'/HA',3X,'CM',3X,'SQ.M/HA',3X,'CM',4X,
     3   'CM'/11X,86(1H-))
C INITIALIZE STAND
      CALL INDD(BA7,STK,SV,NSP)
      KAGE=1
      HDOM=7.0
      MTHIN=1
      AGE=HTF(7.0,SI,NSP,3)
      IF(NAGE.EQ.0)GOTO4
    6 IF(AGE.LT.AGES(KAGE))GOTO4
      KAGE=KAGE+1
      IF(KAGE.LE.NAGE)GOTO6
      NAGE=0
    4 CONTINUE
```

VYTL-2 main program listing (continued).

```
COMPUTE STAND STATISTICS
      BA=0.0
      DO 5 I=1,10
      TF(I)=STK/10.0
      TD(I)=SV(I)
    5 BA=BA+SV(I)**2
      BA=BA*0.00007854*STK/10.0
      DG=SQRT(BA/(STK*0.00007854))
      TF(11)=0.0
      TD(11)=0.0
      CALL TABVOL(TF,TD,NSP,HDOM,VOLUME)
      WRITE(LP,110)AGE,HDOM,STK,DG,BA,SV(1),SV(10),(VOLUME(I),I=2,5),
     1   VOLUME(1)
C TEST FOR THINNING AND PERFORM IF REQUIRED
       IF(MTHIN.GT.NTHIN)GOTO7
      IF(INT(AGE).NE.INT(THAGE(MTHIN)))GOTO7
      FL=THSTK(MTHIN)/STK
      CALL CUT(HDOM,STK,NSP,SV,FL,VOLUME)
      WRITE(LP,120)(VOLUME(I),I=2,5),VOLUME(1)
      MTHIN=MTHIN+1
  110 FORMAT(9X,F5.2,F6.1,F6.0,F5.1,F8.2,F8.1,F6.1,1X,5(F7.2,2X))
  120 FORMAT(/35X,'THINNING YIELDS:-  ',5(F7.2,2X)/)
    7 CONTINUE
C DETERMINE GROWTH INTERVAL AND NEXT AGE
      IF(AGE.GE.RAGE)GOTO12
      IF(NAGE)8,8,9
    8 AGEINT=1.0
      AGE=AGE+1.0
      GOTO 11
    9 AGEINT=AGES(KAGE)-AGE
      IF(AGEINT.GT.1.0)GOTO8
      AGE=AGE+AGEINT
      KAGE=KAGE+1
      IF(KAGE.GT.NAGE)NAGE=0
   11 CONTINUE
      HDOM=HTF(AGE,SI,NSP,1)
      CALL GROW(AGEINT,HDOM,STK,SV,NSP)
      GOTO4
   12 WRITE(LP,130)
  130 FORMAT(11X,35(1H-),' END OF ROTATION ',34(1H-))
      GOTO1
   99 STOP
      END
```

Part 2

PYMOD forest planning program

Description

PYMOD is a forest management program for plantations composed of P.patula, P.radiata and Cupressus lusitanica in even-aged monspecific compartments. The user options controlling the simulation can be divided into five groups:-

1) Forest inventory data. This describes the state of the existing growing stock for each compartment. It may be absent, in which case forest data is generated internally by the planting options described below.

2) Merchantable volume definitions. For each species, upto four merchantable classes may be specified, given by small-end overbark log diameter, and minimum log length.

3) Forest establishment. New compartments may be planted at a specified rate of hectares per annum between given dates, at an estimated site index, and of given stocking and species. This option is sufficiently flexible to allow any historical sequence of planting operations to be carried out, and can be used to estimate yields for forests which have not been inventoried, as well as for future planning of proposed plantations.

4) Thinning schedules. For each species, a minimum interval between thinnings can be specified, together with dominant height for first thinning, and minimum rotation to clearfelling. The stocking for replanting after final felling is also required. The program itself may delay thinnings or final

felling to meet a volume quota limit. The intensity of thinning is specified by the proportion of the stocking to be left uncut and is a constant ratio for all thinnings. e.g. a factor of 0.7 denotes that 70% of the stocking will be left after any thinning.

5) Volume quota. Yield is regulated by allocating the quota of total volume to be cut for each species over each year of the simulation. By setting a very large value, all stands silviculturally ready for cutting are harvested. Smaller values result in the holding over of production from peak harvesting years to meet demand when supply would otherwise be deficient.

In addition, general options control the types of output, and the duration of simulation. The output produced by the program can be divided into three groups:-

1) Descriptions of the control data in the form of readily comprehensible tables.

2) A main output table, giving, for each simulated year, summaries of volumes harvested, and areas and numbers of trees for planting operations. The summary can optionally be broken down either by operation type, or by species, or both.

3) A second stream of output intended to facilitate the preparation of operational plans. In this, details of each compartment harvested are output, together with area, date, logging unit subdivision, stocking, dominant height, and volume per hectare and operation type. The output format is designed to permit subsequent sorting by operational areas, or by operation type or by date, etc. This output stream is optional.

PYMOD data specifications

card type description

1 block comp spp area pyr assyr si hdom stk sv

This card is repeated as many times as required and contains inventory data on each compartment input. It must be punched in a fixed format as described:
block is a forest or management unit identifier punched as digits in columns 1-3.
comp is a compartment identifier, and must consist of two digits and a letter, punched in columns 4-6.
spp is a species code, punched in column 7. The permitted codes are: 1 - cypress, 2- P.radiata, 3 - P.patula.
area is the compartment area in hectares, punched in columns 8 to 12, with an implied decimal point after column 11. Thus 1013.7 ha is punched as 10137 .
pyr is the year of planting, punched in columns 13 to 16. e.g. 1984.
assyr is the year of measurement, in columns 17-20.
si is site index, punched in columns 21-23,with an implied decimal point after column 22. This may be left blank if dominant height is known.
hdom is the stand dominant height in metres, punched in columns 24-26, with an implied decimal point after column 25. It may be left blank for very young stands, in which case si must be given.
stk is the stocking in stems/ha. punched in columns 27-30.
sv consists of a list of 10 diameter percentiles punched in columns 31-34,35-38,39-42, etc., with an implied decimal point before the last digit. The first diameter represents a value such that 5% of the observed stems will be smaller. The

card type — description

1 (cont) second diameter represents the 15% point; the third the 25% point; the fourth the 35% point, and so on, until the tenth which represents the 95% point. Suitable inventory data input cards for PYMOD are generated automatically by the PIP plantation inventory program written by the author and documented separately.

2 -1

This card is simply a terminator for the inventory data. The latter can be omitted entirely, as in the example given here, in which case this card is the first in the deck. The -1 is punched in columns 1 and 2.

3 byr lyr iprt idump iopout

byr is the first year to be simulated. It should be the same as assyr for inventory data if the latter is present.
lyr is the last year to be simulated.
iprt controls the level of detail in the main output, and can take the following code values:

1 - normal output.(see example).
2 - harvesting details are separated by species but not by operations.
3 - harvesting details are separated by operations but not by species.
4 - only totals for all species and operations are given on the output.

idump should be zero. It produces unintelligible intermediate outputs at other values.
iopout is 1 if the second output stream is required, and zero if not. A suitable file or output device must be assigned to channel 4 if iopout is 1.

card type	description
4	merchantable volume names this card has from 1 to 4 names, of 8 characters each, in columns 1-8, 9-16, 17-24, and 25-32. Each name is the name of a merchantable volume class. They are given in the order of value or priority. The first listed must be the one whose specifications are most difficult to fulfil, and the last one the easiest.
5	nsp a species code to which the merchantable class definitions following refer. The code values are either as for spp on card 1, or 4, in which case the definition applies to all species.
6	nc dmin(i) hmin(i) i=1 to nc nc is the number of merchantable classes for this species (max. 4). dmin(i) and hmin(i) are the minimum diameter and minimum length, in centimetres and metres respectively, for each class.
7	-1 cards 5 and 6 may be repeated as many times as necessary. card 7 has a -1 in columns 1 and 2 and terminates the input of merchantable volume specifications.

card type description

8 fyp lyp bno pspp psi parea istk

card type 8 controls the establishment of new forest areas. It may be repeated upto 25 times, with the sequence being terminated by card type 9.
fyp is the first year of a given planting sequence.
lyp is the last year of the planting sequence.
bno is the three digit block code in which planting is to take place.
pspp is the species code, as for spp on card 1.
psi is the estimated site index of the area.
parea is the area in hectares to be planted annually.
istk is the initial stocking to be established, in stems/ha.

9 -1 0 0 0 0 0 0

This card terminates the sequence of establishment options. It has a -1, followed by six spaced zeroes. If there are no establishment options, card 8 can be omitted, and only card 9 need be given.

10 ns inh cyc thf rmin rstk

This card can be repeated for each species, and controls silviculture.
ns is the species code, as for spp on card 1.
inh is the height at which first thinning is carried out. It should be zero if no thinning is to be done.
cyc is the minimum interval in years between thinnings.
thf is the fraction of the stand's stocking to be left after thinning.
rmin is the minimum number of years between planting and clear felling.
rstk is the stocking at which the stand is to be replanted after clear felling.

card type	description
11	-1 0 0 0 0 0

card type 11 terminates the silvicultural specifications and consists of a -1 followed by 5 spaced zeroes.

12	ns fvy lvy vol

card type 12 may be repeated upto 25 times and defines the total volume quota over each year of the simulation for each species.
ns is the species code referred to by this card, as per codes given for spp on card 1.
fvy is the first year in which the volume quota given comes into effect.
lvy is the year in which the volume quota given expires.
vol is the total volume quota. This value represents the maximum total volume of species ns that will be harvested during years fvy to lvy inclusive. Harvesting operations on excess growing stock will be delayed if necessary; and large compartments subdivided into smaller logging units in an attempt to maintain a smooth production within the quota.

13	-1 0 0 0

Card type 13 is the final terminator card, having a -1 and 3 spaced zeroes. It is the last card in the data set.

PYMOD example

In this example, for which input cards and output results are given on the following pages, a proposal for a forest plantation project is examined. This is to consist of two blocks of 5000 ha. each of Cypress and P.patula, to be planted at a rate of 1000 ha. per annum between 1978 and 1982, for each species. The site index values used are averages for each species. Three classes of timber product are considered, being sawnwood, down to a limit of 20 cm. diameter overbark and 2m. length; fencing poles down to 5 cm. diameter and 2 m. length; and fuelwood as residual material down to 5 cm. diameter.

Thinning treatments for the two species are similar, with first thinning at a minimum dominant height of 8 m., and a minimum period between thinnings of 4 years. At each thinning 1 stem in 3 is to be removed, giving a leave fraction of $\frac{2}{3}$. For P.patula, clear felling can occur from age 18 onwards, whilst for Cypress, the clear felling age is delayed to year 30 to take advantage of the slower culmination of mean annual increment for this species.

Harvested volumes in this initial simulation run are specified as 20,000 m^3/yr for each species from 1985 to 1995, increasing in that year to 40,000 m^3, which is maintained until 2005, after which a constant yield of 60,000 m^3/yr is required.

On page 2.9, the input data is shown. The description of this steering data output by the program is shown on page 2.10 On pages 2.11 and 2.12 are shown two sections of the main output table. The first sample (page 2.11) is the initial listing covering the main establishment period. The second sample includes the first clearfelling operations. The operation list given by the second output stream is described on page 2.13 and illustrated on page 2.14.

PYMOD example - listing of input data

```
-1
1977 2077 1 0 1
SAWNWOODPOLES   FUELWOOD
4
3 20 2 5 2 5 0
-1
1978  1982   1  1  18  1000  1600
1978  1982  2  3  23  1000  1600
-1  0  0  0  0  0  0
1  8  4  0.67  30  1600
3  8  4  0.67  18  1600
-1  0  0  0  0  0
1  1985  1995  20000
1  1996  2005  40000
1  2006  2100  60000
3  1985  1995  20000
3  1996  2005  40000
3  2006  2100  60000
-1  0  0  0
```

PYMOD example - program output describing control data

MERCHANTABLE VOLUME DEFINITIONS

SPECIES	CLASS	SMALL-END DIAMETER	MINIMUM LENGTH
ALL			
	SAWNWOOD	20.00	2.00
	POLES	5.00	2.00
	FUELWOOD	5.00	0.00

DESCRIPTION OF FOREST ESTABLISHMENT PROGRAM
(EXCLUDING REGENERATON OF EXISTING COMPARTMENTS)

FIRST YEAR	LAST YEAR	BLOCK	SPECIES	SITE INDEX	AREA /YR	STOCKING /HA
1978	1982	1	CY	18.0	1000.0	1600
1978	1982	2	PP	23.0	1000.0	1600

THINNING TREAMENTS

SPECIES	INITIAL HEIGHT	MINIMUM CYCLE	THINNING FRACTION	MINIMUM ROTATION	RE-PLANT AT
CY	8.0	4	0.670	30	1600
PR	N O T	S P E C I F I E D			
PP	8.0	4	0.670	18	1600

VOLUME CONTROL

SPECIES	FIRST YEAR	LAST YEAR	VOLUME TO BE CUT
CY	1985	1995	20000.0
CY	1996	2005	40000.0
CY	2006	2100	60000.0
PP	1985	1995	20000.0
PP	1996	2005	40000.0
PP	2006	2100	60000.0
PR	NO VOLUMES SPECIFIED: THIS SPECIES WILL NOT BE HARVESTED		

TABLE ØF PLANTING AND CUTTING ØPERATIØNS

YEAR	SPECIES	ØPERATIØN	AREA CUT/PLANTED	NØ. TREES	TØTAL VØLUME (CU.M)	VØLUME CLASSES AS PERCENT ØF TØTAL SAWNWØØD	PØLES	FUELWØØD
1978	CY	PL	1000.0	1600000.				
1978	PP	PL	1000.0	1600000.				
1978	ALL	PL	2000.0	3200000.				
1979	CY	PL	1000.0	1600000.				
1979	PP	PL	1000.0	1600000.				
1979	ALL	PL	2000.0	3200000.				
1980	CY	PL	1000.0	1600000.				
1980	PP	PL	1000.0	1600000.				
1980	ALL	PL	2000.0	3200000.				
1981	CY	PL	1000.0	1600000.				
1981	PP	PL	1000.0	1600000.				
1981	ALL	PL	2000.0	3200000.				
1982	CY	PL	1000.0	1600000.				
1982	PP	PL	1000.0	1600000.				
1982	ALL	PL	2000.0	3200000.				
1985	CY	T1	886.6	528000.	20000.	0.0	91.5	0.3	0.0
1985	CY	ALL	886.6	528000.	20000.	0.0	91.5	0.3	0.0
1985	PP	T1	772.0	528000.	20000.	0.0	90.5	0.0	0.0
1985	PP	ALL	772.0	528000.	20000.	0.0	90.5	0.0	0.0
1985	ALL	T1	1658.6	1056000.	40000.	0.0	91.0	0.1	0.0
1985	ALL	ALL	1658.6	1056000.	40000.	0.0	91.0	0.1	0.0
1986	CY	T1	839.3	587861.	20000.	0.0	91.9	0.2	0.0
1986	CY	ALL	839.3	587861.	20000.	0.0	91.9	0.2	0.0
1986	PP	T1	678.1	648375.	20000.	0.0	91.4	0.0	0.0
1986	PP	ALL	678.1	648375.	20000.	0.0	91.4	0.0	0.0
1986	ALL	T1	1517.4	1236237.	40000.	0.0	91.6	0.1	0.0
1986	ALL	ALL	1517.4	1236237.	40000.	0.0	91.6	0.1	0.0
1987	CY	T1	772.1	672736.	20000.	0.0	92.4	0.1	0.0
1987	CY	ALL	772.1	672736.	20000.	0.0	92.4	0.1	0.0
1987	PP	T1	546.8	290316.	20000.	0.0	92.6	0.0	0.0
1987	PP	ALL	546.8	290316.	20000.	0.0	92.6	0.0	0.0
1987	ALL	T1	1318.9	963052.	40000.	0.0	92.5	0.1	0.0
1987	ALL	ALL	1318.9	963052.	40000.	0.0	92.5	0.1	0.0

PYMOD example - main output table for period 1997 to 2001

TABLE ØF PLANTING AND CUTTING ØPERATIØNS

YEAR	SPECIES	ØPERATIØN	AREA CUT/ PLANTED	NØ. TREES	TØTAL VØLUME (CU.M)	VØLUME CLASSES AS PERCENT ØF TØTAL SAWNWØØD	POLES	FUELWØØD
1997	CY	T2	384.1	198523.	400000.	40.7	59.3	0.0
1997	CY	ALL	384.1	198523.	4000000.	40.7	59.3	0.0
1997	PP	T2	360.8	1920066.	4000000.	28.6	71.4	0.0
1997	PP	ALL	360.8	1920066.	4000000.	28.6	71.4	0.0
1997	ALL	T2	745.0	3905893.	8000000.	34.7	65.3	0.0
1997	ALL	ALL	745.0	3905893.	8000000.	34.7	65.3	0.0
1998	CY	T2	373.8	1596133.	4000000.	41.1	58.9	0.0
1998	CY	ALL	373.8	1596133.	4000000.	41.1	58.9	0.0
1998	PP	T2	364.1	1305800.	4000000.	28.4	71.6	0.0
1998	PP	ALL	364.1	1305800.	4000000.	28.4	71.6	0.0
1998	ALL	T2	737.9	2901933.	8000000.	34.7	65.3	0.0
1998	ALL	ALL	737.9	2901933.	8000000.	34.7	65.3	0.0
1999	CY	T2	373.0	1761600.	4000000.	41.1	58.9	0.0
1999	CY	ALL	373.0	1761600.	4000000.	41.1	58.9	0.0
1999	PP	T2	371.2	1820400.	4000000.	27.7	72.3	0.0
1999	PP	ALL	371.2	1820400.	4000000.	27.7	72.3	0.0
1999	ALL	T2	744.2	3582200.	8000000.	34.4	65.6	0.0
1999	ALL	ALL	744.2	3582200.	8000000.	34.4	65.6	0.0
2000	CY	T2	363.0	2491833.	4000000.	41.4	58.6	0.0
2000	CY	ALL	363.0	2491833.	4000000.	41.4	58.6	0.0
2000	PP	CF	113.6	1940055.	4000000.	56.7	43.3	0.0
2000	PP	ALL	113.6	1940055.	4000000.	56.7	43.3	0.0
2000	ALL	T2	363.0	2491833.	4000000.	41.4	58.6	0.0
2000	ALL	CF	113.6	1940055.	4000000.	56.7	43.3	0.0
2000	ALL	ALL	476.6	4431887.	8000000.	49.0	51.0	0.0
2001	PP	PL	113.6	1817722.	4000000.	41.5	58.5	0.0
2001	PL	ALL	113.6	1817722.	4000000.	41.5	58.5	0.0
2001	CY	T2	360.4	1826088.	4000000.	58.1	41.9	0.0
2001	CY	ALL	360.4	1826088.	4000000.	58.1	41.9	0.0
2001	PP	CF	105.0	3042583.	4000000.	41.5	58.5	0.0
2001	PP	ALL	105.0	3042583.	4000000.	41.5	58.5	0.0
2001	ALL	T2	360.4	1826088.	4000000.	58.1	41.9	0.0
2001	ALL	CF	105.0	3042583.	4000000.	41.5	58.5	0.0
2001	ALL	ALL	465.5	4868671.	8000000.	49.8	50.2	0.0

PYMOD example - explanation of second output stream

The second stream of output, switched on by iopout = 1 on card type 3, may be referred to as an operational list. It contains compartment details for each harvesting operation in a card image format that is suitable for sorting and printing in order to give lists classified by criteria such as block code, thinning number, or compartment number. Only part of the listing is shown overleaf, covering the period from 2009 to 2018 for the example. The columns are as follows:

1. Year of operation
2. Internal program reference number for compartment.
3. Block code.
4. Compartment identifier. Note that all internally generated compartments end with the letter X.
5. Logging unit number - indicates subdivisions of compartments generated when partial harvesting is necessary to remain within the volume quota.
6. Species.
7. Planting year.
8. Area cut in current operation - which may be less than total compartment area.
9. Dominant height in metres.
10. Stocking after the harvesting operation.
11. Volume yield per hectare.
12. Operation type.

PYMOD example - operational list in second output stream

(see previous page for explanation)

1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
2009	3	1	3X	1	CY	1980	373.0	25.0	481.2	128.4	T3
2009	39	1	3X	7	CY	1980	94.4	25.0	481.2	128.1	T3
2009	21	2	4X	2	PP	2004	67.9	28.4	1072.0	217.6	T1
2009	15	2	2X	3	PP	1979	3.0	32.0	0.0	805.7	CF
2009	6	2	1X	1	PP	1978	52.5	32.3	0.0	814.6	CF
2010	4	1	4X	1	CY	1981	174.8	25.0	481.2	128.1	T3
2010	18	1	4X	2	CY	1981	198.7	25.0	481.2	127.2	T3
2010	45	1	4X	4	CY	1981	98.8	25.0	481.2	124.8	T3
2010	23	2	4X	3	PP	2005	65.1	28.9	1072.0	225.9	T1
2010	10	2	5X	1	PP	2001	113.6	14.8	718.2	37.9	T2
2010	11	2	1X	2	PP	1978	49.8	32.6	0.0	823.0	CF
2011	5	1	5X	1	CY	1982	71.3	25.0	481.2	124.8	T3
2011	49	1	5X	3	CY	1982	289.4	25.0	481.2	120.7	T3
2011	22	1	5X	2	CY	1982	55.9	25.0	481.2	120.3	T3
2011	51	1	5X	4	CY	1982	81.4	25.0	481.2	116.2	T3
2011	25	2	4X	4	PP	2006	11.0	29.4	1072.0	234.1	T1
2011	8	2	3X	1	PP	2006	62.4	29.9	1072.0	299.4	T1
2011	27	2	5X	2	PP	2002	101.1	14.8	718.2	37.9	T2
2011	29	2	5X	3	PP	2002	3.9	14.8	718.2	37.9	T2
2011	33	2	2X	1	PP	1979	42.2	32.6	0.0	823.0	CF
2012	17	2	3X	2	PP	2007	52.8	30.4	1072.0	258.5	T1
2012	9	2	4X	1	PP	2003	92.7	14.8	718.2	37.9	T2
2012	5	1	5X	1	CY	1982	71.3	25.3	0.0	423.5	CF
2012	49	1	5X	3	CY	1982	72.5	25.3	0.0	411.5	CF
2012	36	2	3X	2	PP	1980	52.0	32.6	0.0	823.0	CF
2013	19	2	3X	3	PP	2008	39.3	30.8	1072.0	265.7	T1
2013	7	2	2X	1	PP	2008	15.3	31.2	1072.0	337.4	T1
2013	21	2	4X	2	PP	2004	67.9	14.8	718.2	37.9	T2
2013	22	1	5X	2	CY	1982	55.9	25.6	0.0	431.5	CF
2013	51	1	5X	4	CY	1982	81.4	25.6	0.0	419.5	CF
2013	24	1	5X	3	CY	1982	3.3	25.6	0.0	535.5	CF
2013	38	2	4X	1	PP	1981	5.0	32.6	0.0	823.0	CF
2013	31	2	5X	4	PP	1982	46.3	32.3	0.0	814.6	CF
2014	13	2	2X	2	PP	2009	47.4	31.6	1072.0	288.1	T1
2014	23	2	4X	3	PP	2005	65.1	14.8	718.2	37.9	T2
2014	10	2	5X	1	PP	2001	113.6	20.8	481.2	59.8	T3
2014	53	1	5X	5	CY	1982	70.6	25.9	0.0	540.9	CF
2014	4	1	4X	1	CY	1981	44.8	26.1	0.0	487.3	CF
2014	40	2	5X	5	PP	1982	45.1	32.6	0.0	823.0	CF
2015	15	2	2X	3	PP	2010	3.0	32.0	1072.0	294.2	T1
2015	6	2	1X	1	PP	2010	52.5	32.3	1072.0	299.3	T1
2015	25	2	4X	4	PP	2006	11.0	14.8	718.2	37.9	T2
2015	8	2	3X	1	PP	2006	62.4	14.8	718.2	37.9	T2
2015	27	2	5X	2	PP	2002	101.1	20.8	481.2	59.8	T3
2015	29	2	5X	3	PP	2002	3.9	20.8	481.2	59.8	T3
2015	18	1	4X	2	CY	1981	118.2	26.4	0.0	507.5	CF
2015	42	2	5X	1	PP	1982	49.7	32.9	0.0	691.3	CF
2016	11	2	1X	2	PP	2011	49.8	32.6	1072.0	300.8	T1
2016	17	2	3X	2	PP	2007	52.8	14.8	718.2	37.9	T2
2016	9	2	4X	1	PP	2003	92.7	20.8	481.2	59.8	T3
2016	45	1	4X	4	CY	1981	98.8	26.6	0.0	519.9	CF
2016	47	1	4X	5	CY	1981	15.3	26.6	0.0	565.5	CF
2016	44	2	5X	6	PP	1982	44.7	33.2	0.0	838.4	CF
2017	33	2	2X	1	PP	2012	42.2	32.6	1072.0	301.9	T1
2017	19	2	3X	3	PP	2008	39.3	14.8	718.2	37.9	T2
2017	7	2	2X	1	PP	2008	15.3	14.8	718.2	37.9	T2
2017	21	2	4X	2	PP	2004	67.9	20.8	481.2	59.8	T3
2017	20	1	4X	3	CY	1981	105.3	26.8	0.0	570.1	CF
2017	46	2	4X	2	PP	1981	54.5	33.8	0.0	754.5	CF
2018	36	2	3X	2	PP	2013	52.0	32.6	1072.0	300.8	T1
2018	13	2	2X	2	PP	2009	47.4	14.8	718.2	37.9	T2
2018	23	2	4X	3	PP	2005	65.1	20.8	481.2	59.8	T3
2018	10	2	5X	1	PP	2001	113.6	24.9	322.4	69.8	T4
2018	3	1	3X	1	CY	1980	103.9	27.2	0.0	577.4	CF
2018	48	2	4X	5	PP	1981	35.8	34.0	0.0	858.7	CF

PYMOD main program listing

The PYMOD main program is shown on the following pages. The subroutines called are the same as those used by VYTL-2 and are described in part 3 of this document. In the version listed here, there is capacity for 100 compartments, indicated by the dimensions of the arrays AREA,HDOM, STK, SV, SI, BLOCK, COMP, SPP, PYR, LSD, YRLOP, INDEX, ASSYR, LOPC and the variable MAXC. Adjustment of these values will either decrease program size and reduce the number of compartments handled, or increase program size and number of compartments. At present, the binary program produced by this listing and subroutines on an ICL 1900 computer is approximately 16k of 24bit words.

The card reader input channel used is 1, and the line printer output channel is 2. The operational listing produced when iopout = 1 (see data specifications) requires channel 4 to be allocated.

The FORTRAN used is ICL 1900 FORTRAN, but it is compatible with IBM 370 FORTRAN (DOS) except for the way in which free formatted input is handled.

```
*FORTRAN    FOPT
       LIST
       PROGRAM(PYMD)
       INPUT 1=CR0
       OUTPUT 2=LP0
       OUTPUT 4=LP1
       END
       MASTER PYMOD
       REAL AREA(100),HDOM(100),STK(100),SV(10,100),SI(100),
      1VOLTOT(3),TGTVOL(3),VOLUME(6),OUTPUT(8,4,12),INH(3),
      2THF(3),VOL(3,25)
       DIMENSION SVS(10)
       REAL VOLNME(4,2)
       COMMON/DUMP/IDUMP
       COMMON/VLIM/DMIN(3,4),HMIN(3,4)
       INTEGER BLOCK(100),COMP(3,100),SPP(100),PYR(100),LSD(100),
      1YRLOP(100),INDEX(100),ASSYR(100),BYR,LYR,XX,LOPC(100),
      2FYP,LYP,BNO,PSPP,SPPNME(4),OPCODE(12),NVOLC(3),CYC(3),
      3RMIN(3),FVY(3,25),LVY(3,25),RSTK(3)
       DATA XX/'X'/,MAXC/100/,SPPNME/'CY','PR','PP','ALL'/,
      1OPCODE/'PL','T1','T2','T3','T4','T5','T6','T7','T8',
      2 'T9','CF','ALL'/,NVOLC/1,1,1/,INH/0.0,0.0,0.0/
       DATA VXS/0.001/
C INPUT FOREST DATA - TERMINATED BY BLANK CARD
       NCOMP=0
       DO 21 I=1,MAXC
       LSD(I)=-1
   21  COMP(3,I)=1
       DO 2 I=1,MAXC
       READ(1,20)BLOCK(I),(COMP(J,I),J=1,2),SPP(I),AREA(I),PYR(I),
      1    ASSYR(I),SI(I),HDOM(I),STK(I),(SV(J,I),J=1,10)
   20  FORMAT(I3,I2,A1,I1,F5.1,2I4,2F3.1,F4.0,10F4.1)
       IF(BLOCK(I).LE.0)GOTO4
    2  NCOMP=I
    4  READ(1,10)BYR,LYR,IPRT,IDUMP,IOPOUT
   10  FORMAT(10G0.0)
C SECTION TO READ AND PRINT MERCHANTABLE LIMITS
       WRITE(2,50)
   50  FORMAT(/////20X,'MERCHANTABLE VOLUME DEFINITIONS'/20X,31(1H-)//
      1  10X,'SPECIES',4X,'CLASS',7X,'SMALL-END',4X,'MINIMUM'/33X,
      2  'DIAMETER',5X,'LENGTH'/)
        DO 5 I=1,3
       DO 5 J=1,4
       DMIN(I,J)=0.0
    5  HMIN(I,J)=0.0
       READ(1,510)((VOLNME(I,J),J=1,2),I=1,4)
  510  FORMAT(8A4)
   53  READ(1,10)NS
       IF(NS.LE.0)GOTO599
       WRITE(2,520)SPPNME(NS)
  520  FORMAT(13X,A3)
```

```
      K=NS
      IF(NS.EQ.4)K=1
      READ(1,10)NC,(DMIN(K,I),HMIN(K,I),I=1,NC)
      WRITE(2,550)((VOLNME(I,J),J=1,2),DMIN(K,I),HMIN(K,I),I=1,NC)
  550 FORMAT(21X,2A4,6X,F7.2,4X,F7.2)
      IF(NS.LT.4)GOTO53
      DO 54 J=2,3
      DO 54 I=1,4
      DMIN(J,I)=DMIN(1,I)
   54 HMIN(J,I)=HMIN(1,I)
      GOTO53
  599 CONTINUE
C SECTION TO READ IN DETAILS OF ESTABLISHMENT OPERATIONS AND
C PRINT THEM. ALSO TO MAKE ENTRIES COREESPONDING TO INDIVIDUAL
C COMPARTMENTS IN AMIN ARRAYS
      MCOMP=NCOMP
      KEND=1
    6 READ(1,10)FYP,LYP,BNO,PSPP,PSI,PAREA,ISTK
      IF(FYP.LT.0)GOTO69
      GOTO(62,6),KEND
   62 K=LYP-FYP
      MCOMP=MCOMP+1
         IF(MCOMP+K.GT.MAXC)GOTO68
      IF(NCOMP.EQ.MCOMP-1)WRITE(2,600)
      WRITE(2,610)FYP,LYP,BNO,SPPNME(PSPP),PSI,PAREA,ISTK
      DO 61 I=MCOMP,MCOMP+K
      J=I-MCOMP+1
      BLOCK(I)=BNO
      COMP(1,I)=J
      COMP(2,I)=XX
      SPP(I)=PSPP
      AREA(I)=PAREA
      STK(I)=ISTK
      SI(I)=PSI
      ASSYR(I)=FYP+J-1
      PYR(I)=FYP+J-1
      LOPC(I)=1
      YRLOP(I)=BYR-PYR(I)
   61 CONTINUE
      MCOMP=MCOMP+K
      GOTO6
   68 WRITE(2,620)
      KEND=2
      GOTO6
   69 NCOMP=MCOMP
  620 FORMAT(//' ADDITIONAL ESTABLISHMENT REQUESTS ARE SUPPLIED ',
     1    ' BUT ARE IGNORED'/' AS PROGRAM STORAGE IS NOW FULL'//)
  610 FORMAT(10X,I4,I9,4X,I5,6X,A2,7X,F4.1,F8.1,4X,I5)
  600 FORMAT(////27X,'DESCRIPTION OF FOREST ESTABLISHMENT PROGRAM'/
     1 25X,'(EXCLUDING REGENERATON OF EXISTING COMPARTMENTS)'/25X,
     2 48(1H-)//10X,'FIRST',4X,'LAST',4X,'BLOCK',4X,'SPECIES',4X,
     3  'SITE',4X,'AREA',4X,'STOCKING'/10X,'YEAR',5X,'YEAR',24X,
     4 'INDEX',4X,'/YR',5X,'/HA'//)
```

```
C INPUT DETAILS OF THINNING TREATMENTS
    7 READ(1,10)NS,A,I1,B,I2,I3
      IF(NS)75,75,76
   76 INH(NS)=A
      CYC(NS)=I1
      THF(NS)=B
      RMIN(NS)=I2
      RSTK(NS)=I3
      GOTO7
   75 CONTINUE
      IF(NS.GT.0)GOTO7
      WRITE(2,71)
   71 FORMAT(/////30X,'THINNING TREAMENTS'/30X,19(1H-)//
     1 10X,'SPECIES',4X,'INITIAL',4X,'MINIMUM',4X,'THINNING',4X,
     2 'MINIMUM',4X,'RE-PLANT'/21X,'HEIGHT',5X,'CYCLE',6X,
     3 'FRACTION',4X,'ROTATION',6X,'AT'/)
      DO 72 NS=1,3
      IF(INH(NS))73,73,74
   73 WRITE(2,730)SPPNME(NS)
  730 FORMAT(12X,A2,10X,' N O T   S P E C I F I E D')
      GOTO 72
   74 WRITE(2,740)SPPNME(NS),INH(NS),CYC(NS),THF(NS),RMIN(NS),RSTK(NS)
  740 FORMAT(12X,A2,7X,F7.1,6X,I4,5X,F5.3,9X,I4,7X,I5)
   72 CONTINUE
C INPUT VOLUME CONTROL CARDS
      WRITE(2,80)
   80 FORMAT(/////30X,'VOLUME CONTROL'/30X,14(1H-)//10X,'SPECIES',
     1 4X,'FIRST YEAR',4X,'LAST YEAR',4X,'VOLUME TO BE CUT'//)
    8 READ(1,10)NS,IY1,IY2,V
      IF(NS.LT.1)GOTO89
      K=NVOLC(NS)
      FVY(NS,K)=IY1
      LVY(NS,K)=IY2
      VOL(NS,K)=V
      WRITE(2,820)SPPNME(NS),FVY(NS,NVOLC(NS)),LVY(NS,NVOLC(NS)),
     1 VOL(NS,NVOLC(NS))
  820 FORMAT(12X,A2,10X,I4,10X,I4,3X,F14.1)
      IF(NVOLC(NS).EQ.25)WRITE(2,830)
  830 FORMAT(1H+,70X,'NOTE: THIS MUST BE THE LAST CARD FOR THIS ',
     1 ' SPECIES')
      NVOLC(NS)=NVOLC(NS)+1
      GOTO8
   89 DO 88 I=1,3
       NVOLC(I)=NVOLC(I)-1
      IF(NVOLC(I).EQ.0)WRITE(2,880)SPPNME(I)
  880 FORMAT(12X,A2,10X,'NO VOLUMES SPECIFIED: THIS SPECIES',
     1 ' WILL NOT BE HARVESTED ')
   88 CONTINUE
```

```
C FOR ALL COMPARTMENTS,ESTIMATE SITE INDEX IF NOT GIVEN,
C LAST OPERATION CODE, AND YEARS SINCE LAST OPERATION
   11 DO 111 I=1,NCOMP
       AGE=BYR-PYR(I)
      IF(AGE.LE.0.0)GOTO111
C STANDS OLDER THAN 5 YEARS
C ESTIMATE SITE INDEX IF NOT GIVEN
      IF(SI(I).LE.0.0)SI(I)=HTF(AGE,HDOM(I),SPP(I),2)
C SKIP NEXT SECTION IF STANDS ARE TO BE UNTHINNED
      ISP=SPP(I)
      IF(INH(ISP).LE.0.0)GOTO114
C SET OPERATION CODE FOR THINNED STANDS
      FAGE=HTF(INH(ISP),SI(I),ISP,3)
C FIND NO THINNINGS EQUIVALENT TO PRESENT STOCKING
      NTHIN=INT(ALOG(STK(I)/RSTK(ISP))/ALOG(THF(ISP)))
C FIND NEXT THINNING DUE
      NTHIN=NTHIN+1
      IF(NTHIN.GT.9)NTHIN=9
C WORK OUT EQUIVALENT TIME TO THAT NO OF THINNINGS
       YRS=NTHIN*CYC(ISP)
      TAGE=YRS+FAGE
      IF(TAGE.LT.RMIN(ISP))GOTO115
  114 TAGE=RMIN(ISP)
      NTHIN=10
  115 YRLOP(I)=AGE-TAGE
      LOPC(I)=NTHIN+1
C SET INITIAL CONDITION OF INDEX POINTER
  111 INDEX(I)=I
   12 CONTINUE
C PRINT MAIN TABLE HEADING
      WRITE(2,120)((VOLNME(I,J),J=1,2),I=1,4)
  120 FORMAT(1H1/////30X,'TABLE OF PLANTING AND CUTTING OPERATIONS'/
     1 30X,39(1H-)///10X,'YEAR',2X,'SPECIES',2X,'OPER-',2X,'AREA CUT/',
     2 7X,'NO.',6X,'TOTAL VOLUME',3X,'VOLUME CLASSES AS PERCENT OF ',
     3 'TOTAL'/25X,'ATION',3X,'PLANTED',7X,'TREES',7X,'(CU.M)',4X,
     4 4(2X,2A4),2X,'NOT USED'/10X,110(1H-))
C LOOP FROM BASE YEAR TO LAST YEAR OF RUN
      DO 101 IYR=BYR,LYR
C DUMP OUT COMPARTMENTS IF REQUIRED
      IF(IDUMP.EQ.0)GOTO3003
      WRITE(2,3002)IYR
 3002 FORMAT(10X,'DUMP AT YEAR ',I5/)
      DO 3000 I=1,NCOMP
 3000 WRITE(2,3001)BLOCK(I),(COMP(J,I),J=1,2),SPP(I),AREA(I),
     1  PYR(I),SI(I),HDOM(I),STK(I),LOPC(I),YRLOP(I),
     2  (SV(J,I),J=1,10)
 3001 FORMAT(1X,I3,1X,I2,A1,1X,I1,1X,F5.0,1X,I4,1X,2(F4.1,1X),
     1 F6.0,2I4,10F7.2)
 3003 CONTINUE
C SET VOLUMES CUT IN CURRENT YEAR TO ZERO
      DO 102 I=1,3
  102 VOLTOT(I)=0.0
C SET OUPUT ARRAY TO ZERO
      DO 103 I=1,8
      DO 103 J=1,4
      DO 103 K=1,12
  103 OUTPUT(I,J,K)=0.0
```

```
C SELECT VOLUME SPECIES TARGETS FOR THE CURRENT YEAR
      DO 104 NS=1,3
      TGTVOL(NS)=0.0
      NN=NVOLC(NS)
      IF(NN.LE.0)GOTO104
      DO 105 I=1,NN
      IF(IYR.LT.FVY(NS,I).OR.IYR.GT.LVY(NS,I))GOTO105
      TGTVOL(NS)=VOL(NS,I)
      GOTO104
  105 CONTINUE
  104 CONTINUE
      IF(IDUMP.EQ.4)WRITE(2,4001)TGTVOL
 4001 FORMAT('  TGTVOL = ',3G13.5)
C SORT INDEX ARRAY BY OPERATIONAL PRIORITY
      LEX1=NCOMP
      DO 106 II=1,NCOMP
      LEX=LEX1
      IF(LEX.LE.2)GOTO108
      DO 107 J=2,LEX
      I=INDEX(J)
      IO=INDEX(J-1)
      KO=LOPC(IO)
      K1=LOPC(I)
      LO=YRLOP(IO)
      L1=YRLOP(I)
      IF(KO.EQ.1 .AND. K1.NE. 1)GOTO1071
      IF(LO.LT.L1)GOTO1071
      IF(LO.EQ.L1  .AND.  K1.LT.KO)  GOTO1071
      GOTO107
 1071 CONTINUE
      LEX1=J
      K=INDEX(J-1)
      INDEX(J-1)=INDEX(J)
      INDEX(J)=K
  107 CONTINUE
  106 CONTINUE
  108 CONTINUE
      IF(IDUMP.EQ.4)WRITE(2,4002)(INDEX(I),I=1,NCOMP)
 4002 FORMAT('  INDEX = ',(T10,25I4))
C LOOP OVER STANDS IN FOREST IN ORDER OF OPERATION PRIORITY
      II=1
  309 CONTINUE
C ENTRY POINT FOR MAIN LOOP OVER COMPARTMENTS FOR HARVESTING AND
C GROWTH
      IX=INDEX(II)
      STKS=STK(IX)
      DO 1093 I=1,10
 1093 SVS(I)=SV(I,IX)
      IX=INDEX(II)
```

```
C PERFORM CUTTING OPERATIONS IF REQUIRED
      LIX=LOPC(IX)
      NS=SPP(IX)
      IF(TGTVOL(NS).LE.(1.0+VXS)*VOLTOT(NS))GOTO1091
      IF(LIX.EQ.1)GOTO1091
      IF(YRLOP(IX).LT.0)GOTO1091
      F=THF(NS)
      IF(LIX.EQ.11)F=0.0
      OUTPUT(2,NS,LIX)=OUTPUT(2,NS,LIX)+STK(IX)*(1.0-F)*AREA(IX)
      CALL CUT(HDOM(IX),STK(IX),NS,SV(1,IX),F,VOLUME)
      IF(IDUMP.NE.0)WRITE(2,3004)BLOCK(IX),(COMP(J,IX),J=1,2),
     1   OPCODE(LIX),VOLUME
C SPLIT COMPARTMENT INTO SEPARATE LOGGING UNITS
C IF PARTIAL CUTTING IS INDICATED
C IF VOLUME IS SMALL, DON'T BOTHER TO CUT COMPARTMENT.
C RESTORE TO PRECUT STATE AND SKIP
      IF(VOLUME(1)-1.0)2096,2096,2097
 2096 STK(IX)=STKS
      DO 2098 I=1,10
 2098 SV(I,IX)=SVS(I)
      GOTO1091
 2097 CONTINUE
      VV=AREA(IX)*VOLUME(1)
      CUTPCT=(VOLTOT(NS)+VV-TGTVOL(NS))/VV
C 209 INDICATES WHOLE COMPARTMENT TO BE CUT
C 1091 INDICATES MARGINAL YIELD INSIGNIFICANT - NO CUTTING
      IF(CUTPCT.LT.VXS)GOTO209
      IF(1.0-CUTPCT.LT.VXS)GOTO2096
C CHECK ON PROGRAM STORAGE SPACE FOR SPLIT SECTION
      IF(NCOMP.LT.MAXC)GOTO2091
      WRITE(3,2092)
 2092 FORMAT('0  **** INSUFFICIENT PROGRAM SPACE FOR SPLIT LOGGING
     1 UNITS  -  YIELD REGULATION RESTRICTED TO WHOLE COMPARTMENTS')
      GOTO209
 2091 CONTINUE
C COMP(IX) IS ONE ACTUALLY CUT. COMP(NCOMP) IS SUBDIVISION LEFT
      NCOMP=NCOMP+1
       AA=AREA(IX)
      AREA(IX)=AA*(1.0-CUTPCT)
      AREA(NCOMP)=AA*CUTPCT
C CREATE NEW LOGGING UNIT
      DO 2093  I=1,10
 2093 SV(I,NCOMP)=SVS(I)
      HDOM(NCOMP)=HDOM(IX)
      STK(NCOMP)=STKS
      SI(NCOMP)=SI(IX)
      BLOCK(NCOMP)=BLOCK(IX)
      DO 2094 I=1,3
 2094 COMP(I,NCOMP)=COMP(I,IX)
      LSD(NCOMP)=LSD(IX)
      IF(LSD(IX).EQ.-1)LSD(NCOMP)=IX
      LSD(LSD(NCOMP))=LSD(LSD(NCOMP))-1
      COMP(3,NCOMP)=IABS(LSD(LSD(NCOMP)))
      SPP(NCOMP)=SPP(IX)
      PYR(NCOMP)=PYR(IX)
      YRLOP(NCOMP)=YRLOP(IX)
      INDEX(NCOMP)=NCOMP
      ASSYR(NCOMP)=ASSYR(IX)
      LOPC(NCOMP)=LOPC(IX)
  209 CONTINUE
```

```
      IF(IOPOUT.EQ.1)WRITE(4,3005)IYR,IX,BLOCK(IX),
     1   (COMP(J,IX),J=1,3),SPPNME(SPP(IX)),PYR(IX),AREA(IX),
     2   HDOM(IX),STK(IX),VOLUME(1) ,OPCODE(LOPC(IX))
 3005 FORMAT(3X,I4,1X,I3,1X,I3,1X,I2,A1,1X,I2,1X,A3,1X,I4,
     1   1X,F7.1,1X,F6.1,1X,F7.1,1X,F7.1,1X,A3)
 3004 FORMAT(5X,I3,1X,I2,A1,1X,A3,6G13.5)
      OUTPUT(1,NS,LIX)=OUTPUT(1,NS,LIX)+AREA(IX)
      DO 1092 I=1,6
      I3=I+2
 1092 OUTPUT(I3,NS,LIX)=OUTPUT(I3,NS,LIX)+VOLUME(I)*AREA(IX)
      VOLTOT(NS)=VOLTOT(NS)+VOLUME(1)*AREA(IX)
      IF(IDUMP.EQ.4)WRITE(2,4003)NS,VOLTOT(NS)
 4003 FORMAT(' VOLTOT(',I2,') NOW = ',G13.5)
C RESET OPERATION INDICATORS FOLLOWING CUTTING
      IF(LOPC(IX)-10)1095,1096,1097
C PLANTING IS NEXT OPERATION
 1097 YRLOP(IX)=-1
      LOPC(IX)=1
      PYR(IX)=IYR+1
      GOTO1091
C THINNING IS NEXT OPERATION
 1095 LOPC(IX)=LOPC(IX)+1
 1096 YRLOP(IX)=-CYC(NS)
 1091 CONTINUE
C PLANT STANDS DUE FOR ESTABLISHMENT
      IF(LOPC(IX).NE.1.OR.YRLOP(IX).NE.0)GOTO 1098
      IF(STK(IX).LE.0.0)       STK(IX)=RSTK(NS)
      FAGE=HTF(INH(NS),SI(IX),SPP(IX),3)
      LOPC(IX)=2
      YRLOP(IX)=-FAGE
      OUTPUT(1,NS,1)=OUTPUT(1,NS,1)+AREA(IX)
      OUTPUT(2,NS,1)=OUTPUT(2,NS,1)+RSTK(NS)*AREA(IX)
      PYR(IX)=IYR
 1098 CONTINUE
C GENERATE HEIGHT AND STAND TABLE FOR 7 M TALL STANDS
C SKIP GROWTH SECTION IF STAND LESS THAN 7M TALL
      IF(IYR-PYR(IX)-INT(HTF(7.0,SI(IX),SPP(IX),3)+0.5))2001,2002,1099
 2002 CONTINUE
      AGE=IYR-PYR(IX)
      HDOM(IX)=HTF(AGE,SI(IX),SPP(IX),1)
      CALL INDD(HDOM(IX),STK(IX),SV(1,IX),NS)
 1099 CONTINUE
C GENERATE NEW GROWTH FOR NEXT YEAR
      AGE=IYR+1-PYR(IX)
      HDOM(IX)=HTF(AGE,SI(IX),NS,1)
      CALL GROW(1.0,HDOM(IX),STK(IX),SV(1,IX),SPP(IX))
      IF(AGE.LT.RMIN(NS))GOTO2001
      LOPC(IX)=11
      YRLOP(IX)=-1
 2001 YRLOP(IX)=YRLOP(IX)+1
C END OF COMPARTMENT LOOP
  109 CONTINUE
      II=II+1
      IF(II.LE.NCOMP)GOTO309
C SECTION TO OUTPUT RESULTS FOR CURRENT CYCLE
C COMPUT TOTALS FOR OPERATIONS
      DO 1101 J=1,3
      DO 2101 L=1,2
 2101 OUTPUT(L,4,1)=OUTPUT(L,4,1)+OUTPUT(L,J,1)
```

```
      DO 1101 I=1,8
      DO 1101 K=2,11
      DO 2102 L=1,3
      GOTO(2103,2104,2105),L
 2103 M=4
      N=K
      GOTO2102
 2104 M=J
      N=12
      GOTO2102
 2105 M=4
       N=12
 2102 OUTPUT(I,M,N)=OUTPUT(I,M,N)+OUTPUT(I,J,K)
 1101 CONTINUE
C GIVE PRODUCT VOLUMES AS PERCENTAGE OF TOTAL VOLUMES
      DO 1102 K=2,12
      DO 1102 I=4,8
      DO 1102 J=1,4
      IF(OUTPUT(3,J,K).LE.0.0)GOTO1102
      OUTPUT(I,J,K)=OUTPUT(I,J,K)/OUTPUT(3,J,K)*100.0
 1102 CONTINUE
C SELCT PRINT OPTION
      GOTO(1103,1104,1105,1106),IPRT
 1103 ISP=1
      IOP=2
      GOTO1107
 1104 ISP=1
      IOP=12
      GOTO1107
 1105 ISP=4
      IOP=2
      GOTO1107
 1106 ISP=4
      IOP=12
 1107 CONTINUE
C PRINT PLANTING DETAILS
      WRITE(2,1500)
 1500 FORMAT(1X)
      DO 1201 J=ISP,4
      IF(OUTPUT(1,J,1).LE.0.0)GOTO1201
      WRITE(2,1600)IYR,SPPNME(J),OPCODE(1),(OUTPUT(I,J,1),I=1,2)
 1600 FORMAT(10X,I4,3X,2(A3,4X),F9.1,2X,F12.0,2X,F12.0,5(2X,F5.1,3X))
 1201 CONTINUE
C PRINT VOLUME DETAILS
      DO 1202 J=ISP,4
      DO 1202 K=IOP,12
      IF(OUTPUT(1,J,K).LE.0.0)GOTO1202
      WRITE(2,1600)IYR,SPPNME(J),OPCODE(K),(OUTPUT(I,J,K),I=1,8)
 1202 CONTINUE
  101 CONTINUE
C END OF SIMULATION LOOP
      WRITE(2,9999)
 9999 FORMAT(/10X,110(1H-)//' PROGRAM FINISHED O.K.'///)
      STOP
      END
      FINISH
*LINK SEMI VYTL-RTNS(/SEMI)
*END BIN PYHOD(/BIN)
```

Part 3

Subroutine library for VYTL-2 and PYMOD

The subroutines listed here contain specific growth functions for Cupressus lusitanica, Pinus radiata, and Pinus radiata, and together comprise all necessary facilities for simulating growth and yield of these species. The specifications for each routine are as follows:

SUBROUTINE INDD(BA7,STK,SV,NS)

This routine initialises the stand vector SV, which is a real array of dimension 10, so that after the call it contains diameters representing the 5%,15%, 25%, etc. up to the 95% points of the cumulative distribution of stem frquencies for the stand. The diameter percentiles are in centimetres.
NS is the species code, which may have the following values:-

1 Cupressus lusitanica
2 Pinus radiata
3 Pinus patula

STK is the stocking of the stand, in stems/ha.
BA7 is the basal area of the stand at a dominant height of 7 metres. Alternatively it may be zero when the routine is called, in which case a default value is used.
BA7, STK, and NS must be defined when the routine is called. The result returned is in SV, which may be undefined prior to the call.

Normal use of the routine in a growth simulator requires that it should be called for undefined diameter distributions when their dominant height is 7 metres.

FUNCTION HTF(X1,X2,NS,MODE)

This routine uses a function to relate dominant height, age, and site index in three different ways, depending on the value of the integer variable MODE:-

MODE = 1 : X1 is age, X2 is site index, and value of HTF returned is dominant height.
MODE = 2 : X1 is age, X2 is dominant height, and value of HTF returned is site index as dominant height at age 15.
MODE = 3 : X1 is dominant height, X2 is site index and value of HTF is age at which that dominant height will be attained.

NS is the species code, with the same values as for INDD.

SUBROUTINE GROW(AGEINT,HDOM,STK,SV,NSP)

This routines take the cumulative diameter values in the real array SV (dimension 10) and adds to them the increment occurring over an interval AGEINT, which should not be more than 2 years for accurate results. HDOM is the dominant height in metres of the stand at the beginning of the growth period. STK is the stocking. NSP is an integer variable giving species code, and is the same as NS for INDD.
All values are unaltered by a call except for the array SV, whose values will be increased in accordance with the predicted increment.

SUBROUTINE TABVOL(TF,TD,NSP,HDOM,VOLUME)

This routine tabulates volumes for a stand into four merchantable classes, total overbark volume, and waste volume that cannot be allocated to any class. It includes a COMMON area VLIM, defined as follows:

```
COMMON/VLIM/DMIN(3,4),HMIN(3,4)
```

The variables involved are as follows:

TF - a real array of dimension 11 containing tree frequencies per hectare.

TD - a real array containing class mid-diameters corresponding to the TF frequencies.

NSP - a species code as for NS in INDD.

HDOM - a real variable giving dominant height of the stand in metres.

VOLUME - a real array of dimension 6, which may be undefined before the call and which returns the result, stored as follows:

(1) stand total overbark volume, m^3/ha.
(2) merchantable overbark volume for first class.
(3) " " " " 2nd. "
(4) " " " " 3rd. "
(5) " " " " 4th. "
(6) unutilizable overbark volume.

DMIN must be defined prior to the call, and contains minimum diameters for the 4 merchantable classes, with the first dimension representing species code, and the second dimension the merchantable class. A given DMIN(i,j) may be zero in which case that class is ignored. In this way the routine can cope with less than four classes by setting unused values to zero.

HMIN contains minimum log lengths corresponding to each class as for DMIN. If they are zero it simply indicates that there is no length restriction.

FUNCTION TAPER(HEIGHT,DBH,H,NSP)

This routine is called by TABVOL. Given a tree total height HEIGHT, and a tree overbark diameter at breast height DBH, and a point up the tree at height H metres from the ground, it gives the estimated overbark diameter at that point as the value of TAPER. NSP is an integer species code as for NS in INDD.

FUNCTION VOLINT(HEIGHT,HZERO,DBH,HT,NSP)

This routine is called by TABVOL. The value returned as VOLINT is the overbark volume between the heights HZERO and HT metres above ground. Other parameters are as for TAPER.

SUBROUTINE TREVOL(D,H,VOB,VUB,K)

This routine is called from TABVOL. It incorporates Wright's total volume equations based on tree diameter D and stand dominant height H. VOB is total overbark volume. VUB is total under-bark volume. K is a species code which takes the same values as NS in INDD. D,H, and K must be defined when the routine is called, whilst the results are returned in VOB and VUB.

SUBROUTINE THIN(STK,SV,FL,TF,TD)

This routine simulates a thinning, defined by the real variable FL, which is the fraction of the stocking to be left after thinning. STK is the stocking, and SV is the cumulative diameter vector (see INDD). Both must be defined prior to the call, and should represent the stand as it is before thinning. After the call they will have benn modified to represent the after-thinning crop. TF and TD may be undefined when

the routine is called; both are real arrays of dimension 11. After the call, TD contains diameter class mid-values and TF diameter class frequencies for the thinned stems.

FUNCTION DDOM(STK,SV)

This routine is called by GROW. STK is the stocking of the stand in stems/ha. and SV is a real array of dimension 10 containing the cumulative diameter percentiles as described for INDD. Both are unchanged by the call. The result is an estimate of the dominant diameter for the stand, i.e. the mean diameter of the 100 largest trees per hectare.

SUBROUTINE CUT(HDOM,STK,NSP,SV,F,VOLUME)

This routine simulates a harvesting operation by calling THIN and TABVOL in sequence. The parameters are:

HDOM - dominant height in metres. Unchanged by the call.
STK - stocking per ha. After the call this will be reduced according to thinning intensity.
NSP - is the species code, as for NS in INDD.
SV - is the stand vector of 10 diameters as for INDD.
F - is the fraction of the stocking to be left after thinning. If it is zero, a clear felling is performed.
VOLUME returns the yields. It is a real array of dimension 6, as defined for TABVOL.

The program listings for these routines are given on the following pages. They are written in a compatible subset of ICL 1900 and IBM 370 DOS FORTRAN.

```
      SUBROUTINE INDD(BA7,STK,SV,NS)
      DIMENSION B(8,3),SV(10)
      DATA B/
     1-0.6272,12.90,3.15,20.16,-0.88,4.54,-0.00761,0.3249,
     2 13.82,-27.74,26.52,-44.47,-0.655,5.0670,-0.0047,0.2304,
     3 9.167,-14.63,14.00,-11.16,0.1260,4.343,-0.0563,0.2211/
C DERIVE WEIBULL PARAMETERS - BEYOND SPACING OF 3.8 M THESE ARE ASSUMED
C CONSTANT
      SP=SQRT(1.0E4/STK)
      IF(SP.GT.3.8)SP=3.8
      WA=B(1,NS)+B(2,NS)/SP
      WB=B(3,NS)+B(4,NS)/SP-WA
      WG=B(5,NS)+B(6,NS)/SP+B(7,NS)*WA+B(8,NS)*WB
C LOOP THROUGH PERCENTILES COMPUTING DIAMETER
      BA=0.0
      DO 1 I=1,10
      PI=0.1*(I-1)+0.05
      SV(I)=WA+WB*(-ALOG(1.0-PI))**(1.0/WG)
    1 BA=BA+SV(I)**2
      IF(BA7.LE.0.0)RETURN
      BA=BA*STK/10.0*0.00007854
      RATIO=SQRT(BA7/BA)
      DO 2 I=1,10
    2 SV(I)=SV(I)*RATIO
      RETURN
      END
```

```
      FUNCTION HTF(X1,X2,NS,MODE)
C HEIGHT FUNCTION - HAS 3 MODES OF OPERATION
C MODE=1  X1 IS AGE,X2 IS SITE INDEX, RESULT IS DOMINANT HEIGHT
C MODE=2  X1 IS AGE, X2 IS HEIGHT, RESULT IS SITE INDEX
C MODE=3  X1 IS HEIGHT,X2 IS SITE INDEX, RESULT IS AGE
      REAL B(4,3)
      DATA B/
     1   3.47996, -11.7156, 0.0084674, 0.133712,
     2  3.54380, -14.3113, 0.0166401, 0.147441,
     3  3.60684,-17.5132,0.0080572, 0.330819/
      C1=B(1,NS)+B(2,NS)/15.0
      C2=B(3,NS)+B(4,NS)/15.0
      GOTO(1,2,3),MODE
    1 A=X1
      S=(ALOG(X2)-C1)/C2
      HTF=EXP(B(1,NS)+B(2,NS)/A+B(3,NS)*S+B(4,NS)*S/A)
      RETURN
    2 H=X2
      A=X1
      HTF=EXP(C1+C2*((ALOG(H)-B(1,NS)-B(2,NS)/A)/
     1    (B(3,NS)+B(4,NS)/A)))
      RETURN
    3 H=X1
      S=(ALOG(X2)-C1)/C2
      HTF=(B(2,NS)+B(4,NS)*S)/(ALOG(H)-B(1,NS)-B(3,NS)*S)
      RETURN
C           *LON
      END
```

```
      SUBROUTINE GROW(AGEINT,HDOM,STK,SV,NSP)
      DIMENSION SV(10)

      REAL A(3,3),B(6,3),C(3)
C GROWS STAND TABLE USING INDIVIDUAL TREE INCREMENT AND MAXIMUM
C BASAL AREA LIMITING FACTOR
C
C A IS BASAL AREA INCREMENT COEFFICIENT MATRIX
C B IS    DIAMETER  INCREMENT    "         "
       DATA A/
     1 63.9,-0.1219,2.551,
     2 86.3,-0.03382,1.198,
     3 67.8,-0.1292,2.597/
       DATA B/
     1 0.1812,2.936,-0.2054,0.1477,0.1100,-0.0894,
     2 0.0,1.008,-0.1532,0.1629,0.0948,-0.0854,
     3  0.18,3.5,-0.2306,0.1492,0.1478,-0.1112/
       DATA C/18.2,27.4,23.6/
COMPUTE CURENT BASAL AREA
       BA=0.0
       DO 1 I=1,10
    1  BA=BA+SV(I)**2
       BA=BA*STK/10.0*0.00007854
COMPUTE DOMINANT HEIGHT
       DMAX=DDOM(STK,SV)
COMPUTE LIMITING BASAL AREA
       GMAX=A(1,NSP)*(1.0-EXP(A(2,NSP)*HDOM))**A(3,NSP)
       GAMMA=1-BA/GMAX
       BA1=0.0
       DO 2 I=1,10
COMPUTE DIAMETER INCREMENT AND ADD TO TABLE
       J=11-I
       RDOM=SV(J)/DMAX
       IF(RDOM.GT.1.2)RDOM=1.2
       DINC=B(1,NSP)+B(2,NSP)*EXP(HDOM*(B(3,NSP)+
     1      B(4,NSP)*RDOM+B(5,NSP)*GAMMA+B(6,NSP)*RDOM*GAMMA))
       SV(J)=SV(J)+DINC*AGEINT
    2  BA1=BA1+SV(J)**2
       BA1=BA1*STK*0.00007854*0.1
CHECK IF MAXIMUM BASAL AREA EXCEEDED; IF SO,ADJUST DIAMETERS

       IF(BA1.LE.GMAX)RETURN
       IF(HDOM.LT.15.0)RETURN
       RATIO=SQRT(GMAX/BA1)
       DO 3 I=1,10
    3  SV(I)=SV(I)*FATIO
       RETURN
       END
```

```
      SUBROUTINE TABVOL(TF,TD,NSP,HDOM,VOLUME)
COMPUTES VOLUMES IN 4 CLASSES FOR A TABLE OF FREQUENCIES
C AND DIAMETERS TF AND TD FOR SPECIES NSP AND STAND OF DOMINANT
C HEIGHT HDOM
      DIMENSION TF(11),TD(11),VOLUME(6)
      COMMON/VLIM/DMIN(3,4),HMIN(3,4)
CLEAR VOLUME SUM ARRAY
      TOTVOL=0.0
       DO 1 I=1,6
    1 VOLUME(I)=0.0
CYCLE THROUGH CLASSES IN DIAMETER TABLE
      DO 2 IC=1,11
CLASSES WHICH ARE EMPTY ARE SKIPPED
      IF(TF(IC).LE.0.0 .OR. TD(IC).LE.0.0)GOTO2
COMPUTE VOLUME OF CLASS WITH WHOLE TREE TABLE
      DBH=TD(IC)
      CALL TREVOL(DBH,HDOM,VOB,VUB,NSP)
      TOTVOL=TOTVOL+VOB*TF(IC)
C SOLVE FOR HEIGHT ASSUMING FORM FACTOR OF 0.5
      HEIGHT=VOB/(DBH**2*0.00007854*0.5)
      HZERO=0.15
      DO 7 IM=1,4
C SOLVE FOR HEIGHT AT MINIMUMDIAMETER FOR THIS CLASS
C SKIP IF THIS CLASS IS NOT USED
      IF(DMIN(NSP,IM).LE.0.0)GOTO7
      D=DMIN(NSP,IM)
      A=HZERO
      B=HEIGHT
      IF(B-A.LT.HMIN(NSP,IM))GOTO7
      DO 8 I=1,15
      H=(A+B)*0.5
      DD=TAPER(HEIGHT,DBH,H,NSP)
      DIFF=DD-D
      IF(DIFF)11,10,9
    9 A=H
      GOTO8
   11 B=H
    8 CONTINUE
   10 CONTINUE
C TEST WHETHER SECTION LENGTH IS LESS THAN SPECIFIED MINIMUM
C IF IT IS, INCLUDE THIS VOLUME WITH NEXT CLASS
C OTHERWISEADD IT TO VOLUME FOR CURRENT CLASS AND INCREASE HZERO
      IF(H-HZERO.LT.HMIN(NSP,IM))GOTO7
      VV=VOLINT(HEIGHT,HZERO,DBH,H,NSP)
      VOLUME(IM+1)=VOLUME(IM+1)+VV*TF(IC)
      HZERO=H
    7 CONTINUE
C AFTER LAST CLASS ADD RESIDUAL VOLUME TO WASTE COUNTER
      VOLUME(6)=VOLUME(6)+VOLINT(HEIGHT,HZERO,DBH,HEIGHT,NSP)*TF(IC)
    2 CONTINUE
COMPUTE TOTAL VOLUME AS SUM OF OTHERS
      DO 12 I=2,6
   12 VOLUME(1)=VOLUME(1)+VOLUME(I)
      RATIO=TOTVOL/VOLUME(1)
      DO 13 I=1,6
   13 VOLUME(I)=VOLUME(I)*RATIO
      RETURN
      END
```

```
      FUNCTION TAPER(HEIGHT,DBH,H,NSP)
COMPUTES DIAMETER AT HEIGHT H GIVEN SPECIES SPECIFIC TAPER COEFFICIENTS
      DATA TWOPI/6.283185207/
      HR=(HEIGHT-H)/(HEIGHT-1.3)
      T=DBH**2*(HR**2+0.0625*(COS(TWOPI*HR)+1.0))
      IF(T)1,1,2
    1 TAPER=0.0
      RETURN
    2 TAPER=SQRT(T)
      RETURN
      END
```

```
      FUNCTION VOLINT(HEIGHT,HZERO,DBH,HT,NSP)
COMPUTES INTEGRAL OF TAPER FUNCTION AS TREE VOLUME BETWEEN HEIGHT
C LIMITS HZERO TO H
      DATA TWOPI/6.283185207/
      REAL V(2)
      H=HZERO
      K=1
    1 HR=(HEIGHT-H)/(HEIGHT-1.3)
      V(K)=HR**3/3.0+0.0625*(SIN(TWOPI*HR)/TWOPI+HR)
      GOTO(2,3),K
    2 K=2
      H=HT
      GOTO1
    3 VOLINT=HEIGHT*DBH**2*0.00007854*(V(1)-V(2))
      RETURN
      END
```

```
      SUBROUTINE TREVOL(D,H,VOB,VUB,K)
      GOTO(1,2,3),K
C  CUPRESSUS
   1  VOB=-0.017326+0.0001937*D*D+0.00005069*D*H+0.00002296*D*D*H
  11  C=0.875+0.001781*D-0.000014*D*D
      GOTO 20
C  RADIATA
   2  VOB=-9.81889+2.0598*ALOG(D)+0.7875*ALOG(H)
      VOB=EXP(VOB)
  12  C=0.906
      GOTO 20
C  PATULA
   3  VOB=-0.007224+0.00002887*D*D+0.00002077*D*H+0.000032765*D*D*H
  13  C=0.911
      IF(D.GE.58.)GOTO 20
      C=0.80595+0.003704*D- 0.00003255*D*D
  20  CONTINUE
      IF(VOB.LT.0.0)VOB=0.0
      VUB=C*VOB
      RETURN
      END
```

```
      SUBROUTINE THIN(STK,SV,FL,TF,TD)
      DIMENSION SV(10),TF(11),TD(11),PA(11),D(11)
C DETERMINE THINNING DISTRIBUTIONS COEFFICIENT
      C=1.0/FL-1.0
C MAXIMUM DIAMETER
      PA(11)=1.0
      D0=2.0*SV(1)-SV(2)
      TD(1)=(D0+SV(1))/2.0
      D(11)=2.0*SV(10)-SV(9)
C SAVE OLD DIAMETERS
      DO 6 I=1,10
    6 D(I)=SV(I)
      DO 1 I=1,10
      I1=I+1
    1 TD(I1)=(D(I)+D(I1))/2.0
C AFTER THINNING PERCENTILES & THINNING FREQUENCIES
      C1=C+1.0
      C2=1.0/C1
      TF(1)=STK*(0.05-C2*0.05**C1)
      DO 2 I=1,10
      I1=I+1
      P=0.05+(I-1)*0.1
    2 PA(I)=C2*P**C1/FL
      PI=0.1
      DO 22 I=1,10
      I1=I+1
      IF(I.EQ.10)PI=0.05
      TF(I1)=STK*(PI-FL*(PA(I1)-PA(I)))
   22 CONTINUE
C INTERPOLATE NEW DIAMTERS
      I=1
      K=0
    3 K=K+1
      K1=K+1
    5 P=0.05+(I-1)*0.1
      IF(PA(K1).LT.P)GOTO3
      SV(I)=(P-PA(K))/(PA(K1)-PA(K))*(D(K1)-D(K))+D(K)
      I=I+1
      IF(I.LT.11)GOTO5
      STK=STK*FL
      RETURN
      END
```

```
      FUNCTION DDOM(STK,SV)
      DIMENSION SV(10)
      PCNT=10000.0/STK
      NC=11-INT(105.0-PCNT)/10
      IF(NC.GT.10)NC=10
      IF(NC.LT.1)NC=1
      D=0.0
      DO 1 I=1,NC
      K=11-I
    1 D=D+SV(K)
      D=D/NC
      DDOM=D
      RETURN
      END
```

```
      SUBROUTINE CUT(HDOM,STK,NSP,SV,F,VOLUME)
      DIMENSION SV(10),VOLUME(6),TF(11),TD(11)
C PERFORMS SIMULATED THINNINGS AND CLEAR FELLING
      IF(F.LT.0.01)GOTO10
C THINNING
      CALL THIN (STK,SV,F,TF,TD)
      GOTO20
CLEAR FELLING
   10 S=STK/10.0
      DO 11 I=1,10
      TD(I)=SV(I)
   11 TF(I)=S
      TF(11)=0.0
      TD(11)=0.0
      STK=0.0
COMPUTE VOLUME OF REMOVALS
   20 CALL TABVOL(TF,TD,NSP,HDOM,VOLUME)
      RETURN
      END
```