An analysis of correlated curve trend experiments in *Eucalyptus grandis*

by

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(ABSTRACT)

Correlated curve trend (C.C.T.) experiments in *Eucalyptus grandis* on the Zululand coast of South Africa were analyzed. Growth parameters were described as functions of age using Schnute's generalized growth function and parameter estimates were described as functions of stand density. Growth attributes were used as moments of a probability density function to describe a diameter distribution model for the species. Time trends in the relationships between growth parameters and stand density were scrutinized with multiple comparisons of paired means. It was shown that diameter growth in lower size classes ceases under conditions of extreme suppression while growth continues unabated in the larger size classes, resulting in greater dispersion in diameter. Competition mortality was to a large extent confined to the lower size classes and severe mortality results in an apparent increase in mean diameter which precludes use of growth functions which impose an asymptote. Allometric growth was investigated on two different sites and growth trends were shown to be anamorphic between sites. This permits a ratio approach to the estimation of growth and yield on one site based on experimental evidence from another. Thinning effects in terms of diameter and height changes were estimated from simulated thinnings using data from unthinned stands while the results of long-term thinning studies were compared in terms of cumulative volume yields. The age at which mean annual increment culminates was determined and a model for the estimation of m.a.i. as a function of age and stand density was constructed. A critical examination of spacing indices revealed that the slopes thereof were much steeper than those for many other species. The better-known indices of Reineke and Yoda were found to be dependent on age.

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During our sojourn in America, the home fires were kept burning by .
Without her devotion, life would have been so much harder. I was also helped by many South African foresters in various ways. I wish in particular to thank and . Among those who shall unfortunately remain nameless are those who planned, planted and maintained the Langepan and Nyalazi experiments, particularly those who had to do the extensive measuring work through the life of these stands.

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Chapter I

Introduction

South Africa was very poorly endowed with natural forests. As the population of the country expanded following colonization, the demand for timber increased to the detriment of what little forest there was. The advent of railroads and the discovery of gold in the Transvaal led to the severe over-utilization of the available resources. The patches of indigenous forest were then supplemented by plantations of exotic conifers, particularly Mexican and southern pines, and hardwoods of the genera *Eucalyptus* and *Acacia*.

Currently there is no exploitation of natural forest remnants. These are managed solely for conservation purposes with harvesting confined to dead and moribund trees. The country relies on plantation forestry for its supply of both hardwood and softwood timber. In this context, *Eucalyptus grandis* today has a greater commercial importance than any other hardwood on the southern subcontinent of Africa. There are some 297 695 ha. planted to *E. grandis* in South Africa alone (anon. 1987). This represents about

78% of eucalypt plantations or about 26% of the total afforested area in the country. Only 21 222 ha. or 7.1% of the *E. grandis* is in public ownership. Half of the *E. grandis* occurs in the province of Natal which includes the Zululand forestal region where the experiments described herein are situated (See Figure 1 on page 4.).

The more important aims of production in terms of hectares allocated to the species are mining timber (47.3%), pulpwood (38.6%), sawtimber (8.2%) and poles (5.4%). Annual sales are approximately 480 000 m^3 sawtimber and veneer logs, 190 000 m^3 poles, 1.6 million tonnes[1] mining timber and 1.9 million tonnes pulpwood. An age-class distribution for the country is shown in Table 3 on page 108. *E. grandis* has been planted in South Africa since before the beginning of this century, but, during those pioneering days of the South African forest industry, the species was known as *E. saligna.* It is thus often referred to colloquially as either "grandis" or "saligna", the latter in particular being used by tradesmen. The controversy surrounding the name has been described by Poynton (1979).

Even in recent times the species was denoted as saligna/grandis on stock maps and similar documents as the two species are such close allies as to be indistinguishable to the untrained observer. Foresters also have difficulty discriminating between the two (Marsh, 1957) despite the fact that identification is simple on morphological grounds, based on the degree of protrusion of valves from the capsules. A view of the tree itself, from any distance, is inadequate for identification but *E. grandis* usually exhibits the better stem form of the two. Older stands may consist of mixtures or include morphological variants or intermediate forms of the two species (Poynton, 1979).

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[1] Metric ton or 1000 kg.

E. grandis is a native of Australia, in particular of New South Wales and Queensland. The latitude over which the range can be considered continuous is from 29° S to 33° S.

Early imports of seed from Australia were not only of the "incorrect" species, the precise localities from which the seed was collected was not known (Poynton, 1979) and this situation endured until the beginning of the Second World War. In recent times much greater care has been taken of such matters and it is now known that certain provenances, such as that from Coff's Harbour, perform consistently better than others. There has also been a major tree breeding effort for the species. However, the establishment of the experiments in Zululand upon which this study is based precede the genetic improvement program.

The people concerned with the early plantings of exotic species were of European descent and the plantations were established according to criteria based on their experience. It soon transpired that their concepts of rotation length and management regimes were not suited to local conditions and experimentation was initiated. The experimentation was uncoordinated and the results lacked generality.

In order to rectify this situation, Alexander James O'Connor conceived the so-called correlated curve trend (C.C.T.) experiments. His aim was to "devise a system of research which, while involving the use of only a limited number of plots, will yield, for a given locality and species, all the information required for a complete exposition of the effects of the development of trees of the growing space provided for them." (O'Connor, 1935).

In all, twenty seven experiments in ten species were planted, starting with *Pinus patula* and *P. roxburghii* at Weza in November, 1936. During two years, nineteen of the C.C.T.

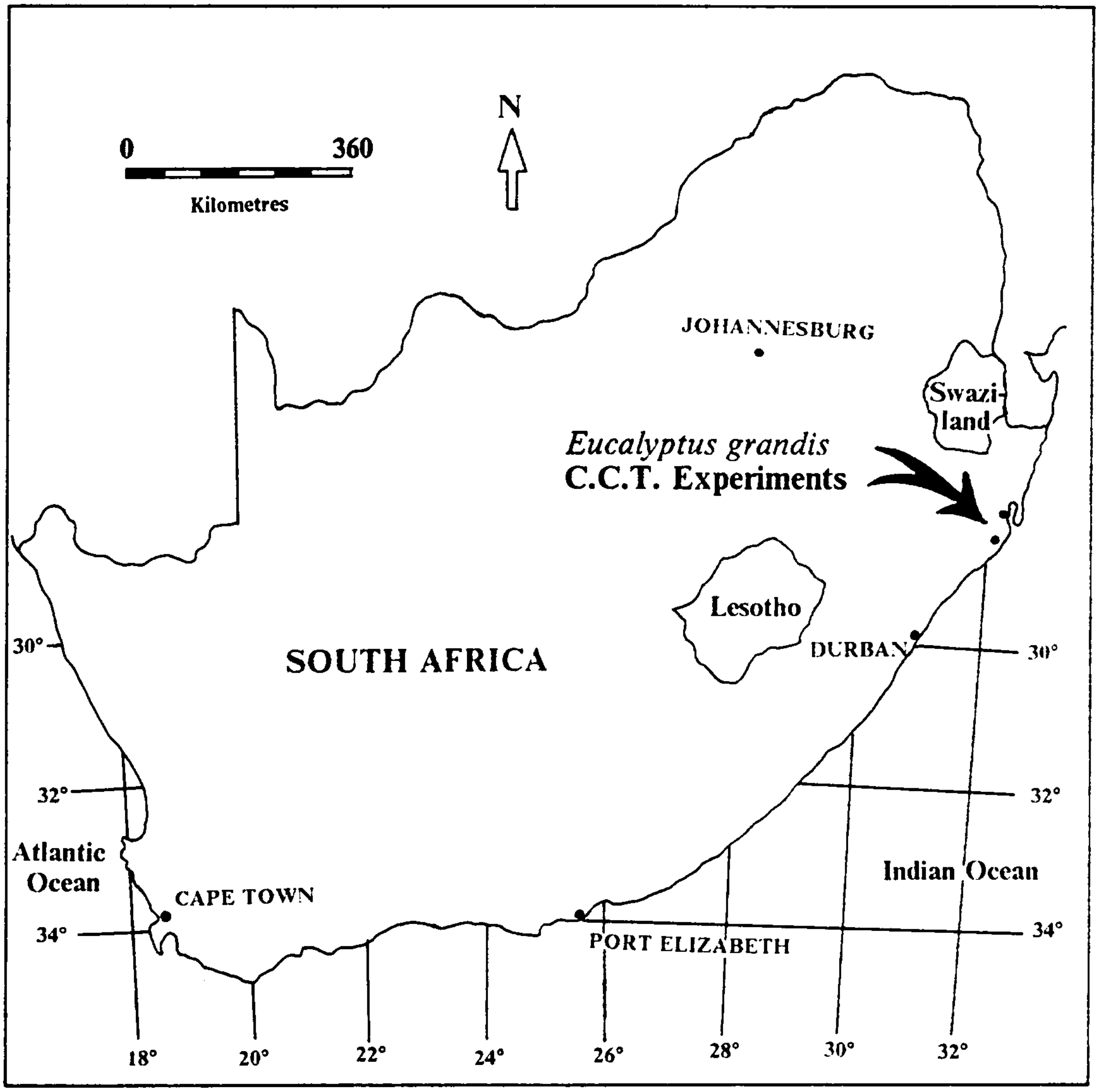

Figure 1. Locality map: Position of C.C.T. experiments in relation to South Africa.

experiments were planted.[2] The tremendous investment in manpower required by the C.C.T. experiments later brought them into disfavor and subsequent spacing research was based on the clinal designs using polar coordinate grids advocated by Nelder (1962).

The C.C.T. experiments in *E. grandis* with which this study is concerned are situated on the coastal plain of Zululand (Figure 1 on page 4), along the eastern seaboard of South Africa. There are three replications of a C.C.T. experiment at Langepan on KwaMbonambi State Forest (32^{0} 13′ E, 28^{0} 16′ S) and a further single experiment at Nyalazi State Forest (32^{0} 23′ E, 28^{0} 12′ S). The former was planted in the spring of 1952 and the latter in 1957. Nyalazi is considered to be a far poorer site for *E. grandis* than KwaMbonambi. There are no further C.C.T. experiments in *E. grandis* or other hardwoods at present.

The origin of the seed for the C.C.T. experiments is unknown. It is known that the plants for the Langepan trial were raised in a nursery at Port Durnford State Forest and those for Nyalazi at Dukuduku State Forest. The stock used at Langepan is superior to that used at Nyalazi where there is a wide variety of morphological characteristics atypical of *E. grandis.*

E. grandis is very susceptible to frost when young. Even though it can withstand light frost once the pole stage has been reached, the incidence of frost is the most important factor in the planting of the species. Along the coast it is susceptible to salt scorch which damages the crowns while seldom causing death.

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[2] Details of all the C.C.T.'s planted have been provided by Bredenkamp (1984a).

The best months for planting *E. grandis* are generally November to March although in Zululand the cooler months of May to June are better. Most *E. grandis* plantations, however, are regenerated by means of coppice. This technique is, of course, unsuitable for thinned stands. Fertilization produces excellent results and application at time of planting is highly recommended. Various application rates and mixtures of fertilizers have been recommended (Schönau and Stubbings, 1987). Complete weed control, particularly of grasses, is of utmost importance in the establishment of eucalypts. Standard management regimens prescribe planting at 1200 stems per hectare (S/ha) with clearfelling ages ranging from 6 or 7 years for mining timber to more than 20 years in sawtimber stands (Loveday, 1987).

South Africa is relatively arid. The annual rainfall averages 464 mm but 21% of the country gets less than 200 mm *per annum* (p.a.). Commercial forestry is restricted to the higher rainfall areas and hardwood production particularly so. The Langepan experiment is situated in the humid zone, and the Nyalazi experiment in the subhumid zone, of the summer rainfall region, as defined by Poynton (1962). The annual rainfall at Langepan is approximately 1400 mm. The annual distribution thereof is shown in Figure 4 on page 134. During an abnormally dry year in 1959, rainfall of 978.4 mm was measured, the lowest on record, but it nevertheless represented 67% of the mean. By contrast the maximum rainfall on record was 2166.5 mm and fell during 1956. There is no sharp differentiation between wet and dry seasons. The rainfall from October to April is fairly constant and accounts for 70% of the annual precipitation. Rainfall is cyclonic and severe lightning storms occur.

The warm Mozambique current flowing down the eastern coast has a stabilizing influence on temperature and the range is small. The mean annual temperature is 21.8 °C, the warmest month is January with a mean maximum of 30.9 °C and the coolest month is June with a mean minimum of 11.9 ° C. Frost is a newsworthy event (Bredenkamp, 1980). A tabular summary of some of the more important climactic factors appears as Table 4 on page 109. The seasonal distribution of rainfall is represented in a Walter (1961) diagram in Figure 5 on page 135. This method is used to indicate limiting periods of precipitation and temperature for plant growth. No evidence of such limiting factors is indicated for Zululand at any stage.

The altitude of the Langepan experiment is about 60 m. above mean sea level while that of Nyalazi is about 43 m. For all practical purposes both experiments are situated equidistant from the Indian Ocean. In the case of Langepan, the land between it and the sea is occupied by a narrow strip of pine plantation, but chiefly by open grassland. The coastal dune is covered with near-climax indigenous *Acacia* forest. Nyalazi on the other hand is separated from the sea by a strip of pine forest and Lake St. Lucia while the coastal dunes are, to a large extent, covered with *P. elliottii* and *P. caribaea* plantations.

The coastal plain is particularly flat and there are no outstanding topographical features. The plain itself is an elevated marine platform which consists essentially of a thick deposit of wind-borne sand underlain by almost horizontal Cretaceous to Recent beds which dip slightly seawards. There are strong indications that the sands have been deposited at intervals and not during a geologically short period. Stratified parent material along the coast is the result of alternating dry and wet cycles during the Quarternary.

The parent material at the experimental sites is a loose drift sand underlain by finer texture sands. According to the South African binomial classification the soil would be a Fernwood series of Fernwood form. The equivalent USDA classification would be a Quartzipsamment while it would be named a Dystric Rhegosol under the the FAO system. A soil profile description is provided as Table 5 on page 110. Details of a soil analysis appear as Table 6 on page 111.

Essentially the sands are very acidic, of extremely low fertility and with little or no horizon development. Due to wind transportation the soils consist largely of medium sand (0.1 to 1.0 mm) with no coarse or fine sand and very little silt or clay. There is a general absence of coarse material in the form of stones or boulders. Little or no weathering takes place due to the paucity of weatherable minerals in the sand and as a rule leaching does not result in the formation of accumulation zones. There are however occasional iron-concretionary layers indicating temporary groundwater and impeding clayey layers.

The soil is poor in organic matter due to rapid decomposition resulting from the moist subtropical climate and the aerobic condition of the surface soils. It is covered by the litter of the last six to eighteen months only, depending on the density of the canopy. Generally the organic matter content is less than 1%.

The moisture storage capacity of the soil is very low. Field capacity is to the order of 3.3%. The wilting point determined at -15 ATM is 2%, this being the classic expression which has no bearing specifically on the growth potential of *E. grandis*. Fortunately for the forest industry, this shortcoming is moderated by great soil depth.

The goal of this study was an analysis of the experiments introduced above, the details of which are described in detail in *Chapter III*. The specific objectives were:

1. to produce a diameter distribution model for plantation grown monocultures of *E. grandis* based on stand density in terms of stems per hectare (S/ha).

2. to investigate the influence of stand density on growth parameters.

3. to investigate changes in diameter distribution under conditions of extreme suppression. Under conditions of advanced competition-mortality there is a surge in quadratic mean diameter growth which may be attributable to a disproportionate degree of mortality in the smaller diameter classes and not to an increase in diameter growth of individual trees.

4. to ascertain the age of culmination of stand volume increment and the implications thereof to forest management.

5. to determine the validity of Reineke's stand density index (Reineke, 1933), Yoda's law of self-thinning (Yoda *et al*, 1963) and other empirical relationships to describe stand growth of *E. grandis*, including O'Connor's S-curve postulation for the C.C.T. experiments.

Chapter II

Literature review

The data on which this study is based emanate from spacing experiments of a particular design; the aim of the study was to produce a diameter distribution yield model for a particular species and to investigate the suitability of criteria for the quantification of stand density for that species. The literature survey therefore covers three topics:

1. C.C.T. experiments and the modeling of *E. grandis*

2. diameter distribution models

3. spacing indices

The spacing indices covered in the survey are those of Reineke and Yoda together with relative spacing.

C.C.T. experiments and modeling of E. grandis

A review of publications concerning the C.C.T. experiments in South Africa up to late 1983 was presented by Bredenkamp (1984a). Although over one hundred papers published at that stage dealt with, or had reference to, the C.C.T.'s (to a greater or lesser extent), only a few dealt with *E. grandis*.

The first work presenting results of the *E. grandis* C.C.T. experiments was that of Burgers (1976) who presented graphs showing the development of mean height and diameter over time for the full range of stand densities included in the experiments. The sets of curves were provided in smoothed form and original data were not presented. The curves had been hand-fitted and parameter estimates were not available.

Several candidate growth functions for the description of *E. grandis* growth up to the age of twenty two years were compared by Bredenkamp (1977). Richards' (1959) function was found most suitable; the function can be written as

$$Y_t = A\,(1 - \beta\, e^{-k\,t})^{1/(1-m)} \tag{1}$$

where t is age.

Richards' function was fitted by the method developed by Stevens (1951). It then takes the form

$$Y_t = \alpha + \beta\, \gamma^t \tag{2}$$

Use of this method precludes the estimation of m in the Richards function above but the function was nevertheless found to be eminently suited for the description of basal area growth, diameter development, mean height development and stand volume growth of unthinned stands. The growth of unthinned stands of *E. grandis* was simulated in a deterministic model without any provision for silvicultural treatments, mortality or site differences. The model performed very poorly when attempts were made to estimate growth under conditions of advanced suppression.

The estimation of m through iterative techniques and graphical determination of minimal sum of squared deviations for the same *E. grandis* data was described by Van Laar and Bredenkamp (1979). It was shown that, in the description of basal area growth, m is non-zero only for widely spaced plantations although in the case of mean dbh $m = 0$ for all stand densities. Diameter growth could thus be adequately modeled with an equation having only three parameters while caution had to be exercised with direct basal area prediction for wider spacings. The relationships between crown diameter and stand density in the Langepan *E. grandis* C.C.T. experiment as well as that between crown length and stand density were also investigated and were described with linear equations.

In both Bredenkamp (1977) and Van Laar and Bredenkamp (1979), the development of growth parameters over age was modeled and sets of curves were then smoothed by recovery of parameter estimates from their relationship with nominal stand density. In order to obviate the problems with the estimation of m , Bredenkamp (1983) used linear equations to model growth parameters against stand density independently for each enumeration of the C.C.T. experiments and then recovered the parameter estimates from their relationship with time. Validation showed some trends for dbh and height produced by resultant sets of equations which were not supported by the data, but these were not evident in the response of volume. The discrepancies having been masked by the pronounced effects of stand density and age on mean tree volume.

Growth of thinned stands of *E. grandis* can be estimated from the growth of an unthinned stand of the same density (Burgers, 1971, Bredenkamp, 1982b). The technique is based on the assumption that growth over a specified size interval is equivalent, irrespective of whether that size was reached via thinning or not. What is of prime importance is the age of the stand and the fact that a thinning is assumed to have a rejuvenating effect, resulting in accelerated growth. Growth of *E. grandis* on one site can be adequately estimated based on a proportion of the height growth and volume production on another, thus assuming an anamorphic relationship (Bredenkamp, 1982b). Diameter estimates are derived from the volume and height predictions after weighting. A worked example to demonstrate the practical application of these techniques was presented by Bredenkamp (1984b).

The equations developed to model the growth of unthinned *E. grandis* stands (Bredenkamp, 1977), manipulations to simulate thinning effects and a weighting technique to calibrate model predictions for sites of differing growth potential (Bredenkamp, 1982b, 1984b) were put together in a simulation program written in BASIC (Bredenkamp, 1986). The simulation is at stand level and predicts stand mean diameter and mean stand height only. There is no provision for mortality or estimation of spread of size classes.

Two different approaches to modeling mortality in *E. grandis* were taken by Bredenkamp (1988). The first made use of an analytically derived model developed by Clutter and Jones (1980). The model, which predicts survival, is

$$S_2 = \left[S_1^{b_{00}} - b_{01}\left(A_2^{b_{02}} - A_1^{b_{02}}\right)\right]^{1/b_{00}} \tag{3}$$

where:-

S_2 = stand density surviving at age A_2

S_1 = stand density surviving at age A_1

A_2 = age for which estimate of survival is required

A_1 = age for which previous estimate of survival is known

b_{xx} = parameters estimated[3]

A second empirical model used was

$$S_a = b_0 + b_1 A^2 + b_2 A^{-1} + b_3 A^{-2} \tag{4}$$

The coefficients of this equation were modeled as segmented functions of nominal stand density with a specified join point as

$$b_0 = \begin{cases} S_n e^{b_{197} S_n} \ for \ S_n > S_j \\ S_n \ elsewhere \end{cases} \tag{5}$$

$$b_1 = \begin{cases} b_{198}(S_n - S_j) + b_{199}(S_n - S_j)^2 \ for \ S_n > S_j \\ 0 \ elsewhere \end{cases} \tag{6}$$

$$b_2 = \begin{cases} (S_n - S_j)^{b_{200}(S_n - S_j)} \ for \ S_n > S_j \\ 0 \ elsewhere \end{cases} \tag{7}$$

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[3] All parameter estimates denoted as b_{xx} are provided in Table 24 on page 129 through Table 27 on page 132.

$$b_3 = \begin{bmatrix} b_{201}(S_n - S_j) + b_{202}(S_n - S_j)^2 \ for \ S_n > S_j \\ 0 \ elsewhere \end{bmatrix} \tag{8}$$

where:-

S_a = stand density surviving at age A (S/ha)

S_n = nominal stand density (S/ha)

S_j = stand density at join point (S/ha)

e = base of natural logarithms

The Chapman-Richards function (Pienaar and Turnbull, 1973) was found to be insufficiently flexible to model the continued diameter growth of certain treatments in the *E. grandis* C.C.T. experiments by Bredenkamp and Gregoire (1988). Once a large proportion of trees had succumbed from competition-induced mortality in overstocked stands, there was an apparent flush of renewed diameter growth. This was adequately modeled with a more flexible generalized growth function developed by Schnute (1981).

Diameter distribution models

Diameter distributions are modeled empirically or as a probability density function (p.d.f.) of unimodal distributions where the parameters are estimated from stand attributes. A wide variety of probability density functions have been used with greater or lesser success in modeling diameter distributions. In recent decades the emphasis fell on the beta, Johnson's S_B and Weibull p.d.f.'s and these have all been successfully used in a wide variety of applications. In particular, since Bailey and Dell (1973) showed how well diameter distributions can be fitted by the Weibull function, and the cumulative density function thereof exists in closed form, the Weibull p.d.f. is the most frequently used diameter distribution function. It is not used to the exclusion of other distributions however. A bivariate distributional approach was taken by Hafley, Smith and Buford (1982) and Hafley and Buford (1985) in which the Johnson's S_{BB} distribution was used to recover information about both the diameter and height distributions of unthinned *P. taeda* stands.

The Weibull p.d.f. can be written as

$$f(x) = (c/b)[(x-a)/b]^{c-1}e^{-[(x-a)/b]^c} \tag{9}$$

where

a = location parameter, ≥ 0

b = scale parameter, > 0

c = shape parameter, > 0

x = random variable of interest (diameter), $\geq$ a

One of the reasons for the popularity of the Weibull distribution is that it is sufficiently flexible in terms of shape that it can accommodate almost all forms required for a diameter distribution. Skewness is determined by the parameter c. When $c = 3.6$ the distribution is symmetrical, when $c < 3.6$ the distribution is positively skewed and when $c > 3.6$ it is negatively skewed. A value for c less than one results in a reverse J-shaped curve (Bailey and da Silva, 1986).

The equation above is the three parameter form of the Weibull density. If one lets Z = x - a, the two parameter Weibull density is obtained. This reduced form is useful when moment-based systems of equations result in convergence problems (Burkhart, Knoebel and Beck, 1983). The two parameter form can be written

$$P(X - x) = e^{-(\frac{x}{b})^c} \tag{10}$$

(Amateis, Burkhart and Burk, 1986)

The cumulative distribution function (c.d.f.) for the Weibull distribution is

$$\begin{aligned} F(X) &= 1 - e^{-(\frac{x-a}{b})^c} \qquad && (a \leq X < \infty) \\ &= 0, && otherwise \end{aligned} \tag{11}$$

Therefore F(X) is the proportion of trees per unit area having diameters less than or equal to X. The proportion of a population with values greater than a lower limit L and less than an upper limit U is thus

$$P(L < X < U) = e^{-[(U-a)/b]^c} - e^{-[(L-a)/b]^c} \tag{12}$$

There is no upper limit on the random variable X in the Weibull p.d.f. and there will always be a small probability in association with an upper tail. A truncation rule advocated by Clutter *et al* (1983) is to nullify the first upper-tail class with a frequency less than 0.5, together with all classes above that, and adjust the frequency of the next smallest class to obtain a cumulative frequency equal to the total number of trees.

Expected yields can be obtained from diameter distributions with a class-interval-free method developed by Strub and Burkhart (1975). The yields per unit area are calculated as

$$V = N \int_L^U g(D)\, f(D)\, dD \tag{13}$$

where

V = volume per unit area

N = stems per unit area

D = dbh

$g(D)$ = volume equation for individual trees

$f(D)$ = probability density function for D

(L,U) = product merchantability limits

Attributes predicted from a whole stand model were used to solve for the parameters of the diameter distribution probability density function by Hyink (1980), making use of the relationship given by the class-interval-free equation. This brought about consistency between stand yield estimates based on whole stand models and diameter distribution based models. Both the beta and Weibull probability density functions were used by Frazier (1981) to approximate diameter distributions of unthinned plantations. Convergence problems were encountered and problems with illogical crossovers caused by independent estimation of moments were avoided by predicting the logarithm of the variance of the moments. The second moment was then obtained algebraically via the first moment and the coefficient of variation.

The Weibull, lognormal and S_B distributions were evaluated by Green (1981) for the estimation of the marginal distribution of the parameters of a basal area growth function. The Weibull proved to be considerably better than the others.

Diameter distributions of thinned plantations were described with the Weibull function by Bailey, Abernethy and Jones (1980) and by Matney and Sullivan (1982a, 1982b), using the concepts described by Frazier (1981).

If a Weibull probability distribution function is used to model the diameter distribution of a stand, the distribution can be projected to a successive interval by use of the following nonlinear relationship (Bailey, 1980a).

$$X_2 = b_0 + b_1(X_1 - b_2)^{b_3} \tag{14}$$

where X_i is diameter at time i.

A three parameter Weibull distribution was used by Frazier (1981) to obtain a stand diameter distribution prior to first thinning. The diameter distribution is then grown through application of a transformation that regenerates untruncated and truncated Weibull distributions. In essence the location parameter is adjusted according to the percentage increase in the root quadratic mean diameter produced by the thinning. The rate and slope parameters are then recovered. Thinning from below results in a left truncated Weibull which can be written as

$$f_a(x) = f_0(x)/[1 - F_0(a_t)] \tag{15}$$

By definition the left truncated Weibull is

$$f(x) = cb^{-1}[(x-a)/b]^{c-1}e^{-[(x-a)/b]^c + [(a_t-a)/b]^c} \tag{16}$$

The number of trees below a tally limit were predicted with a logit model by Burk and Burkhart (1984). A three-parameter, left-censored Weibull distribution as described by Zutter *et al* (1982) was then fitted to the diameter data using the method of moments, having conditioned the arithmetic mean dbh ($\overline{D}_a$) equation such that $\overline{D}_a < \overline{D}_q$. The location parameter was found from $\overline{D}_q$ and basal area with an equation defined to be always positive. The left-censored Weibull can also be written

$$f(x) = (c/b)\,(x/b)^{c-1} e^{(t/b)^c - (x/b)^c} \tag{17}$$

where t = left truncation point. Examples of the p.d.f. and c.d.f. for 2 and 3 parameter, left, right, as well as left and right truncated distributions are provided by Zutter *et al* (1982).

The Johnson S_B was shown by Hafley and Schreuder (1977) to be consistently better than a number of well-known p.d.f.'s for the description of diameter distributions. The Johnson S_B p.d.f. was also found to outperform the Weibull in the description of heavy-tailled diameter distributions of *P. patula* (Von Gadow, 1987).

There is a drawback to the S_B in the lack of a closed form expression of the c.d.f. but as the distribution is a transformation of the standard normal it is easy to obtain the proportion of trees in a specified diameter class from a standard normal table.

A two-stage procedure using a left truncated Weibull function for thinned stands was introduced by Cao, Burkhart and Lemin (1982). The aim was to search for parameters of the Weibull such that resulting stand basal area and mean dbh estimates were in agreement with stand variables predicted from regression equations.

The Weibull was found to be insufficiently flexible for the modeling of thinned stands by Cao (1983). Functions in the form of a modified Weibull c.d.f. were joined together to form a segmented c.d.f. Five percentile points were used to determine the c.d.f. and care was taken to ensure continuity of the function at the join points as well as continuity of the derivative of the function at the join points. This allowed the addition of row, low and selection thinnings to the model in use as well as a combination of the options, different methods being applied sequentially. Logical results were obtained. A similar approach was taken by Cao and Burkhart (1984) who modeled thinned pine plantations using a segmented Weibull cumulative distribution to derive empirical diameter distributions from predicted stand attributes. In the case of unthinned stands there was no advantage in use of the segmented c.d.f. over the three-parameter Weibull distribution but the segmented c.d.f. is very flexible and was found to be superior in the case of thinned stands. It was thus recommended for modeling irregular data.

The modified Weibull c.d.f. employed by Cao and Burkhart (1984) incorporates two additional coefficients, e_j and d_j, which results in the following segmented c.d.f.:

$$F_j(x) = e_j \left[1 - d_j \, e^{-\frac{(x-a_j)}{b_j}^{c_j}} \right] \tag{18}$$

for $x_j \leq x \leq x_{j+1}$, $j = 1, 2, \ldots, n-1$.

The d_j and e_j can be considered scale parameters of the c.d.f. and need to be adjusted whenever convergence cannot be obtained. The method incorporates a search technique for the solution of an equation which yields the location coefficient a_j.

A generalized framework for the prediction of diameter distributions and yields was developed by Hyink and Moser (1983).

Parameter estimates for the Weibull probability density function were obtained by Hyink's (1980) parameter recovery procedure by Knoebel, Burkhart and Beck (1986). The recovery method was preferred as it provides compatible whole stand and diameter distribution estimates of stand attributes. Together with the general diameter distribution yield function of Strub and Burkhart (1975) shown above, integration over the range of diameters provided estimates of stand attributes such as dbh, basal area and cubic volume on a per unit area basis. Solution of the system of equations for recovery of the parameters of the probability density function was via the method of moments technique. However, this resulted in convergence problems and the Weibull probability density function was reduced to the two parameter form with the location parameter either set equal to a constant or predicted outside the system of equations.

In the prediction of diameter distributions for *P. elliottii*, the Weibull p.d.f was described by Bailey *et al* (1982) with linear prediction equations for the location parameter and two exponential equations for percentiles of the distribution. This technique was followed by Amateis *et al*, (1984), who solved a system of three equations with three unknowns of the form

$$X_p = a + b\,(-ln\,(1-p))^{(1/c)} \tag{19}$$

to get estimates of the parameters a, b and c of the Weibull distribution, X_p being an equation for the p^{th} percentile.

Four prediction equations were used by Bailey *et al* (1985) to find the parameters of the Weibull distribution for *P. taeda*. The location parameter, a, was predicted directly. This was used together with the 50^{th} and 95^{th} percentiles to determine the shape parameter, c. A prediction equation for the quadratic mean dbh was used to determine the scale parameter b .

Regression equations developed by Burk and Burkhart (1984) were used by Cao (1987) to derive the parameters of a Weibull diameter distribution from the Schumacher and Coile model. Complete compatibility for both volume and basal area could not be found and there were consistent differences in results obtained via the Weibull versus regression predictions.

Parameters of a p.d.f. were projected over time with a growth function by Daniels and Burkhart (1988) following the results of Bailey (1980b). It was found that a transformation is provided by a basal area growth function which will regenerate the initial p.d.f. family.

Spacing indices

Stand density index.

Stand density index (SDI) is an expression for density of stocking in even-aged forests usually attributed to Reineke (1933) although the relationship between stand density and size had been used by Frothingham twenty years earlier. The index is obtained with reference to a limiting relationship between mean tree size and the number of trees per unit area. This limiting relationship is of the form

$$N = \alpha \overline{D}_q^{\beta} \tag{20}$$

Reineke found that plotting the number of trees per acre against the corresponding average diameter for fully stocked stands resulted in a straight line when logarithmic paper was used. For many species the slope of this line was -1.605 but the level differed with species and he thus represented the curve by

$$\log N = -1.605 \log D + k \tag{21}$$

The slope is generally less for more tolerant species (Zeide, 1987).

Reineke based his stand density index on a quadratic mean dbh ($\overline{D}_q$) of ten inches so that when dbh and stems per unit area are known

$$SDI = N(10/\overline{D}_q)^{\beta} \tag{22}$$

The implication is that all stands at the limiting stand density have the same SDI irrespective of mean dbh. It is apparent that SDI is only of consequence in fully stocked stands.

A degree of confusion in the literature regarding the relationship of SDI to age and site quality was pointed out by Parker (1978). While older papers show no correlation between SDI and age or site quality, more recent papers reported conflicting results. At moderate levels of stand density Parker (1978) found significant correlations between SDI and age in one species and none in the others tested. Similarly there were significant correlations between SDI and site index in some species and not in others. Under conditions of intense competition, no significant correlations between SDI and age or site index were found for any species.

Relative spacing.

Relative spacing (RS) is defined as the ratio of the mean distance between neighbouring trees to the average dominant height of the stand. With square spacing this becomes

$$RS = \frac{\sqrt{10000/(S/ha)}}{H_d} \tag{23}$$

where H_d is the dominant height in meters.[4]

For any site quality and initial age, all stands of a given species approach a common minimum relative spacing asymptote with time. For a given height growth curve, this asymptote establishes the maximum stand density for any given age (Clutter *et al*, 1983).

Relative spacing was originally proposed as a management tool by Wilson (1946) and was based on the concept of maintaining a relatively constant rate of growth within stands. The original work on these lines has been traced to Denmark in 1851 (Wilson, 1979). Relative spacing varies with species and crown class but is not affected by site index. However, annual height increment results in a density measure increase when stand density is not affected by mortality (Honer, 1972). The trend of relative spacing over time is determined by the relationship of height increment to mortality. As competition mortality is virtually nil in early years, relative spacing is affected by height growth alone. With crown closure, the increasing mortality rate starts to play the more important role (Parker, 1978) and relative spacing remains constant when the percentage height increment rate is one-half the percentage mortality rate

[4] Relative spacing is unaffected by units of measure and eq. (23) gives the same result as the more commonly used imperial form.

$$\frac{(\partial H/\partial A)}{H} = -\frac{1}{2}\ \frac{(\partial N/\partial A)}{N} \tag{24}$$

According to Wilson (1979) it is axiomatic "that any expression of stand density which sacrifices the number of trees becomes inappropriate for use as a guide to thinning." The merit of relative spacing lies in its independence of species and age and its universality to systems of measurement.

Curves depicting relative spacing trends toward a limiting density were generated by Parker (1978) using a model based on the ratio of relative spacing to minimal relative spacing. These define upper stocking limits.

The first derivative of relative spacing with respective height was used to predict a sudden decline (= crash) in basal area in high density stands by Harrison and Daniels 1987. When the derivative is near zero, a biophysical limit to stand density is indicated.

Power law for self-thinning.

Empirically derived size-density relationships by Yoda (Yoda *et al*, 1963) were brought to the attention of the Western world by Drew and Flewelling (1977). The 3/2 power law identifies the maximum mean tree size-density relationship for a given species as, for a large number of species, the relationship between the logarithms of mean stem volume and stand density was a straight line with slope of -1.5. The gradient of the self-thinning line can also be expressed as 56° (Hutchings and Budd, 1981). This line is referred to as the maximum size-density relationship. It is assumed that plants have identical growth rates for all their parts and self-thinning must occur when the species fully occupies the site. Individual trees within a stand may develop beyond the -3/2 boundary but the average for a given stand cannot. The 3/2 power law can be written as

$$ln\,(w) = ln\,(C) - 3/2\; ln\,(\rho) \qquad (25)$$

where ρ is trees per unit area, w is weight and C a constant of proportionality or the intercept. The name given to the law, however, comes from the nonlinear form,

$$w = kN^{-3/2} \qquad (26)$$

Another form is found when total plant mass per unit, W, the product of w and N is used

$$W = k\,N^{-1/2} \qquad (27)$$

As weight and volume are proportional, the 3/2 power law applies to volume as well as to weight. It estimates maximum mean tree volume as a function of density where the condition is maintained by substantial mortality.

The limiting density defined by the 3/2 power law was used to predict the growth of *P. pinaster* by Barreto (1988a) who found that the basal area of a stand at the limiting density is constant (Barreto 1988b), form factor changes only with stand density and not with age (Barreto 1988c) and the relative mortality rate (RMR) is constant for a given species and age as

$$\partial X \,/\, \partial t = -\,1/2\; X\; RMR \qquad (28)$$

and

$$\partial V \,/\, \partial t = -\,3/2\; V\; RMR \qquad (29)$$

where X = mean dbh or mean height or dominant height or standing volume and V = mean tree volume (Barreto, 1988d).

Due to conceptual uncertainties concerning the 3/2 power law, Harrison and Daniels (1987) chose not to model self-thinning trajectories directly. However, the relationship is implicit in their model which redistributes a constant mass of foliage among a decreasing number of stems.

The literature pertaining to the law in question has been reviewed by Zeide (1987) and Weller (1987). They concluded that the law can be true in two cases. In the first, all the factors of stand dynamics unaccounted for by Yoda's Law must be nonexistent. In the second, the factors influencing the rate of self-thinning must cancel each other. It is shown that some of these factors do oppose each other but rarely balance, and the rate of self-thinning therefore changes with age, species and site quality. Furthermore, the line of self-thinning is generally a curve, and not a straight line with constant slope as postulated. The expected value of the slope will exceed -3/2 for those stands growing under optimal conditions and those retaining a closed canopy over a prolonged period of time. There are wide deviations in slope with values ranging from -0.96 to -3.75 reported.

It is concluded by Zeide (1987) that "the law violates accepted knowledge about forest stands and contradicts the facts..." while Weller (1987) stated "the thinning rule as a quantitative law should be discarded, and the many claims made for the generality, theoretical importance, and applicability of the rule should be carefully re-evaluated."

Chapter III

Experimental design for the correlated curve trend experiments in *Eucalyptus grandis*

The underlying philosophy behind the layout of the *E. grandis* experiments was essentially similar to that of the older and better-known experiments in pines as described by O'Connor (1935), Marsh (1957) and Bredenkamp (1984a). The major difference in comparison to the experiments in conifers being only in the range of stand densities tested. Each experiment was divided into two sections. In one the growth of unthinned stands was to be investigated and this section was referred to as the basic series. In the other, the effects of various thinning regimens and other silvicultural practices were to be assessed. These were referred to as the thinning plots. Although there were many other similarities, the *E. grandis* experiments were amended to incorporate experience gained from the pine experiments. The basic series and thinning series will be dealt with separately here below.

In the basic series, twelve nominal stand densities were established in September, 1952: 6726, 4304, 2965, 1482, 988, 741, 494, 371, 247, 124, 62 and 25 stems per hectare (S/ha). These densities will be referred to as plots 1 to 12 respectively. The imperial equivalent of these densities and the number of stems planted per plot are shown in Table 7 on page 112. The basic series treatments were replicated in three blocks.

In order to avoid suppression by grass and weeds, the plots were planted at stocking levels much in excess of the nominal stand density and then thinned "in advance of competition". This was achieved by planting plots 1 to 3 at the most dense level, 6726 S/ha, and the rest at 2965 S/ha. The diameter growth of the plots was assessed at frequent intervals. It was planned that as soon as the mean diameter of plots 4 to 12 exceeded that of plots 1 to 3 by 2.5 mm (one-tenth of an inch), it would be construed that competition effects had been manifested in the very dense plots and all plots with the exception of plot 1 were to be thinned to the stand densities shown in the fourth column of Table 1 on page 32. However, this was found to be impractical to apply for the very first thinning as the stems at that stage were green and glaucous, irregular in cross-section and with very short internodal distances. The timing of the thinning was therefore based on a rule of thumb developed in *P. patula* where it was found that competition set in soon after the mean height reached twice the planting espacement. This implies a relative spacing of ca. 0.5 and the first thinning thus took place in March of 1954. This was eighteen months after planting.

Three months later the mean dbh of plots 4 to 12 differed from that of plot 3 by 2.5 mm and plots 5 to 12 were thinned to 988 S/ha. At two and a half years after planting the mean of plots 6 to 12 differed from plot 5 and plots 6 to twelve were thinned to 741 S/ha.

This process was repeated until plot 12 was thinned to 25 S/ha at six years and four months after planting. This is shown in Table 1 on page 32.

Selection of trees to be removed in all the thinnings of the plots in the basic series was to be at random. However it was soon discovered that this practice resulted in an undesirable spatial arrangement with large holes in the canopy. For all thinnings other than the first, silvicultural selection was done and the better trees were favored.

The rest of the experiment, the so-called thinning plots, consisted of eight thinning treatments and there were two blocks or replications thereof. Thinning was carried out at pre-specified ages and was irrespective of stage of development or size. The thinning treatments all started out with planting at 2965 S/ha but can be considered as being in three categories and are shown with rounded values in Table 2 on page 33.

The first group of plots, numbers 13 to 16, formed the "mathematically co-ordinated" sequence. All thinnings were to halve the stand density every four years until all plots were at 124 S/ha. To keep treatments within feasible limits, however, the first thinnings of plots 15 and 16 were advanced.

The second sub-group was formed by plots 17 and 18. These were to be subjected to similar degrees of suppression and then released to differing extents. They were grown at very dense levels until 8 years when they were thinned to different levels and thereafter left unthinned.

The final group of plots 19 and 20 were grown at different stand densities, released at differing degrees to similar stand densities simultaneously and then left without further thinning.

Table 1. List of spacings and stand densities (S/ha) aimed for in the basic series of the *Eucalyptus grandis* experiments.

Plot no.	Spacing (m)	Age at which "thinning" took place.									
		0	1.50	2.08	2.58	3.58	4.08	4.75	5.17	5.67	6.50
1	1.2	6726									
2	1.5	6726	4304								
3	1.8	6726	2965								
4	2.6	2965	1482								
5	3.2	2965	1482	988							
6	3.7	2965	1482	988	741						
7	4.5	2965	1482	988	741	494					
8	5.2	2965	1482	988	741	494	371				
9	6.4	2965	1482	988	741	494	371	247			
10	9.0	2965	1482	988	741	494	371	247	124		
11	12.7	2965	1482	988	741	494	371	247	124	62	
12	18.3	2965	1482	988	741	494	371	247	124	62	25

Table 2. List of stand densities (S/ha) aimed for in the thinning plots of the *Eucalyptus grandis* experiments.

Plot no.	Age at which thinning was carried out (years)								
	0	1	4	8	12	16	20	24	Final
13	3000			2000	1000	500	250	125	125
14	3000		2000	1000	500	250	125		125
15	3000	2000	1000	500	250	125			125
16	3000	1000	500	250	125				125
17	3000			1000					1000
18	3000			500					500
19	3000			500					500
20	3000	1000		500					500

As stand density differed so widely, plot sizes in the basic series were varied. The standard size for research plots was 0.04 ha., (one-tenth of an acre) but this would have been too small to allow for an adequate number of trees representing the lower stand densities. As shown in Table 7 on page 112, three plot sizes were used, 0.04, 0.08 and 0.16 ha. Despite this variation in plot size, the largest plots have only ten trees per plot, i.e. in plots 10 and 11, and a mere four for the widest stand density, plot 12. By contrast, the narrowest spacings started out with 272 trees per plot.

Each of the measurement plots was surrounded by a buffer zone which was kept at the same stand density as the plot itself. It can be seen from Figure 2 on page 35 that the buffer zone is in all cases as least as wide as the width of the measured plot, that is a minimum of 20 m (66 ft.). The numbering of the plots in the diagram indicates the block, shown alphabetically, and the treatment applied to that plot.

As the plots varied considerably in size, the randomization for the allocation of treatments to plots was restricted. The three blocks were kept apart as separate entities although they were adjacent. As far as the basic series was concerned, the plots were sorted by size. Plots of similar size being kept adjacent and treatments allocated at random within the size groups. In the case of the thinning plots it appears as if there was an attempt to keep plots from similar groupings (Table 2 on page 33) adjacent but it is not consistently so. This is mere speculation as this aspect of the the layout was never documented.

The Langepan experiment covers 62 ha. (153 ac.), but not all of the area is occupied by measurement plots and accompanying buffer strips. A strip on the seaward side and along both long edges was set aside as a windbreak. Although the plots were laid out, the third block of the thinning plots was never established; the plots were designated

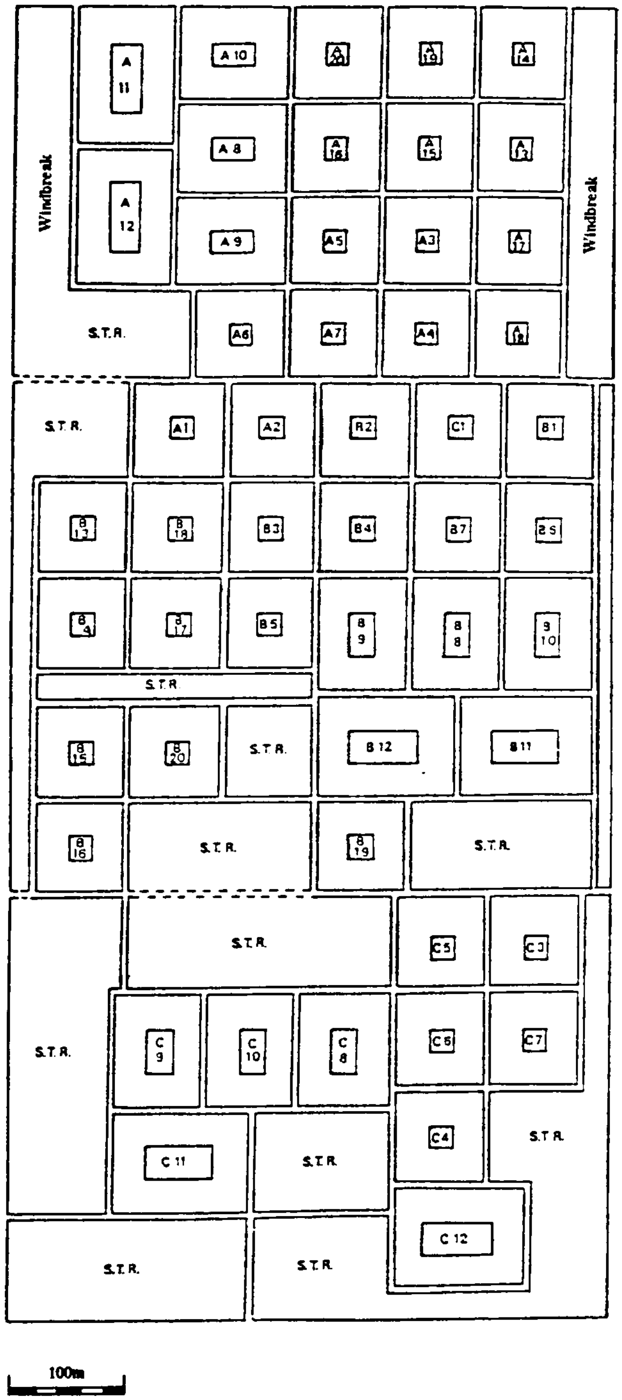

Figure 2. Layout of Langepan experiment: Scale diagram showing size of plots and allocation of treatments together with sample tree reserves (S.T.R.). The letters indicate blocks and the numbers denote treatments.

sample tree reserves and kept at stand densities similar to those in the basic series. Provision was thereby made for surplus testing material and sample trees in order to obviate any demands for destructive sampling within the experiment proper. When two plots failed at the Nyalazi experiment, where one block of all twenty treatments was established some years later, the plots were simply relocated in sample tree reserves which were already at the desired stocking. As the Nyalazi experiment is not replicated, it covers a considerably smaller area than the Langepan experiment, without being a small field trial. The layout of the Nyalazi experiment is shown as Figure 3 on page 37

Measurements, 23 in most of the plots, have been made at irregular, unevenly spaced, intervals as shown in Table 8 on page 113.

At every measurement the dbh of every tree was determined by means of a dbh (circumference) tape. In the early years, the height of every tree was also measured by means of range rods. Later, Blume Leiss hypsometers were used and not all heights were measured in every case. On several occasions only certain plots (particularly in the thinning plots) had heights measured. In recent times heights have been measured with Suunto hypsometers, again measuring sufficient trees (minimum 25 whenever possible) for an adequate dbh/height regression only. For the past two measurements no heights were determined in the most dense plots. The trees are so tall, and in such close proximity, that accurate measurement is impossible.

At all times each tree has been numbered and the dimensions were recorded on a per tree basis. Trees removed in thinnings were recorded as such, as were those found dead and subsequently removed for safety considerations.

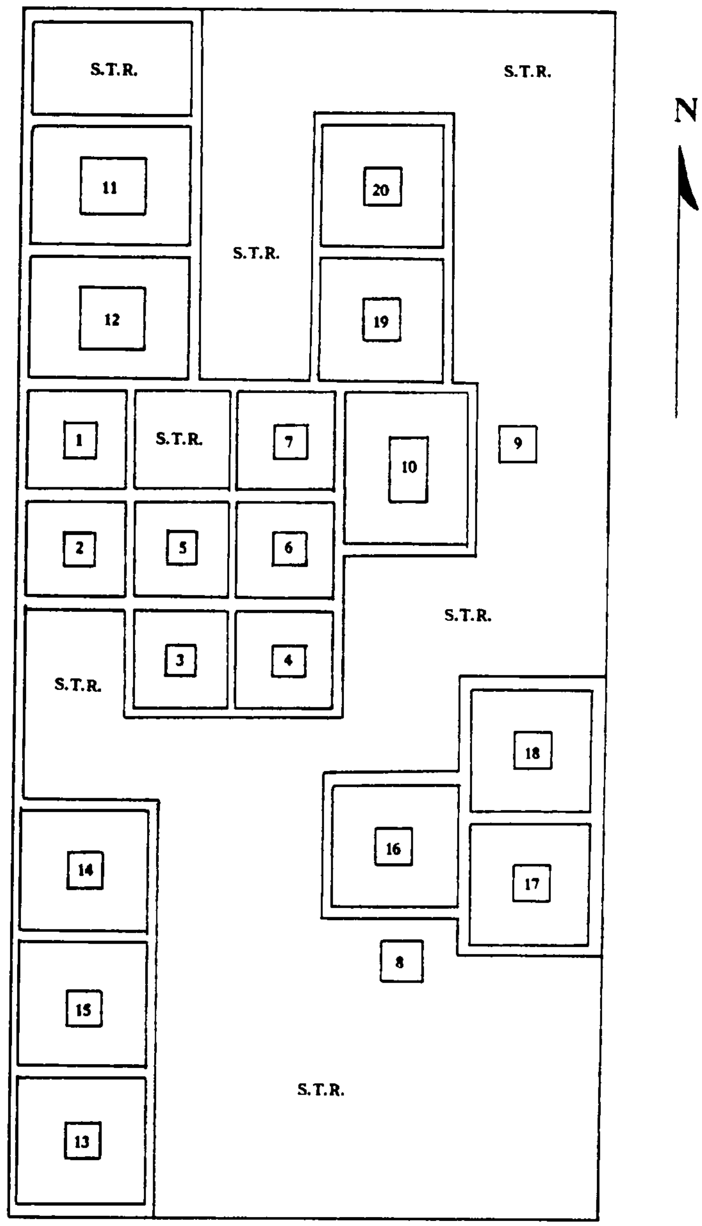

Figure 3. Layout of Nyalazi experiment: Scale diagram showing size of plots and allocation of treatments. S.T.R. denotes sample tree reserves.

There are several factors which complicate the analysis of C.C.T. experiments. Amongst these are restricted randomization in the allocation of treatments to plots, unequal plot sizes, unequal numbers of observations per plot and the thinning in advance of competition which was used to establish the experiments.

Any potential effect of restricted randomization will be ameliorated by the width of the buffer strips surrounding each plot. These are so wide that it can safely be assumed that treatment effects between plots are completely independent of each other and one need not be concerned about systematic effects. Furthermore, the coastal plain is so flat and the soil so uniform that there is little danger of a fertility trend being influential. Even in a worst-case scenario restricted randomization is only a minor aspect of contamination. In this case systematic effects will also not be uniform as only a few treatments are involved.

The differences in numbers of observations per plot is very large. At very young ages there may have been as many as 272 stems alive on the most densely planted plots. After establishment thinnings had been completed, there were only four trees per plot for the least dense treatments. See Table 7 on page 112. In respect of dbh, the precision of the estimate of the mean will increase with increasing number of stems. This is true of mean height too, but to a lesser degree as not all heights were determined. However, the number of stems measured per plot does not affect experimental error or error degrees of freedom, the effect thereof is partitioned off as subsampling error.

The question of differing plot sizes is naturally closely allied to the above-mentioned concerns. The aim of increased plot size was to allow a larger sample for increased precision of estimation. The increased plot size went hand-in-hand with increased width of buffer strips, ensuring independence between adjacent plots.

The greatest influence of the thinning before competition lies with a considerable reduction in experimental error brought about by application of spacing treatments after early hazards are past. Treatment application took place over a considerable period and the results would have been clearer had thinning to final stocking taken place following planting mortality. One could also postulate a different genotypic composition to the "heavily thinned" plots as compared to those planted to the final stand density. Thus, the thinning treatments may have confounded density with other factors, but the effect of this confounding is probably small.

It is proposed to solve the problems introduced during establishment by approaching the analysis as if the experiment had been established at the nominal stand densities at the age of 6.5 years (the age at which the final thinning in the basic series took place) and then consider the basic series of the C.C.T. as a designed experiment with twelve treatments. The thinning sections will be treated similarly but be regarded as separate entities. This assumption implies that growth trajectories prior to the age of 6.5 years are ignored (and by implication considered equivalent) in order to make the analysis tractable. As detailed above, there are salient features distinguishing the C.C.T. design from a designed experiment where the objective is to control all features not directly of concern with the experiment. However, in this case, hypothesis testing is not out of the realm of reason and progress with experimental analysis would be severely hampered without the assumption. Comparisons will be made at specific ages and it will be ascertained whether groupings of similar treatments change with the passing of time. Obviously inference to a thinned stand would be at the risk of the user but this also applies in the case of experiments planted at the desired stand density.

Chapter IV

Modeling the growth of unthinned stands of *Eucalyptus grandis*

The growth of unthinned stands of *E. grandis* was modeled by describing the growth of each attribute independently over age with a suitable growth function and then determining the relationship between the parameter estimates of the growth function and nominal stand density[5], N_0. In order to describe diameter distributions by means of the Weibull p.d.f., using the method of moments, quadratic mean dbh ($\overline{D}_q$), arithmetic mean dbh ($\overline{D}_a$) and minimum dbh ($\overline{D}_m$) were modeled separately. Both mean top height ($\overline{H}_t$) and regression mean height ($\overline{H}_r$) were modeled. Parameter prediction was used to predict estimates of these five attributes as functions of age and N_0.

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[5] The term nominal is used for the stand density at which the stands were established by thinning before the onset of competition; as opposed to the stand density at which planted.

A surge of renewed growth in mean dbh[6], following what had appeared to be an asymptotic level, precluded the use of commonly used growth functions to model the development of $\overline{D}_q$ with age for the three most dense stand densities i.e. 2965, 4304 and 6726 S/ha, (Bredenkamp and Gregoire, 1988)[7]. A more flexible growth function, that of Schnute (1981), was found to be eminently suited for the task at hand. The form of the function used can be written as

$$Y_t = \left[b_0^{b_3} + (b_1^{b_3} - b_0^{b_3}) \frac{1 - e^{-b_2(t - T_1)}}{1 - e^{-b_2(T_2 - T_1)}} \right]^{\frac{1}{b_3}} + \varepsilon \tag{30}$$

where:

Y_t = Parameter of interest.

t = Age of interest.

T_1 = Age at beginning of interval.

T_2 = Age at end of interval.

b_0 = Y_{T_1} = size at age T_1.

b_1 = Y_{T_2} = size at age T_2.

b_2 = Constant relative rate of the relative growth rate.

= constant acceleration in growth rate.

b_3 = Incremental relative rate of the relative growth rate.

= incremental acceleration in growth rate.

ε = Stochastic departure from the mean trend.

Note that the parameters of Schnute's function have been renamed to emphasize that all four parameters are being estimated. In the original formulation b_0 to b_3 are denoted

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6 This is an artifact of mortality as is shown in *Chapter V.*

7 This was subsequently found to be the case with $\overline{D}_a$, $\overline{D}_m$, $\overline{H}_t$ and $\overline{H}_r$ as well

as y_1 , y_2, a and b. The Schnute function was used to model all those attributes described as functions of age.

Quadratic mean breast height diameter.

Quadratic mean dbh ($\overline{D}_q$) was determined on a per plot basis for each enumeration as the square root of the mean of the squared diameters; dbh having been measured by diameter tape.

Schnute's function was fitted to the means of the three blocks for each of the twelve stand density (treatment) data series independently. Means across blocks were computed prior to fitting to reduce the autocorrelation. The curves were fitted with T_1 and T_2 fixed at 1.50 and 32.83 years respectively. These values span the range of plantation ages available for modeling.

The parameter estimates for the Schnute model were predicted by individually establishing their relationship with the nominal stand density (N_0), the number of stems per hectare at which the thinning-in-advance-of-competition had been geared.

In the case of b_0 , the first of the size parameters, the relationship was adequately described with

$$\ln b_{0_{D_q}} = b_{03} + b_{04} \ln N_0 + b_{05} \ln^2 N_0 \qquad (31)$$

where R^2 = 0.75 and MSE = 0.0047[8]. In testing the hypothesis that the parameters have a value of zero, the probability of a greater Student's t was less than 0.001 in all three instances.

The best estimates of b_1 were found with

$$ln\, b_{1_{D_q}} = b_{06} + b_{07} \ln N_0 + b_{08} N_0 \tag{32}$$

where R^2 = 0.98 and MSE = 0.0055. The probability of a greater t was less than 0.006 for all three coefficients when it was tested whether these differed from zero. The fit of the two models used to estimate size parameters is shown as Figure 6 on page 136. The shape of the b_0 versus N_0 relationship is an artifact of correlation between parameter estimates and not a reflection of size of organism at time T_1. Scrutiny of raw data showed no indication of an effect of spacing on mean diameter at age 1.5 years and no observable effect is expected at such an early stage of development. The mean diameter at 1.50 years could have been used to specify the size parameter ($\overline{D}_{q_{T_1}}$) instead of estimating it as b_0. By estimating b_0, however, a more generally applicable growth function is obtained. The displayed parabolic trend has little practical significance, the range being less than 15 mm. The functional form used to represent b_1 permits an increase in size of $\overline{D}_q$ at high densities, to allow for the increase in dbh resulting from mortality, instead of imposing an asymptotic constraint. This increase in mean dbh is the reason for using Schnute's growth function and is further elaborated upon in *Chapter V*. This parameter estimates the size (dbh) at 32.83 years of age.

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8 Estimates of R^2 and mean squared error are reported despite their limitations in respect to second-stage models such as these. Although the coefficients can be regarded as random variables analogous to seemingly unrelated regression, second-stage estimates are not unbiased. Formal statistical tests are not appropriate and real alpha-levels are unknown. Furthermore, underlying assumptions concerning error are not obeyed and the reader is referred to Ferguson and Leech (1978) for a comprehensive overview of this topic.

More difficulty was encountered with b_2, the first of the shape parameters. It will be shown later that b_2 is consistently difficult to describe. In the case of $\overline{D}_q$ it appears as if b_2 is relatively unaffected by N_0 for densities below 741 to 985 S/ha. This is the level at which mortality starts to play a role as shown by Bredenkamp (1988). The function selected to model b_2 is

$$ln\,(b_{2_{D_q}} + 0.125) = b_{09} + b_{10}\ \ln\ N_0 + b_{11}N_0 \tag{33}$$

where $R^2 = 0.99$ and MSE = 0.0092. (The factor of 0.125 was added to each parameter estimate to ensure positive values for the taking of logarithms. The cases where b_2 assumes a negative value are the cases where mortality caused an increase in mean diameter). In this case the observed significance level (p-value) was less than 0.004 for each of the coefficients. A plot showing the fit appears as the upper diagram in Figure 7 on page 137. A cursory inspection of the distribution of the data points suggests this might be equally well modeled with an untransformed cubic polynomial. This is not the case and it will be shown later that good estimates of the shape parameter for low values of N_0 are essential with use of the Schnute model.

The second of the shape parameters, more particularly that governing the incremental acceleration, b_3, was modeled with

$$b_{3_{D_q}} = b_{12} + b_{13}\ \ln\ N_0 + b_{14}\ln^2 N_0 \tag{34}$$

The correlation coefficient R^2 = 0.99 and MSE = 0.0116. The p-values are smaller than 0.0003 for each of the parameter estimates. The fit is shown diagramatically at the bottom of Figure 7 on page 137.

The preceding four equations were used to obtain parameter estimates for the Schnute growth function for each N_0 and the estimated values of $\overline{D}_q$ were plotted against observed treatment means. This had been done as routine during the model selection process. With the above equations there were no reasons for concern as the estimates closely mimicked trends. In the case of 124 S/ha there is a consistent underestimate and in the case of 1482 S/ha an overestimate. These are the only two stand densities for which $\hat{\overline{D}}_q$ does not fall entirely between the smallest and largest values of $\overline{D}_q$ as computed independently for the three blocks.

Having established the functional relationships between the parameters and N_0, the twelve parameter estimates for equations 24 through 27 were re-estimated simultaneously by means of the derivative-free secant method implemented as method DUD in SAS (1985). The parameter estimates replacing b_{03} through b_{14} appear in Table 24 on page 129 page = yes. as b_{15} through b_{26} respectively.

Scrutiny of the correlations between the parameter estimates revealed very strong dependencies within each of the four satellite models. In particular, the estimate of the intercept is highly correlated with the other terms of the sub model in each case. This is not unexpected. The simultaneous fitting accounted for 99.5% of the sum of squared deviations from the mean and an approximate R^2 is 0.995 with MSE of 585.6.

A visual presentation of the fit of the model against original data is shown as Figure 8 on page 138 where predicted values are superimposed on observed for three stand density levels spanning the range of treatments. Predicted values for all twelve stand densities tested are shown with data excluded in Figure 9 on page 139. The trends exhibited at young ages are not entirely satisfactory in all cases.

Arithmetic mean breast height diameter.

As in the case for $\overline{D}_q$, the development of arithmetic mean dbh ($\overline{D}_a$) could be described with well-known growth functions for only the wider spacings. An apparent resurgence in diameter growth after advanced mortality dictated the use of the Schnute model to describe the growth of $\overline{D}_a$ as had been done for $\overline{D}_q$. Here, too, there was a marked crossover with the $\overline{D}_a$ of lesser values of N_0 at advanced ages.

The estimated parameters of the Schnute model were regressed on N_0 and described with the following equations.

$$ln\ b_{0_{D_a}} = b_{27} + b_{28} ln\ N_0 + b_{29} \ln^2 N_0 \tag{35}$$

$$ln\ b_{1_{D_a}} = b_{30} + b_{31} ln\ N_0 + b_{32} \ln^2 N_0 + b_{33} \ln^3 N_0 \tag{36}$$

$$b_{2_{D_a}} = b_{34} + b_{35} N_0 + b_{36}\ N_0^2 + b_{37} N_0^3 \tag{37}$$

$$ln\ b_{3_{D_a}} = b_{38} + b_{39} ln\ N_0 + b_{40} \ln^2 N_0 \tag{38}$$

The correlation coefficients for the above are 0.80, 0.99, 0.97 and 0.99 respectively. The MSE are 0.0072, 0.0012, 0.0003 and 0.0053 respectively. The fitted curves and the parameter estimates are shown diagrammatically as Figure 10 on page 140 and Figure 11 on page 141.

Here again the fitted curve to b_0 is strongly concave. Specification of a straight line (using the mean as estimate) performed markedly poorer than the curve above when the model was verified, however. It can be seen from Figure 36 on page 166 that spacing has no measureable effect on mean tree volume, and by implication on $\overline{D}_q$ and $\overline{D}_a$, at very young ages.

As was the case with $\overline{D}_q$, it was found that severe perturbations resulted if the model selected for b_2 did not describe the data adequately. An underestimate of the parameter at low stand densities resulted in a complete change to the character of the Schnute fit, turning monomolecular or sigmoid shapes into concave-up parabolas. The cubic polynomial used above to model b_2 in *Equation* (37) was considerably better than any other model evaluated. Regression analysis showed both the quadratic and cubic terms to be significantly different from zero (p = 0.01, 0.02) whereas the linear component was not significant in the presence of the other two. The linear component was nevertheless retained as b_2 plays such a crucial role in the shape of the curves.

Having established the relationships between the coefficients and N_0, all fourteen parameters (b_{27} to b_{40}) were re-estimated simultaneously with the derivative-free secant method as for $\overline{D}_q$. The resultant parameter estimates appear as b_{41} to b_{54} in Table 24 on page 129. There is no insurance that estimates of $\overline{D}_a$ will be less than $\overline{D}_q$, a property required for the recovery of the moments of the Weibull distribution. Visual inspection suggested there was no need for concern, however.

Minimum breast height diameter

The development of the minimum breast height diameter was modeled to serve as the location parameter for the diameter distribution. It was clear from the outset that $\overline{D}_m$

behaves somewhat differently when compared to $\overline{D}_q$ or $\overline{D}_a$. Not only are the values lower, for obvious reasons, but an apparent asymptotic value is reached very early and rather abruptly. As a result, difficulties were encountered with the modeling of the parameter estimates as functions of N_0.

The size at age T_1 was described with

$$b_{0_{D_m}} = b_{55} + b_{56} \log N_0 \tag{39}$$

where $R^2 = 0.40$ and MSE = 22.11. The slope term differs significantly from zero (p = 0.02) despite the very poor apparent fit.

The second size parameter was estimated with

$$b_{1_{D_m}} = b_{57} + b_{58} N_0^{b_{59}} \tag{40}$$

where an approximate $R^2 = 0.99$ and MSE = 1530.97. The fit is shown as Figure 12 on page 142.

The estimation of b_2, the parameter defining the constant acceleration in growth rate proved to be difficult. One of the main reasons was the proximity of the estimate for $N_0 = 25$ to zero. An underestimate resulting in a negative value for b_2 causes a complete change in the shape of the function (Bredenkamp and Gregoire, 1988). Examples of the effect of small errors in estimation, which are nevertheless positive, are shown in Figure 15 on page 145.

Perusal of the data points in the upper figure of Figure 13 on page 143 suggests that a straight line from top left to bottom right would be adequate to model the shape parameter. This is not so. It is imperative that the curve track the values for low N_0 closely in order to simulate the shape of the minimum dbh development. None of the better-known linear and nonlinear functions which were fitted gave satisfactory results. Segmented functions, as follows, were therefore fitted. The join point was selected subjectively according to a visual inspection of the data.

$$b_{2_{D_m}} = \begin{cases} b_{ii} + b_{jj}\, N_0 + b_{kk}\, N_0^2 & \textit{where } N_0 \leq 741 \\ X + b_{ll}(N_0 - 741)^{b_{mm}} & \textit{where } N_0 > 741 \end{cases} \tag{41}$$

where X = the upper function evaluated at 741 S/ha.

The two functions were fitted simultaneously in a nonlinear procedure as this is more efficient from a statistical perspective than the independent fitting of the two functions would be. The result is shown as Figure 14 on page 144. Ostensibly this procedure yielded excellent results when curves fitted with recovered parameters were plotted against observed data from all twelve treatments. However, when stand densities other than N_0 were simulated, undesirable inconsistencies were detected. As a compromise, it was decided to sacrifice a good fit for N_0 = 25 S/ha and use a single function which provides consistently good estimates for all other values of N_0 and which is not plagued with the cusp shown by the segmented regression result. The model selected was the gamma function fitted as

$$b_{2_{D_m}} = b_{60} + b_{61} N_0^{b_{62}}\ e^{(b_{63} N_0)} \tag{42}$$

where $N_0 \geq 62$ S/ha. An approximate R^2 = 0.895 and MSE = 0.0207.

The second shape parameter, b_3, was adequately described with a cubic polynomial as

$$b_{3_{\overline{D}_m}} = b_{64} + b_{65}N_0 + b_{66}N_0^2 + b_{67}N_0^3 \quad (43)$$

The correlation coefficient exceeded 0.99 and MSE = 0.1421. The results of fitting the shape parameters is shown in Figure 13 on page 143. The coefficients all differ significantly from zero.

Attempts to estimate all the $\overline{D}_m$ parameters simultaneously failed, even when the above nonlinear functions were replaced by simple linear models.

Mean top height.

Mean top height ($\overline{H}_t$) was defined as the regression estimate of height corresponding to the quadratic mean dbh of the 10% thickest trees (trees larger than the 90^{th} percentile) in each plot for each enumeration. The regression equation was from the log height - reciprocal dbh function described by Michaeloff (1943) and found suited for the description of height/diameter relationships by Ek (1973) and Green (1981).

Being a function of dbh, the top height development also exhibited an upswing at advanced ages in the most dense treatments and again the Schnute growth function was resorted to.

The first of the size parameters was described with

$$b_{0_t} = b_{68} + b_{69} ln\, N_0 + b_{70} \ln^2 N_0 \quad (44)$$

Where $R^2 = 0.60$ and MSE $= 0.044$. The probability of a greater t was 0.055 for the quadratic term but it was retained in the model even though it is known that variance estimates are not unbiased. Here again the quadratic effect portrays rather strange behavior which can be attributed to lack of independence with other coefficients as opposed to a reflection of the influence of stand density on top height of a stand at very young age.

The second size parameter was described with

$$b_{1_{H_t}} = b_{71} + b_{72} \ln N_0 + b_{73} \ln^2 N_0 \tag{45}$$

Where $R^2 = 0.94$ and MSE $= 0.896$ while the null hypotheses for the parameter estimates were not accepted with the probability of a greater $|t|$ of 0.002 or less. The fit of these functions is shown as Figure 16 on page 146.

The same model as used for the size parameters was used for the first of the shape parameters after applying a log transformation to the b_2 estimates. A scatter plot of the $b_{2_{H_t}}$ estimates against the logarithm of stand density displayed very little structure. The relationship was first described with a straight line but this did not perform well when estimates from recovered parameters were checked against the data. The model used was selected as it had consistently provided the best fit for other parameters, not because it was assumed that there was a sound reason for the relationship to reveal the shape displayed in the top half of Figure 17 on page 147. The function is

$$ln\ b_{2_{H_t}} = b_{74} + b_{75} \ln N_0 + b_{76} \ln^2 N_0 \tag{46}$$

The correlation coefficient is 0.72 with MSE = 0.181 and the probabilities associated with parameter estimates are 0.017 or less. The fit of this, and the next, equation is shown in Figure 17 on page 147.

The last of the parameters was described with

$$b_{3_{H_t}} = b_{77} + b_{78}\ \ln\ N_0 + b_{79}\ln^2 N_0 \tag{47}$$

which resulted in a poor fit with $R^2 = 0.39$, MSE = 0.034 and p-values barely reaching commonly accepted significance levels at 0.001, 0.053 and 0.044 respectively.

The above twelve parameters were subsequently estimated simultaneously and b_{68} through b_{79} were replaced with b_{80} through b_{91}. An approximate R^2 for the simultaneous fit is 0.985.

As the influence of stand density on top height is small (top height is frequently quoted as density independent), plots of top height on age for various densities are not very revealing. A considerable amount of crossing over occurs and this presents a confusing picture as shown in Figure 18 on page 148.

Better insight is gained through perusal of Figure 19 on page 149. This shows a linear relationship at young ages which becomes progressively more curvilinear with increasing age and a shifting maximum. At young ages the maximum top height is at high stand densities (2000 S/ha) and with time the maximum is found at ever decreasing stand densities. It is apparent that as age increases, so does the variability of top heights.

Mean height development with age.

Mean height ($\overline{H}_r$) was defined as the regression height corresponding to $\overline{D}_q$ from the log height/reciprocal dbh relationship. The same relationships used to model the parameters of $\overline{H}_t$ in equations 44 through 47 were used for $\overline{H}_r$ and the parameter estimates for b_{68} through b_{79} were used as starting values for the simultaneous estimation of the parameters of the $\overline{H}_r$ development. The parameter estimates appear as b_{92} through b_{103} in Table 25 on page 130.

As was shown for $\overline{H}_t$, the changing relationship of mean height to stand density with time is presented. It appears as Figure 20 on page 150.

Recovery of the diameter distribution.

The location parameter of the Weibull distribution, a_W, is found for a particular age by solving for the four parameters of the Schnute model describing the development of $\overline{D}_m$ using equations (40) through (43) and inserting the stand density at that particular age. Similarly estimates of $\overline{D}_q$ and $\overline{D}_a$ are obtained through solution of equations (31) through (34) and (35) through (38) respectively. Having found $\hat{\overline{D}}_m$, the scale (b_W) and shape (c_W) parameters of the Weibull distribution are obtained such that the first two non-central moments of the predicted distribution match the values calculated for $\hat{\overline{D}}_q$ and $\hat{\overline{D}}_a$, following the method described by Burk and Burkhart (1984). The equations used are

$$b_W = (\overline{D}_a)/\Gamma_1 \tag{48}$$

and

$$\overline{D_q^2} - \overline{D_m^2} - 2\overline{D}_m(\overline{D}_a - \overline{D}_m) - (\overline{D}_a - \overline{D}_m)^2\,\Gamma_2 / \Gamma_1^2 = 0 \tag{49}$$

where

$$\Gamma_k \;=\; \Gamma(1 + k/c_w)$$

The program listed in *Appendix C* incorporates a subroutine taken from Burk and Burkhart (1984) which finds b_W and c_W given $\overline{D}_q$, $\overline{D}_a$ and $\overline{D}_m$. The listed program contains a check to ensure $\overline{D}_q > \overline{D}_a > \overline{D}_m$ which may or may not first be weighted to make provision for differences in site.

Changes with time in "unthinned" E. grandis stands.

It is of interest to know which treatments yield results which could be considered similar in *E. grandis*, and how groupings of treatments yielding similar results change with time. This was investigated by means of analyses of variance carried out for each enumeration from the age of 6.50 years onwards. This is the age at which the final "thinning before the onset of competition" took place and after which no further interventions occurred. The C.C.T. experiments are being regarded as being of a randomized complete block design after the age of 6.50 years as discussed in *Chapter III*. At no stage were significant differences detected between blocks and therefore data from all blocks were pooled, thus releasing an additional degree of freedom for testing purposes. The model used treats each of the variables measured as a function of nominal stand density alone. For each enumeration where significant differences ($p > 0.05$) among treatments were encounttered, multiple comparisons among treatment means were carried out, using the Student-Newman-Keuls (Ott, 1984) procedure. This procedure was selected as it controls the type I experimentwise error rate, is more conservative than the commonly-used Duncan's multiple-range test but also decreases the critical value according to the number of steps between means, thus not being as demanding as Tukey's or Scheffé's tests.

It has been shown that the number of observations varies widely between treatments. This results in a violation of the assumptions underlying the analysis of variance as the mean is determined with greater precision in the treatments having the greater number of observations. The variance is inversely proportional to the sample size and it is desirable to weight each mean inversely proportional to the variance. The number of observations in each mean was thus selected to weight the squared residuals of the variables used in the multiple comparison procedures. The result was that no significant differences could be detected for any of the variables screened, with the exception of $\overline{D}_q$, when the Student-Newman-Keuls test was used. Duncan's multiple range test showed some differences after weighting but the effect of the weighting was so marked that even least significant difference tests failed to declare ostensibly large differences to be significantly so. The results of the single weighted multiple range tests is presented as Table 9 on page 114. The changes in groupings with time are shown by means of contour charts, no significant differences being detected, for any variable other than $\overline{D}_q$. These appear as Table 10 on page 115 to Table 15 on page 120.

Quadratic mean dbh

At no time during the development of the stands were any significant differences detected between blocks in terms of $\overline{D}_q$. There were highly significant differences between treatments at each enumeration and the results of range tests are shown in Table 9 on page 114. It should be noted that the rankings of $\overline{D}_q$ remain unchanged with time when mean diameter is taken across blocks. It is unequivocal that $\overline{D}_q$ increases with decreasing N_0 and this holds true across time. Despite that, at no stage were the two treatments planted at the highest stand density ever significantly different. With increasing time, competition effects caused progressively less-dense treatments (in terms of N_0) to join the pool of suppressed stands among which differences are not significant. A contour chart showing treatment means which are similar based on a contour interval of 100 mm. is shown as Table 10 on page 115. The wider the spacing, the greater the rate of change with time and the greater the degree of separation between treatment results. The four most dense treatment differ little between themselves and change relatively little with time.

Minimum dbh

Ranking for $\overline{D}_m$ remains consistent in terms of N_0 over time except for very dense plantings where the lowest $\overline{D}_m$ is found at progressively lower values of N_0. Note that no statistically significant differences were detected. This can be ascribed to heavy mortality starting in the lowest diameter classes of the most dense stands and then the process is repeated in progressively less dense stands. A contour plot of treatment results is shown as Table 11 on page 116. The four most dense spacings show virtually no change in minimum diameter over twenty four years while the wider spacings show rapid increase.

Basal area

Rankings in terms of basal area changed very little with time and no statistically differences were detected between treatment means. The trend is the mirror image of that of $\overline{D}_q$; the greater the stand density the greater the stand basal area. The highest basal area is found in stands with the highest stand density even though this is where the highest mortality is. It will be shown later that mortality is concentrated in the smallest diameter classes and these contribute the least toward stand basal area. The stand with N_0 = 988 S/ha appears to cause the most disturbance in rankings, tending towards a higher basal area from the age of 15 to 20 and then losing that position and falling to a level lower in the rankings than it had. With the passing of time, fewer and fewer differences are shown to be different. This lends some credence to the concept that basal area tends to a common asymptote irrespective of the stand density at which a stand is established. The contour chart shown as Table 12 on page 117 shows that the wider spacings hardly increase in basal area over long intervals as the site is not occupied sufficiently. The trends in basal area are as expected.

Mean height

The higher the stand density, the lower the ranking in terms of mean height. The converse, however, does not apply. The highest rankings are almost exclusively from stands with N_0 in the range 124 S/ha to 371 S/ha. This can also be seen in Figure 20 on page 150. There were no statistically significant differences between mean height detected by multiple comparison of ranked means. A contour chart for mean height is shown as Table 13 on page 118. It shows the greater mean height to be found where N_0 is in the range of 62 to 371 S/ha and also shows that mean height is depressed more by the dense spacings than the wider spacings. It is of interest to note that the mean height for N_0 = 741 S/ha does not appear to be any higher than expected, yet this treatment consistently outranks the others in terms of basal area and stand volume.

Top height

Top height was defined as the regression height of the quadratic mean of the 10% thickest trees. Rankings do not follow the trends shown by $\overline{D_q}$, however, nor are they unaffected by stand density. The denser the stand density the lower $\overline{H_t}$ is but the converse does not apply. No significant differences were detected between means. The optimum range of stand density in terms of top height is 124 to 741 S/ha and the popular notion that $\overline{H_t}$ is independent of stand density is not supported as this does not apply across the wide range of stand density tested at Langepan. Note the definition of top height is based on the diameter of dominant trees and not the absolute tallest trees in the stand. The contour chart is shown as Table 14 on page 119.

Stand volume.

No statistically significant differences were detected between means across the full range of stand densities tested. However, at all stages it was found that the stands representing 741 S/ha carried the highest volume. It will be shown in the section dealing with mean annual increment (*Chapter VIII*) that this particular stand density appears as an anomaly in this regard. The stands with the lowest stand density carry the least volume The contour chart shown as Table 15 on page 120 shows the stand volume to be strongly affected by stand density while $N_0 = 741$ yields a volume which is consistently higher than expected. The stand density in the least dense treatments is so low that stand volume does not increase sufficiently to change the category defined by the lowest contour line.

Chapter V

Diameter growth of *Eucalyptus grandis* under conditions of extreme suppression

The Schnute growth function was selected for the modelling of growth parameters of *E. grandis* primarily for its ability to track renewed growth after what had appeared to be an asymptote transpired to be only a plateau. For all practical purposes it appeared as if mean stand diameter growth in the most dense treatments had ceased by the end of the twelfth growing season (See Figure 8 on page 138). In those plots mean dbh was 139 mm, and the ubiquitous Chapman-Richards model indicated an asymptotic dbh of 167 mm. By contrast, in other treatments, the "free-growing" trees had already attained a mean dbh of 519 mm.

An investigation was undertaken to ascertain whether dbh growth of trees which survived really had ceased for a period and, if not, how such growth may be distributed. The data from the most dense treatments for the enumerations of July, 1964, and November, 1968, were therefore selected to test the hypothesis that the small (ca. 17 mm.)

measured increase in quadratic mean dbh between the ages of 11 years and 10 months and sixteen years and 2 months in *E. grandis* planted at extremely dense stand stocking levels in Zululand was a real increase in the population mean and not merely an artifact of mortality in the smaller dbh classes. A second, associated null-hypothesis was that there was no increase in variation of dbh over the interval. The null hypotheses thus imply that there was not a positive location shift in mean dbh or an increase in dispersion of dbh for the four years. In the normal course of events both would be expected to increase over time.

The data are not independent. Under conditions of extreme suppression the smaller trees will be adversely affected to a greater degree than the larger trees. Between-tree competition is asymmetric and the growth of the smaller of any pair of trees is depressed more than the growth of the larger.

The investigation proceeded by means of paired samples of dbh at the beginning of the interval matched with dbh at the end of the interval on a per-tree basis. Thus only surviving trees were in the sample. Scrutiny of the distribution of differences between matched pairs showed it to be highly skewed to the right. The distribution has a very pronounced peak at zero indicating that a large proportion of the trees did not grow in girth over the interval. A scatter plot of the data appears as Figure 21 on page 151 and this clearly indicates that only the larger trees increased in size and thus deviate from the zero growth line indicated as the null hypothesis. Use of Kolmogorov-Smirnoff and Kuiper tests provided very strong evidence (DNS = 3.37) against the null hypothesis of a Gaussian distribution. This was reinforced by Randles'(1980) distribution-free test for symmetry (U = 0.44) and it was apparent that normal parametric procedures would be inappropriate for the study.

The sign test and Wilcoxon's signed rank test provided the means to strongly reject the null-hypothesis that the median difference between the 1964 and 1968 measurements is zero and it is concluded that mean dbh did indeed increase significantly over the interval. The Hodges-Lehman estimate of the median increase is 26 mm. which is enclosed by a 95% confidence interval of (25.5, 28.5) mm. The large sample thus made possible the specification of an extremely narrow confidence interval for the increase. Note that the median increase is 50% more than the mean increase of 17.3 mm. taken across replications.

Not only location differences are important and the Moses rank-like test (Hollander and Wolfe, 1973) for equal dispersion in paired samples provided very strong evidence ($p = 0.0002$) that the variance in dbh increased over the specified interval. As only surviving trees were included in the sample, the recorded increase in mean dbh bespeaks a real increase in the population mean and not merely a manifestation of variation change within a population where the mean has remained constant or changed very little.

These results indicate that diameter growth does occur under conditions of extreme suppression. During the interval of interest, stand density dropped from 3377 to 2982 S/ha on average across replications (see Figure 22 on page 152). This is a 11.7% loss in growing stock. It is growth under such conditions that results in the very steep slopes of Reineke's SDI and Yoda's self-thinning line as will be described in *Chapter IX*. However, the smaller trees have not increased in size and as a result variability in the diameter assortment has increased. This provides additional evidence against too-high stocking rates, as addressed by Bredenkamp and Schutz (1984), which result in stands being less uniform in terms of diameter assortment.

A second question concerning diameter growth under conditions of intense competition is the apparent surge in diameter growth, following significant mortality within the densest stands, which precluded use of the Chapman-Richards model to describe the diameter development with age. Quadratic mean dbh is by definition determined with stem count of the sample in the denominator of the equation. Mortality in the smallest degree must reduce the denominator and by the mere definition of the parameter, increase mean dbh (obviously the numerator is also reduced). This increase will be more marked when the trees which succumb are from the lower end of the diameter distributions as these contribute relatively less to the numerator of the equation.

Whether there is an upswing in dbh growth over and above this arithmetic increase was investigated by comparing the trends of mean diameter growth from a single population defined in two different ways. The bench mark is provided by the quadratic mean dbh, determined in the normal fashion, based on all trees found alive at each enumeration. The variable set of quadratic mean dbh estimates is based solely on those trees which survived until the most recent enumeration. This means the denominator in the definition formula is a constant through the life of the stand. The population of diameters consists of the arithmetic means across replications of $\overline{D}_q$ for each enumeration of the treatment with the most dense spacing from the age of twelve onwards. The results are shown in Figure 23 on page 153. The means based on the surviving trees are consistently higher but the difference diminishes with time as the samples on which the means are based become increasingly more similar. Mean dbh is continually increasing but there is no indication of an upswing which can be ascribed to anything over and above normal diameter growth. The dbh/age trend is virtually linear with a small bulge at 22 years. This deviation from the linear occurs at a time when there was an exceptional amount of mortality (See Figure 22 on page 152) which followed nearly a decade of below-average rainfall (See Figure 4 on page 134).

It is concluded that mean diameter growth of dominant trees continues irrespective of the degree of competition and the rate of growth of the dominant trees is not markedly affected by increased growing space made available through the mortality of suppressed trees.

Chapter VI

A comparison of growth between the Nyalazi and Langepan experiments

In order for the results of the Langepan experiment to be used with a reasonable degree of confidence at another site, it is desirable to know that the height/age relationships for the sites being compared are anamorphic. A site index equation incorporating stands as old as the experimental stands in question does not exist. There is no information available which might indicate whether polymorphism need be included and for purposes of the discussion which follows, there is no interest in site index *per se*. The interest is in allometric relationships of the components of stand volume where time is excluded.

The relationships between Nyalazi and Langepan were scrutinized on the basis of size (in terms of $\overline{D}_q$ and $\overline{H}_r$) at comparable ages. Fourteen approximately similar ages ranging from 2.50 to 27.83 years were selected for comparison. The mean absolute difference in age pairs was 0.29 years with the smallest difference in age being one month and the greatest being 10 months (nearly 3% of the age for the case in question). For the combined set of paired observations, the size at Nyalazi was considered a function of the size at Langepan as it was known *a priori* that growth at Nyalazi is poorer than at Langepan.

In the case of $\overline{D}_q$ it was found that

$$\overline{D}_{q_{NYALAZI}} = b_{153} + b_{154}\ \overline{D}_{q_{LANGEPAN}} + b_{155}\ \overline{D}^2_{q_{LANGEPAN}} \tag{50}$$

where $R^2 = 0.97$ and MSE = 756.6. The null-hypothesis that the quadratic component is zero was rejected with $P < 0.0001$, while for $\overline{H}_r$,

$$\overline{H}_{r_{NYALAZI}} = b_{156} + b_{157}\ \overline{H}_{r_{LANGEPAN}} \tag{51}$$

where $R^2 = 0.91$ and MSE = 6.7. The null-hypothesis of zero quadratic component was not rejected, $P < 0.41$.

The relationship between Nyalazi and Langepan in terms of mean tree volume ($\bar{v}$), determined according to the equations provided by Bredenkamp and Loveday (1984), was described as

$$\bar{v}_{NYALAZI} = b_{158} + b_{159}\ \bar{v}_{LANGEPAN} + b_{160}\ \bar{v}^2_{LANGEPAN} \tag{52}$$

The null-hypothesis that $b_{160} = 0$ was rejected with a probability of greater $|t|$ being less than 0.0001. Scrutiny of regression diagnostics indicated that the strength of the quadratic component could be attributed to two high-leverage data points. Both of these had values for $v_{LANGEPAN}$ in excess of 8 m^3. As these trees are considerably larger than any found under normal management and are extremely influential, they were excluded from the regression with the result that all indications of a quadratic component were removed ($P \geq |t| < 0.33$)[9]. The resultant linear equation was

$$\bar{v}_{NYALAZI} = b_{161} + b_{162}\ \bar{v}_{LANGEPAN} \tag{53}$$

where R^2 = 0.94 and M.S.E. = 0.065.

Although the significant quadratic trend in the dbh relationship will not influence the weighting technique (described later in *Chapter VI*) it was investigated further. Quadratic mean dbh is by definition a function of basal area and stand density and these two components were compared at equivalent ages using the techniques described above for $\overline{D}_q$, $\overline{H}_r$ and $\bar{v}$. In the case of stand density, N, the number of stems per hectare surviving at the age in question, the relationship is clearly linear. The additional variation explained when a quadratic coefficient was introduced to the linear model is negligible. The probability of finding a greater absolute value of t to test the null-hypothesis that the quadratic coefficient is zero was 0.94. The relationship can be described with

$$N_{NYALAZI} = b_{188} + b_{189}\, N_{LANGEPAN} \tag{54}$$

where R^2 = 0.97.

When the above was repeated for stand basal area (BA), a significant quadratic term was found. Scrutiny of the data revealed substantial differences in basal area during the early years. This could be ascribed to differences in timing of the thinnings in advance of competition. In general, thinnings at Nyalazi took place a few months later than those at Langepan. The result thereof, for particular enumerations, was that stands at

[9] The volumes of such exceptionally large trees are extrapolations beyond the data base on which the volume equations were fitted.

Nyalazi carried nearly twice the basal area of stands at Langepan of the same age. Once these cases had been identified and removed, all traces of a quadratic relationship disappeared ($P > |t|$, H_0: $b_2 = 0$, $=$ 0.96) and the relationship could be described as

$$BA_{NYALAZI} = b_{190} + b_{191}\ BA_{LANGEPAN} \tag{55}$$

The relationships are shown diagrammatically in Figure 24 on page 154, Figure 25 on page 155, Figure 26 on page 156, Figure 28 on page 158 and Figure 27 on page 157. The third-mentioned, the mean tree volume relationship, shows the two high-leverage data points which were not included in the fitting of the line as shown.

The relationships are well-defined and strongly linear in the case of height comparisons, the basis for site index quantification. The well-developed quadratic component in the diameter relationship is a surprising result which would not be detected were a narrower range of N_0 to be investigated. Fortunately the quadratic relationship is a monotonically increasing one (the coefficients are to be found in Table 26 on page 131) and there is thus every indication that growth at Nyalazi can be confidently predicted as a ratio of growth at Langepan, particularly as the weighting of predictions is on the basis of mean tree volume and mean tree height, not on mean diameter. Until evidence can be found to corroborate or reject this supposition, it will therefore be assumed that height and volume growth of *E. grandis* on any suitable site can be expressed directly as a proportion of such growth at Langepan.

The weighting algorithm.

Growth predictions for sites differing in growth potential to Langepan were made by weighting estimates based on the model developed from Langepan data. The weights are based on the ratio of mean tree height and mean tree volume between the two sites for stands which are of the same age and were planted at the same density, the Langepan values being estimated according to those criteria. The height and volume ratios thus determined are retained as constants for the stand in question.

When growth is simulated for a particular regime, the results are expressed in terms of mean dbh and mean height at Langepan. Mean tree volume is determined from these. The estimates of mean tree volume and mean height are then weighted with the applicable constants. The estimate of weighted mean dbh is obtained from manipulation of the volume equation where weighted mean height and weighted mean tree volume are the regressors and weighted mean dbh is the response.

Survival is based on the weighted estimate of survival at Langepan according to the empirical model described earlier (*Equation* 4), again using a simple ratio approach.

As an example of the weighting technique, suppose an 8-year old stand planted at 1200 S/ha has a mean dbh of 170 mm. and a mean height of 25 m. Mean tree volume is then 0.209 m^3 . A stand grown at Langepan could be expected to have an equivalent values of 196.23 mm., 23.81 m. and 0.277 m^3 respectively. The weighting factors will thus be 25/23.81 or 1.05 for mean height and 0.209/0.277 or 0.75 for mean tree volume. Were the stand to be grown to twelve years, Langepan estimates would be 229.5 mm., 29.84 m. and 0.44 m^3. After weighting the height and mean tree estimates with the above factors, expected mean dbh is found from the volume equation and the dbh weighting factor is found to be 0.85. The estimated values for the "other" site are then 195.37 mm., 31.34 m. and 0.33 m^3.

The survival weighting would be 1.02 were the 8-year old stand to have 1000 S/ha surviving at that stage. At twelve years it is expected that 993 S/ha will be alive and the resultant expected weighted stand volume will be 332.68 m^3/ha.

Chapter VII

Modeling the growth of thinned stands of *Eucalyptus grandis*

In order to model the effects of thinning, so-called "chainsaw effects", thinning was simulated using data from unthinned treatments in the basic series of plots at Langepan. As only low-thinning is practised in South Africa, only thinning from below was investigated. For each plot having $N_0 \geq 247$ S/ha (to ensure reasonable sample size) and for each enumeration after the age of 6.50 years, mean diameter, minimum diameter, mean height and top height were calculated as described in *Chapter IV*. Diameter observations[10] were ranked and categorized into twenty size classes, the size class limits being specific to each plot for each point in time. Trees were then "removed" from below, one class at a time and each class removed represented a 5% thinning. After each class was removed, the four parameters mentioned above were calculated for that degree of thinning. The coefficients of the log height/reciprocal dbh relationship used for the

[10] The simulation was based on 34074 diameter observations.

calculation of mean and top height were held constant on a per-plot basis for all thinning simulations. The degree of thinning ranged from 5% through 60% with the no-thinning level retained as benchmark. There were 3718 simulated observations available for modelling.

The first parameter to receive attention was regression mean height of a stand and the response variable modelled was the ratio of mean height after thinning ($\overline{H}_{at}$) to mean height before thinning ($\overline{H}_{bt}$). This was constrained to ensure a positive result as the log-height/reciprocal-of-dbh relationship used ensures that mean stand height cannot decline.

The initial screening of potential variables was by means of forward and backward selection using stepwise regression. Variables meeting the significance levels for entry into the model, regardless of priority, were retained. Final selection was based on Mallows' C_p and PRESS statistics. The latter was calculated through a subroutine in PROC MATRIX of SAS (1985). The model yielding the smallest value for both criteria was

$$ln\,(\overline{H}_{at}\,/\overline{H}_{bt} - 1) = b_{163} + b_{164}\,TP + b_{165}\,S/ha_{bt} + b_{166}\,(\overline{D}_q\ -\ \overline{D}_m)^2 + b_{167}\,\overline{H}_{bt}/\overline{D}_q \quad (56)$$

where TP = percentage stems removed in thinning from below and the parameter estimates appear in Table 26 on page 131.

However, the stand density before thinning and the spread of diameters have a very minor role to play, albeit both are highly significant components ($P > F < 0.0001$). Their inclusion contributes virtually nothing to R^2 while resulting in larger variance in prediction through overfitting. Their exclusion is supported by PRESS and collinearity diagnostics. The final model selected is

$$ln\,(\overline{H}_{at}\,/\overline{H}_{bt}-1)=b_{168}+b_{169}\,TP+b_{170}\,\overline{H}_{bt}\,/\,\overline{D}_q \tag{57}$$

where $R^2 = 0.762$.

It is of interest to note that the height/diameter ratio was consistently selected to be the most influential variable in screening procedures. By contrast, although highly significant statistically, the ratio is relatively unimportant in the production of a chainsaw increase in top height brought about by thinning. In this case the best model amongst those scrutinized is

$$ln\,(\overline{H}_{t_{at}}\,/\,\overline{H}_{t_{bt}}-1)=b_{171}+b_{172}\,TP+b_{173}\,S/ha_{bt}+b_{174}\,\overline{H}_{t_{bt}}\,/\,\overline{H}_{r_{bt}} \tag{58}$$

where $R^2 = 0.47$. Here the top height/mean height ratio proved to be the most influential variable.

The thinning-increase in mean and minimum diameter can be found through manipulation of the Weibull distribution for which the moments were modelled in *Chapter IV*. One need only truncate the lower diameter classes until the required proportion of the stand density has been removed and then repeat the calculation of the mean. However, there are cases when it will be more convenient to have direct access to a prediction equation and the chainsaw effect on mean- and minimum dbh were modelled in conjunction with mean- and top height.

The model selected to model mean diameter increase with thinning is

$$\ln\,(\overline{D}_{q_{at}}\,/\,\overline{D}_{q_{bt}}-1)=b_{175}+b_{176}\,TP+b_{177}\,D_m+b_{178}\,\overline{H}_r\,/\,\overline{D}_{q_{bt}} \tag{59}$$

Here R^2 is 0.758. This equation (59) is only marginally better in terms of fit statistics than the more parsimonious

$$\ln\ (\overline{D}_{q_{at}} / \overline{D}_{q_{bt}} - 1) = b_{179} + b_{180}\ TP + b_{181}\ \overline{H}_r / \overline{D}_{q_{bt}} \qquad (60)$$

where R^2 = 0.754 but C_p increases from 16.2 to 71.5. The latter form is provided for cases where D_m is unknown. The simulation program listed in *Appendix C* requires D_m for weighting stands in areas of growth potential different to Langepan. The former equation is used to estimate the thinning increase in $\overline{D}_q$ as $\overline{D}_m$ is generated internally in the program for Langepan conditions.

The model selected to estimate the increase in minimum dbh brought about by thinning is

$$\ln\ (\overline{D}_{m_{at}} / \overline{D}_{m_{bt}} - 1) = b_{182} + b_{183}\ TP + b_{184}\ \overline{H}_r / \overline{D}_{m_{bt}} + b_{185}\ \overline{H}_r / \overline{D}_q \qquad (61)$$

where R^2 is 0.90.

In similar vein, the regression mean height can be found from top height and *vice versa* with

$$\ln\ (\overline{H}_t / \overline{H}_r\ - 1) = b_{188} + b_{189}\ \overline{H}_r / \overline{D}_q + b_{189}\ (\overline{D}_q - \overline{D}_m) \qquad (62)$$

where R^2 = 0.71 and M.S.E. = 0.229.

Changes with time in thinned stands of E. grandis

As detailed in Table 2 on page 33 and described in *Chapter III*, there are eight thinning treatments appended to two of the replications of the Langepan C.C.T. experiment in *E. grandis*. Thinning treatments can be regarded as being in three categories. The first, plots 13 through 16, were termed the "mathematically co-ordinated series." These plots received the same thinning treatments in terms of intensity, as well as number and length of interval between interventions. The essential difference was the age at which thinnings were initiated as this was four years later for each treatment in sequence. Analysis was in terms of cumulative stand volume defined as the standing volume of the stand (m^3/ha) at the time of the enumeration plus the accumulated volume removed in thinning operations after the age of four years. Volume lost due to mortality was not included.

For an unknown reason, tree heights were not recorded for plot 15 at any stage prior to the age of 10 years. In order to obtain an estimate of such heights for the calculation of volume, height/dbh regressions were computed from pooled data of plots 13, 14 and 16 for each enumeration. Mean height for plot 15 was then estimated from $\overline{D}_q$ determined in plot 15 and coefficients of the pooled height/dbh equation. Mean height for plots 13, 14 and 16 were obtained from plot-specific regressions.

At no stage were significant differences in replications or treatments in terms of cumulative stand volume detected through analysis of variance for the data of each enumeration from the age of 6.5 years onward. As a result no paired comparisons of means are valid. The differences between the highest and lowest volumes are as much as 20%, or

250 m^3/ha, and the ranked means are presented in Table 22 on page 127. The reader is again cautioned that none of these differences are significant. In terms of standing volume, no significant differences were detected after the stands were fifteen years old. Prior to that, they appeared to be ranked in two groups, the stands thinned earlier and those thinned later. Although it must be borne in mind that no significant differences were detected, once all thinning treatments had been applied, it appeared as if the stands thinned earliest carried the greatest standing volume and produced the least cumulative volume. Conversely those thinned later carried the least volume and produced the greatest volume. For purposes of this exercise, all thinnings at ages 6.50 years and earlier were considered thinnings to waste and thinning yields were disregarded.

The remaining four thinning treatments were designed as two matched pairs of treatments. In the first, stands were planted at the same stand density and thinned with different degrees of release once competition had commenced.[11] In the second pair, stands at different "initial" stand densities were thinned to the same stand density and left. Details of the treatments appear in Table 2 on page 33. Very few statistically significant differences were detected. There is no difference in terms of stand density between treatments 18 and 19 and at no stage are there significant differences in terms of volume produced. In the earlier years the stands with the highest stand density carry the greatest volume but from the age of twenty years they start to fall behind. These changing trends do not result in significant differences within the time interval investigated. Also, despite non-significant differences, the stand thinned earliest at all stages carried the least volume and also produced the least accumulated over time. This appears anomolous and certainly contrary to expectation. It is known, however, that these plots were heavily

[11] Note that in the unthinned stands, nearly one third of the planted stems had succumbed to mortality by that age.

infested with weeds following the thinning (C.J. Schutz, personal communication) and it can be surmised that they never recovered. The results of comparisons of paired means are presented in Table 23 on page 128.

The thinning algorithm.

The thinning algorithm tracks the growth of $\overline{D}_q$ and $\overline{H}_r$ through time with arithmetic increases at times of thinning and lateral adjustment to the growth trajectory of an unthinned stand grown at the stand density to which thinned, as shown in Figure 29 on page 159. The lateral adjustment keeps the size of the growth parameter constant while shifting the time scale to an index age where the stand would have attained the given size if it had been grown at the stand density to which it is being thinned. The period prior to the first thinning is simulated using the unthinned model as described in *Chapter IV* and the arithmetic increase is calculated by means of *Equation* (59). The age at which the next operation takes place, whether a subsequent thinning or clearfelling, is determined as the length of the interval between operations added to the index age. A new index age is obtained following each operation and the index age is always less than the actual age.

In the case of mean height no lateral shift in the trajectory takes place. Mean height is not directly correlated with stand density, as in the case with diameter, and the shift could be either positive or negative depending on the degree of thinning. The thinning effect is always positive and is added by means of *Equation* (56) and the mean height then follows a trajectory equidistant to that of the stand density to which the stand is being thinned.

Chapter VIII

Mean annual volume increment in *Eucalyptus grandis* at Langepan

The age at which mean annual volume increment (m.a.i.) reaches a maximum is a statistic having considerable significance for forest management. Although it is simply the average annual growth at any given year, the yield of timber is maximized over perpetual rotations if clearfelling takes place at the age where m.a.i. reaches a maximum, rather than at the age where timber yield reaches a maximum (Leuschner, 1984). The age at which m.a.i. culminates is therefore a good initial estimate of rotation length as it is based on productive capability of the stand. Continuous use of any other rotation age must result in a lower annual production on average. The rotation based on m.a.i. results in maximum volume production. However, rotation age based on m.a.i. is also related to site quality. Trees grow more slowly on poorer sites and this leads to an increase in rotation age. As a result of the importance of m.a.i., the behavior thereof was investigated independently of the modelling effort.

For each enumeration of each plot, mean tree volume was estimated from quadratic mean dbh and regression mean height through use of the volume equations for *E. grandis* provided by Bredenkamp and Loveday (1984). Stand volume was found as the product of mean tree volume and the number of stems per hectare alive and m.a.i. as the quotient of stand volume and stand age. The units thereof are thus m^3/ha p.a. Mean m.a.i. was found as the average across replications and plotted against stand age for each treatment. Three distinct patterns were revealed. For N_0 of 124 S/ha or less, the trend was a continually increasing monomolecular type. For N_0 between 247 S/ha and 988 S/ha the m.a.i. appeared to tend towards an asymptotic value while the more dense treatments exhibited the shape usually exemplified in texts (Clutter *et al* 1983; Avery and Burkhart, 1983; Leuschner, 1984), namely a steep ascent to a relatively flat plateau followed by a gradual decline. See the upper graph in Figure 31 on page 161. Note that m.a.i. curves for values of 988, 2965 and 6726 S/ha for N_0 are not indexed. For all practical purposes they coincide.

As the data reach well beyond the rotation age used in practice and an asymptote is suggested, it would have been tempting to describe the m.a.i. development with an asymptotic model. The imposition of an asymptote by a model is undesirable as the implied asymptote can be misinterpreted and misused (Knight, 1968). The m.a.i. development was therefore described with

$$Mean\ \ m.a.i. = b_l + b_j \ln Age + b_k\, Age \tag{63}$$

Equation (63) was fitted to each treatment and provided an adequate fit to the data up to well beyond normal rotation age. In several instances the model tended to underestimate m.a.i. at advanced ages, as described for dense treatments above.

The age of culmination was found by equating the first derivative of the above equation (63) to zero and solving for age:

$$\frac{\partial m.a.i.}{\partial age} = \frac{b_1}{age} + b_2 \tag{64}$$

It follows that

$$Age_{m.a.i.\ culmination} = b_1 / b_2 \tag{65}$$

The age at which m.a.i. culminates was then regressed on nominal stand density and fitted with

$$Age_{m.a.i.\ culmination} = b_{138} + b_{139} \ / \ ln\ N_0 \tag{66}$$

R^2 is 0.89 and M.S.E. = 8.31. The fit of this equation is shown in Figure 30 on page 160.

It is apparent that the age of m.a.i. culmination is considerably higher than the rotation age used in practice for stands other than sawtimber stands. Consequently an investigation was conducted to determine at which ages certain proportions of maximum m.a.i. are attained. These ages were found by solution of the following equation to find the smaller of the two roots. Instead of applying a graphical technique, a numerical search was carried out to find values of X (= age) which would result in a difference of less than 0.001 between the two sides of the equation[12].

[12] This model form emanates from the fitting of m.a.i. as a function of age as in *Equation (63)*

$$-ln\, X = \frac{b_l - m.a.i.}{b_j} + \frac{b_k}{b_j}\, X \qquad (67)$$

The results are presented in Table 17 on page 122.

It is apparent that, due to the steepness in slope of the m.a.i./age development, a considerable proportion of the maximum m.a.i. can be attained in a substantially shorter period of time. For example, with a nominal stand density of 988 S/ha, 90% of the maximum m.a.i. is reached in 54% of the time it would take for m.a.i. to culminate. However, any rotation shorter than the time required to attain maximum m.a.i. will of necessity provide a yield smaller than what is possible to achieve on a sustained basis.

An estimate of m.a.i. was obtained from the unthinned stand model (which will be denoted as Model I in subsequent discussion concerning m.a.i.) for comparison with each observed value. There is a great deal of variation due to a compounding effect in the estimation of two variables. For example, in the case of N_0 at 5.67 years, an underestimate of 14% in $\overline{D}_q$ and an underestimate of 9.5% in $\overline{H}_r$ result in an underestimate of $m.\hat{a}.i.$ to the order of 36%. The observed and estimated values of m.a.i. were compared for each N_0 by means of paired-comparison t-tests. The results are shown in Table 18 on page 123.

Statistically significant differences between observed and estimated m.a.i. are detected in five of the twelve spacing treatments. In two of these cases, the significant difference is less than one m^3 per hectare *per annum* A serious underestimation occurs in the case of N_0 = 1482, however, where the mean difference is 7.59 m^3. The overall mean difference between observed and estimated m.a.i. from the unthinned Model I is 0.75 m^3 per hectare *per annum*, with a standard error of 0.37, across all replications and all treatments. The results are presented in Table 18 on page 123.

The estimates of m.a.i. from the unthinned model (Model I) were also compared with "observed" values of m.a.i. on a per-enumeration basis, again using paired-comparison t-tests to test the null-hypothesis of no difference between estimates. The null-hypothesis was rejected at ages 5.67, 10.17 and 18.17 years when the mean differences were 4.46, 3.37 and 2.91 m^3/ha p.a. respectively. The results of the t-tests are shown as Table 20 on page 125.

The parameter estimates (b_m) from the m.a.i./age relationship as fitted with *Equation* 63 were described as functions of N_0 by means of cubic polynomials such as

$$Coefficient_m = b_i + b_j \ \ln \ S/ha + b_k \ \ln^2 S/ha + b_l \ \ln^3 S/ha \tag{68}$$

The R^2 for the three fittings of parameter estimates are respectively 0.93, 0.85 and 0.79. The higher order components would not all have passed rigorous statistical scrutiny but they were nevertheless all retained and the following twelve parameter model was fitted:-

$$m.a.i. = b_{0_m} + b_{1_m} \ \ln \ Age + b_{2_m} \ Age \tag{69}$$

where

$$b_{0_m} = b_{141} + b_{142} \ S/ha + b_{143} \ (S/ha)^2 + b_{144} \ (S/ha)^3 \tag{70}$$

$$b_{1_m} = b_{145} + b_{146} \ S/ha + b_{147} \ (S/ha)^2 + b_{148} \ (S/ha)^3 \tag{71}$$

$$b_{2_m} = b_{149} + b_{150} \ S/ha + b_{151} \ (S/ha)^2 + b_{152} \ (S/ha)^3 \tag{72}$$

and where R^2 is 0.94. This is Model II.

As for Model I, validation was by means of paired comparison t-tests across both N_0 and age of measurement as shown in Table 19 on page 124 and Table 21 on page 126. Both models perform equally poorly at very low stocking levels but Model II has smaller deviations from the observed m.a.i. when compared across age and stand density. The advantage of Model II is in the direct estimation of m.a.i. without dependence on a mortality function.

Despite the fact that prediction of observed m.a.i. appears to be poor, Model II does particularly well when it is used to mimic the fitted curves of m.a.i./age as shown in Figure 31 on page 161. It is apparent that the level of the 6726 S/ha curve is too high. This can be attributed to the cubic term of the intercept. It is also readily apparent that Model II is considerably over-parameterized. Twelve terms to describe a relatively simple response must of necessity lead to redundancies amongst the parameters. A further model was therefore fitted in which each variable and interaction from those in Model II appears only once and stepwise regression was used to select a more parsimonius model. The model selected is

$$m.a.i. = b_{192} + b_{193} N \ln A + b_{194} \ln N \ln A + b_{195} \ln N \ln^2 A + b_{196} \ln^2 N \ln^2 A \quad (73)$$

where N is stand density (S/ha), A is age (years) and $R^2 = 0.91$. The regression analysis showed each parameter estimate to differ significantly from zero with $p > |t| \leq 0.0001$.

Chapter IX

A critical look at spacing indices at Langepan

During the design phase of the C.C.T. project O'Connor used three principles as starting points: Apart from (a) accident and disease, and (b) factors such as grass competition and differences in exposure, the following hold true:

1. In any given locality the size attained by a tree of a particular species at a given age must be related to the growing space previously at its disposal; all other factors influencing its size are fixed by the locality.

2. Trees planted at a given spacing will, until they start competing with each other, exhibit the absolute or normal standard of growth for the species and locality.

3. Trees planted at a given spacing and left to grow unthinned will exhibit the absolute or normal standard of growth for the species, locality, and the particular density of stock in question.

It is of interest to note that genotypic expression is ignored in the above and, although accident and disease are included, it is assumed that there are no other interactions with insects, herbivores, interspecific competition and allelopathy, for example. However, O'Connor postulated that an S-curve would define the boundary between the free-growing zone and the zone of suppression when mean tree volume was plotted against stand density. Whether O'Connor was aware of the work of Reineke published two year's earlier is cause for speculation as there are striking similarities between the two concepts. The essential difference being a question of scaling as the latter used logarithms and O'Connor used untransformed variables. Reineke's SDI and Yoda's power law have been widely investigated in the forestry world whereas O'Connor's premise is largely unknown. The feasibility for use of each of these with *E. grandis* was examined.

Stand density index

The slope of the line defining Reineke's SDI is found from the relationship between the logarithm of the number of stems per unit area to the logarithm of quadratic mean diameter. The slope is unaffected by units of measurement or base of logarithm although the latter markedly influences the position of the intercept. In this study, SDI was based on a tree with a dbh of 250 mm. for metric usage and the definition formula is thus

$$SDI_{250} = S/ha\,(250/\overline{D}_q)^{b_{104}} \tag{74}$$

A scatter plot indicated that the least dense plots had not yet approached a limiting density. The initial investigation was thus limited to stands where N_0 exceeds 100 S/ha and age exceeds 23 years. Thus only the last three sets of enumeration data for 10 plots per replication were included. A straight line was fitted and an estimate of -2.329 was obtained for b_{104}, the slope term whereas R^2 was 0.96. Use of common logarithms resulted in an intercept of 8.75 and natural logs resulted in an intercept of 20.12. The expected ratio of the slopes is ln(10) or 2.302. The slope is considerably steeper than the -1.6 found by Reineke (1933) for a wide range of species.

The data set was expanded to include all enumerations after the age of 10 years (thus ten sets of measurements in all) from all treatments where $N_0 \geq 124$ S/ha for each replication. This resulted in 30 subsets of 10 observations for which SDI relationships could be fitted. A single regression model was fitted to the pooled data using 29 binary indicator variables according to the method described by Neter and Wasserman (1974).

The model fitted can be written

$$\ln N = \beta_0 + \delta_1 X_1 + \ldots + \delta_{29} X_{29} + \beta_1 \ln \overline{D}_q + \gamma_1 (X_1 \ln \overline{D}_q) + \ldots + \gamma_{29} (X_{29} \ln \overline{D}_q) \quad (75)$$

where X_i = 1 if observation is from age_i, $replication_j$; 0 otherwise.

In order to test jointly whether the intercepts and slopes of the 30 SDI lines can be considered equivalent, the above model was tested against the reduced model

$$\ln N = \beta_0 + \beta_1 \ln \overline{D}_q \quad (76)$$

The F-statistic used to null-hypothesis of no difference between the SDI lines was constructed as

$$F = \frac{\dfrac{SSE_{reduced} - SSE_{full}}{df_{reduced} - df_{full}}}{MSE_{full}} \quad (77)$$

In the case of the joint testing an F-value of 11.23 was found and the null hypothesis was not accepted.

In order to test whether the slopes of the SDI lines are the same, the following full model was fitted

$$\ln N = \beta_0 + \beta_1 \ln \overline{D}_q + \gamma_1(X_1 \ln \overline{D}_q) + ... + \gamma_{29}(X_{29} \ln \overline{D}_q) \tag{78}$$

In this case *Equation* (77) yielded an F-value of 22.73 and the null-hypothesis is clearly not accepted. In order to test whether the intercepts are all the same, i.e. $H_0 = \delta_1 = \delta_2 = ... = \delta_{29}$ the following full model was fitted

$$\ln N = \beta_0 + \delta_1 + ... + \delta_{29} + \beta_1 \ln \overline{D}_q \tag{79}$$

Application of *Equation* (77) yielded an F-value of 20.94 and the null-hypothesis is again clearly not accepted. The conclusion drawn is that the slope and intercept of the SDI line vary with age.

Overlaid plots of the 30 fitted lines are shown in Figure 33 on page 163. These indicate a trend with lines tending away from the parallel, having decreasing slope with increasing age. The slopes shown in Figure 33 on page 163 range from -2.16 to -2.84 with an overall mean of -2.51 from averaging all the slope values. The relationship between the coefficients of the SDI lines and age were further investigated by means of regression. The intercept coefficient is best described by

$$Intercept_{SDI} = b_{105} + b_{106}\, Age \tag{80}$$

where R^2 = 0.59 and the probability of a greater t for the slope is 0.0001. There were no higher terms of any statistical significance. However, the slope coefficient of the SDI lines can be described as

$$Slope_{SDI} = b_{107} + b_{108}\,Age + b_{109}\,Age^2 \tag{81}$$

where R^2 = 0.76 and the p-values for the linear and quadratic terms are respectively 0.001 and 0.047 respectively.

The implication of the above is that SDI is significantly affected by age. With increasing age, the slope becomes progressively less steep while the level of the intercept is falling. It is clear that the lines defining SDI are thus not parallel. However use of the quadratic results in potentially undesirable extrapolation properties and the slope term was therefore described with an hyperbola where R^2 = 0.80 and MSE = 0.0045. A more appropriate expression of stand density index, using the model formulated by Reineke, in the case of *E. grandis* therefore would be

$$SDI_{250} = S/ha\,(250/\overline{D}_q)^{b_{186} + b_{187}\,/\,Age} \tag{82}$$

Examples of SDI lines based on this relationship for selected ages, showing changing slope, appear in Figure 34 on page 164 and the parameter estimates appear in Table 26 on page 131.

O'Connor's S-curve.

It was postulated by O'Connor that periodic measurements of trees planted at a range of stand densities would permit the deduction of when competition started. A curve connecting the starting points of competition would denote the boundary between a free-growing zone and a zone of suppression as shown in Figure 35 on page 165. As the S-curve has potential use as base for a spacing index, it was investigated whether a S-curve could be defined for *E. grandis* For each enumeration, mean tree volume was plotted against stand density (N_0) in descending order of magnitude as shown in Figure 36 on page 166. There is no indication of an inflection (or shoulder as postulated by O'Connor) at the onset of competition. As some information may be hidden by the choice of scale, an enlarged version showing some of the earlier enumeration data is presented as Figure 37 on page 167. There is no graphical evidence that a S-curve could be defined and it is concluded that inter-tree competition begins very early, even at wide spacings. The result thereof is a much-reduced and ill-defined free-growing zone and there is no justification to pursue the matter any further.

Power-law of self-thinning.

The power-law of self-thinning (Yoda *et al*, 1963) is based on the straight-line relationship of mean tree volume to stand density on a log-log scale. The self-thinning relationship is a simple transformation of Reineke's SDI. The concept has received much attention in the forestry literature and as a consequence the applicability thereof to *E.*

grandis was also investigated. As the wider spacings in the Langepan study have still not reached a limiting stand density, the Yoda relationship is curvilinear, not linear. The investigation was therefore restricted to stands where N_0 exceeds 100 S/ha, thus avoiding any apparent curvilinearity in the relationship. The base equation was fitted to those stands older than 23 years as had been done for Reineke's SDI. The resultant equation is

$$\log_{10} v = b_{110} + b_{111} \log_{10} N_0 \tag{83}$$

where $R^2 = 0.93$ and M.S.E. = 0.008.

When this model was fitted independently to the data of each enumeration after the age of ten, the slope coefficients ranged from -0.91 to -0.80 with an arithmetic mean of -0.87. Similarly the intercepts ranged from 2.02 to 2.82 with a mean of 2.50. It was apparent that both parameters are strongly affected by age. The regression of the parameter estimates on age resulted in

$$Intercept_{Yoda} = b_{112} + b_{113} \,/\, Age \tag{84}$$

where $R^2 = 0.98$ and M.S.E. = 0.0015[13]. The hypothesis that b_{114} is zero was rejected with $P > |t| = 0.012$

$$Slope_{Yoda} = b_{115} + b_{116}\, Age \tag{85}$$

where $R^2 = 0.60$ and M.S.E. = 0.0005. The parameter estimates from the above two equations were combined in the form of *Equation* (83) and fitted again. The resultant equation is thus

[13] Note that estimates of variance are not unbiased.

$$\log_{10} v = b_{117} + b_{118} / Age + b_{119} \log_{10} N_0 + b_{120} Age \log_{10} N_0 \tag{86}$$

with an R^2 of 0.97.

Relative spacing

For each enumeration, relative spacing (RS) was calculated for each plot of the basic series as

$$RS = \frac{\sqrt{10000/(S/ha)}}{H_d} \tag{87}$$

When plotted against age at time of enumeration, a typical inverse-J trend was revealed *except* where N_0 = 6726 S/ha. In this latter case there was some indication of a slight increase in RS, after the age of twenty years, following a plateau of fiteen years duration. An inverse-J trend is to be expected where dominant height increases and stand density remains relatively constant. However, if the rate of change of stand density due to mortality is rapid, as is the case with the very dense stands, it is not unreasonable for RS to increase, particularly if height growth is also diminished. The RS/age relationship is shown in Figure 38 on page 168 and Figure 39 on page 169.

Means were taken across replications and for each N_0, the relationship between relative spacing and age was described with

$$RS = b_l + b_j A^{b_k} \tag{88}$$

Examination of the residuals against predicted values showed disquietingly strong structure, indicating an inadequate model. However, the sizes of the residuals were very small. All the structure was concentrated at the lowest end of the scale, for the smallest values of the predicted values, and therefore no further attention was paid to this aspect. When predicted values were plotted against observed RS, no notable discrepancies could be detected, except for the case of $N_0 = 6726$ S/ha where the fitted model could, of course, not track the slight upswing.

Examination of the relationship between the parameter estimates from the fitting of Equation (88) and N_0 revealed further inverse-J relationships. These were well-defined for b_i and b_j while the relationship between b_k and N_0 is poorly defined, there being only a limited range of values (-1.97,-1.72) for b_k .

The intercept term was described with

$$b_{0_{RS}} = b_{122} + b_{123}\, N_0^{b_{124}} \tag{89}$$

where an approximate $R^2 > 0.99$ and MSE < 0.0001. The rate term was described with

$$b_{1_{RS}} = b_{125} + b_{126}\, N_0^{b_{127}} \tag{90}$$

where $R^2 > 0.99$ and MSE = 0.018. The shape term, b_k was described as a line with

$$b_{2_{RS}} = b_{128} + b_{129}\, N_0 \tag{91}$$

where $R^2 = 0.50$ and MSE = 0.0029.

The coefficients estimated in the three equations above were used as starting values to obtain parameter estimates of

$$RS = b_{130} + b_{131}\, N_0^{b_{132}} + (\, b_{133} + b_{134}\, N_0^{b_{135}}\,) A^{b_{136} + b_{137} N_0} \tag{92}$$

where an approximate $R^2 > 0.99$ and MSE = 0.0022.

The efficacy of the fitting of *Equation* 92 was evaluated by perusal of the differences between estimated and calculated values observed over time, for each N_0. Differences fluctuate in sign and are relatively large up to the age of 2.5 years. The apparent fluctuation being due to differences between replications. Beyond 2.5 years differences are generally much smaller than 20% of the calculated value. There is a general tendency for the model to underestimate (positive differences) relative spacing between the ages of 5 and 20 years and a tendency to overestimate RS thereafter. Despite the fact that differences tend to be small, relative differences are as great as 0.35 in extreme cases.

The availability of good estimates of both RS and top height implies a possible method of estimating stand survival through

$$N_t = \frac{10000}{(\overline{H}_d\, \hat{RS})^2} \tag{93}$$

Surviving stand density (N_t) was estimated for each enumeration using the above equation where $\overline{H}_d$ is the mean of three replications and $\hat{RS}$ is estimated via *Equation* (92). A general pattern, with the exception of the three treatments with the highest N_0, is an underestimate until the fifth year, a period of "adequate" estimation until the fifteenth year and underestimation thereafter. Survival in the most dense treatments is adequately estimated until the fifth year and overestimated thereafter. These trends indicate inadequacies in the decay model used to describe the RS/age relationship.

The technique described here is clearly unsuitable for estimation of survival. Differences are large at virtually all ages and the trend is for increasingly poor estimation with advancing age. Even at low N_0 where no mortality is expected, mortality is estimated to be severe via the RS estimation. This is demonstrated for a range of N_0 in Figure 40 on page 170.

A potential link between mortality and relative spacing was investigated by means of standard analysis of variance. For each enumeration, all trees were classified in deciles according to recorded d.b.h. and mortality was expressed as a proportion of the number of trees which had died per decile subsequent to the previous enumeration. The lengths of the periods between enumerations varied from one month to five years. The proportions of trees which died are shown in Table 16 on page 121. It is immediately apparent that the greater proportion of mortality, indeed 95% of the mortality recorded in the unthinned stands of *E. grandis* at Langepan, is from the lower third of the diameter distribution. The second-to-last entry of Table 16 on page 121 shows the numbers of deaths which have been recorded, per decile. The last entry shows the percentage of mortality by d.b.h. classes.

It was postulated that the proportion of trees which died (the table entries from Table 16 on page 121) is determined by d.b.h. class (= decile), relative spacing and age, together with possible interactions. Relative spacing proved to be of consequence only in the absence of age as a predictor. Of the variables screened, only age, d.b.h. class and an age-class interaction had significant numerical associations with mortality as defined above. The probabilities of a greater F-value for the three are 0.0001, 0.013 and 0.048 respectively and the null-hypothesis of no influence of age and size class is strongly rejected while there is strong evidence of an influential interaction term. The influence thereof is tenuous, however, as only 29% of the variation is accounted for.

Perusal of Figure 38 on page 168 shows that RS tends to a limit. The lowest recorded RS for a plot at Langepan is 0.046. This value was not maintained; it subsequently increased at the next enumeration[14]. The minimum values (other than for the 0.046) attained by the five highest stand densities ($N_0 \geq 988$ S/ha) are 0.057, 0.052, 0.050, 0.051 and 0.050 respectively. It appears as if 0.05 is a limiting level of RS, and thus stand density, for *E. grandis* and could therefore be considered a representation of "a measure of the ultimate depths of suppression" referred to by Marsh (1961). The value of 0.05 for RS cannot be used as a self-thinning line. Considerable competition mortality occurred in the high-density plots when RS had values in excess of 0.05 and 0.10 could be used as a rule of thumb to identify a stand as being in jeopardy of a crash in stand density.

In conclusion of the subject of spacing indices, it is clear that not one of SDI, power law of self-thinning, O'Connor's S-curve or relative spacing is without problems in defining a limiting density for *E. grandis*. A major contributing factor to this problem is the species' ability to continue in growth (See *Chapter V*) despite severe crowding. This results in very steep slopes for SDI and self-thinning lines as well as declining RS without concomitant decline in stem number. Inter-tree competition starts too early for O'Connor's S-curve to be defined and the potential of the curve could not be assessed. RS is however the preferred guide as it incoporates not only stand density but also site index and age which are implicit in dominant height.

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[14] RS in loblolly pine reaches a minimum (ca. 0.125 - 0.175) and then also increases slightly (Burkhart, personal communication).

Chapter X

Recommendations and Conclusions

There are problems associated with the analysis of the C.C.T. experiments, particularly in that the thinnings during the establishment phase may have an unknown influence on later growth trajectories. These influences cannot be quantified. Nevertheless, these experiments cover a wide range of replicated stand densities and represent an irreplaceable resource. It can be argued that they have served their purpose, being well past normal rotation age for the species but it is exactly this aspect which makes the results even more interesting and valuable for modeling purposes. It is recommended that the C.C.T. experiments be retained for as long as feasible with a full enumeration every fifth year at the very least. These should also be supplemented with additional experiments established with growing stock which will reflect the tremendous strides in recent decades in terms of genetic improvement. These should utilize experimental designs not fraught with the difficulties introduced by the C.C.T. establishment procedures and attempts should be made to cover a wide range of growing sites, more representative of the industrial range than Zululand alone. Throughout this study, differences between blocks were found to be non-significant. This implies that blocking did not result in an increase in efficiency and nothing was gained therefrom. It also implies that inference to other sites is strictly limited.

The major problem encountered with the modeling of *E. grandis* which remains unresolved is the question of prediction of mortality. A survival equation based on Clutter's analytical model (Bredenkamp, 1988) proved to be essentially unusable. An empirical model based on the Langepan data is useful but it has major deficiencies. It is recommended that the matter be pursued with emphasis on the distribution of deaths amongst size classes and use of the $\overline{H}_r : \overline{D}_q$ ratio as predictor.

Predictions by the model described in this study gave good results when validated against independent data from the Nyalazi C.C.T. experiment with the exception of $\overline{D}_m$. As this estimate forms the location parameter of the diameter distribution it is of great importance and this aspect requires further attention. It is important to note (as shown in Table 11 on page 116) that minimum dbh increases very little, if at all, at dense spacings. This has a profound influence on the diameter distribution at dense spacings.

As regards spacing indices for *E. grandis*, it is clear that O'Connor's postulation is not feasible while Reineke's index and Yoda's law are not age independent. Relative spacing holds a lot of promise. An absolute minimum value of relative spacing for *E. grandis* has been determined but the level at which there is a very real danger of severe mortality is not fixed. Further work is required to establish practical guidelines which can be used to flag potential crises in simulation routines.

Scrutiny of parameters based on the mean, such as mean diameter, alone is insufficient to determine the growth status of stands of *E. grandis*. Increasing diameter in overstocked stands may be attributed to growth in upper size classes only. The mining industry in particular, which is the largest single market for the species, has stringent minimum and maximum size standards and a large proportion of a stand may be stagnant at sub-minimum size when an increase in the mean can be attributed to growth in already over-sized material. Decreased planting densities or early respacement thinnings can effectively be used to maintain optimum spacing.

There is no doubt that the vast majority of South African plantations of *E. grandis* are managed on rotations which are too short in terms of optimum volumetric recovery. Mean annual increment culminates from the twefth year onwards, depending on stand density, at Langepan. The acceleration in increment is very rapid and a substantial proportion of the maximum potential yield can be harvested when the rotation length is shortened within reasonable limits but the long-term result will be a substantial loss in fibre. An increase in rotation length to age of m.a.i. culmination can have a considerable impact on the total yield over several rotations.

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Appendix A

Tables

Table 3. **Age class distribution for *E. grandis* in South Africa as at March, 1986**

Age	Area (ha)
0- 1	33287
1- 2	32269
2- 3	30745
3- 4	28887
4- 5	25446
5- 6	23166
6- 7	22112
7- 8	19248
8- 9	13056
9-10	13382
10-11	9532
11-12	7648
12-13	6057
13-14	3781
14-15	3910
15-16	2815
16-17	2605
17-18	1786
18-19	1528
19-20	1455
20-21	826
21-22	862
22-23	503
23-24	505
24-25	482
25-26	135
26-27	189
27-28	42
28-29	63
29-30	83
30-34	287
> 35	727

Table 4. Summary of the climate at Langepan.

Tabular summary of the more important climatic variables at Langepan.

Climatic factor	Units	Period (years)	Jan.	Feb.	Mar.	Apr.	May	Jun.
Rainfall	mm/month	24	155.0	156.2	142.6	151.9	112.4	68.1
Evaporation	mm/month	8	22.6	19.6	18.9	13.5	10.5	10.2
Sunshine	hours/day	7	7.2	7.3	7.1	6.7	7.0	7.6
Windrun	km/day	6	192.3	180.8	166.9	152.6	150.4	151.5
Max. temperature	°C	7	30.9	29.2	28.7	27.0	24.8	23.0
Min. temperature	°C	7	21.4	20.8	19.9	18.1	14.9	11.9
Radiation	α^1	8	513.3	511.9	444.9	351.4	311.2	307.7
			Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Rainfall	mm/month	24	72.8	70.2	86.5	137.4	126.3	115.0
Evaporation	mm/month	8	10.5	14.6	15.9	18.0	18.3	22.0
Sunshine	hours/day	7	7.5	7.6	6.6	6.8	6.2	7.1
Windrun	km/day	6	164.2	199.3	215.9	206.8	209.5	210.0
Max. temperature	°C	7	23.3	24.7	25.6	26.3	27.2	29.2
Min. temperature	°C	7	12.0	13.8	16.0	17.0	18.4	20.4
Radiation	α^1	8	308.1	358.5	396.2	436.2	477.9	524.8

α^1 = gram calories per cm^2 per day.

Table 5. Soil profile description for Langepan

Depth (mm)	Horizon	Description
0 - 300	A1	Moist, mottled by faunal activity and organic matter, black (10YR2/1) to greyish brown (2.5Y5/2) sand, loose, structureless, with abundant tree roots, moderate permeability and gradual transition.
300 - 900	A3	Moist, brown (10YR5/3) sand with some darker streaks from faunal activity, loose, structureless, with abundant/frequent tree roots, rapid permeability and gradual transition.
> 900	C	Moist, yellowish brown (10YR5/4) sand, loose, structureless, with frequent tree roots and rapid permeability.

Table 6. Soil analysis for Langepan

Component	Horizon A1	Horizon A2	Horizon A3
Sand	92	92	93
Silt	4	0	0
Clay	4	7	7
Total soil separates (%)	100	100	100
Ca	0.20	0.18	0.13
Mg	0.45	0.41	0.37
K	0.06	0.05	0.04
Na	0.05	0.02	0.02
Exchangeable cations (me/100 g soil)	0.76	0.66	0.56
S-value (me/100 g clay)	19.00	9.43	8.00
P (mg/kg)	12.00	6.00	2.00
Al (mg/kg)	41.00	25.00	32.00
pH (H_2O)	4.58	5.23	5.15
pH (KCl)	3.73	4.18	4.20
Organic carbon (%)	0.59	0.21	0.14
CEC (me/100 g soil)	< 1	< 1	< 1
EA (mg/100 g soil)	0.66	0.42	0.58

Table 7. Plot sizes and observations per treatment for the eucalypt C.C.T. experiments

Plot number	Plot size		Stand density		Stems per plot
	(ha)	(ac)	(S/ha)	(s.p.a.)	
1	0.04	0.1	6726	2722	272
2	0.04	0.1	4304	1742	174
3	0.04	0.1	2965	1200	120
4	0.04	0.1	1482	600	60
5	0.04	0.1	988	400	40
6	0.04	0.1	741	300	30
7	0.04	0.1	494	200	20
8	0.08	0.2	371	150	30
9	0.08	0.2	247	100	20
10	0.08	0.2	124	50	10
11	0.16	0.4	62	25	10
12	0.16	0.4	25	10	4

Table 8. Measurement intervals for the *E. grandis* C.C.T. experiments.

Langepan			Nyalazi		
Year	Month	Age	Year	Month	Age
1954	3	1.50	1960	2	2.51
1954	5	1.67	1960	8	3.01
1954	10	2.08	1961	2	3.51
1955	1	2.33	1961	10	4.17
1955	4	2.58	1962	2	4.51
1956	4	3.58	1962	7	4.92
1956	10	4.08	1963	2	5.51
1957	6	4.75	1963	5	5.76
1957	11	5.17	1964	5	6.76
1958	5	5.67	1965	5	7.76
1958	11	6.17	1966	5	8.76
1959	3	6.50	1967	5	9.76
1960	11	8.17	1969	8	12.01
1962	11	10.17	1971	8	14.01
1964	7	11.83	1973	8	16.01
1966	11	14.17	1975	8	18.01
1968	11	16.17	1977	7	19.92
1970	11	18.17	1979	8	22.01
1972	11	20.17	1981	8	24.01
1975	2	22.42	1983	9	26.09
1977	3	24.50	1986	4	28.67
1980	7	27.83			
1985	7	32.83			

Table 9. Comparison of paired means for quadratic mean diameter.

Means underscored by the same line are not significantly different according to the Student-Newman-Keuls procedure, using weighted analysis of variance, p = 0.05

Age	Nominal stand density (S/ha)											
	25	62	124	247	371	494	741	988	1482	2965	4304	6726
8.17	405	384	371	325	299	272	251	218	188	159	134	132
10.17	496	467	442	374	334	300	274	235	203	173	148	143
11.83	564	525	490	403	355	319	289	250	214	182	154	151
14.17	634	575	530	430	378	336	305	262	223	192	162	160
16.17	682	605	556	446	391	344	314	270	228	198	172	169
18.17	722	639	586	469	407	360	327	280	236	204	180	177
20.17	777	673	611	489	424	376	335	290	248	216	199	197
22.42	785	699	621	499	431	382	345	299	259	230	221	212
24.50	823	725	647	513	447	395	354	310	269	243	231	225
27.85	867	775	669	527	457	406	361	322	278	255	247	236
32.83	892	788	696	551	488	418	369	331	290	285	276	257

Table 10. Contour chart for quadratic mean diameter.

Contour intervals are 100 mm. apart.

Age	Nominal stand density (S/ha)											
	25	62	124	247	371	494	741	988	1482	2965	4304	6726
8.17	405	384	371	325	299	272	251	218	188	159	134	132
10.17	496	467	442	374	334	300	274	235	203	173	148	143
11.83	564	525	490	403	355	319	289	250	214	182	154	151
14.17	634	575	530	430	378	336	305	262	223	192	162	160
16.17	682	605	556	446	391	344	314	270	228	198	172	169
18.17	722	639	586	469	407	360	327	280	236	204	180	177
20.17	777	673	611	489	424	376	335	290	248	216	199	197
22.42	785	699	621	499	431	382	345	299	259	230	221	212
24.50	823	725	647	513	447	395	354	310	269	243	231	225
27.85	867	775	669	527	457	406	361	322	278	255	247	236
32.83	892	788	696	551	488	418	369	331	290	285	276	257

Table 11. Contour chart for minimum diameter.

Contour intervals are 100 mm. apart.

Age	Nominal stand density (S/ha)											
	25	62	124	247	371	494	741	988	1482	2965	4304	6726
8.17	372	334	308	269	219	199	159	91	71	42	35	32
10.17	460	364	364	305	233	207	160	93	76	43	36	33
11.83	522	444	401	323	238	211	166	135	84	43	40	31
14.17	582	473	429	331	243	215	172	138	86	50	44	43
16.17	625	488	446	342	246	218	175	138	86	52	51	48
18.17	654	511	461	356	255	223	177	139	88	55	52	49
20.17	702	516	477	359	259	223	178	140	87	57	55	53
22.42	720	527	481	363	259	223	185	140	95	64	60	54
24.50	742	534	492	366	262	225	180	140	100	81	75	66
27.85	792	576	500	364	264	225	182	140	100	90	85	83
32.83	825	571	514	383	262	219	178	137	102	92	91	82

Table 12. Contour chart for basal area.

Contour intervals are 10 square metres apart.

Age	Nominal stand density (S/ha)											
	25	62	124	247	371	494	741	988	1482	2965	4304	6726
8.17	3	7	13	20	26	28	36	37	40	42	42	49
10.17	5	11	19	27	32	35	41	44	46	49	49	56
11.83	6	13	23	32	37	39	42	49	50	53	53	61
14.17	8	16	27	36	42	44	46	54	54	57	58	65
16.17	9	18	30	39	44	46	49	57	58	59	60	67
18.17	10	20	33	43	48	50	52	60	61	62	64	70
20.17	12	22	36	46	52	55	56	64	64	65	68	70
22.42	12	23	37	48	54	57	58	64	65	68	69	70
24.50	13	25	41	51	58	61	61	66	67	67	71	75
27.85	12	28	43	54	60	64	64	70	70	71	73	78
32.83	12	29	47	59	66	66	67	67	68	71	78	81

Table 13. Contour chart for regression mean height.

Contour intervals are 5 metres apart.

Age	Nominal stand density (S/ha)											
	25	62	124	247	371	494	741	988	1482	2965	4304	6726
8.17	26	25	25	26	27	26	27	25	24	21	19	20
10.17	30	31	31	32	33	32	32	30	27	24	23	23
11.83	32	34	35	36	36	34	34	32	29	27	24	24
14.17	36	37	39	38	38	36	37	34	31	28	26	26
16.17	37	38	40	40	40	38	38	35	32	29	27	27
18.17	39	41	42	42	42	39	39	36	33	30	28	28
20.17	41	43	45	44	44	40	40	37	34	31	30	30
22.42	44	46	48	47	46	42	42	39	36	36	32	34
24.50	48	51	52	51	49	45	44	42	38	37	33	35
27.85	50	53	54	53	51	46	46	44	40	38	36	37
32.83	55	55	57	55	54	51	51	46	46	43	40	39

Table 14. Contour chart for top height.

Contour intervals are 5 metres apart.

Age	Nominal stand density (S/ha)											
	25	62	124	247	371	494	741	988	1482	2965	4304	6726
8.17	27	26	26	27	28	28	30	28	27	25	22	25
10.17	31	31	32	33	34	34	36	34	32	30	28	30
11.83	33	35	35	37	38	37	38	37	35	34	30	32
14.17	36	38	39	40	41	40	42	40	38	36	33	35
16.17	38	41	41	42	43	41	43	41	40	38	35	36
18.17	40	42	44	44	45	42	44	43	41	39	36	38
20.17	42	44	46	46	47	43	45	43	43	41	39	39
22.42	45	49	49	49	50	47	49	46	45	46	42	42
24.50	49	53	53	54	54	50	52	50	49	48	44	44
27.85	52	55	56	56	56	52	54	52	51	50	46	46
32.83	55	58	57	58	57	58	60	52	55	53	51	45

Table 15. Contour chart for stand volume.

Contour intervals are 200 cubic metres apart.

Age	Nominal stand density (S/ha)											
	25	62	124	247	371	494	741	988	1482	2965	4304	6726
8.17	26	60	112	187	254	278	378	342	332	312	271	339
10.17	45	107	198	307	394	414	530	480	460	436	395	449
11.83	63	145	268	393	478	510	630	521	566	540	459	527
14.17	84	188	349	498	576	590	752	611	657	640	544	625
16.17	101	216	397	563	657	640	825	667	716	692	607	671
18.17	118	253	465	647	748	712	900	738	784	755	664	741
20.17	141	291	529	738	857	794	976	817	865	840	762	853
22.42	158	332	601	828	938	880	1084	888	921	1042	835	954
24.50	190	396	700	954	1076	983	1248	979	1001	1052	888	950
27.85	171	466	786	1046	1178	1138	1355	1089	1096	1122	1027	1066
32.83	197	505	890	1174	1381	1356	1557	1189	1233	1216	1118	1202

Table 16. Proportion mortality by diameter class

Age	Dbh decile									
	1	2	3	4	5	6	7	8	9	10
2.08	0.04	0.01	0	0	0	0	0	0	0	0
2.58	0.59	0.09	0.02	0	0	0	0	0	0	0
2.67	0.39	0.04	0	0	0	0	0	0	0	0
3.58	0.75	0.46	0.09	0.01	0	0	0	0	0	0
4.08	0.69	0.57	0.14	0.05	0	0	0	0	0	0
4.17	0.79	0.56	0.17	0	0.02	0	0	0	0	0
4.75	0.09	0.09	0.03	0.01	0	0.01	0	0	0	0
5.17	0.03	0.05	0.03	0	0	0.01	0	0.01	0	0
5.67	0.05	0.01	0.03	0.02	0.02	0	0	0	0	0
6.50	0.17	0.11	0.12	0.01	0.02	0	0	0	0	0
8.17	0.15	0.19	0.08	0.02	0.01	0.02	0	0.02	0	0
10.17	0.13	0.04	0.01	0	0	0	0	0	0	0
11.83	0.24	0.06	0.01	0	0	0	0.02	0	0	0
14.17	0.34	0.08	0.06	0.01	0	0	0	0	0	0
16.17	0.21	0.06	0.02	0	0	0	0	0	0	0
18.17	0.53	0.24	0.02	0.01	0.05	0	0	0	0	0
20.17	0.57	0.38	0.03	0	0	0	0	0.05	0	0
22.42	0.48	0.10	0.04	0.01	0	0	0	0	0	0
24.50	0.66	0.42	0.15	0.10	0.08	0.09	0	0	0.04	0.05
27.83	0.54	0.31	0.06	0	0.05	0	0	0	0	0
32.83	0.44	0.25	0.08	0	0.03	0	0	0	0	0
Number	356	376	215	17	11	5	1	3	1	1
%	36.10	38.13	21.80	1.72	1.11	0.50	0.10	0.30	0.10	0.10

Table 17. Proportions of maximum m.a.i. attained and age at which attained by nominal stand density.

N_{nom} (S/ha)	$m.a.i._{max}$ (m^3)	Proportion of m.a.i.			
		100%	90%	80%	70%
		Age at which proportion reached			
25	7.42	35.94	19.9	15.0	12.0
62	16.30	36.70	20.1	15.1	11.9
124	28.01	29.98	17.1	13.1	10.5
247	37.65	24.09	14.0	10.8	8.8
371	43.57	21.69	12.4	9.6	7.7
494	42.40	19.20	11.6	9.1	7.4
741	53.32	16.87	9.6	7.3	6.0
988	44.40	15.19	8.2	6.1	4.8
1482	46.22	14.38	7.6	5.4	4.2
2965	44.68	15.49	7.6	5.3	4.0
4304	38.56	14.48	5.5	3.3	2.1
6726	44.18	13.30	5.9	4.0	2.8

Table 18. Paired comparison t-tests of m.a.i. estimates, Model I.

N_{nom}	Mean	Std. error	t	$P > \|t\|$
25	-0.34	0.14	-2.37	0.0297
62	0.58	0.15	3.76	0.0015
124	1.56	0.48	3.21	0.0051
247	-0.41	0.54	-0.77	0.4512
371	-0.83	0.47	-1.73	0.1013
494	-3.57	0.82	-4.36	0.0004
741	2.52	1.18	2.13	0.0479
988	1.25	1.56	0.80	0.4334
1482	3.25	2.35	1.38	0.1853
2965	7.59	1.50	5.04	0.0001
4304	-1.28	0.68	-1.87	0.0799
6726	-1.04	1.45	-0.72	0.4838

Table 19. Paired comparison t-tests of m.a.i. estimates, Model I.

N_{nom}	Mean	Std. error	t	$P > \|t\|$
25	1.16	0.26	4.45	0.0004
62	-1.68	0.60	-2.78	0.0129
124	-1.29	0.28	-4.56	0.0003
247	-0.60	0.38	-1.59	0.1302
371	1.11	0.57	1.95	0.0675
494	-0.39	0.64	-0.62	0.5452
741	5.60	0.84	6.62	0.0001
988	-1.55	0.95	-1.63	0.1207
1482	-1.11	0.82	-1.35	0.1962
2965	-2.39	0.59	-4.04	0.0009
4304	-4.68	0.61	-7.63	0.0001
6726	2.84	0.52	5.41	0.0001

Table 20. Paired comparison t-tests of m.a.i. estimates, Model I.

Age	Mean	Std. error	t	$P > \lvert t \rvert$
3.54	-0.29	1.28	-0.23	0.8226
4.08	0.20	1.89	0.11	0.9169
4.17	0.48	1.34	0.36	0.7273
4.75	3.31	1.75	1.89	0.0856
5.17	3.72	1.77	2.10	0.0599
5.67	4.46	1.95	2.28	0.0433
6.50	3.24	1.79	1.81	0.0972
8.17	1.49	1.51	0.99	0.3447
10.17	3.37	1.33	2.53	0.0279
11.83	2.73	1.26	2.17	0.0527
14.17	0.70	1.13	0.62	0.5505
16.17	-1.63	0.89	-1.84	0.0934
18.17	-2.91	0.90	-3.22	0.0082
20.17	-2.10	0.96	-2.18	0.0518
22.42	-0.91	1.67	-0.55	0.5940
24.50	-0.30	1.52	-0.20	0.8465
27.83	-1.34	1.66	-0.81	0.4359
32.83	-0.78	1.68	-0.47	0.6506

Table 21. Paired comparison t-tests of m.a.i. estimates, Model II.

Age	Mean	Std. error	t	$P > \|t\|$
3.58	-2.31	0.79	-2.91	0.0143
4.08	-0.34	0.75	-0.46	0.6529
4.17	-1.99	0.66	-3.02	0.0129
4.75	0.84	0.67	1.24	0.2404
5.17	1.24	0.84	1.47	0.1691
5.67	2.05	0.99	2.06	0.0639
6.50	0.88	1.02	0.87	0.4046
8.17	-1.31	1.27	-1.03	0.3246
10.17	1.17	1.20	0.97	0.3534
11.83	1.13	1.13	1.00	0.3409
14.17	-0.07	1.10	-0.07	0.9492
16.17	-1.76	1.06	-1.66	0.1260
18.17	-2.23	1.05	-2.11	0.0583
20.17	-1.67	1.02	-1.64	0.1293
22.42	-1.09	1.08	-1.01	0.3347
24.50	-0.25	1.10	-0.23	0.8252
27.83	0.19	0.91	0.21	0.8360
32.83	1.44	1.10	1.31	0.2175

Table 22. Comparison of paired means for co-ordinated thinning treatments

Treatments underscored by the same line are not significantly different according to the Student-Newman-Keuls procedure.

Age	Ranked means (cubic metres) by treatment number							
	Standing volume				Cumulative volume			
	14	13	15	16	14	13	15	16
6.50	273	266	260	227	273	266	260	227
	13	14	15	16	14	15	13	16
8.17	328	298	209	183	377	338	337	325
	13	14	15	16	14	13	15	16
10.17	464	440	336	295	519	472	464	437
	13	14	15	16	13	14	15	16
11.83	495	406	266	200	634	625	556	525
	13	14	15	16	14	13	15	16
14.17	608	522	354	280	740	700	644	604
	13	16	14	15	14	13	15	16
16.17	500	332	311	201	807	768	708	657
	13	14	16	15	14	13	15	16
18.17	586	401	392	293	897	854	799	777
	16	13	15	14	13	14	15	16
20.17	457	411	361	326	955	945	868	781
	16	15	14	13	13	14	15	16
22.42	552	458	401	264	1077	1020	965	877
	16	15	14	13	13	15	14	16
24.50	627	557	418	404	1175	1064	1037	952
	16	15	14	13	13	15	14	16
27.83	693	692	483	475	1246	1198	1102	1017
	16	15	13	14	13	15	14	16
32.83	806	775	637	624	1408	1282	1243	1131

Table 23. Comparison of paired means for suppression / release treatments

Treatments underscored by the same line are not significantly different according to the Student-Newman-Keuls procedure.

Age	Ranked means (cubic metres) by treatment number							
	Standing volume				Cumulative volume			
6.50	18 285	19 280	17 272	20 249	18 285	19 280	17 273	20 249
8.17	17 276	19 196	20 193	18 182	19 369	18 368	17 359	20 309
10.17	17 424	19 344	18 316	20 307	19 518	17 507	18 502	20 423
11.83	17 512	19 455	18 415	20 384	19 628	18 601	17 595	20 500
14.17	17 610	19 573	18 533	20 472	19 746	18 719	17 693	20 588
16.17	17 676	19 670	18 598	20 518	19 843	18 784	17 758	20 634
18.17	19 762	17 761	18 678	20 595	19 935	18 864	17 843	20 711
20.17	17 864	19 853	18 770	20 667	19 1026	18 957	17 947	20 783
22.42	19 940	17 922	18 869	20 746	19 1113	18 1055	17 1004	20 863
24.50	19 1102	17 1060	18 1028	20 812	19 1275	18 1214	17 1143	20 928
27.83	19 1257	18 1234	17 1166	20 904	19 1430	18 1421	17 1249	20 1021
32.83	18 1567	19 1456	17 1270	20 1033	18 1753	19 1629	17 1353	20 1150

Table 24. Parameter estimates (page 1 of 4) for equations used in the text.

Parameter estimates			
b_{00}	0.90000000	b_{01}	4.15463000
b_{02}	0.26201000	b_{03}	4.71009050
b_{04}	-0.44835231	b_{05}	0.03499684
b_{06}	7.93266997	b_{07}	-0.31477782
b_{08}	6.6834E-05	b_{09}	-1.96644603
b_{10}	0.11422787	b_{11}	-4.4026E-04
b_{12}	2.34478071	b_{13}	-0.85597232
b_{14}	0.12146773	b_{15}	5.01862831
b_{16}	-0.46341579	b_{17}	0.03045493
b_{18}	7.67104177	b_{19}	-0.25585254
b_{20}	2.1577E-05	b_{21}	-1.90556513
b_{22}	0.12354804	b_{23}	-0.00112536
b_{24}	2.61415977	b_{25}	-1.11569335
b_{26}	0.16532866	b_{27}	5.15880587
b_{28}	0.62390048	b_{29}	0.04880137
b_{30}	3.50750165	b_{31}	2.18340173
b_{32}	0.44624495	b_{33}	0.02551234
b_{34}	0.10059995	b_{35}	1.8445E-05
b_{36}	2.5235E-08	b_{37}	2.4730E-12
b_{38}	0.03027381	b_{39}	0.21871888
b_{40}	0.04626240	b_{41}	7.82286532
b_{42}	-1.52720376	b_{43}	0.11909433
b_{44}	4.86170088	b_{45}	1.36292473
b_{46}	-0.29203529	b_{47}	0.01645560
b_{48}	0.11588416	b_{49}	-6.5075E-05
b_{50}	6.0513E-09	b_{51}	-1.7535E-13
b_{52}	-2.19287705	b_{53}	0.51381589
b_{54}	-0.01058736	b_{55}	25.22846893

Table 25. Parameter estimates (page 2 of 4) as numbered in the text.

Parameter estimates			
b_{56}	-2.16021135	b_{57}	-66.37408016
b_{58}	2853.95775826	b_{59}	-0.35911124
b_{60}	-1.41196659	b_{61}	1.01956435
b_{62}	0.10553616	b_{63}	-2.1136E-04
b_{64}	0.98597660	b_{65}	-1.1275E-03
b_{66}	1.2439E-06	b_{67}	-1.0360E-10
b_{68}	4.29253030	b_{69}	-0.46945772
b_{70}	0.04755131	b_{71}	40.36561098
b_{72}	7.10235565	b_{73}	-0.70653178
b_{74}	-9.90390971	b_{75}	1.90811416
b_{76}	-0.13559797	b_{77}	3.14779386
b_{78}	-0.52068965	b_{79}	0.04456285
b_{80}	4.03586696	b_{81}	-0.33157965
b_{82}	0.03206879	b_{83}	41.11184238
b_{84}	6.73865595	b_{85}	-0.67591020
b_{86}	-9.25404331	b_{87}	1.92926457
b_{88}	-0.15331335	b_{89}	3.25171009
b_{90}	-0.58563750	b_{91}	0.05737662
b_{92}	5.82090766	b_{93}	-1.09423682
b_{94}	0.10000476	b_{95}	48.78030101
b_{96}	4.47221278	b_{97}	-0.67290280
b_{98}	-13.55794511	b_{99}	3.71936808
b_{100}	-0.32795534	b_{101}	3.58362038
b_{102}	-0.79052608	b_{103}	0.07812522
b_{104}	-2.32902549	b_{105}	9.74398821
b_{106}	-0.03282496	b_{107}	-3.13390702
b_{108}	0.04572313	b_{109}	-0.00062403
b_{110}	2.80676271	b_{111}	-0.92249425

Table 26. **Parameter estimates (page 3 of 4) as numbered in the text.**

Parameter estimates			
b_{112}	3.12827607	b_{113}	-10.98338136
b_{114}	-0.00730759	b_{115}	-0.80416866
b_{116}	-0.00349890	b_{117}	2.96094385
b_{118}	-4.90059074	b_{119}	-0.97845223
b_{120}	0.00228474	b_{121}	-0.00453273
b_{122}	0.03704172	b_{123}	3.43667541
b_{124}	-0.66183208	b_{125}	0.24430881
b_{126}	56.17622479	b_{127}	-0.54426942
b_{128}	-1.80125386	b_{129}	-0.00002456
b_{130}	0.02084014	b_{131}	2.75552633
b_{132}	-0.58480616	b_{133}	0.01304617
b_{134}	51.51601868	b_{135}	-0.51024842
b_{136}	-1.81739319	b_{137}	0.00003593
b_{138}	-2.48597103	b_{139}	139.14909021
b_{140}	0.65190486	b_{141}	204.22291192
b_{142}	-109.43331489	b_{143}	16.27429711
b_{144}	-0.70762187	b_{145}	-57.00254404
b_{146}	20.52802416	b_{147}	-0.06231745
b_{148}	-0.15490466	b_{149}	-3.71737307
b_{150}	2.86912924	b_{151}	-0.68972401
b_{152}	0.04532331	b_{153}	-31.56935248
b_{154}	1.05099258	b_{155}	-0.00027121
b_{156}	1.64217246	b_{157}	0.85145229
b_{158}	-0.00933267	b_{159}	0.71539137
b_{160}	-0.01735840	b_{161}	0.04301529
b_{162}	0.62434996	b_{163}	-9.75444925
b_{164}	0.04281418	b_{165}	-0.00018279
b_{166}	-8.7801E-06	b_{167}	42.87628269

Table 27. Parameter estimates (page 4 of 4) as numbered in the text.

Parameter estimates			
b_{168}	-9.34455074	b_{169}	0.04281418
b_{170}	36.48700962	b_{171}	-14.85023305
b_{172}	0.01844972	b_{173}	-0.00036669
b_{174}	8.55370112	b_{175}	-8.30008116
b_{176}	0.04705581	b_{177}	0.00156850
b_{178}	32.95372899	b_{179}	-7.30221840
b_{180}	0.04705581	b_{181}	27.02034788
b_{182}	-4.25270096	b_{183}	0.03557104
b_{184}	2.62098376	b_{185}	13.62817596
b_{186}	-2.16292929	b_{187}	-6.19666895
b_{188}	-21.85784053	b_{189}	1.19663778
b_{190}	-4.00362376	b_{191}	0.87932692
b_{192}	-39.22290107	b_{193}	-0.00124813
b_{194}	9.00424022	b_{195}	-1.15817325
b_{196}	-0.06159971	b_{197}	-1.4715E-04
b_{198}	-5.4383E-04	b_{199}	4.4966E-08
b_{200}	1.5065E-04	b_{201}	-2.32671024
b_{202}	4.1381E-05	b_{202}	0.00000000

Appendix B

Figures

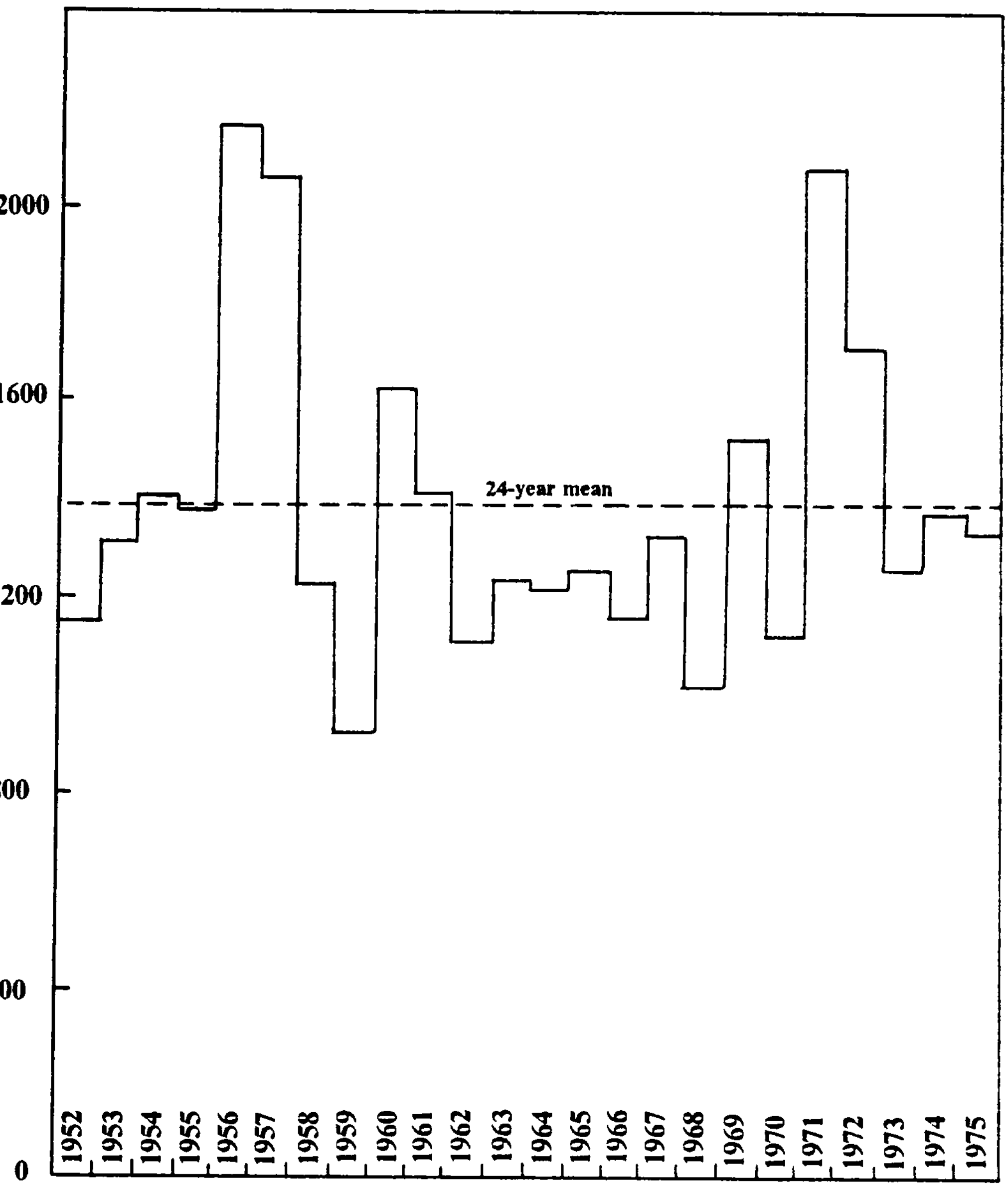


Figure 4. Distribution of rainfall in Zululand: Annual rainfall in millimetres as determined at Langepan

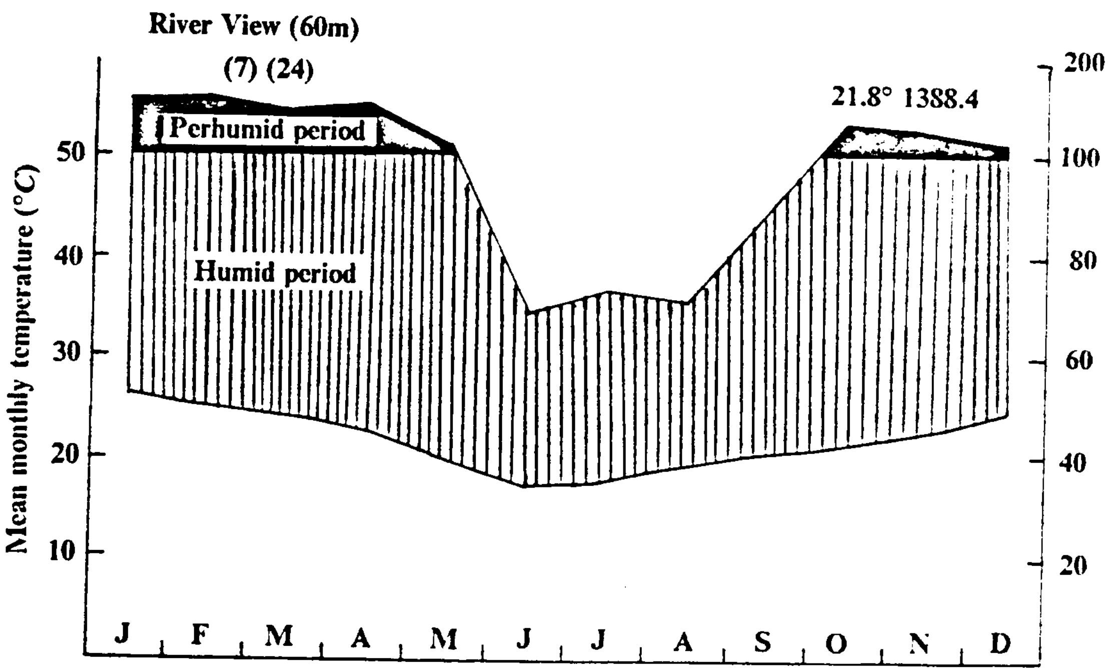
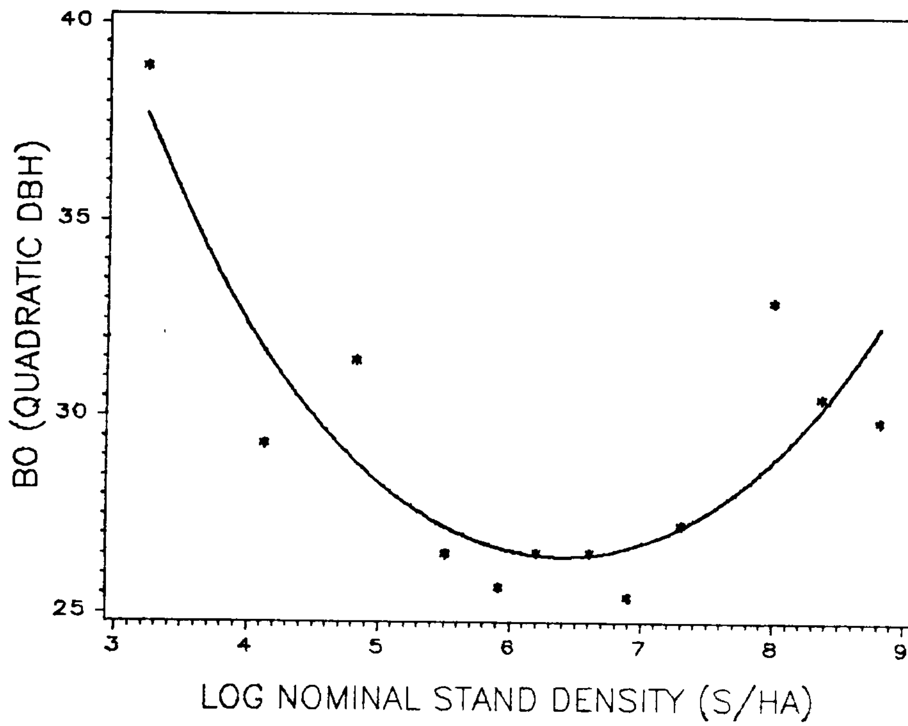


Figure 5. Walter diagram: Determination of limiting factors for plant growth at Langepan.



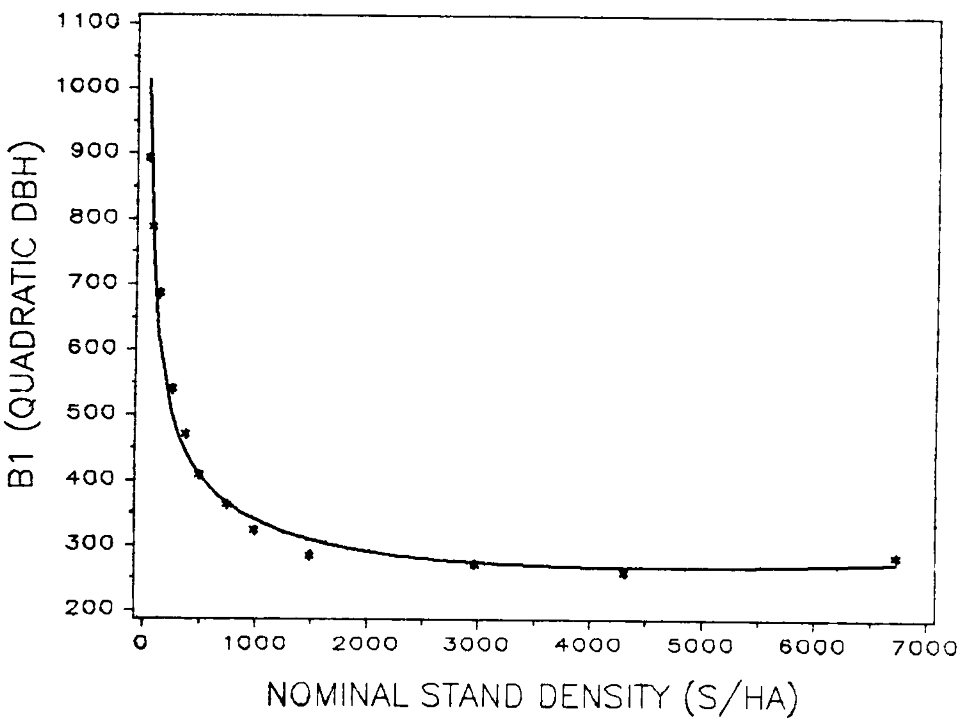
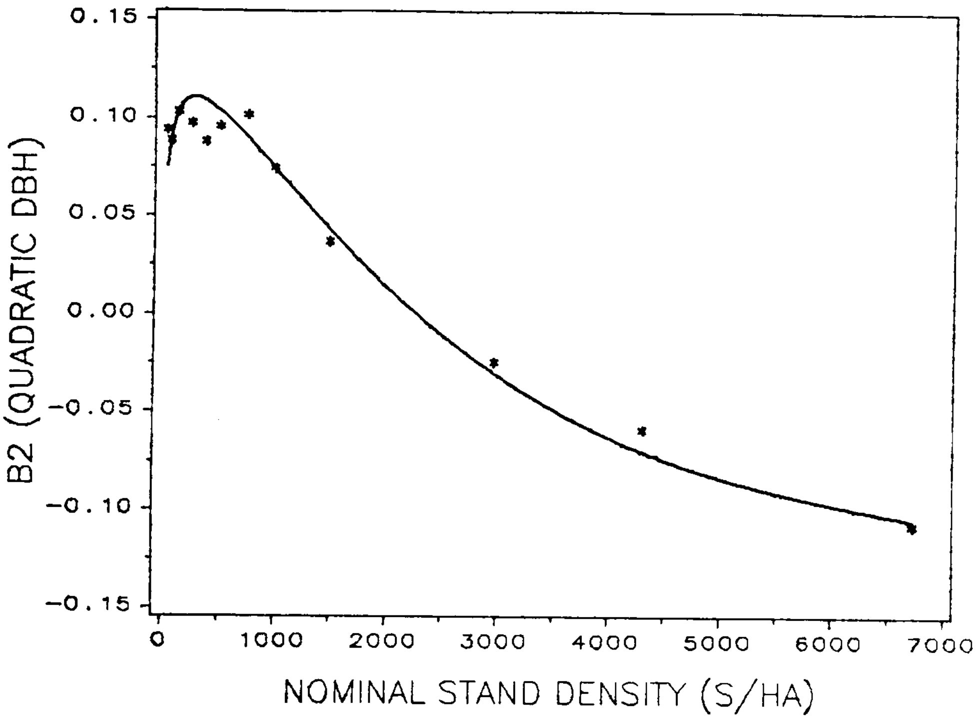


Figure 6. Estimates of size parameters for quadratic mean diameter: Estimate of size at age = 1.50 (above) and at age = 32.83 years (below) as a function of nominal stand density.



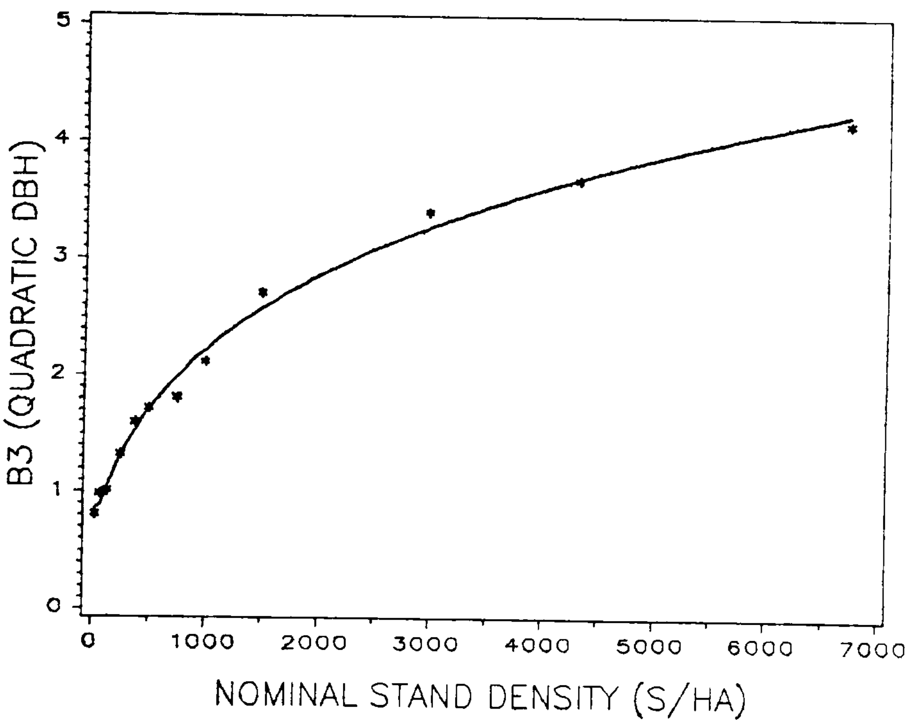


Figure 7. Estimates of rate parameters for quadratic mean diameter: Estimate of constant acceleration (above) and incremental acceleration rates (below) as a function of nominal stand density.

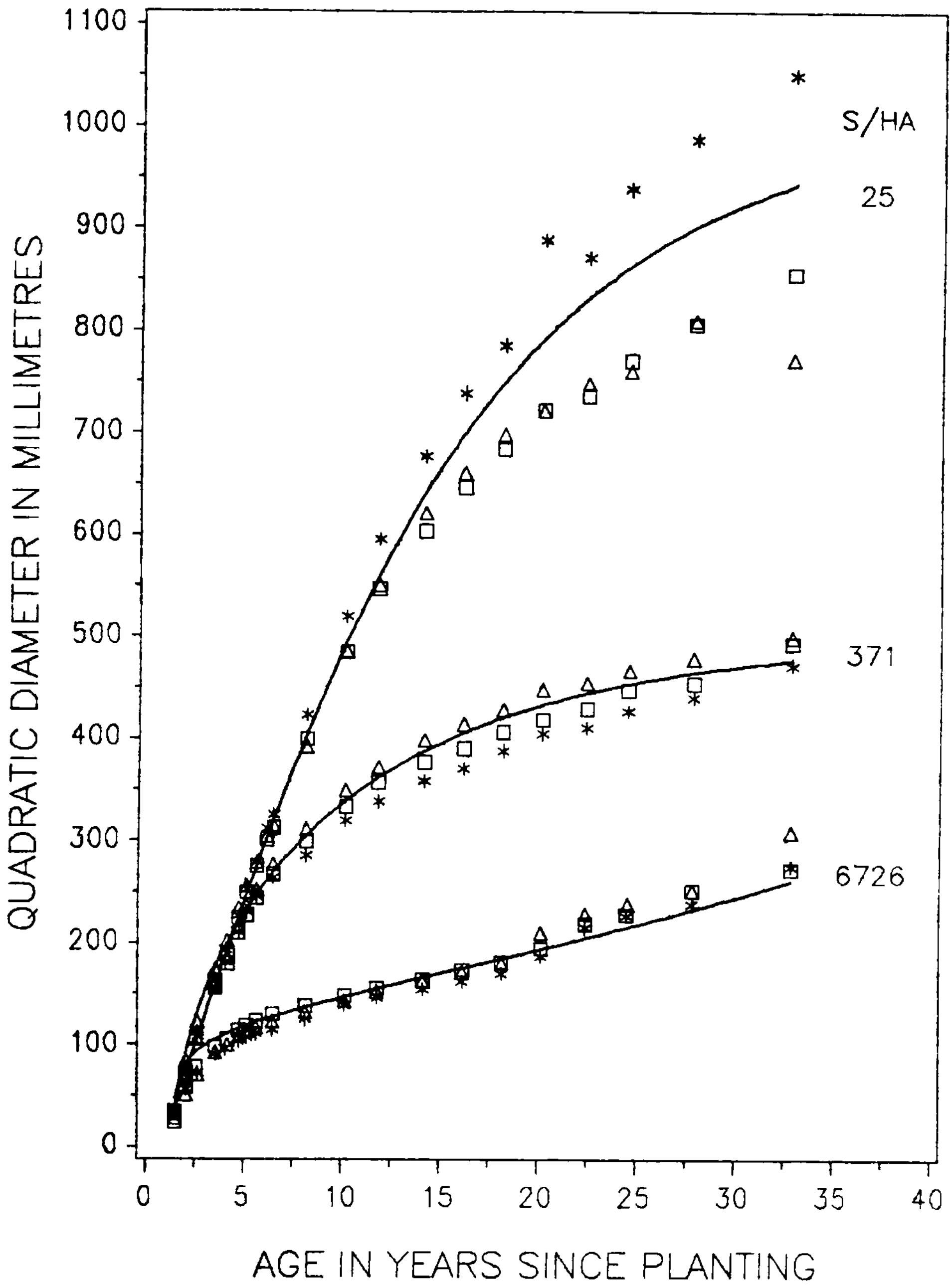


Figure 8. Evaluation of parameter recovery for quadratic mean diameter: Plot of predicted dbh against observed dbh for a few treatment levels at Langepan.

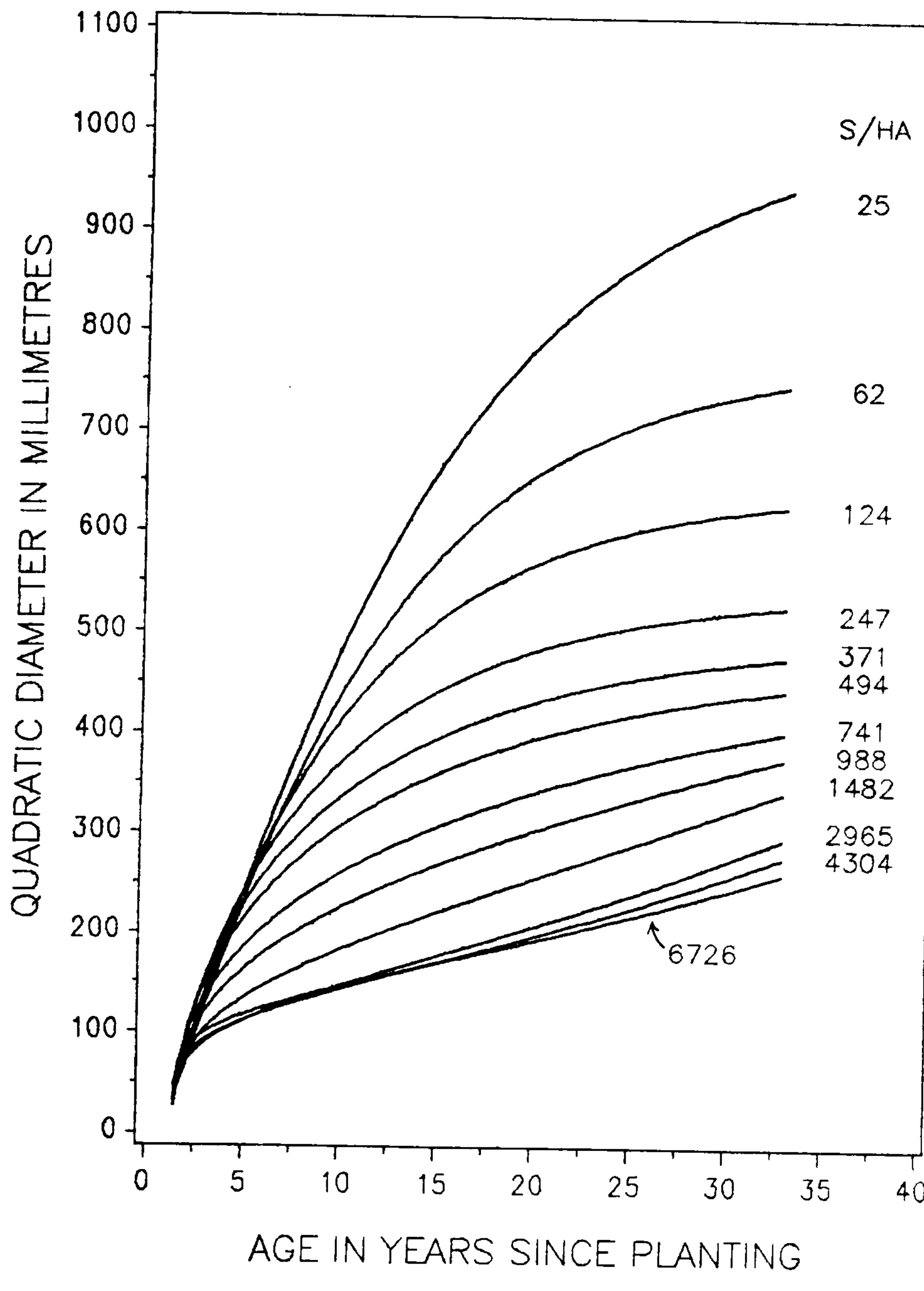


Figure 9. Evaluation of parameter recovery for quadratic mean diameter: Plot of predicted dbh for the full range of treatment levels at Langepan.

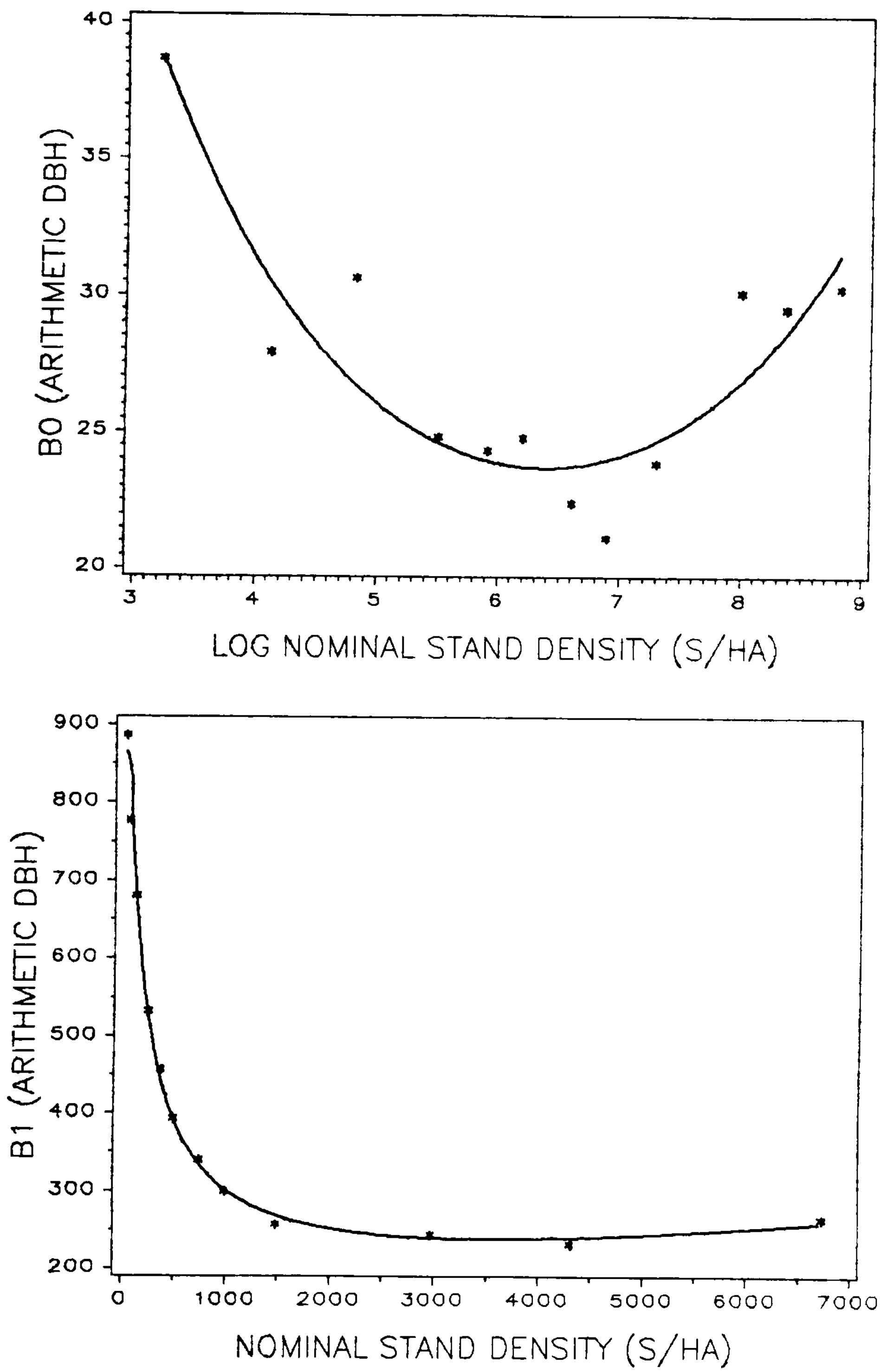


Figure 10. Estimates of size parameters for arithmetic mean diameter: Estimate of size at age = 1.50 (above) and at age = 32.83 years (below) as a function of nominal stand density.

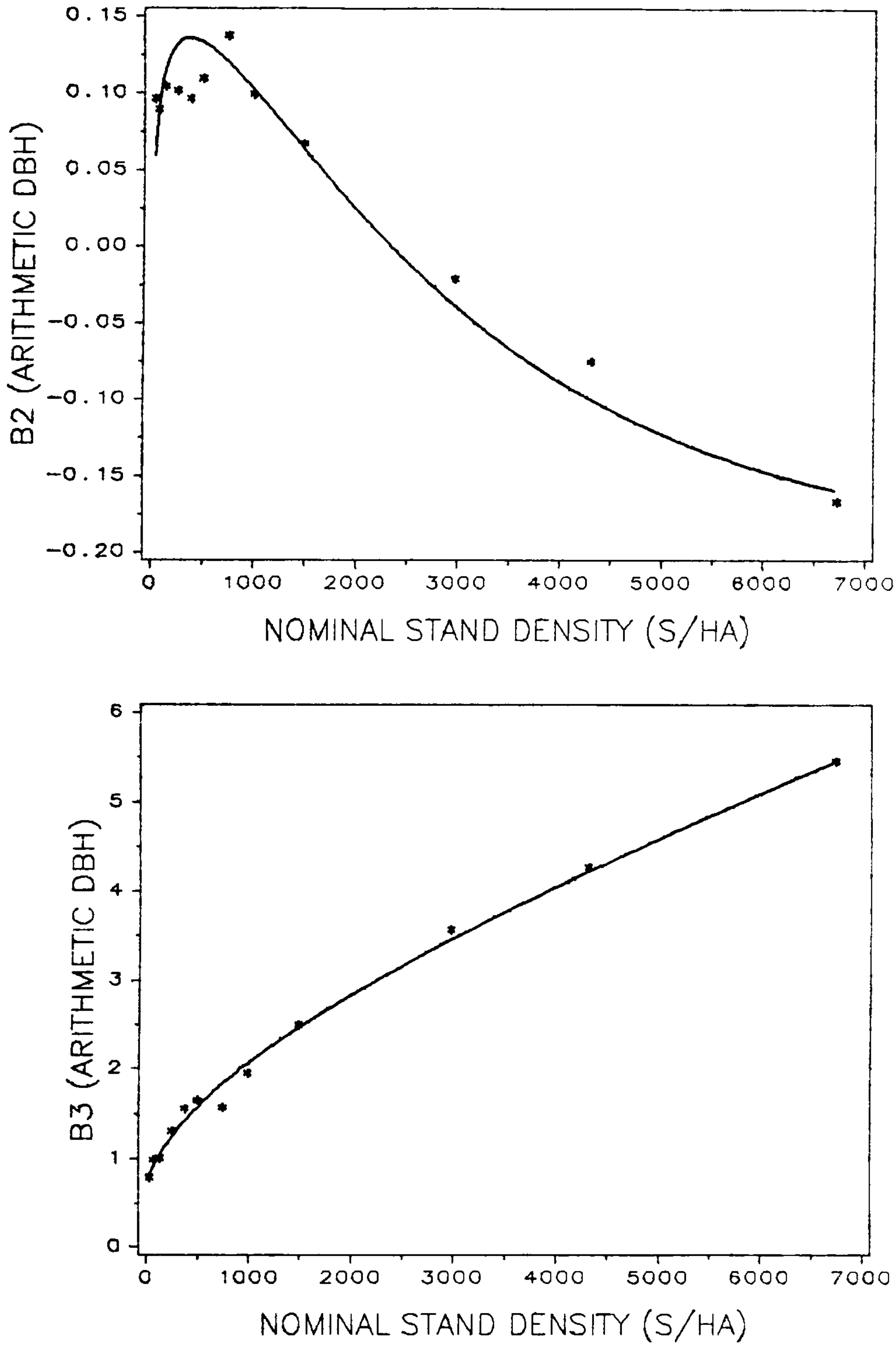


Figure 11. Estimates of rate parameters for arithmetic mean diameter: Estimate of constant acceleration (above) and incremental acceleration rates (below) as a function of nominal stand density.

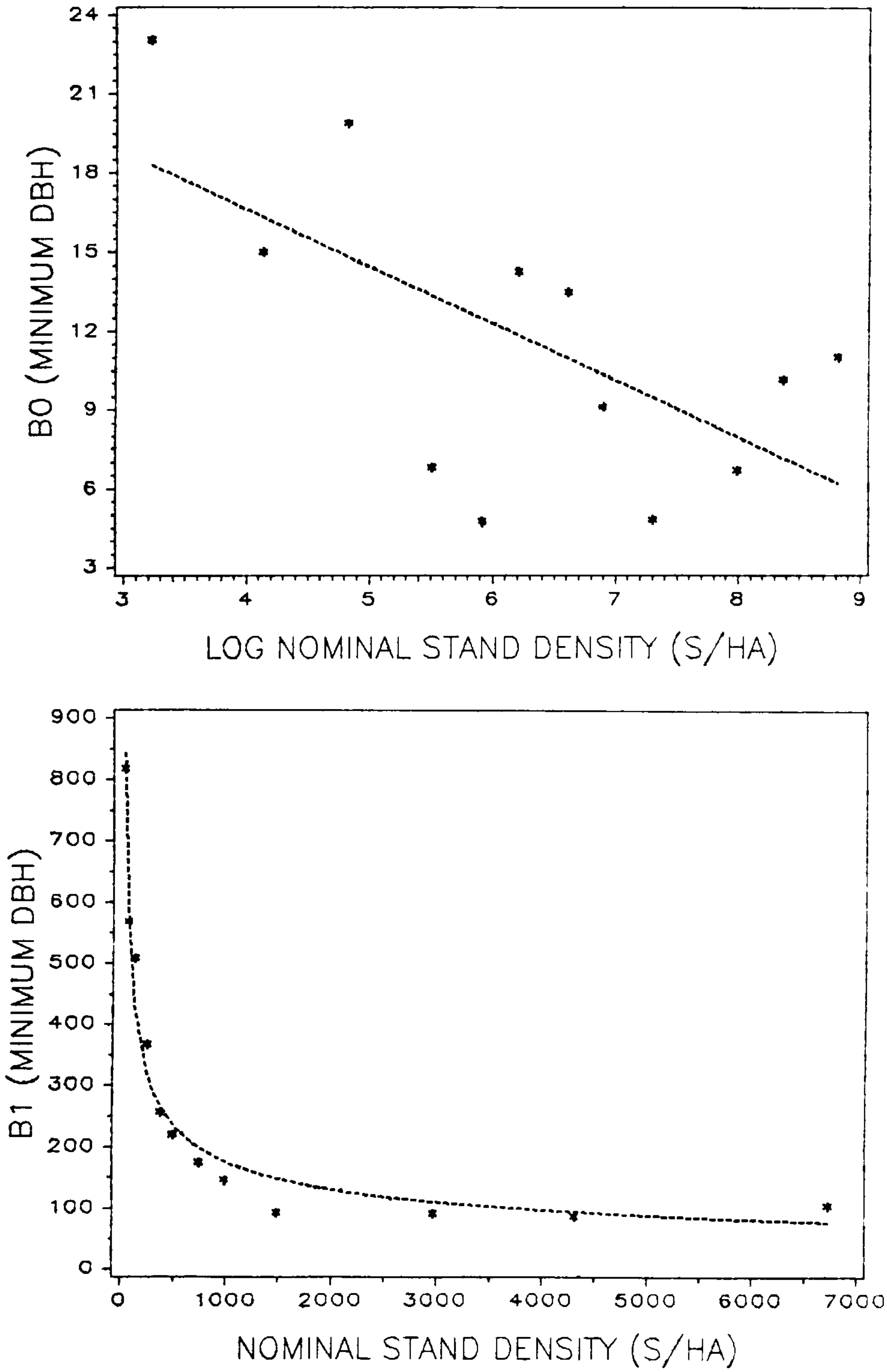


Figure 12. Estimates of size parameters for minimum mean diameter: Estimate of size at age = 1.50 (above) and at age = 32.83 years (below) as a function of nominal stand density.

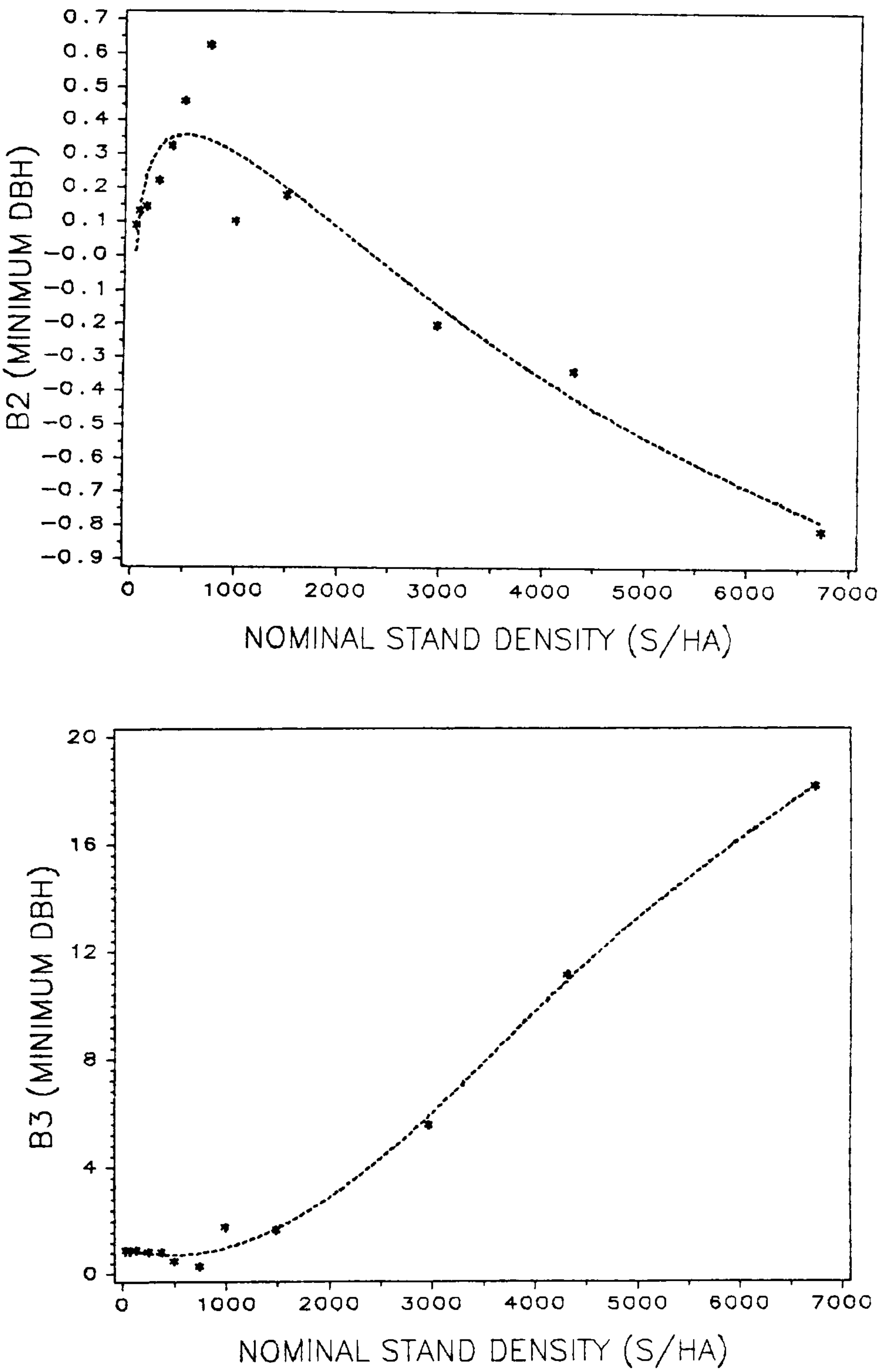


Figure 13. Estimates of rate parameters for minimum mean diameter: Estimate of constant acceleration (above) and incremental acceleration rates (below) as a function of nominal stand density.

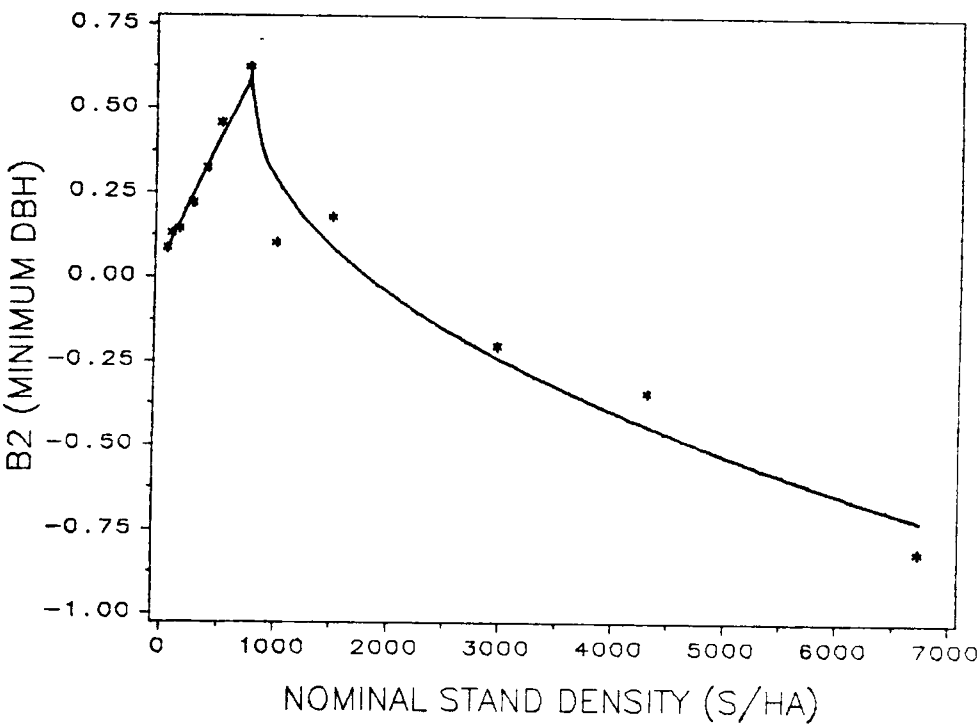
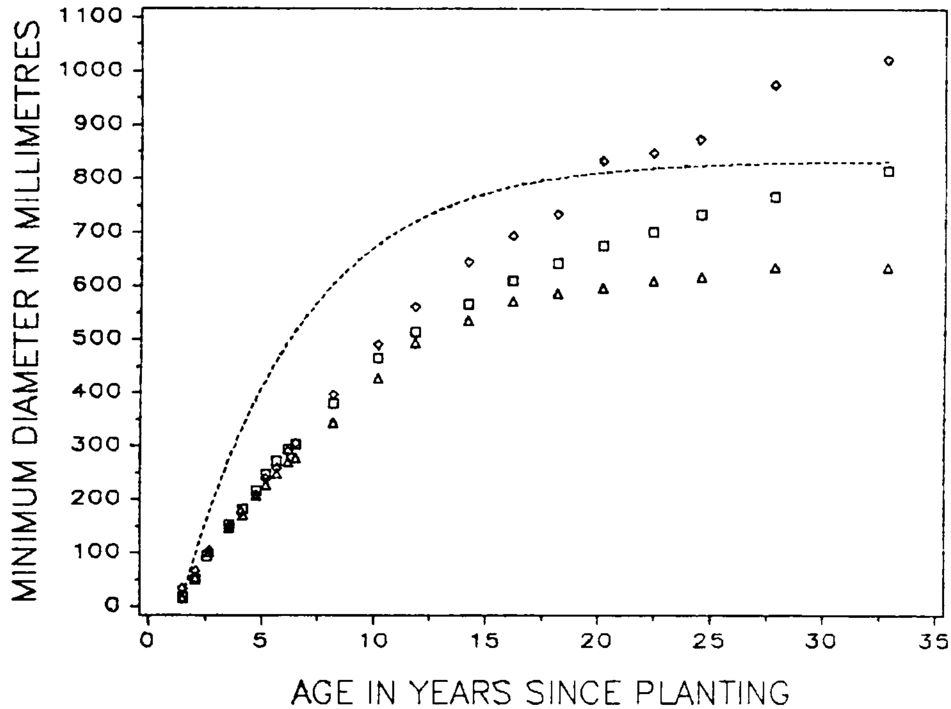


Figure 14. Use of segmented regression to model a shape parameter: Two functions fitted simultaneously to describe the shape parameter of minimum dbh.



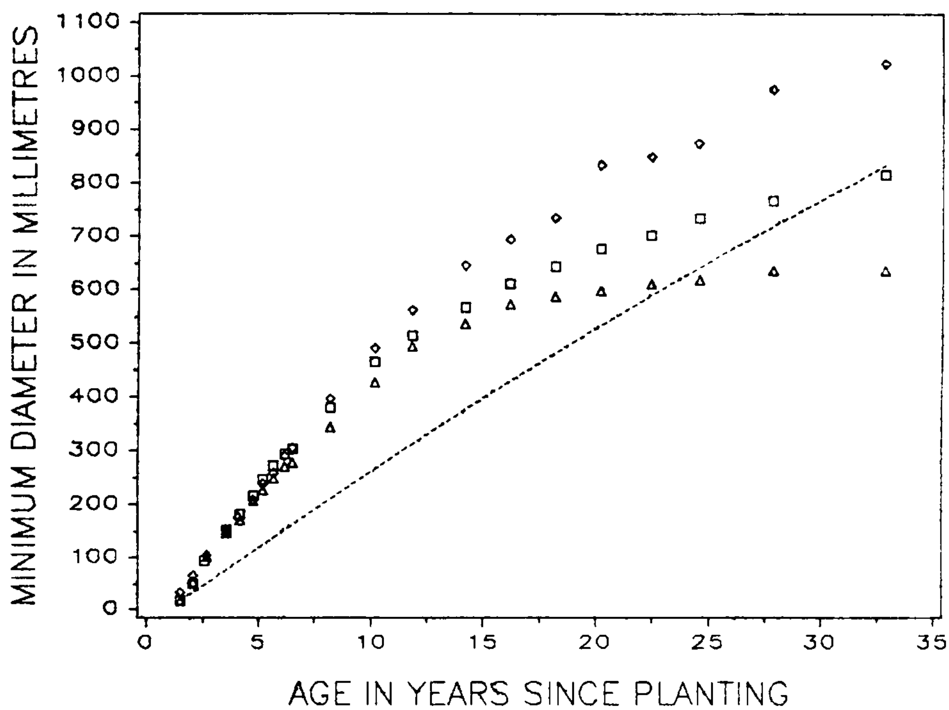


Figure 15. Example of sensitivity of Schnute model to parameters: Effect of over-estimation of the rate parameter with a cubic polynomial (above) and under-estimation with a gamma function (below). Both cases are for 25 S/ha.

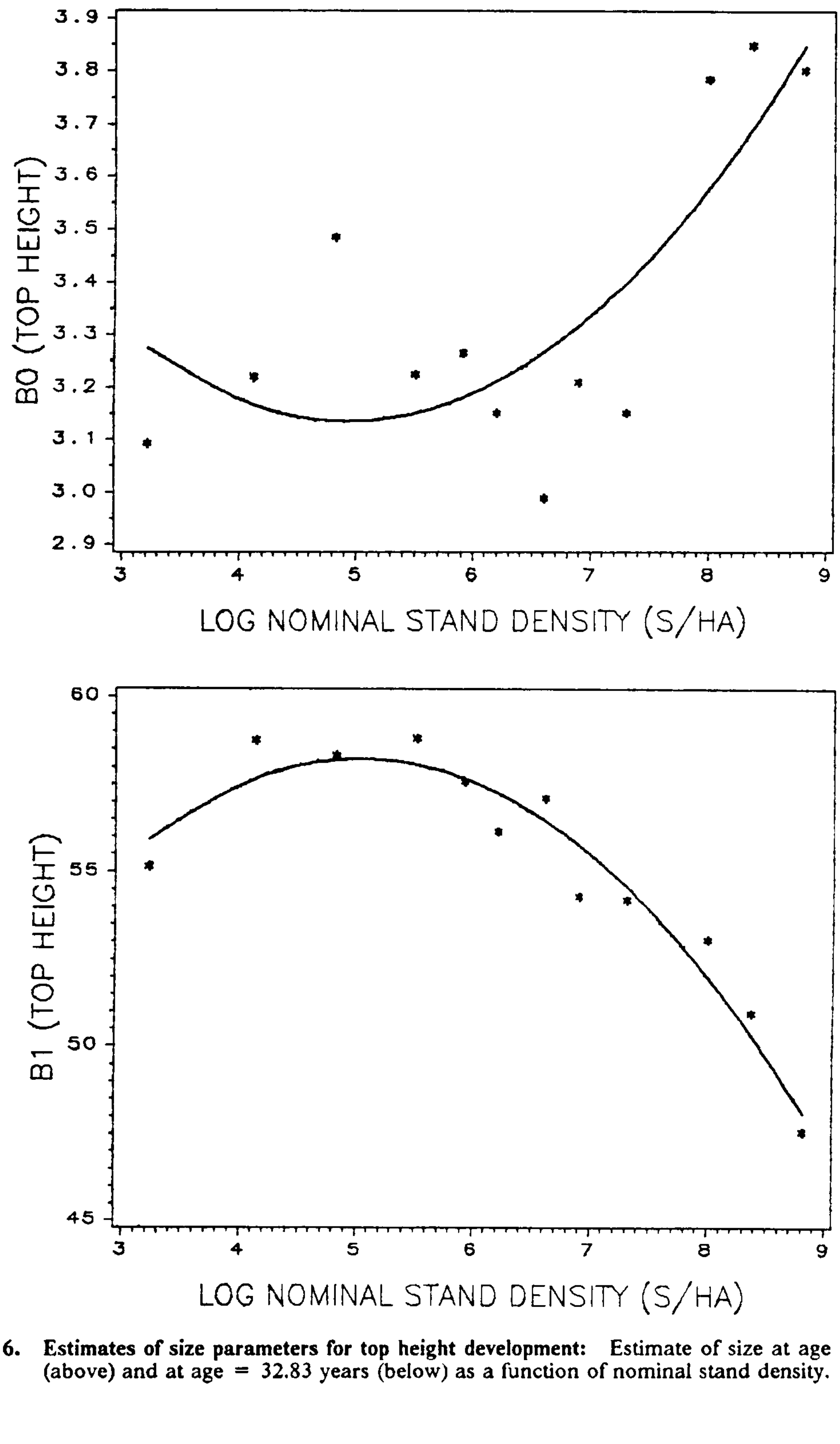


Figure 16. Estimates of size parameters for top height development: Estimate of size at age = 1.50 (above) and at age = 32.83 years (below) as a function of nominal stand density.

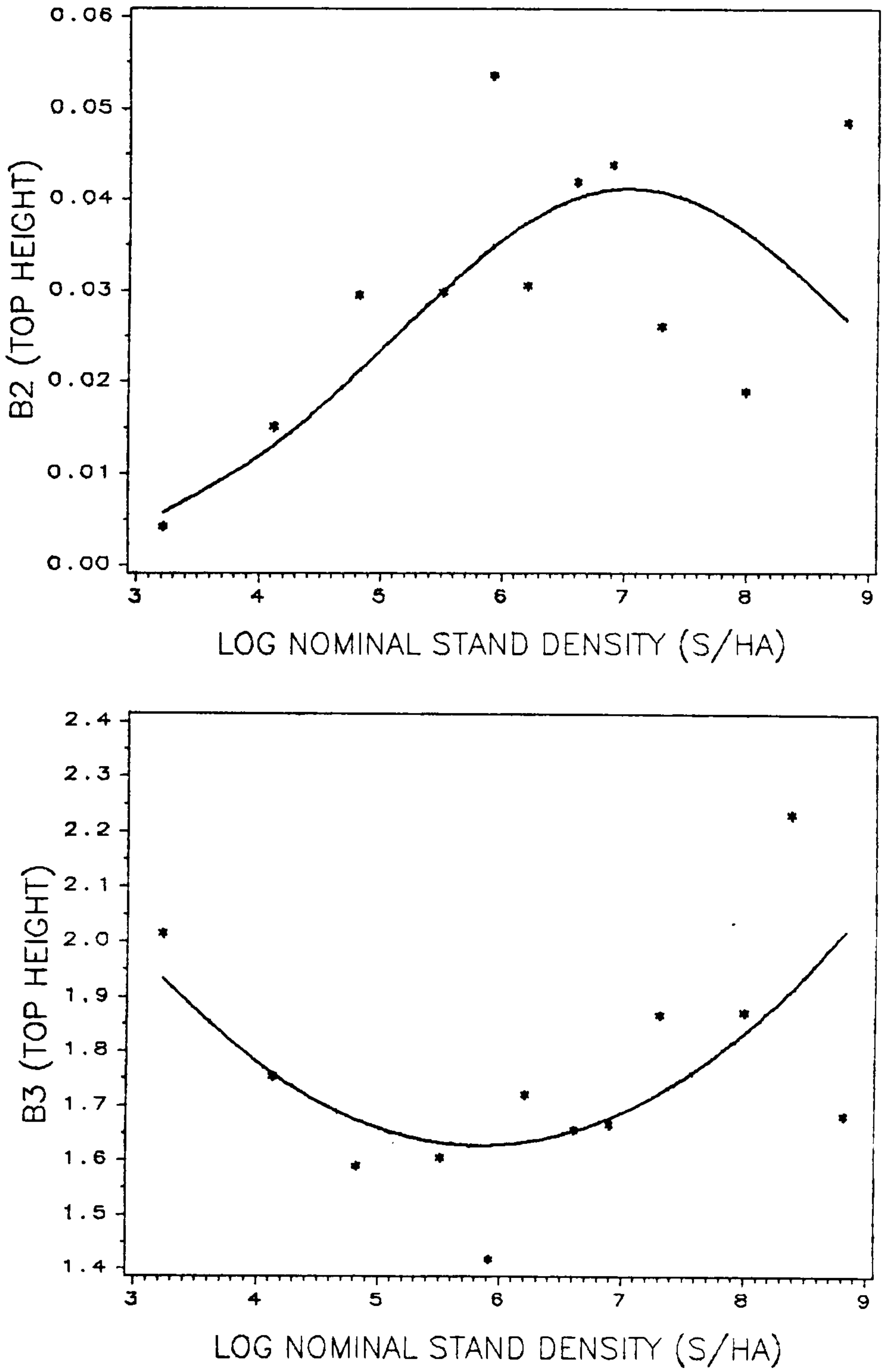


Figure 17. Estimates of rate parameters for top height development: Estimate of constant acceleration (above) and incremental acceleration rates (below) as a function of nominal stand density.

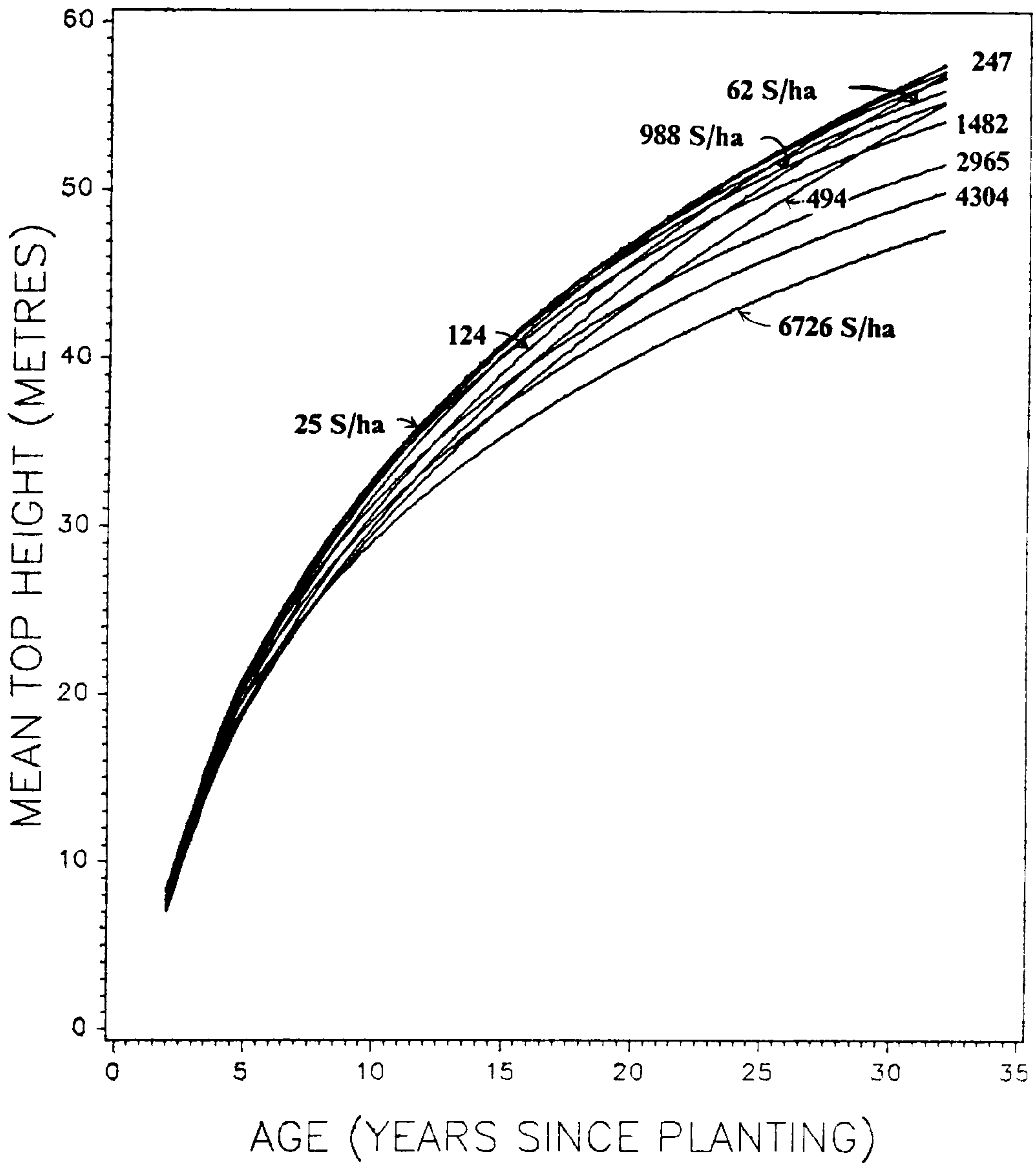


Figure 18. Evaluation of top height model: Predicted values for top height showing extensive crossings as found in the data.

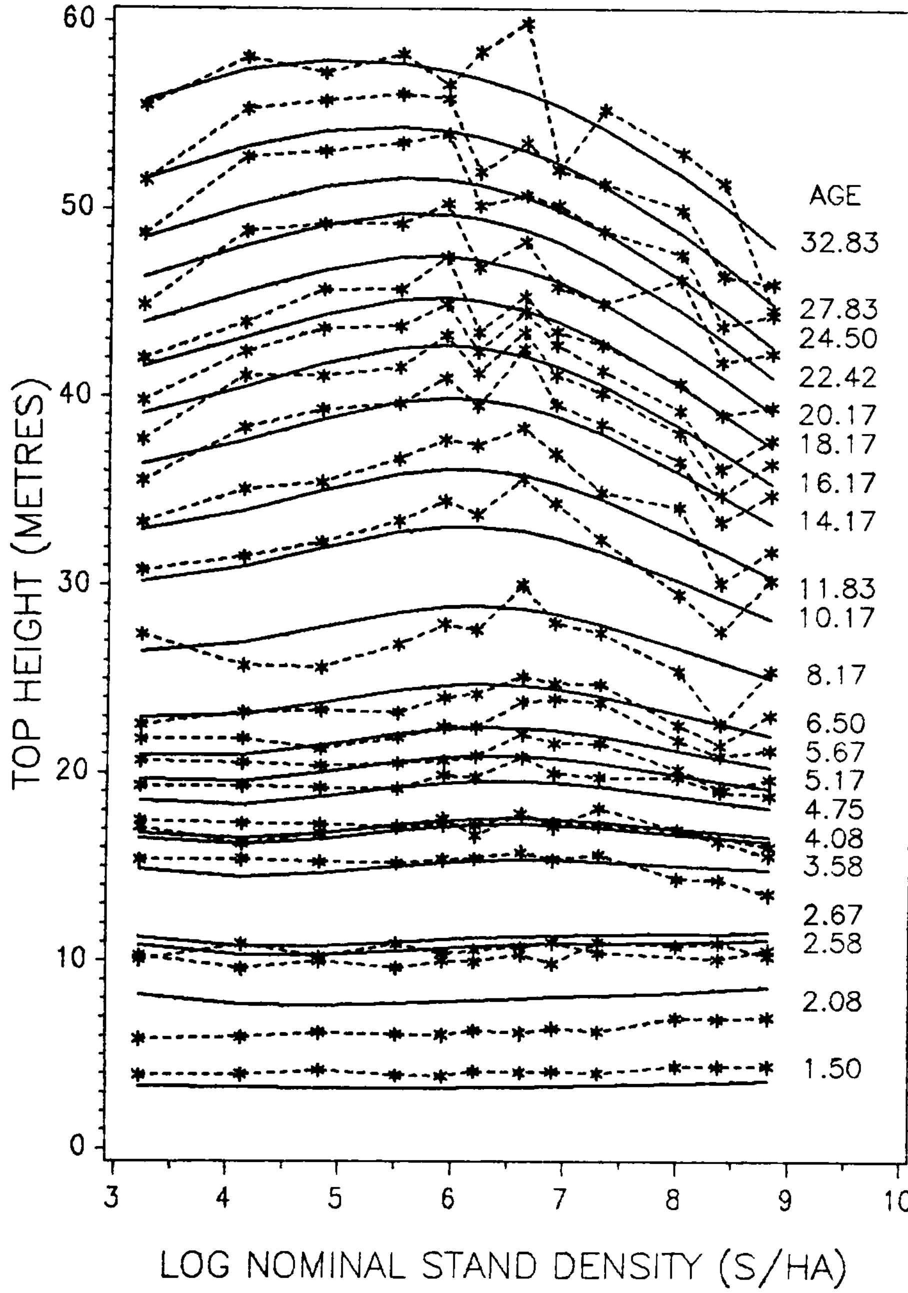


Figure 19. Prediction of stand top height: Plot of predicted top height against observed for Langepan for each enumeration.

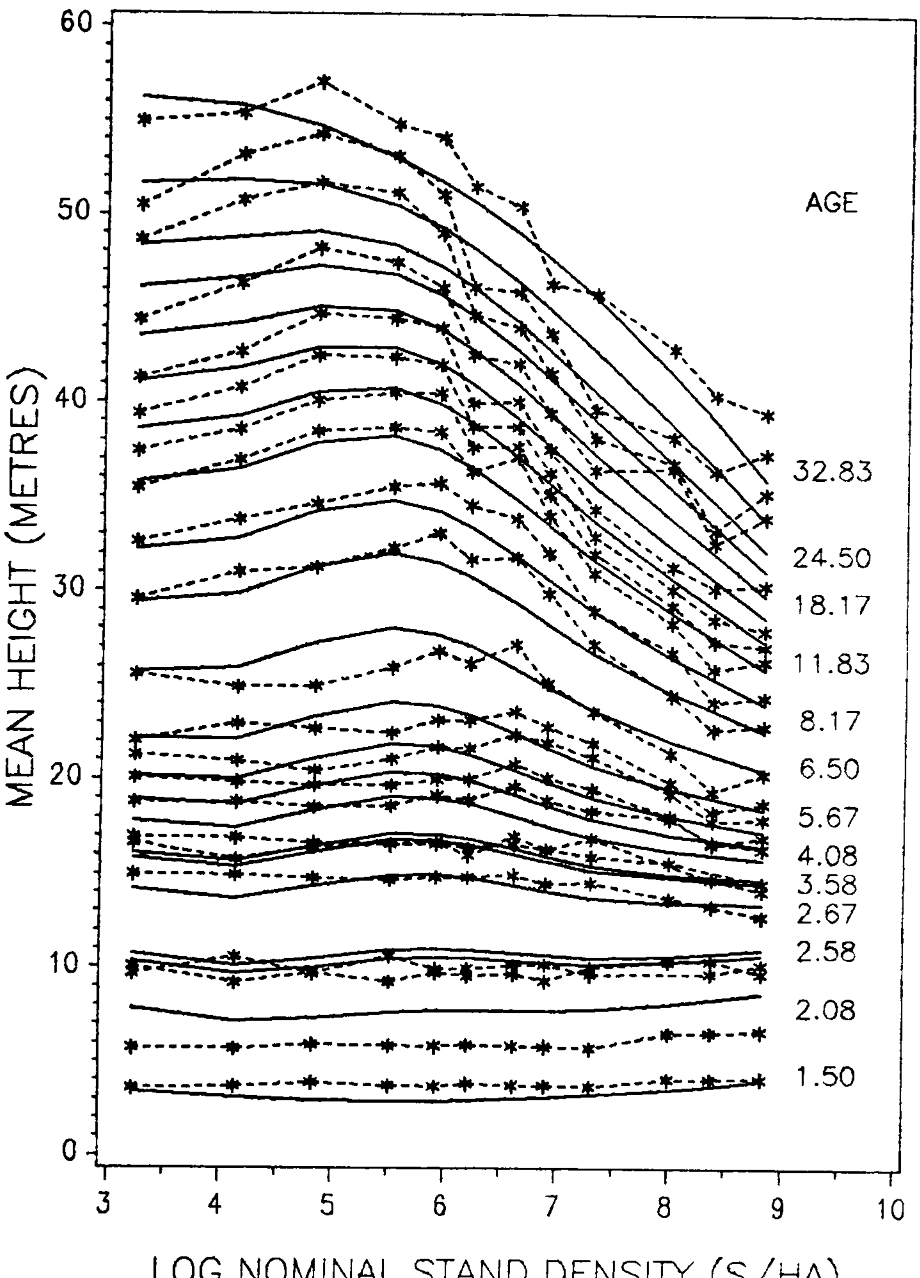


Figure 20. Prediction of mean stand height: Plot of predicted mean height against observed for Langepan for each enumeration.

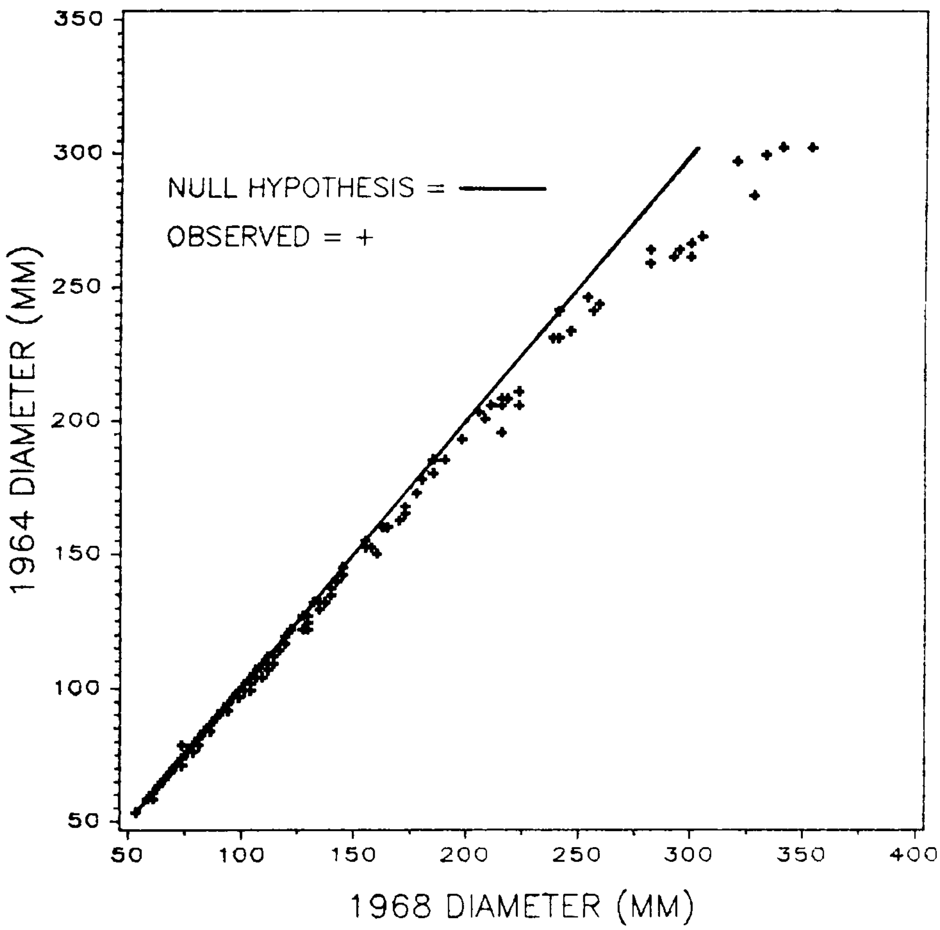


Figure 21. Quadratic dbh growth under conditions of extreme suppression: Diagonal line indicates zero growth in D_q over the interval while points to the right indicate positive growth. Note that only the larger trees have grown.

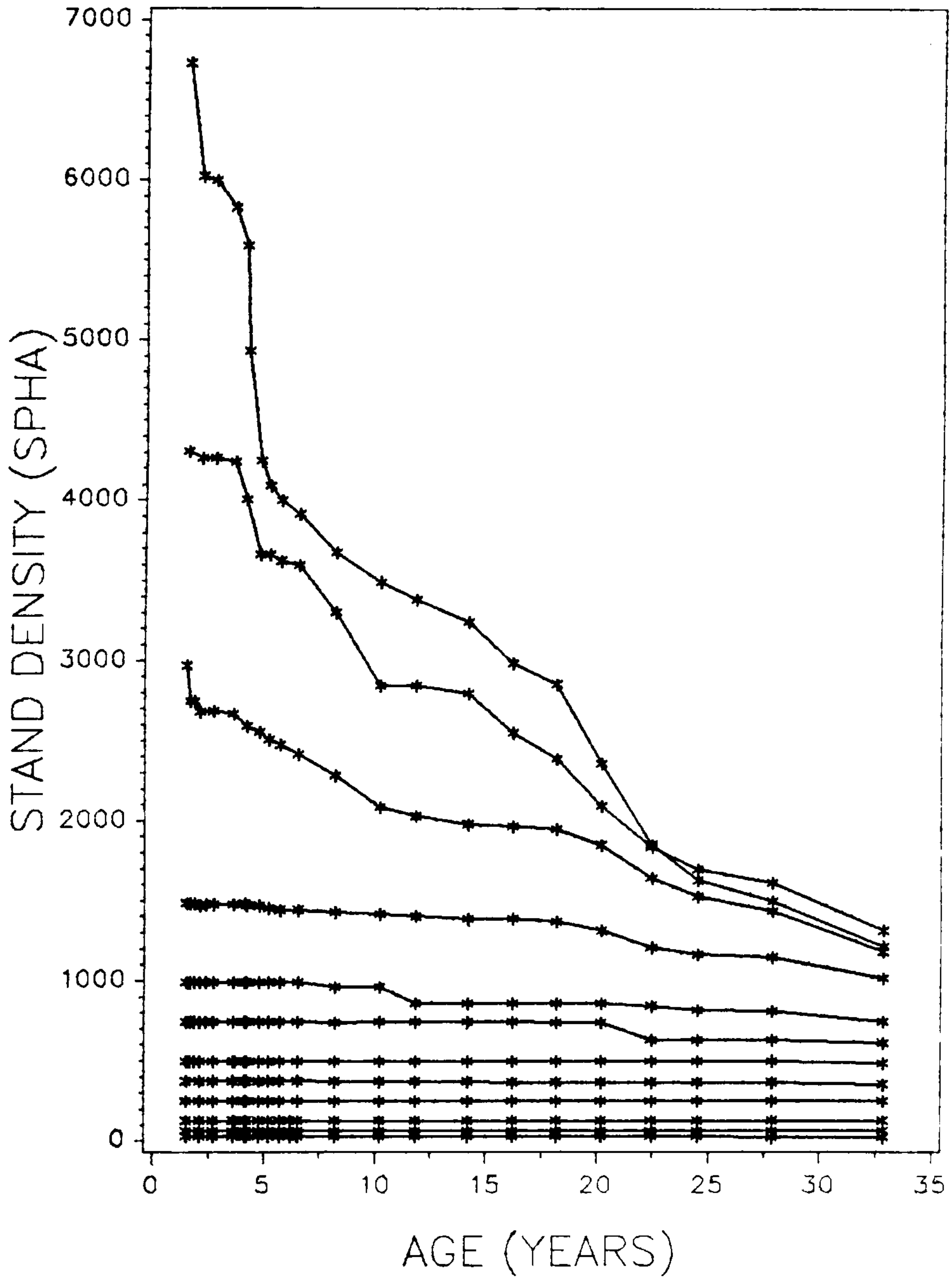


Figure 22. Mortality over time at Langepan: Surviving stand density shown as a function of age at Langepan.

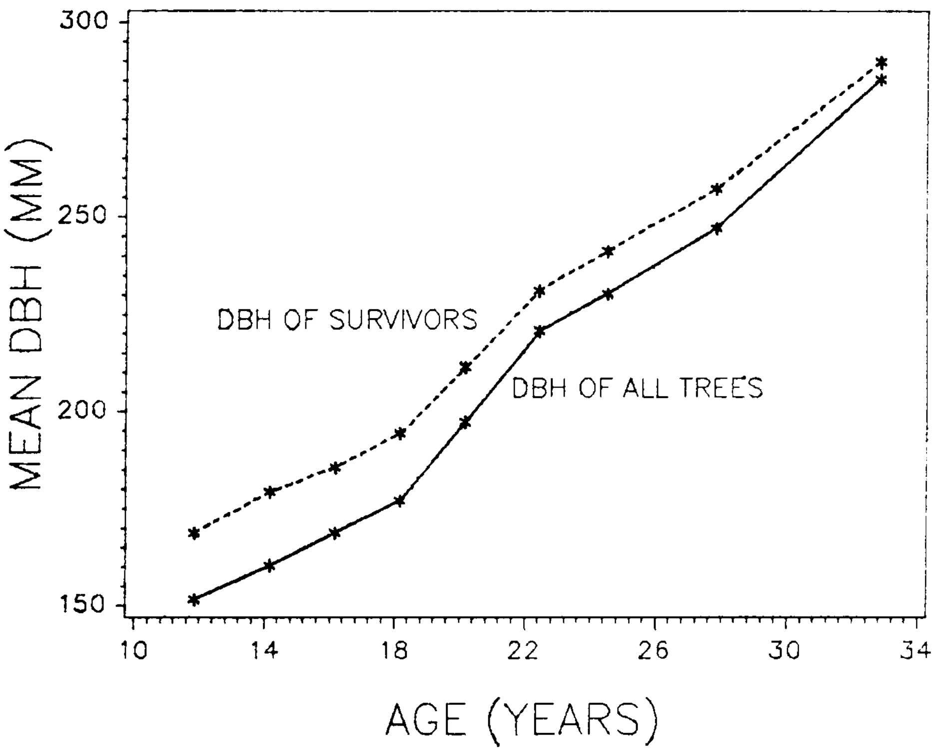


Figure 23. Quadratic dbh growth under conditions of extreme suppression: Means for upper line are based on trees which survived until age 32.83 while the lower line indicates $\bar{D}_q$ calculated in the normal way.

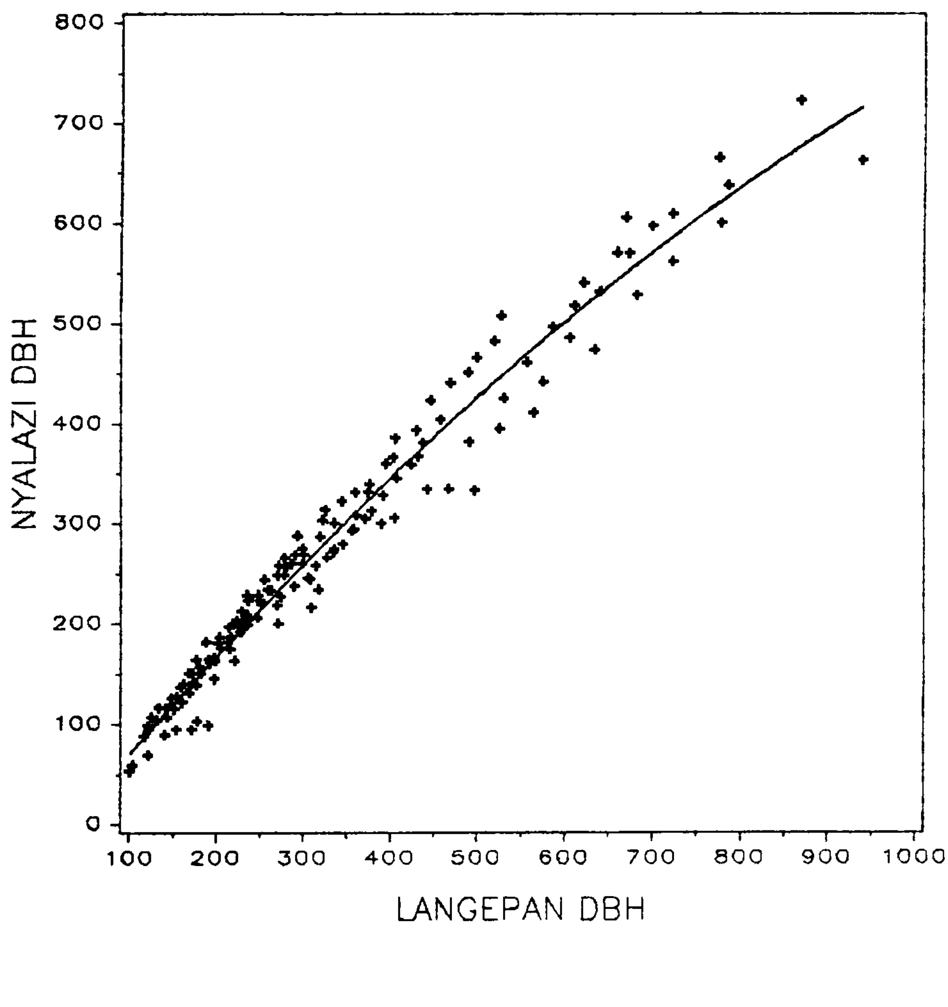


Figure 24. Comparison in quadratic dbh recorded at Nyalazi and Langepan: Quadratic mean dbh at Nyalazi plotted against quadratic mean dbh at Langepan at approximately similar ages. The quadratic component is significant.

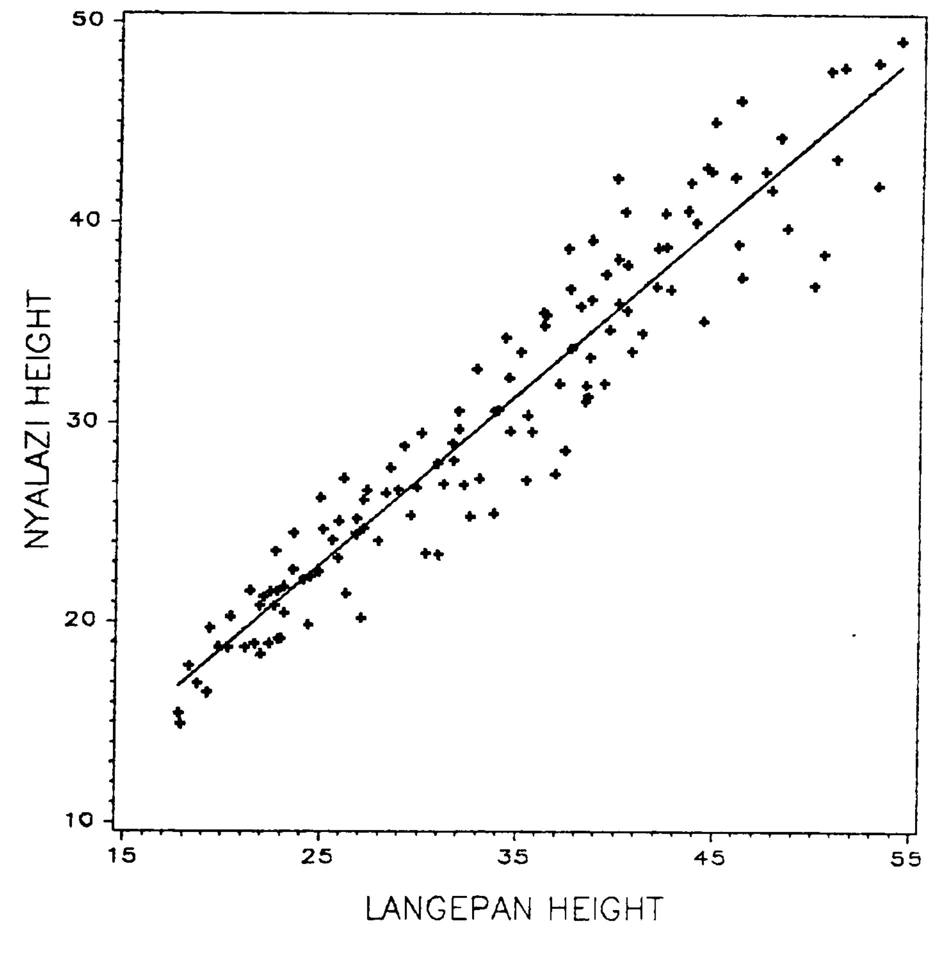


Figure 25. Comparison in mean height recorded at Nyalazi and Langepan: Height at Nyalazi plotted against height at Langepan at approximately similar ages.

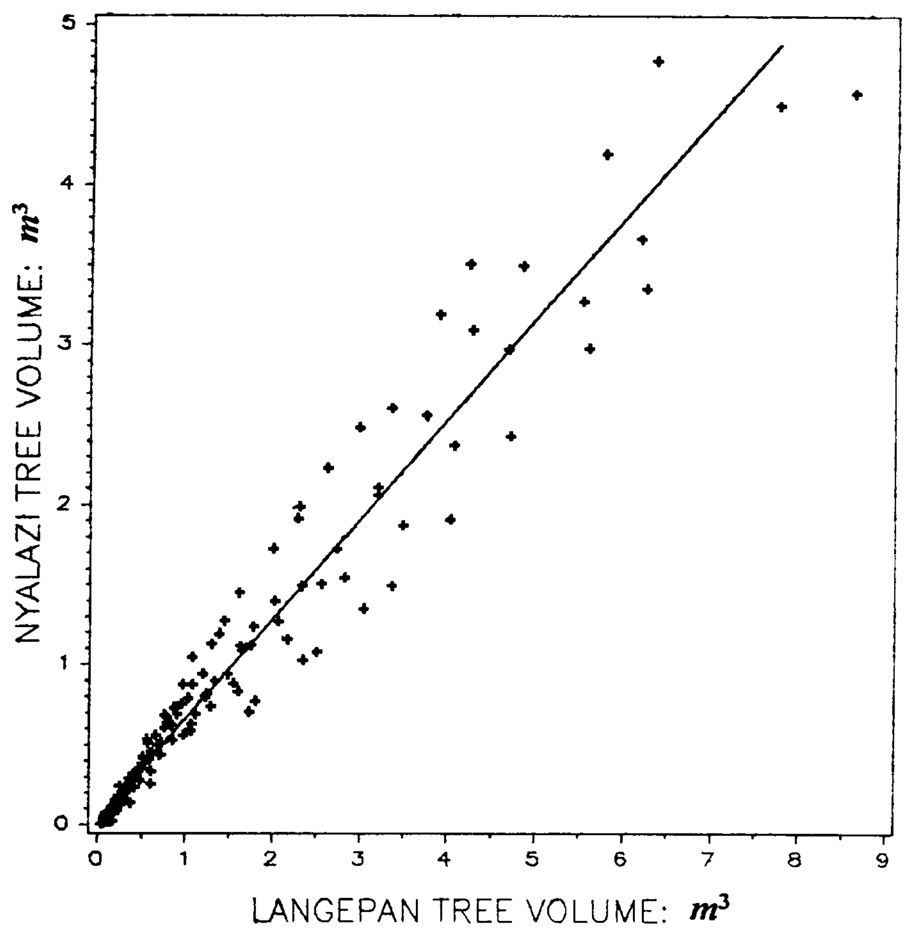


Figure 26. Comparison in volume estimated at Nyalazi and Langepan: Mean tree volume at Nyalazi plotted against volume at Langepan at approximately similar ages.

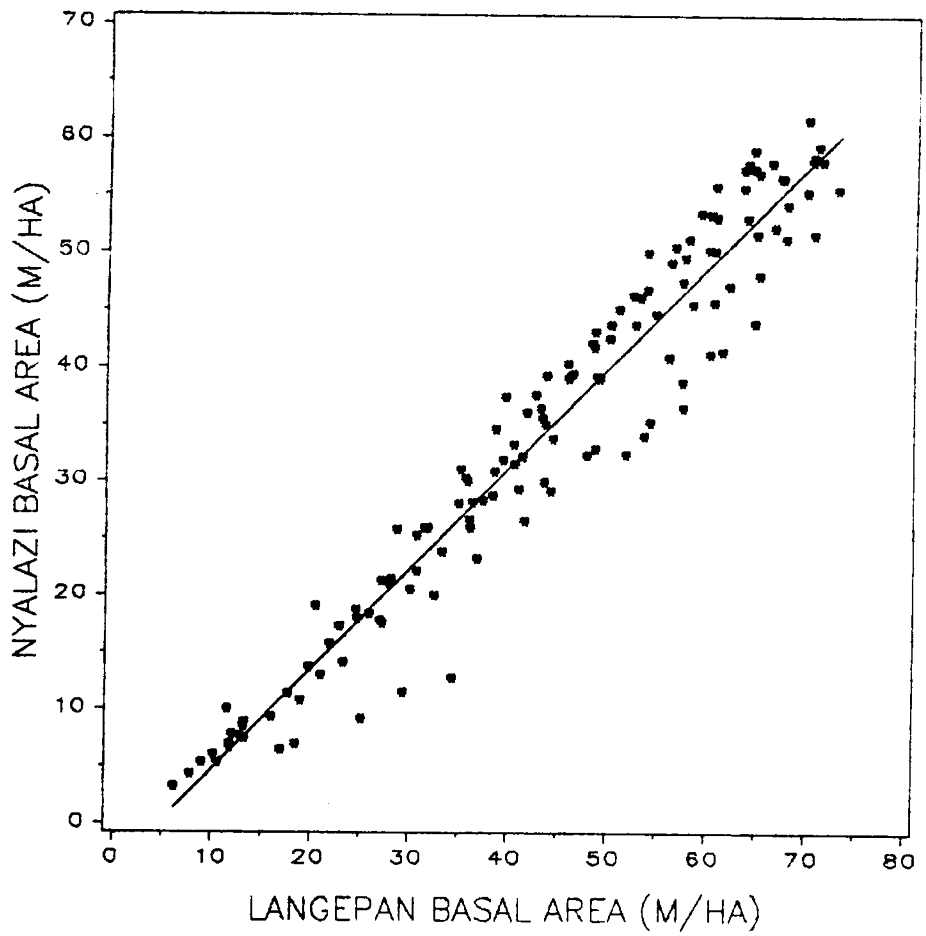


Figure 27. Comparison in basal area recorded at Nyalazi and Langepan: Stand basal area at Nyalazi plotted against stand basal area at Langepan at approximately similar ages.

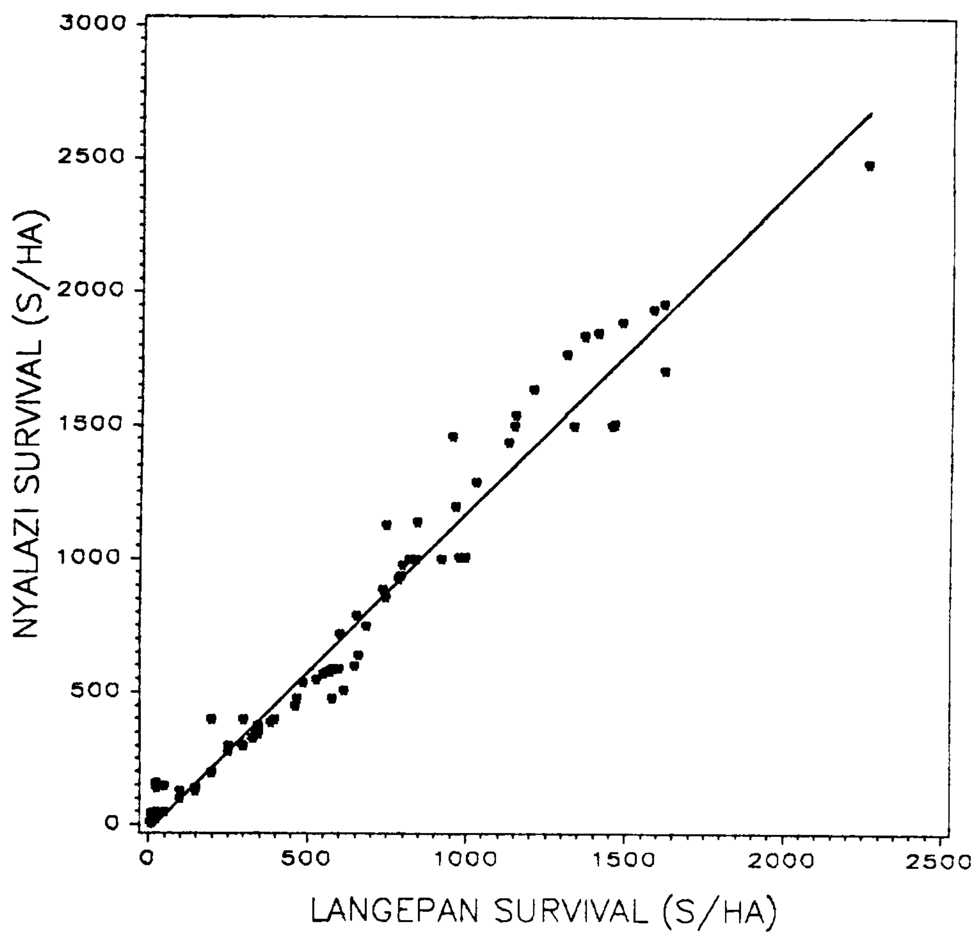


Figure 28. Comparison in survival recorded at Nyalazi and Langepan: Surviving stand density at Nyalazi plotted against stand density at Langepan at approximately similar ages.

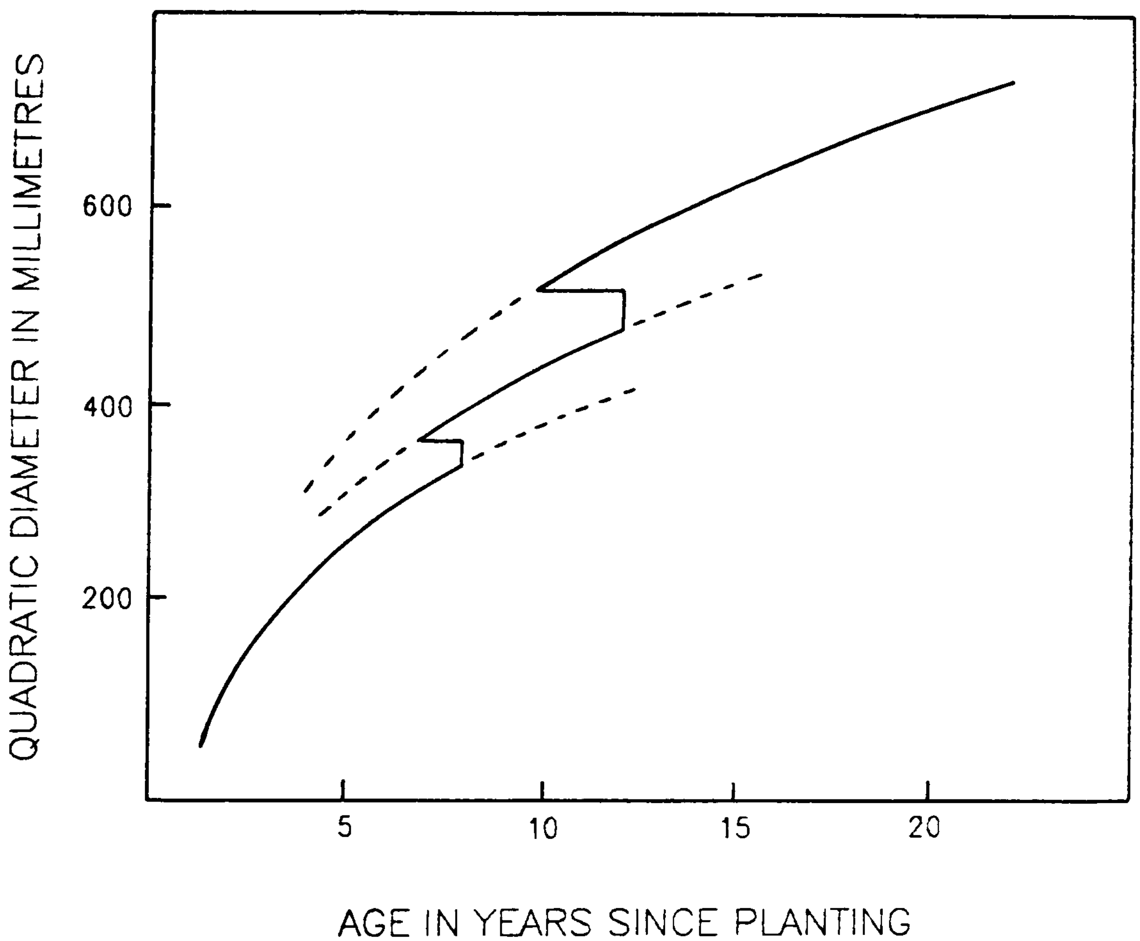


Figure 29. **The thinning algorithm:** Simulated development of quadratic mean dbh with thinning modelled as a lateral shift between growth trajectories.

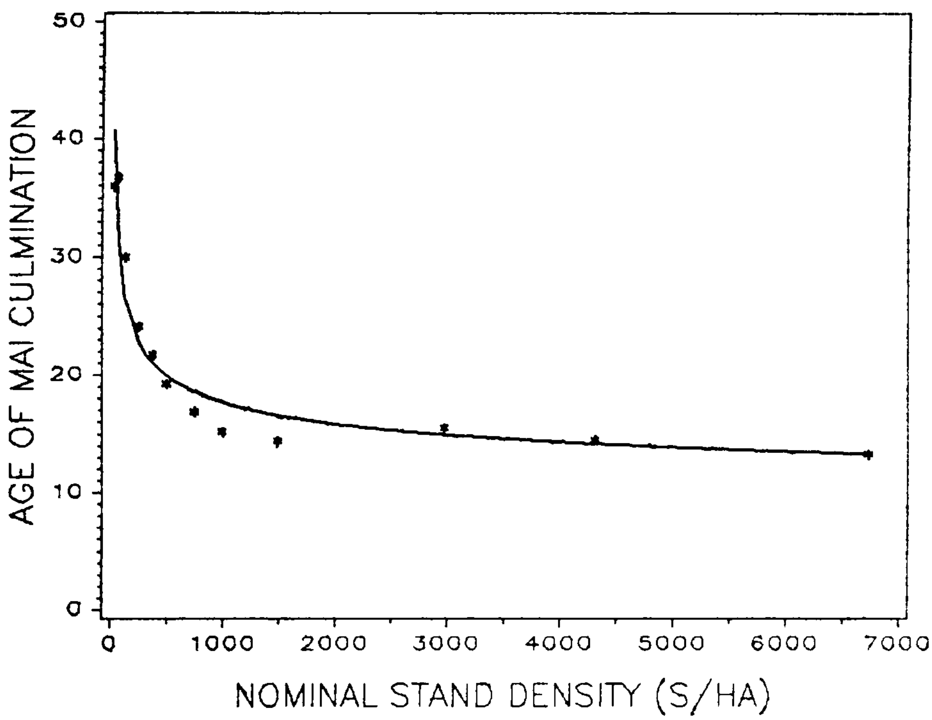


Figure 30. Age of culmination of m.a.i.: Regression of age of culmination of m.a.i. on nominal stand density.

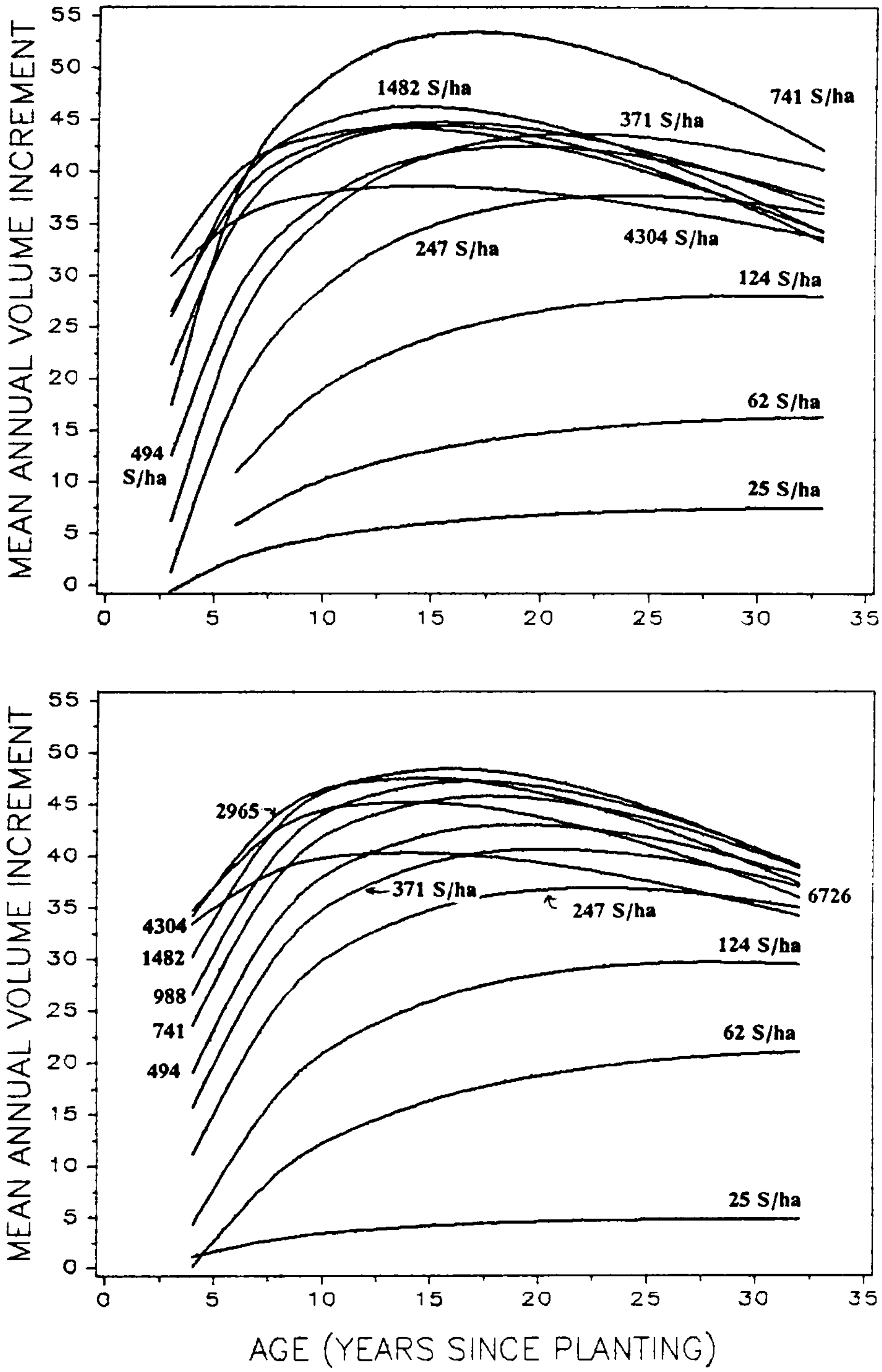


Figure 31. Development of m.a.i. with age at Langepan: Differing patterns of development for different levels of stand density, as fitted (above) and from predicted parameters (below).

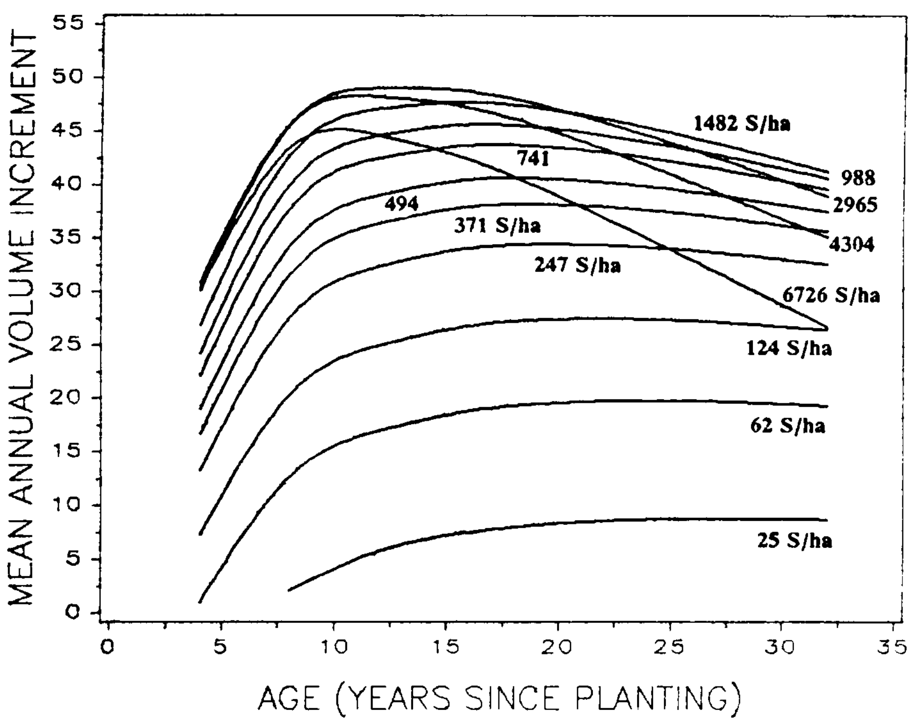


Figure 32. Development of m.a.i. with age at Langepan: Prediction of m.a.i./age relationship with a more parsimonious model.

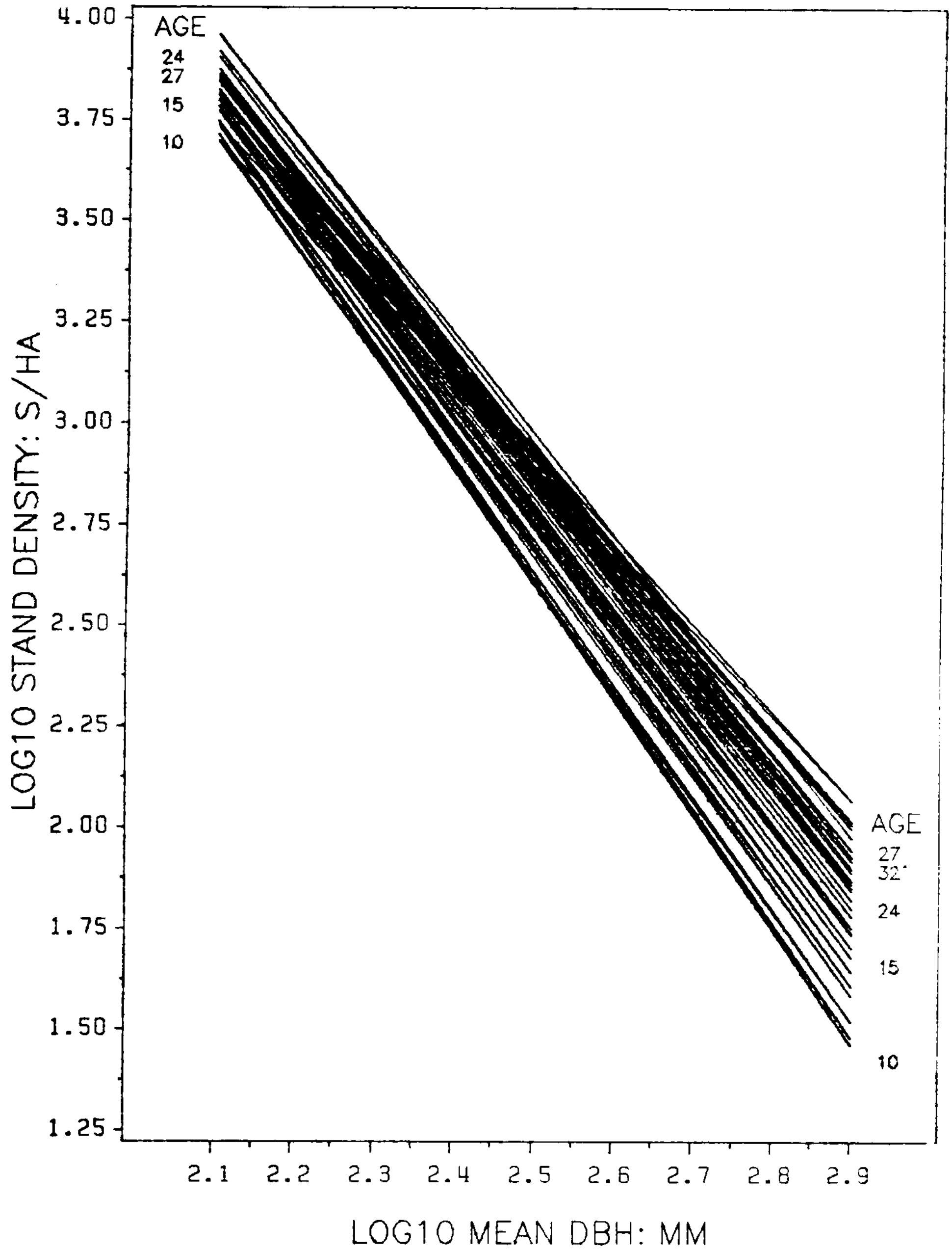


Figure 33. SDI for a range of ages: Changing slope and intercept of the stand density index line for Langepan in stands older than ten years and experiencing competition mortality.

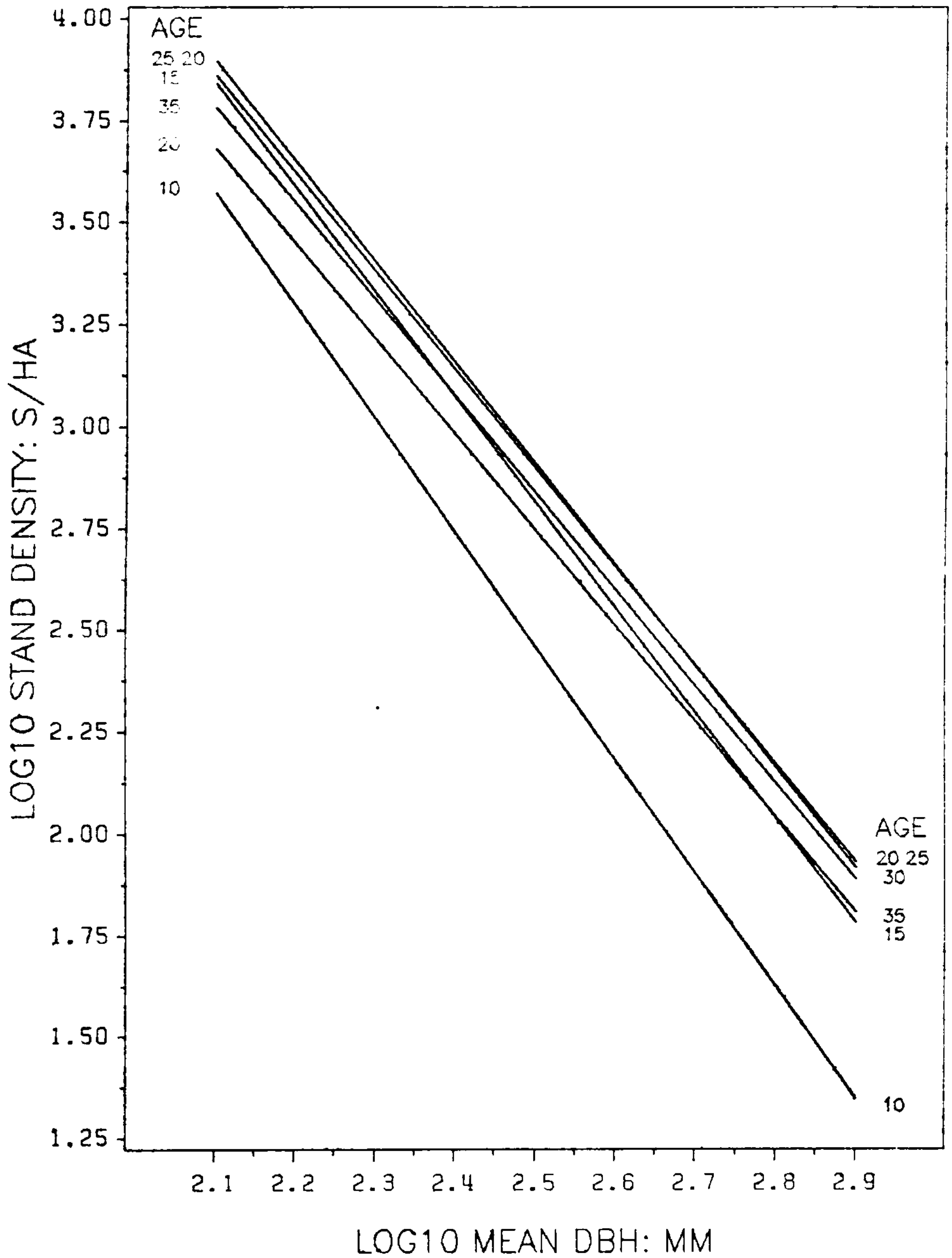


Figure 34. Smoothed estimates of SDI at Langepan: Estimated slope and intercept of the stand density index line as functions of age in older stands.

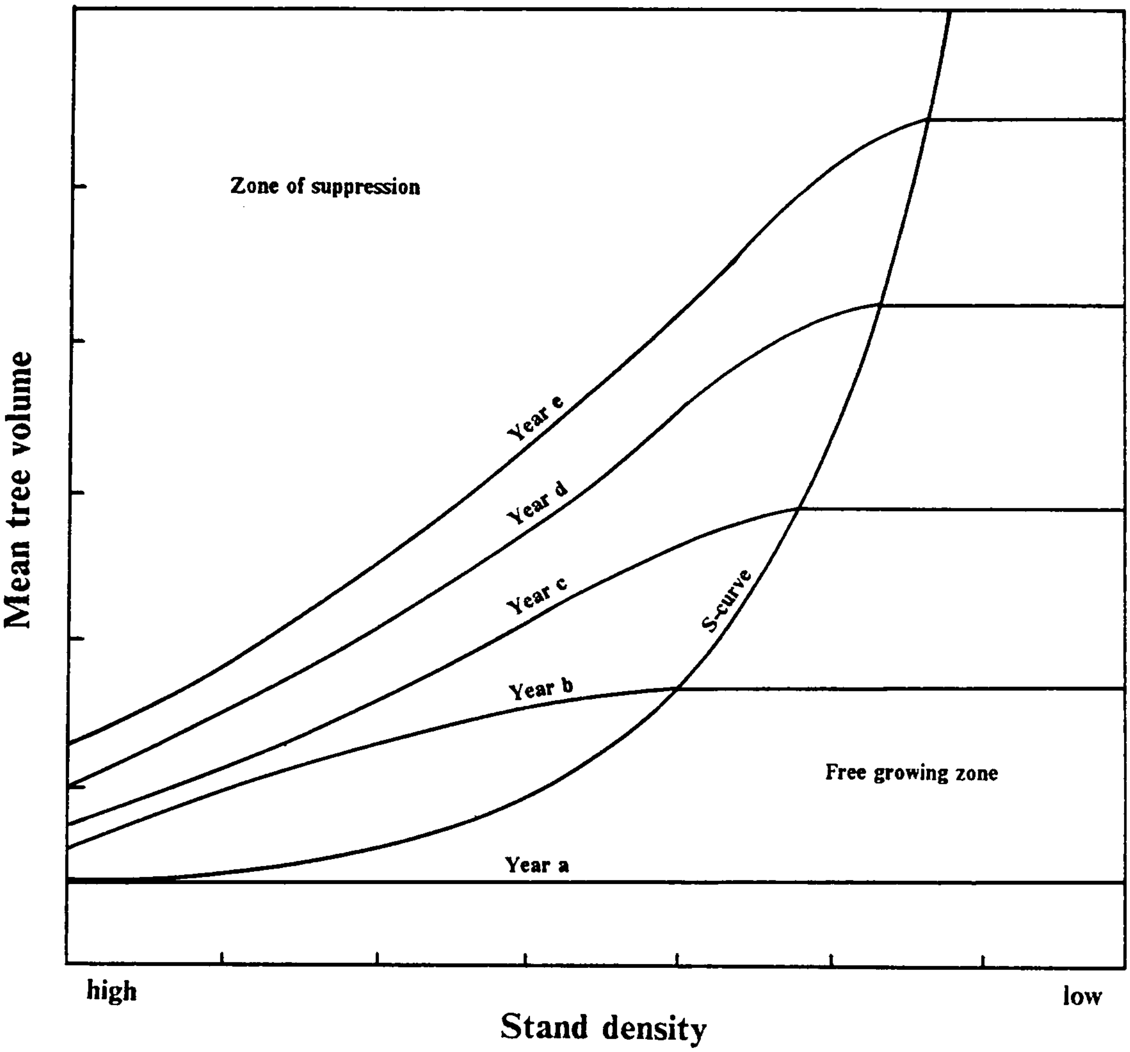


Figure 35. O'Connor's S-curve postulation: It was postulated that the onset of competition would define a boundary between the zones of free-growth and suppression.

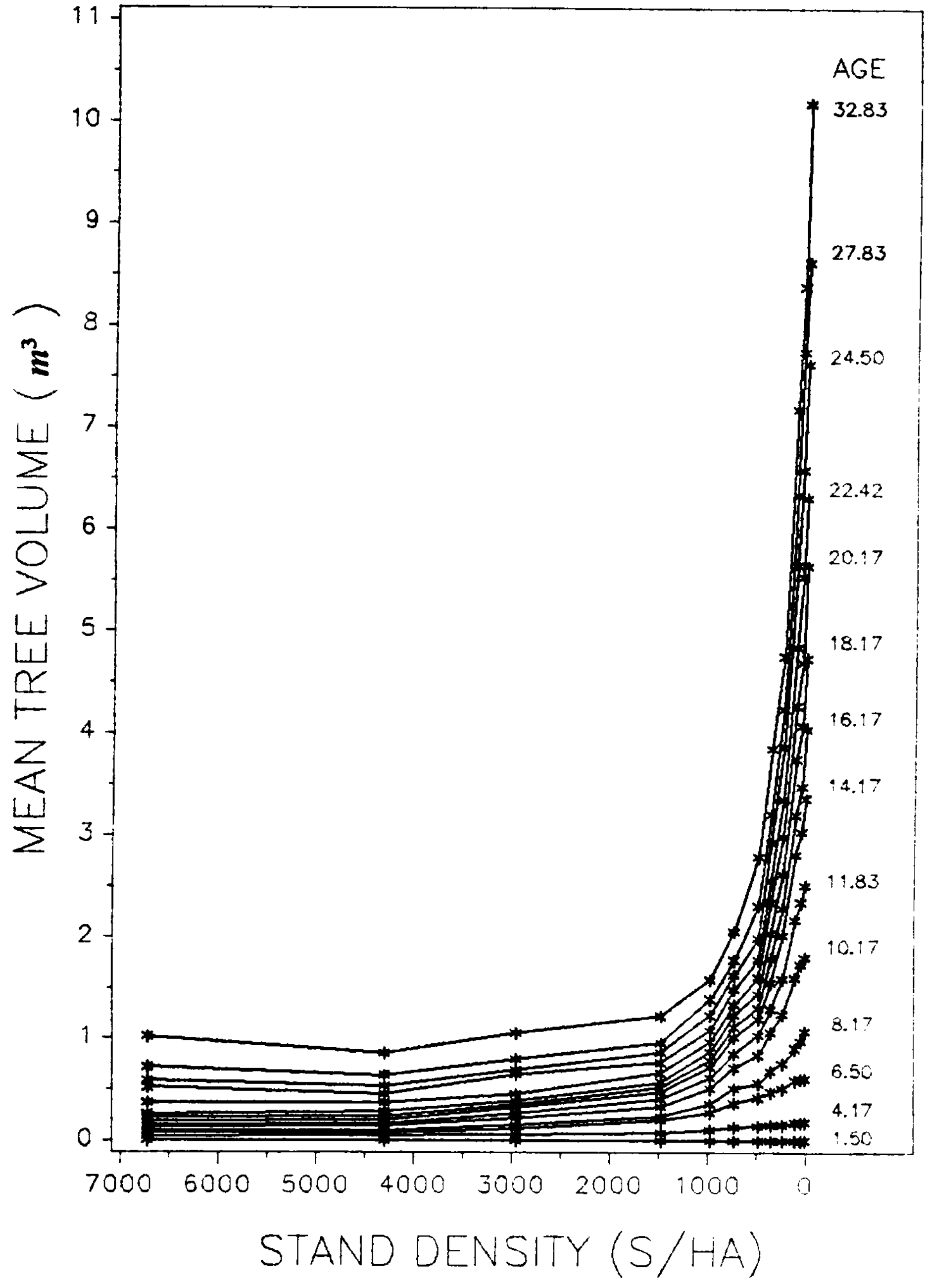


Figure 36. O'Connor's S-curve fitted to Langepan data: The plot of mean tree volume against nominal stand density gives no indication at to the position of a s-curve.

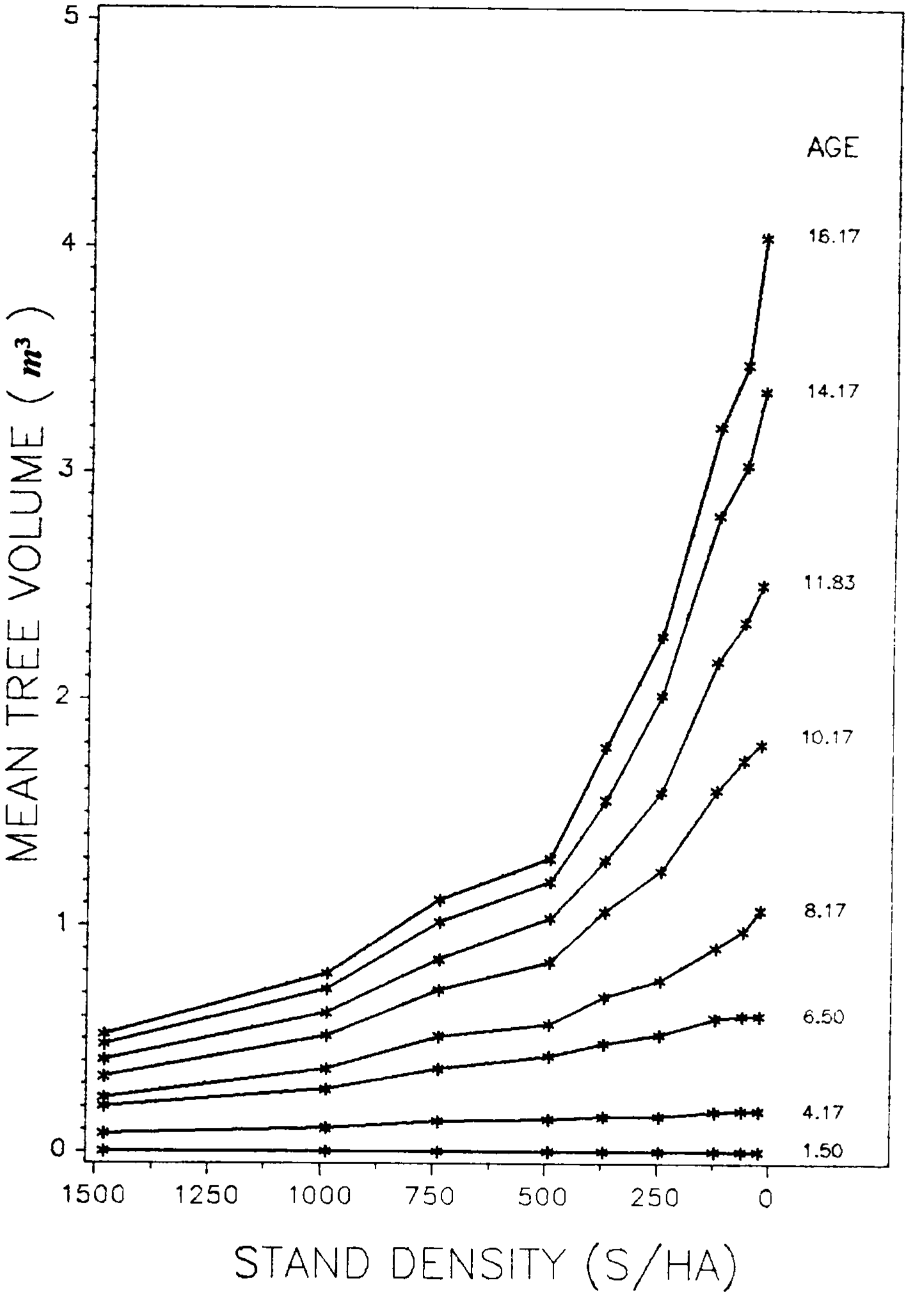


Figure 37. A closer look at O'Connor's S-curve postulation: An enlargement of the mean tree volume / nominal stand density relationship for clarity in the search for a series of inflection points.

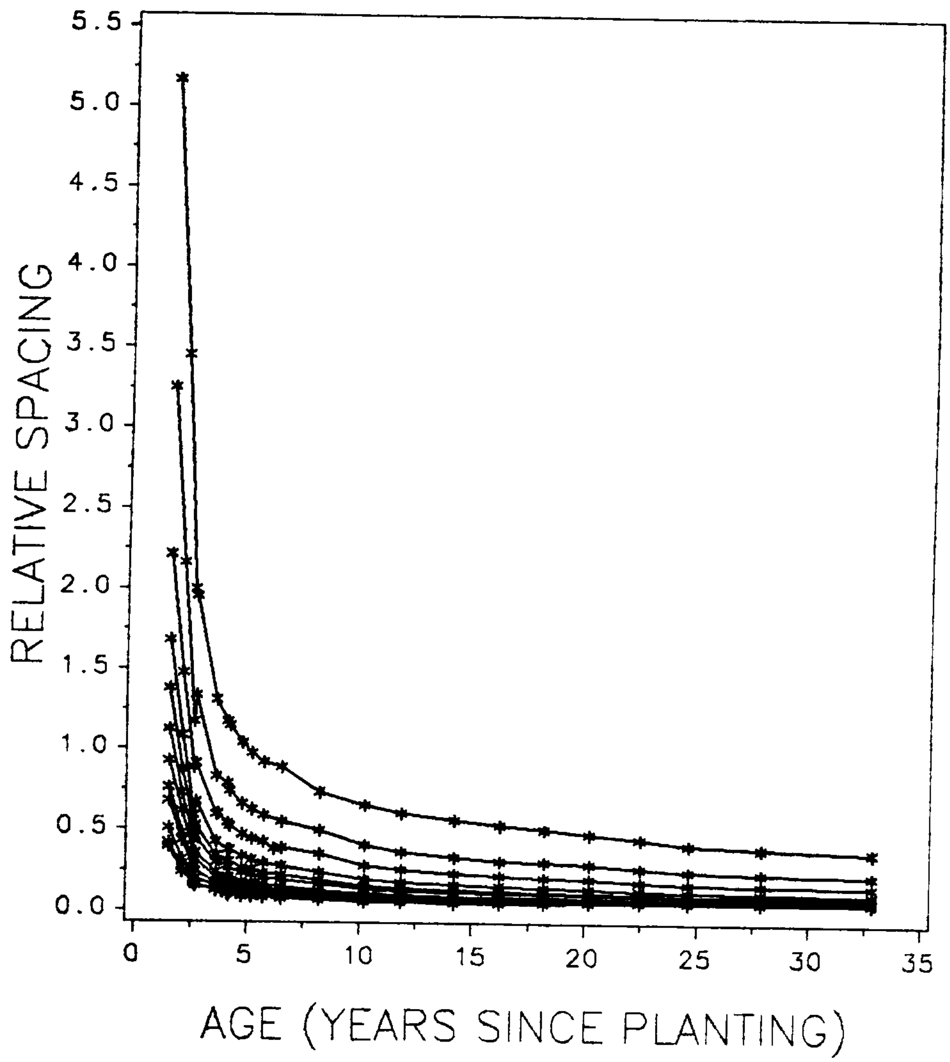


Figure 38. Relative spacing over age fitted to all data: When viewed across a long interval, relative spacing appears to approach an asymptote from an early age. This is an artefact of scale.

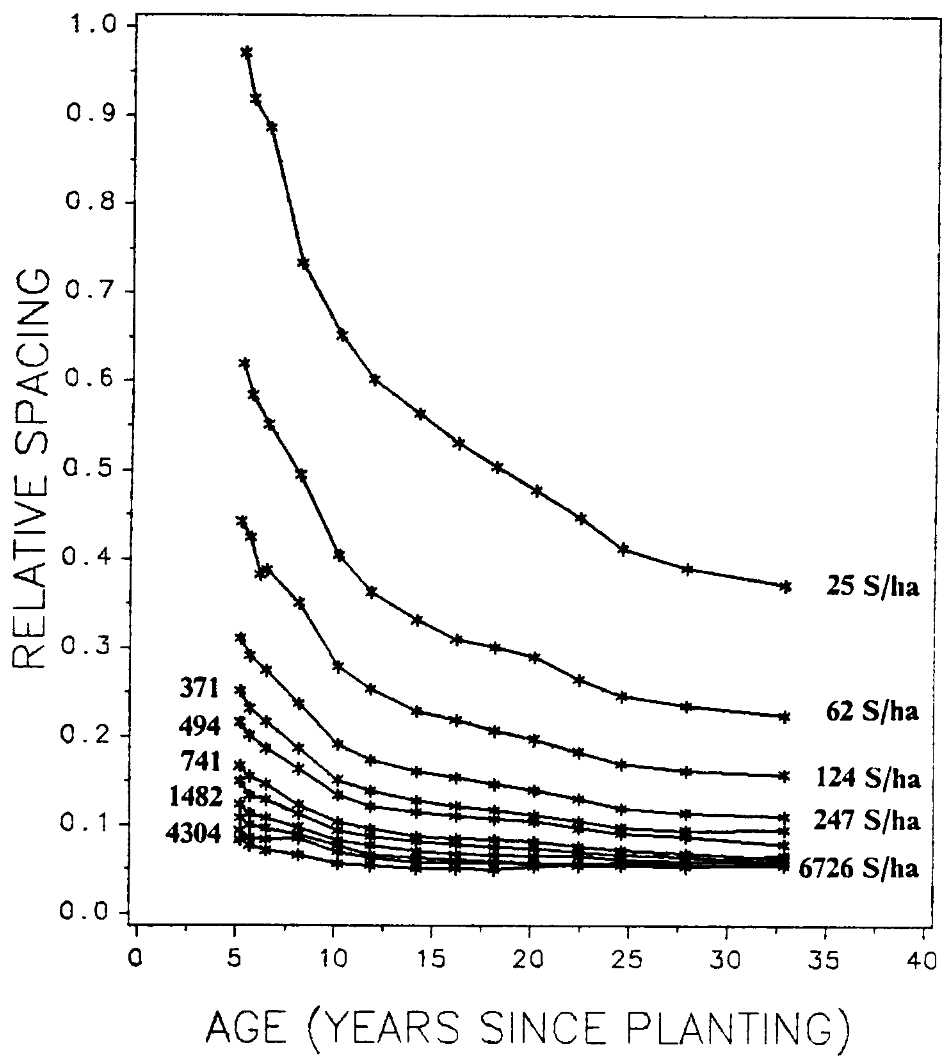


Figure 39. Relative spacing over age at later stages: With the highest values of relative spacing at early ages removed, enhancing the scale, it is apparent that only the most dense stands appear to have reached a common asymptote.

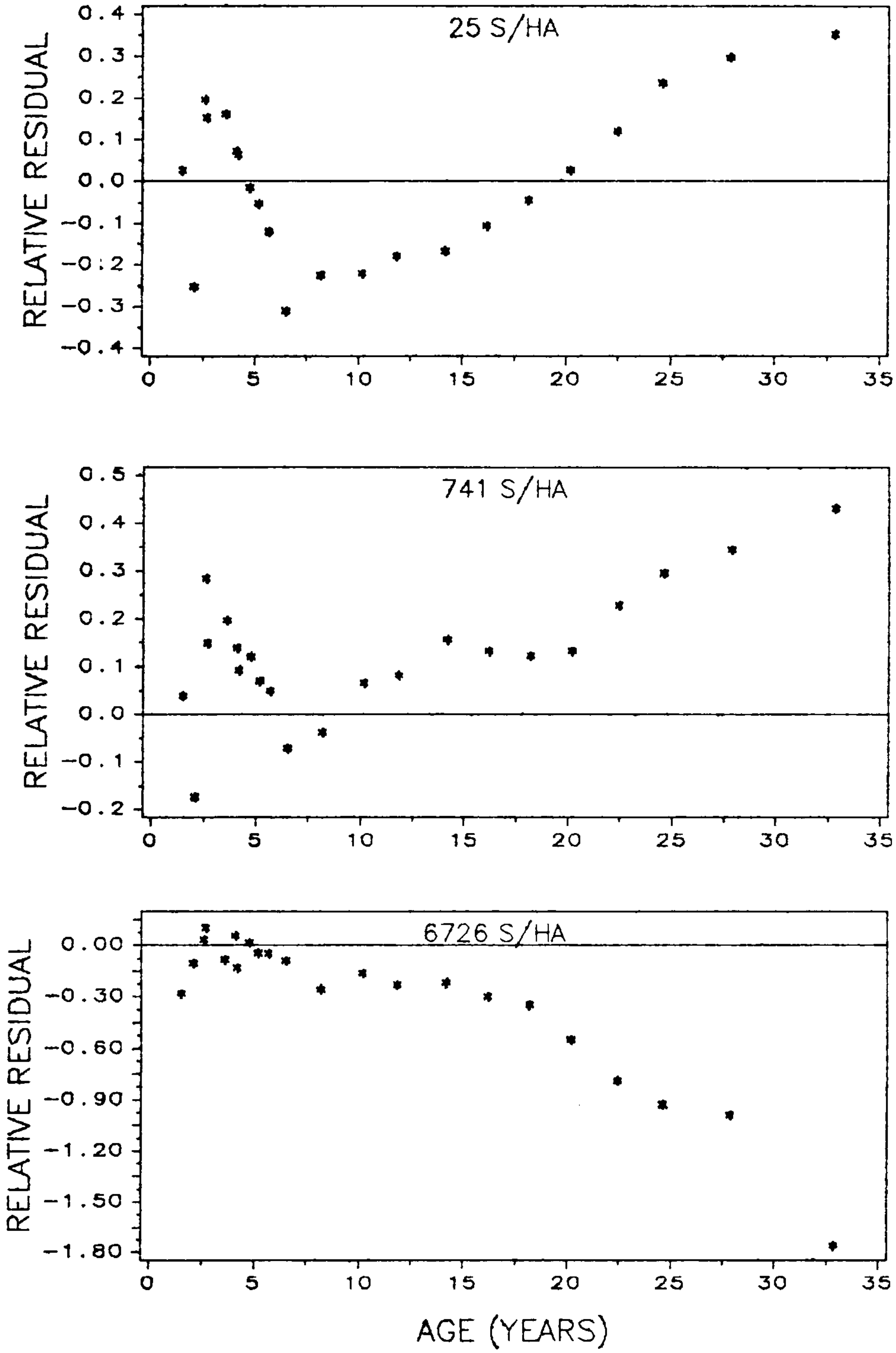


Figure 40. Prediction of stand survival via relative spacing: Relative residuals for the prediction of survival for a range of nominal stand density levels.

Appendix C

Basic Program

Source code for E. grandis growth simulation program

The following is the source code for the simulation of growth of *E. grandis* at Langepan and a weighting procedure to enable one to estimate growth at other sites for which growth data are available. The program is written in BASIC for MS-DOS.

```
10 COLOR 7,1,1: CLS : KEY OFF
20 GOSUB 100                          'title page
30 GOSUB 300                          'introductory screen
40 GOSUB 600                          'input for weighting
50 GOSUB 1300                         'select thinnings
60 ON ANSW1 GOSUB 1500, 1500, 1900, 2700, 8200  'distribute thinnings
70 GOSUB 6200                         'print no-thinning results table
80 GOSUB 8270                         'quit to DOS

100 REM
110 REM Title screen
120 REM
130 LOCATE  5,34: PRINT "GRANDIS";
140 LOCATE 10,17: PRINT "A program in BASIC to simulate the growth of"
150 LOCATE 11,20: PRINT "managed stands of Eucalyptus grandis"
160 LOCATE 18,61: PRINT "Brian Bredenkamp"
170 LOCATE 18,5: PRINT "Version 2.0"
180 LOCATE 19,6: PRINT "July 1988"
190 LOCATE 25,26: PRINT "Press any key to continue";
```

```
200 IF INKEY$="" GOTO 200
210 RETURN

300 REM
310 REM Introductory screen
320 REM
330 CLS: LOCATE  5,34: PRINT "GRANDIS";
340 LOCATE  9,7
350 PRINT "This programme is based on data emanating from C.C.T. experiments"
360 LOCATE 10,7
370 PRINT "at Langepan and Nyalazi on the coastal plain of Zululand, South"
380 LOCATE 11,7
390 PRINT "Africa. Provision is made for the weighting of estimates for"
400 LOCATE 12,7
410 PRINT "areas of dissimilar growth.
420 LOCATE 14,7
430 PRINT "If the user wishes to weight the predictions, estimates of minimum"
440 LOCATE 15,7
450 PRINT "dbh, arithmetic dbh, quadratic dbh, mean height and survival for"
460 LOCATE 16,7
470 PRINT "the stand being evaluated will be required."
480 LOCATE 19,7
490 PRINT "In the absence of estimates, predictions are for Zululand conditions.";
500 LOCATE 25,26: PRINT "Press any key to continue";
510 IF INKEY$="" GOTO 510
520 RETURN

600 REM
610 REM Screen for selection of weighting alternative
620 REM
630 CLS: LOCATE  5,31: PRINT "GRANDIS";
640 LOCATE 9,3
650 PRINT "Do you have data with which to adjust the Langepan predictions"
660 LOCATE 9,70: PRINT "Y/N ?";
670 GOSUB 6000                          'evaluation of Y/N input
680 ON YN GOSUB 800, 800, 800, 1100, 1100     'answer to yes/no
690 RETURN

800 REM
810 REM Input of data for weighting
820 REM
830 CLS: LOCATE  5,34: PRINT "GRANDIS";
840 LOCATE 7,8
850 INPUT "At what stand density (S/ha) was the stand planted        "; SPHA0W
860 LOCATE 9,8
870 INPUT "At what stand density (S/ha) is it at time of interest    "; SPHA1W
880 IF SPHA1W < SPHA0W*.1 THEN GOTO 11200          'error trap for mortality
890 LOCATE 11,8
900 INPUT "At what age (years) is the stand at time of interest      "; AGE0W
910 LOCATE 13,8
920 INPUT "What is the minimum dbh (mm) at time of interest          "; DBHMW
930 LOCATE 15,8
940 INPUT "What is the arithmetic dbh (mm) at time of interest       "; DBHAW
950 LOCATE 17,8
960 INPUT "What is the quadratic dbh (mm) at time of interest        "; DBHQW
970 LOCATE 19,8
980 INPUT "What is the mean height (m) at time of interest           "; HGHT0W
990 DBHQ=DBHQW: HTMEAN=HGHT0W: GOSUB 4800: VOL0W=VOL   'get mean tree volume
1000 LOCATE 25,26: PRINT "Press any key to continue";
1010 IF INKEY$="" GOTO 1010
1020 GOSUB 2900                          'calculate weightings
1030 GOSUB 3210                          'print weightings
1040 RETURN
```

```
1100 REM
1110 REM Screen informing user of zero weighting
1120 REM
1130 CLS: LOCATE  5,34: PRINT "GRANDIS";
1140 LOCATE 10,7
1150 PRINT "You have chosen the zero weighting option and all predictions will"
1160 LOCATE 11,7
1170 PRINT "be based on  Langepan conditions";
1180 HTPC=1: VOLPC=1: LIVEPC=1: DBHPC=1          'allocate neutral weights
1190 LOCATE 25,26: PRINT "Press any key to continue";
1200 IF INKEY$="" GOTO 1200
1210 RETURN

1300 REM
1310 REM Screen to select number of thinning operations
1320 REM
1330 CLS: LOCATE  2,33: PRINT "GRANDIS";
1340 LOCATE 5,15: PRINT "Select the thinning schedule you wish to simulate";
1350 LOCATE 8,13: PRINT "1.  No-thinning pulpwood regime";
1360 LOCATE 10,13: PRINT "2.  Single thinning mining timber/poles regime";
1370 LOCATE 12,13: PRINT "3.  Two thinning sawtimber regime";
1380 LOCATE 14,13: PRINT "4.  Quit and return to DOS";
1390 GOSUB 7900                          'evaluate above response
1400 RETURN

1500 REM
1510 REM No thinning choice
1520 REM
1530 CLS: LOCATE  2,33: PRINT "GRANDIS";
1540 LOCATE 5,15: PRINT "You have selected the no thinning option";
1550 LOCATE 8,12: INPUT "At which stand density (S/ha) are you planting"; SPHA0
1560 LOCATE 10,12: INPUT "At which age do you intend to clearfell    "; AGENT
1570 SPHA=SPHA0: AGE=AGENT
1580 GOSUB 3400                          'calculate quadratic dbh
1590 GOSUB 3700                          'calculate arithmetic dbh
1600 GOSUB 4000                          'calculate minimum dbh
1610 GOSUB 4200                          'calculate top height
1620 GOSUB 4400                          'calculate mean height
1630 GOSUB 4600                          'calculate survival
1640 GOSUB 4800                          'calculate mean tree volume
1650 IF DBHA > DBHQ OR DBHM > DBHA THEN GOSUB 8100
1660 DBHQNT=DBHQ: DBHANT=DBHA   'rename variables
1670 DBHMNT=DBHM: TOPHTNT=HTTOP 'rename variables
1680 MNHTNT=HTMEAN: SALIVENT=SALIVE: VOLNT=VOL         'rename variables
1690 STVOLNT=VOLNT*SALIVENT                    'calculate stand volume
1700 DBHQEST=DBHQNT: DBHAEST=DBHANT 'rename variables
1710 DBHMEST=DBHMNT: MNHTEST=MNHTNT 'rename variables
1720 TOPHTEST=TOPHTNT: SALIVEST=SALIVENT: VOLEST=VOLNT
1730 GOSUB 5770                          'weight all estimates
1740 DBHQNTWD=DBHQWD: DBHANTWD=DBHAWD 'rename variables
1750 DBHMNTWD=DBHMWD   'rename variables
1760 VOLNTWD=VOLWD: STVOLNTWD=STVOLWD                'rename variables
1770 TOPHTNTWD=HTTOPWD: MNHTNTWD=HTMEANWD             'rename variables
1780 SALIVENTWD=SALIVEWD                         'rename variable
1790 TR=SALIVENTWD: A=DBHMNTWD   'Weibull names
1800 D1=DBHANTWD: D21=DBHQNTWD   'Weibull names
1810 LOCATE 25,26: PRINT "Press any key to continue";
1820 IF INKEY$="" GOTO 1820
1830 RETURN

1900 REM
1910 REM Single thinning choice
```

```
1920 REM
1930 CLS: LOCATE 1,33: PRINT "GRANDIS";
1940 LOCATE 7,15: PRINT "You have selected the one-thinning choice";
1950 LOCATE 10,8: INPUT "At which stand density do you intend to plant"; SPHA2
1960 LOCATE 12,8: INPUT "At which age do you intend to thin"; AGE2
1970 LOCATE 14,8: INPUT "To which stand density will you thin"; SPHA3
1980 LOCATE 16,8: INPUT "At which age do you intend to clearfell"; AGE3
1990 SPHA=SPHA2: AGE=AGE2
2000 GOSUB 3400                          'calculate quadratic dbh
2010 GOSUB 3700                          'calculate arithmetic dbh
2020 GOSUB 4000                          'calculate minimum dbh
2030 GOSUB 4200                          'calculate top height
2040 GOSUB 4400                          'calculate mean height
2050 GOSUB 4600                          'calculate survival
2060 GOSUB 4800                          'calculate mean tree volume
2070 IF DBHA > DBHQ OR DBHM > DBHA THEN GOSUB 8100
2080 DBHQBT1=DBHQ: DBHABT1=DBHA                  'rename variables
2090 DBHMBT1=DBHM: TOPHTBT1=HTTOP                 'rename variables
2100 MNHTBT1=HTMEAN: SALIVEBT1=SALIVE: VOLBT1=VOL 'rename variables
2110 STVOLBT1=VOLBT1*SALIVEBT1              'calculate stand volume
2120 STVOLBT1W=VOLBT1*VOLPC*SALIVEBT1*LIVEPC 'calculate stand volume weighted
2130 SPHATHIN1=SALIVEBT1-SPHA3              's/ha removed in thinning
2140 IF SPHA3 > SALIVEBT1 THEN GOTO 10800      'error trap
2150 B1=-8.30008116#: B2=4.705581E-02: B3=.0015685: B4=32.95372899#
2160 THINPC=SPHATHIN1/SALIVEBT1             'thinning percentage
2170 IF THINPC > .5 THEN GOSUB 11400        'error trap
2180 B5=B1+B2*THINPC+B3*DBHMBT1+B4*MNHTBT1/DBHQBT1 'increase in mean dbh
2190 DBHQAT1=DBHQBT1*(EXP(B5)+1)            'dbhq after 1st thinning
2200 B6=-9.75444925#: B7=4.281418E-02: B8=-1.8279E-04
2210 B9=-8.7801*10^-6: B10=42.87628269#
2220 B11=B6+B7*THINPC+B8*SALIVEBT1+B9*(DBHQBT1-DBHMBT1)^2
2230 B11=B11+B10*MNHTBT1/DBHQBT1
2240 MNHTAT1=MNHTBT1*(EXP(B11)+1)           'mean height after 1st thin
2250 HTINCR=MNHTAT1-MNHTBT1                'chainsaw increase in mean height
2260 SPHA=SALIVEBT1: AGE=AGE3: GOSUB 4400   'calculate mean height
2270 MNHTBCF=HTMEAN+HTINCR                 'unweighted mn ht before felling
2280 MNHTBCFW=MNHTBCF*HTPC                 'weighted mean ht before felling
2290 MNHTBT1W=MNHTBT1*HTPC                 'weighted mean ht before thinning
2300 TOPHTBT1W=TOPHTBT1*HTPC               'weighted mean ht before thinning
2310 SALIVEBT1W=SALIVEBT1*LIVEPC           'weighted survival
2320 SPHA=SPHA3: DBHI=DBHQAT1: GOSUB 5200   'get index age for dbhi (quad)
2330 IAGEFELL=INDEXAGE+(AGE3-AGE2)          'index age for clearfelling
2340 SPHA=SPHA3: AGE=IAGEFELL: GOSUB 3400   'calculate quadratic mean dbh
2350 HTMEAN=MNHTBCF: GOSUB 4800: VOLCFW=VOL*VOLPC 'calculate mean tree volume
2360 VOLWT=VOLCFW: HTWT=MNHTBCFW: GOSUB 5700 'get dbh weighting
2370 IF DBHPC=1 THEN GOTO 2390              'retain no weighting
2380 DBHPC=DBHQ/DBHWT                      'temp transform to mm
2390 DBHQBCFW=DBHQ*DBHPC                   'weight dbh observation
2400 DBHQBT1W=DBHQBT1*DBHPC                'weight dbh observation
2410 DBHABT1W=DBHABT1*DBHPC                'weight dbh observation
2420 DBHMBT1W=DBHMBT1*DBHPC                'weight dbh observation
2430 DBHQBCF=DBHQ                          'rename variable for print
2440 DBHQ=DBHQBT1W: HTMEAN=MNHTBT1W: GOSUB 4800 'get mean vol before thin
2450 IF DBHPC=1 THEN STVOLBT1W=STVOLBT1
2460 ELSE STVOLBT1W=VOL*SALIVEBT1W           'weighted stand volume
2470 HTMEAN=MNHTBCF: DBHQ=DBHQBCF: GOSUB 4800 'calculate mean tree volume
2480 STVOLBCF=VOL*SPHA3: STVOLBCFW=VOLCFW*SPHA3 'calculate stand volume at cf
2490 IAGEFELL=INDEXAGE+(AGE3-AGE2)          'index age for clearfelling
2500 SPHA=SPHA3: AGE=IAGEFELL: GOSUB 3700   'calculate arithmetic mean dbh
2510 DBHABCF=DBHA: DBHABCFW=DBHA*DBHPC      'apply weighting to dbha
2520 B182=-4.25270096#: B183=3.557104E-02
2530 B184=2.62098376#: B185=13.62817596#
```

```
2540 H5=B182+B183*THINPC+B184*MNHTBT1/DBHMBT1+B185*MNHTBT1/DBHQBT1
2550 DBHMAT1=DBHMBT1*(EXP(H5)=1): SPHA=SPHA3: GOSUB 5010 'iage for dbhm
2560 IAGEFELL=INDEXAGE+(AGE3-AGE2)         'index age for clearfelling
2570 SPHA=SPHA3: AGE=IAGEFELL: GOSUB 4000    'calculate minimum dbh
2580 DBHMBCF=DBHM: DBHMBCFW=DBHM*DBHPC       'apply weighting to dbhm
2590 TR=SPHA3: A=DBHMBCFW : D1=DBHABCFW: D21=DBHQBCFW 'Weibull names
2600 GOSUB 6700                             'print the results to the screen
2610 END

2700 REM
2710 REM Two thinning choice
2720 REM
2730 CLS: LOCATE 1,33: PRINT "GRANDIS";
2740 LOCATE 7,15: PRINT "You have selected the two-thinning choice";
2750 LOCATE 10,14: PRINT "Unfortunately this is still being developed.";
2760 LOCATE 25,20: PRINT "Press any key to return to DOS";
2770 IF INKEY$="" GOTO 2770
2780 GOTO 8200                              'choice of another run or exit

2900 REM
2910 REM Evaluation of weighting inputs at Langepan level
2920 REM
2930 SPHA=SPHA0W: AGE=AGE0W
2940 GOSUB 3400                             'calculate quadratic dbh
2950 GOSUB 3700                             'calculate arithmetic dbh
2960 GOSUB 4000                             'calculate minimum dbh
2970 GOSUB 4200                             'calculate top height
2980 GOSUB 4400: HTLAN=HTMEAN                      'calculate mean height
2990 GOSUB 4600                             'calculate survival
3000 IF DBHA > DBHQ OR DBHM > DBHA THEN GOSUB 8100 'check sizes
3010 GOSUB 4800: VOLLAN=VOL                 'calculate mean tree volume
3020 VOLPC=VOL0W/VOLLAN: HTPC=HGHT0W/HTLAN   'calculate weighting factors
3030 LIVEPC=SPHA1W/SALIVE
3040 DBH1=LOG(VOLLAN)/LOG(10)               'part of dbh weighting
3050 DBH2=1.10704*LOG(HTLAN)/LOG(10)         'part of dbh weighting
3060 DBHQWD=EXP((DBH1+4.23284-DBH2)*LOG(10)/1.71536)+2 'weight dbh ends
3070 DBHQWD=DBHQWD*10: DBHPC=DBHQW/DBHQWD    'temp transform to mm
3080 RETURN

3200 REM
3210 REM Screen displaying weighting factors
3220 REM
3230 CLS: LOCATE 2,33: PRINT "GRANDIS": LOCATE 5,22
3240 PRINT "The following factors will be used to weight Langepan predictions"
3250 LOCATE 10,22: PRINT "The height weight will be";
3260 LOCATE 10,50: PRINT USING "#.##"; HTPC
3270 LOCATE 13,22: PRINT "The volume weight will be";
3280 LOCATE 13,50: PRINT USING "#.##"; VOLPC
3290 LOCATE 16,22: PRINT "The survival weight will be";
3300 LOCATE 16,50: PRINT USING "#.##"; LIVEPC
3310 LOCATE 25,26: PRINT "Press any key to continue";
3320 IF INKEY$="" GOTO 3320
3330 RETURN

3400 REM
3410 REM Calculation of quadratic mean diameter
3420 REM
3430  B0=5.01862831#:  B1=-.463415788#
3440  B2=.030454931#:  B3=7.671041769#
3450  B4=-.255852536#: B5= 2.1577E-05
3460  B6=-1.905565128#: B7=.123548043#
3470  B8=-1.125365E-03: B9= 2.614159773#
3480  B10=-1.115693348#: B11=.165328655#
```

```
3490  B0Y=EXP(B0+B1*LOG(SPHA)+B2*LOG(SPHA)^2)
3500  B1Y=EXP(B3+B4*LOG(SPHA)+B5*SPHA)
3510  B2Y=EXP(B6+B7*LOG(SPHA)+B8*SPHA)-.125
3520  B3Y=B9+B10*LOG(SPHA)+B11*LOG(SPHA)^2
3530  B4Y=B0Y^B3Y + (B1Y^B3Y - B0Y^B3Y)
3540  B5Y=1 - EXP(-B2Y * (AGE - 1.5 ))
3550  B6Y=1 - EXP(-B2Y * (32.83 - 1.5 ))
3560  DBHQ=(B4Y*B5Y/B6Y) ^ (1/B3Y)
3570 RETURN

3700 REM
3710 REM Calculation of arithmetic mean diameter
3720 REM
3730 C0=7.822865316#: C1=-1.527203756#
3740 C2=.119094328#: C3=4.861700882#
3750 C4= 1.362924731#: C5=-.29203529#
3760 C6= .016455601#: C7=.115884161#
3770 C8=-6.5075E-05: C9=6.3859*10^-9: C10=-2.05296*10^-13
3780 C11=-2.19287705#: C12=.513815893#: C13=-.010587363#
3790 C0Y=EXP(C0+C1*LOG(SPHA)+C2*LOG(SPHA)^2):
3800 C1Y=EXP(C3+C4*LOG(SPHA)+C5*LOG(SPHA)^2+C6*LOG(SPHA)^3)
3810 C2Y=C7+C8*SPHA+C9*SPHA^2+C10*SPHA^3
3820 C3Y=EXP(C11+C12*LOG(SPHA)+C13*LOG(SPHA)^2)
3830 C4Y=C0Y^C3Y + (C1Y^C3Y - C0Y^C3Y)
3840 C5Y=1 - EXP(-C2Y * (AGE - 1.5 ))
3850 C6Y=1 - EXP(-C2Y * (32.83 - 1.5 ))
3860 DBHA=(C4Y*C5Y/C6Y) ^ (1/C3Y)
3870 RETURN

4000 REM
4010 REM Calculation of minimum mean diameter
4020 REM
4030 D0=25.22846893#: D1=-2.16021135#: D2=-66.37408016#: D3=2853.95775826#
4040 D4=-.35911124#: D5=-1.41196659#: D6= 1.01956435#: D7=.10553616#
4050 D8=-2.1136*10^-4: D9=.9859766#: D10=-1.1275*10^-3
4060 D11=1.2439*10^-6: D12=-1.036*10^-10
4070  D0Y=D0+D1*LOG(SPHA)
4080  D1Y=D2+D3*SPHA^D4
4090  D2Y=D5+D6*SPHA^D7*EXP(D8*SPHA)
4100  D3Y=D9+D10*SPHA+D11*SPHA^2+D12*SPHA^3
4110  D4Y=D0Y^D3Y + D1Y^D3Y - D0Y^D3Y
4120  D5Y=1 - EXP(-D2Y * (AGE - 1.5 ))
4130  D6Y=1 - EXP(-D2Y * (32.83 - 1.5 ))
4140  DBHM=(D4Y*D5Y/D6Y)^(1/D3Y)
4150 RETURN

4200 REM
4210 REM Calculation of top height
4220 REM
4230 E0=4.033586696#: E1=-.33157965#: E2=3.206879E-02: E3=41.11184238#
4240 E4=6.73865595#: E5=-.66759102#: E6=-9.25404331#: E7=1.92926457#
4250 E8=-.15331335#: E9=3.25171009#: E10=-.5856375#: E11=5.137662E-02
4260  E0Y=E0+E1*LOG(SPHA)+E2*LOG(SPHA)^2
4270  E1Y=E3+E4*LOG(SPHA)+E5*LOG(SPHA)^2
4280  E2Y=EXP(E6+E7*LOG(SPHA)+E8*LOG(SPHA)^2)
4290  E3Y=E9+E10*LOG(SPHA)+E11*LOG(SPHA)^2
4300  E4Y=E0Y^E3Y + E1Y^E3Y - E0Y^E3Y
4310  E5Y=1 - EXP(-E2Y * (AGE - 1.5 ))
4320  E6Y=1 - EXP(-E2Y * (32.83 - 1.5 ))
```

```
4330  HTTOP=(E4Y*E5Y/E6Y)^(1/E3Y)
4340 RETURN

4400 REM
4410 REM Calculation of mean height
4420 REM
4430 F0=5.82090766#: F1=-1.09423682#: F2=.10000476#: F3=48.78030101#
4440 F4=4.47221278#: F5=-.6729028#: F6=-13.55794511#: F7=3.71936808#
4450 F8=-.32795534#: F9=3.58362038#: F10=-.79052608#: F11= 7.812523E-02
4460 F0Y=F0+F1*LOG(SPHA)+F2*LOG(SPHA)^2
4470 F1Y=F3+F4*LOG(SPHA)+F5*LOG(SPHA)^2
4480 F2Y=EXP(F6+F7*LOG(SPHA)+F8*LOG(SPHA)^2)
4490 F3Y=F9+F10*LOG(SPHA)+F11*LOG(SPHA)^2
4500 F4Y=F0Y^F3Y + F1Y^F3Y - F0Y^F3Y
4510 F5Y=1 - EXP(-F2Y * (AGE - 1.5 ))
4520 F6Y=1 - EXP(-F2Y * (32.83 - 1.5 ))
4530 HTMEAN=(F4Y*F5Y/F6Y)^(1/F3Y)
4540 RETURN
4600 REM
4610 REM Estimation of survival
4620 REM
4630 IF SPHA <= 875 THEN SALIVE = SPHA : GOTO 4720
4640 G4=-1.4715*10^-4: G5=-5.4383*10^-4: G6=4.4966*10^-8
4650 G7=1.5065*10^-4: G8=-2.3267: G9=4.1381*10^-5
4660 G0=SPHA*EXP(G4*SPHA)
4670 G1=G5*(SPHA-875)+G6*(SPHA-875)^2
4680 G2=(SPHA-875)^(G7*(SPHA-875))
4690 G3=G8*(SPHA-875)+G9*(SPHA-875)^2
4700 SALIVE= G0+G1*AGE^2+G2*AGE^-1+G3*AGE^-2
4710 IF SALIVE < 875 THEN SALIVE = 875
4720 RETURN

4800 REM
4810 REM Calculation of volume
4820 REM
4830 IF DBHQ < 70 OR HTMEAN <1.4 THEN GOTO 10400   'zero volume for small trees
4840 V1=-11.16217: V2=3.65167: V3=1.1476
4850 V4=-4.98199: V5=1.32829: V6=1.17827
4860 V7=-5.3901: V8=1.4146: V9=1.29911
4870 V10=10^(V1+V2*LOG(DBHQ+100)/LOG(10)+V3*LOG(HTMEAN)/LOG(10))
4880 V11=10^(V4+V5*LOG(DBHQ-70)/LOG(10)+V6*LOG(HTMEAN)/LOG(10))
4890 V12=10^(V7+V8*LOG(DBHQ-60)/LOG(10)+V9*LOG(HTMEAN)/LOG(10))
4900 IF DBHQ < 200 THEN VOL = V10
4910 IF DBHQ >= 200 AND DBHQ < 400 THEN VOL=V11
4920 IF DBHQ >= 400 THEN VOL=V12
4930 RETURN

5000 REM
5010 REM Subroutine for calculation of index age i.r.o. minimum mean dbh
5020 REM
5030  B55=25.22846893#: B56=-2.16021135#: B57=-66.37408016#
5040  B58=2853.95775826#: B59=-.35911124#: B60=-1.41196659#
5050  B61=1.01956435#:  B62=.10553616#: B63=-2.1136E-04
5060  B64=.9859766#:  B65=-.0011275: B66=1.2439E-06: B67=-1.036E-10
5070  B0Y=B55+B56*LOG(SPHA)
5080  B1Y=B57+B58*SPHA^B59
5090  B2Y=B60+B61*SPHA^B62*EXP(B63*SPHA)
5100  B3Y=B64+B65*SPHA+B66*SPHA^2+B67*SPHA^3
5110  B4Y=B0Y^B3Y + (B1Y^B3Y - B0Y^B3Y)
5120 H1=(DBHI^B3Y-B0Y^B3Y)*(1-EXP(-B2Y*(32.83-1.5))) 'coefficients from dbhq
```

```
5130 H2=B1Y^B3Y-B0Y^B3Y
5140 INDEXAGE=1.5-(LOG(1-H1/H2)/B2Y)
5150 RETURN

5200 REM
5210 REM Subroutine for calculation of index age i.r.o. quadratic mean dbh
5220 REM
5230  B0=5.01862831#:  B1=-.463415788#
5240  B2=.030454931#:  B3=7.671041769#
5250  B4=-.255852536#:  B5= 2.1577E-05
5260  B6=-1.905565128#:  B7=.123548043#
5270  B8=-1.125365E-03:  B9= 2.614159773#
5280  B10=-1.115693348#:  B11=.165328655#
5290   B0Y=EXP(B0+B1*LOG(SPHA)+B2*LOG(SPHA)^2)
5300   B1Y=EXP(B3+B4*LOG(SPHA)+B5*SPHA)
5310   B2Y=EXP(B6+B7*LOG(SPHA)+B8*SPHA)-.125
5320   B3Y=B9+B10*LOG(SPHA)+B11*LOG(SPHA)^2
5330   B4Y=B0Y^B3Y + (B1Y^B3Y - B0Y^B3Y)
5340 H1=(DBHI^B3Y-B0Y^B3Y)*(1-EXP(-B2Y*(32.83-1.5))) 'coefficients from dbhq
5350 H2=B1Y^B3Y-B0Y^B3Y
5360 INDEXAGE=1.5-(LOG(1-H1/H2)/B2Y)
5370 RETURN

5500 REM
5510 REM Subroutine for calculation of index age i.r.o. arithmetic mean dbh
5520 REM
5530  B1=5.15880587#: B2=.62390048#: B3=4.880137E-02: B4=3.50750165#
5540  B5=2.18340173#: B6=.44624495#: B7=2.551234E-02: B8=.10059995#
5550  B10=2.523E-08#: B11=2.473E-12: B12=3.027381E-02: B13=.21871888#
5560  B14=.0462624
5570   B0Y=EXP(B1+B2*LOG(SPHA)+B3*LOG(SPHA)^2)
5580   B1Y=EXP(B4+B5*LOG(SPHA)+B6*LOG(SPHA)^2+B7*LOG(SPHA)^3)
5590   B2Y=B8+B9*SPHA+B10*SPHA^2+B11*SPHA^3
5600   B3Y=B9+B10*LOG(SPHA)+B11*LOG(SPHA)^2
5610   B4Y=B0Y^B3Y + (B1Y^B3Y - B0Y^B3Y)
5620 H1=(DBHI^B3Y-B0Y^B3Y)*(1-EXP(-B2Y*(32.83-1.5))) 'coefficients from dbha
5630 H2=B1Y^B3Y-B0Y^B3Y
5640 INDEXAGE=1.5-(LOG(1-H1/H2)/B2Y)
5650 RETURN

5700 REM
5710 REM Subroutine to get diameter weighting via volume equation
5720 REM
5730 DBH1=LOG(VOLWT)/LOG(10)              'part of dbh weighting
5740 DBH2=1.10704*LOG(HTWT)/LOG(10)        'part of dbh weighting
5750 DBHWT=10*EXP((DBH1+4.23284-DBH2)*LOG(10)/1.71536)+2 'weight dbh ends
5760 RETURN

5770 REM
5780 REM Subroutine for applying weights to dbh and height for no-thin option
5790 REM
5800 HTMEANWD=MNHTEST*HTPC                  'weight mean tree height
5810 HTTOPWD=TOPHTEST*HTPC                  'weight top height
5820 VOLWD=VOLEST*VOLPC                     'weight mean tree volume
5830 SALIVEWD=SALIVEST*LIVEPC               'weight survival
5840 STVOLWD=VOLWD*SALIVEWD                 'calculate weighted standvolume
5850 DBHQWD=DBHQEST*DBHPC                   'weight quadratic dbh
5860 DBHAWD=DBHAEST*DBHPC                   'weight arithmetic dbh
5870 DBHMWD=DBHMEST*DBHPC                   'weight minimum dbh
5880 RETURN
```

```
6000 REM
6010 REM Pause for yes/no input
6020 REM
6030 A$=""
6040 WHILE INSTR(" YyNn",A$)<=1
6050 A$=INKEY$
6060 WEND
6070 YN=INSTR(" YyNn",A$)
6080 RETURN

6200 REM
6210 REM Printing the expected means table to the screen for no-thin option
6220 REM
6230 CLS: LOCATE 1,34: PRINT "GRANDIS";
6240 LOCATE 3,21: PRINT "Tabular summary of expected values";
6250 LOCATE 5,34: PRINT "Langepan        Your site";
6260 LOCATE 7,34: PRINT USING "####.##          ####.##"; DBHQNT;DBHQNTWD
6270 LOCATE 7,2: PRINT "Dbh(q) before any thinning";
6280 LOCATE 7,61: PRINT "mm";
6290 LOCATE 8,34: PRINT USING "####.##          ####.##"; DBHANT;DBHANTWD
6300 LOCATE 8,2: PRINT "Dbh(a) before any thinning";
6310 LOCATE 8,61: PRINT "mm";
6320 LOCATE 9,34: PRINT USING "####.##          ####.##"; DBHMNT;DBHMNTWD
6330 LOCATE 9,2: PRINT "Dbh(m) before any thinning";
6340 LOCATE 9,61: PRINT "mm";
6350 LOCATE 10,34: PRINT USING "####.##          ####.##"; TOPHTNT;TOPHTNTWD
6360 LOCATE 10,2: PRINT "Height(t) before any thinning";
6370 LOCATE 10,61: PRINT " m";
6380 LOCATE 11,34: PRINT USING "####.##          ####.##"; MNHTNT;MNHTNTWD
6390 LOCATE 11,2: PRINT "Height(r) before any thinning";
6400 LOCATE 11,61: PRINT " m";
6410 LOCATE 12,34: PRINT USING "####.##          ####.##"; STVOLNT;STVOLNTWD
6420 LOCATE 12,2: PRINT "Volume before any thinning";
6430 LOCATE 12,61: PRINT "m3/ha";: LOCATE 13,34
6440 PRINT USING "####             ####   "; SALIVENT ;SALIVENTWD
6450 LOCATE 13,2: PRINT "Survival before any thinning";
6460 LOCATE 13,61: PRINT " S/ha";
6470 LOCATE 25,18: PRINT "Do you want to print the table   Y/N?";
6480 GOSUB 6000                          'evaluate Y/N answer
6490 IF YN=2 OR YN=3 THEN GOSUB 7400          'answer is yes to print
6500 IF YN=4 OR YN=5 THEN GOTO 6510           'answer is no to print
6510 LOCATE 25,18: PRINT "Do you want the diameter distribution  Y/N?";
6520 GOSUB 6000                          'evaluate Y/N answer
6530 IF YN=2 OR YN=3 THEN GOSUB 8400          'answer is yes to Weibull
6540 IF YN=4 OR YN=5 THEN GOTO 8200           'answer is no to Weibull
6550 LOCATE 25,18: PRINT "      Press any key to continue         ";
6560 IF INKEY$="" GOTO 6560
6570 RETURN

6700 REM
6710 REM Printing the expected means table to the screen for one-thinning option
6720 REM
6730 CLS: LOCATE 1,34: PRINT "GRANDIS";
6740 LOCATE 3,21: PRINT "Tabular summary of expected values";
6750 LOCATE 5,34: PRINT "Langepan        Your site";
6760 LOCATE 7,34: PRINT USING "####.##          ####.##"; DBHQBT1;DBHQBT1W
6770 LOCATE 7,2: PRINT "Dbh(q) before any thinning";
6780 LOCATE 7,61: PRINT "mm";
6790 LOCATE 8,34: PRINT USING "####.##          ####.##"; DBHABT1;DBHABT1W
6800 LOCATE 8,2: PRINT "Dbh(a) before any thinning";
6810 LOCATE 8,61: PRINT "mm";
6820 LOCATE 9,34: PRINT USING "####.##          ####.##"; DBHMBT1;DBHMBT1W
6830 LOCATE 9,2: PRINT "Dbh(m) before any thinning";
```

```
6840 LOCATE 9,61: PRINT "mm";
6850 LOCATE 10,34: PRINT USING "####.##          ####.##"; TOPHTBT1;TOPHTBT1W
6860 LOCATE 10,2: PRINT "Height(t) before any thinning";
6870 LOCATE 10,61: PRINT " m";
6880 LOCATE 11,34: PRINT USING "####.##          ####.##"; MNHTBT1;MNHTBT1W
6890 LOCATE 11,2: PRINT "Height(r) before any thinning";
6900 LOCATE 11,61: PRINT " m";
6910 LOCATE 12,34: PRINT USING "####.##          ####.##"; STVOLBT1;STVOLBT1W
6920 LOCATE 12,2: PRINT "Volume before any thinning";
6930 LOCATE 12,61: PRINT "m3/ha";: LOCATE 13,34
6940 PRINT USING "####          ####   "; SALIVEBT1 ;SALIVEBT1W
6950 LOCATE 13,2: PRINT "Survival before any thinning";
6960 LOCATE 13,61: PRINT " S/ha";
6970 LOCATE 16,2: PRINT "Dbh(q) before clearfelling";
6980 LOCATE 16,34: PRINT USING "####.##          ####.##"; DBHQBCF;DBHQBCFW
6990 LOCATE 16,61: PRINT "mm";
7000 LOCATE 17,2: PRINT "Dbh(a) before clearfelling";
7010 LOCATE 17,34: PRINT USING "####.##          ####.##"; DBHABCF;DBHABCFW
7020 LOCATE 17,61: PRINT "mm";
7030 LOCATE 18,2: PRINT "Dbh(m) before clearfelling";
7040 LOCATE 18,34: PRINT USING "####.##          ####.##"; DBHMBCF;DBHMBCFW
7050 LOCATE 18,61: PRINT "mm";
7060 LOCATE 19,2: PRINT "Height(t) before clearfelling";
7070 LOCATE 19,34: PRINT USING "####.##          ####.##"; TOPHTBCF;TOPHTBCFW
7080 LOCATE 19,61: PRINT " m";
7090 LOCATE 20,2: PRINT "Height(r) before clearfelling";
7100 LOCATE 20,34: PRINT USING "####.##          ####.##"; MNHTBCF;MNHTBCFW
7110 LOCATE 20,61: PRINT " m";
7120 LOCATE 21,2: PRINT "Volume before clearfelling";
7130 LOCATE 21,34: PRINT USING "####.##          ####.##"; STVOLBCF;STVOLBCFW
7140 LOCATE 21,61: PRINT "m3/ha";
7150 LOCATE 22,2: PRINT "Survival before clearfelling";: LOCATE 22,34
7160 PRINT USING "####          ####   "; SPHA3 ; SPHA3
7170 LOCATE 22,61: PRINT " S/ha";
7180 GOTO 7230
7190 LOCATE 25,18: PRINT "Do you want to print the table    Y/N?";
7200 GOSUB 6000                           'evaluate Y/N answer
7210 IF YN=2 OR YN=3 THEN GOSUB 7400             'answer is yes to print
7220 IF YN=4 OR YN=5 THEN GOTO 6510              'answer is no to print
7230 LOCATE 25,18: PRINT "Do you want the diameter distribution  Y/N?";
7240 GOSUB 6000                           'evaluate Y/N answer
7250 IF YN=2 OR YN=3 THEN GOSUB 8400             'answer is yes to Weibull
7260 IF YN=4 OR YN=5 THEN GOTO 8200              'answer is no to Weibull
7270 LOCATE 25,18: PRINT "      Press any key to continue          ";
7280 IF INKEY$="" GOTO 7280
7290 RETURN

7400 REM
7410 REM Subroutine to send output to the printer
7420 REM
7430 GOSUB 10600                          'switch printer on
7440 LPRINT TAB(2) "GRANDIS";
7450 LPRINT TAB(66) "Version 2.0"
7460 LPRINT
7470 LPRINT TAB(20) "Tabular summary of expected values"
7480 LPRINT: LPRINT
7490 LPRINT TAB(5) "Age";
7500 LPRINT TAB(9) USING "##.#"; AGENT;           'age of interest
7510 LPRINT TAB(14) "years";
7520 LPRINT TAB(44) "Unweighted";
7530 LPRINT TAB(57) "Weighted"
7540 LPRINT
7550 LPRINT TAB(5) "Dbh(q) before any thinning";
```

```
7560 LPRINT TAB(45) USING "####.##"; DBHQNT;
7570 LPRINT TAB(57) USING "####.##"; DBHQNTWD;
7580 LPRINT TAB(5) "Dbh(a) before any thinning";
7590 LPRINT TAB(45) USING "####.##"; DBHANT;
7600 LPRINT TAB(57) USING "####.##"; DBHANTWD;
7610 LPRINT TAB(5) "Dbh(m) before any thinning";
7620 LPRINT TAB(45) USING "####.##"; DBHMNT;
7630 LPRINT TAB(57) USING "####.##"; DBHMNTWD;
7640 LPRINT TAB(5) "Height(t) before any thinning";
7650 LPRINT TAB(45) USING "####.##"; TOPHTNT;
7660 LPRINT TAB(57) USING "####.##"; TOPHTNTWD;
7670 LPRINT TAB(5) "Height(r) before any thinning";
7680 LPRINT TAB(45) USING "####.##"; MNHTNT;
7690 LPRINT TAB(57) USING "####.##"; MNHTNTWD;
7700 LPRINT TAB(5) "Volume before any thinning";
7710 LPRINT TAB(45) USING "####.##"; STVOLNT;
7720 LPRINT TAB(57) USING "####.##"; STVOLNTWD;
7730 LPRINT TAB(5) "Survival before any thinning";
7740 LPRINT TAB(45) USING "####   "; SALIVENT;
7750 LPRINT TAB(57) USING "####   "; SALIVENTWD;
7760 LPRINT
7770 RETURN

7900 REM
7910 REM Pause for input of choice of four options
7920 REM
7930 A$=""
7940 WHILE INSTR(" 1234",A$)<=1
7950 A$=INKEY$
7960 WEND
7970 ANSW1=INSTR(" 1234",A$)
7980 RETURN
8100 REM
8110 REM Switching quadratic and arithmetic dbh where necessary
8120 REM
8130 IF DBHQ < DBHA THEN SWAP DBHQ,DBHA
8140 IF DBHA < DBHM THEN SWAP DBHM,DBHA
8150 IF DBHQ < DBHA THEN SWAP DBHQ,DBHA
8160 RETURN

8200 REM
8210 REM Final screen and return to DOS
8220 REM
8230 CLS: LOCATE 1,33: PRINT "GRANDIS";
8240 LOCATE 7,18: PRINT "You are about to exit from GRANDIS";
8250 LOCATE 10,14: PRINT "Do you wish to run the program again    Y/N ?";
8260 GOSUB 6000                          'evaluation of Y/N input
8270 IF YN=2 OR YN=3 THEN RUN                      'answer is yes
8280 CLS: END

8400 REM
8410 REM Subroutine to calculate the parameters of the Weibull distribution
8420 REM
8430 GOSUB 9600
8440 GOSUB 9500                          'rename the variables
8450 DEF FNCDF(X)=1-EXP(-1*((X-A)/B)^C)
8460 GOSUB 9000                          'get Weibull parms

8600 REM
8610 REM Printing the output table
8620 REM
8630 CLOW=0: K%=A: A1=6                  'a1 is top line of table
```

```
8640 CLS: LOCATE 1,34: PRINT "GRANDIS"
8650 LOCATE 3,18: PRINT "The expected diameter distribution will be..."
8660 LOCATE 5,23: PRINT "Dbh class(cm)        S/ha"
8670 XK=K%
8680 XUP=XK+.5: CUP=FNCDF(XUP): CTR=(CUP-CLOW)*TR
8690 IF CTR<.1 THEN 8730
8700 LOCATE A1,25: PRINT USING "  ###        ####.#";K%,CTR;: PRINT
8710 A1=A1+1: A2=A2+CTR                          'count and sum s/ha
8720 IF A1=24 OR A1=48 OR A1=72 GOTO 8750          'set depth of table
8730 IF K%>(A+5) AND CTR<.1 THEN 8800              'kick out at end of table
8740 K%=K%+1: CLOW=CUP: GOTO 8670
8750 A1=6                                          'reset start line of table
8760 LOCATE 25,22: PRINT "Press any key for the rest of the table"
8770 IF INKEY$="" GOTO 8770
8780 CLS: LOCATE 1,18: PRINT "Continuation of diameter distribution table"
8790 LOCATE 3,26: PRINT "Dbh class      S/ha": GOTO 8730
8800 LOCATE A1+1,40: PRINT USING "####.#"; A2      'sum of stand densities
8810 LOCATE A1+1,48: PRINT "S/ha";
8820 LOCATE 24,10: PRINT "Do you want the Weibull parameters      Y/N";
8830 GOSUB 6000
8840 IF YN=2 OR YN=3 THEN GOSUB 10010                    'input is yes
8850 IF YN=4 OR YN=5 THEN GOTO 9810                      'input is no

9000 REM
9010 REM Programme for the recovery of Weibull parameters
9020 REM Adapted from Burk and Burkhart 1984
9030 REM
9040 SHAPEL=1: SHAPEU=5: 'this program will not work properly with shapel<.1
9050 IER%=0: A#=A: B=0: C=0: D22#=D22: D1P=D1: D2P=D22: IFLAG%=0
9060 D1#=D1P: XN#=SHAPEL: C#=XN#: GOSUB 9230: FXN#=FVAL#
9070 IF FXN#<0 THEN GOTO 9090 ELSE IER%=2
9080 IF IFLAG%<>0 THEN IER%=3: RETURN ELSE D1P=D1P+.01: GOTO 9060
9090 XN1#=SHAPEU: C#=XN1#: GOSUB 9230: FXN1#=FVAL#
9100 IF FXN1#>0 THEN GOTO 9110 ELSE IER%=2: IFLAG%=1: D1P=D1P-.01: GOTO 9060
9110 FOR J%=1 TO 5
9120 TEMP#=(XN#+XN1#)/2#: C#=TEMP#: GOSUB 9230: FTEMP#=FVAL#
9130 IF FTEMP#*FXN#<0 THEN XN1#=TEMP#
9140 FXN1#=FTEMP# ELSE XN#=TEMP#: FXN#=FTEMP#
9150 NEXT
9160 FOR J%=1 TO 100
9170 TEMP#=XN#-FXN#*(XN#-XN1#)/(FXN#-FXN1#)
9180 XN1#=XN#: FXN1#=FXN#: XN#=TEMP#: C#=XN#: GOSUB 9230: FXN#=FVAL#
9190 IF FXN#>-.00001# AND FXN#< .00001# THEN GOTO 9220
9200 NEXT
9210 IER%=1: D2P=D22#-FXN#
9220 B=B#: C=C#: RETURN
9230 REM function for recovering weibull parameters
9240 ZX#=1#+1#/C#: GOSUB 9280: G1#=GAMMA#
9250 ZX#=1#+2#/C#: GOSUB 9280: G2#=GAMMA#
9260 B#=(D1#-A#)/G1#
9270 FVAL#=D22#-A#*A#-2#*A#*B#*G1#-B#*B#*G2#: RETURN
9280 REM double precision gamma for an argument > +1
9290 N%=ZX#-.5#: XI#=N%: N%=XI#-1#
9300 FRAC#=ZX#-XI#
9310 TEMP1#=.988205891#+FRAC#*(-.897056937#+FRAC#*(.918206857#))
9320 GAMMA#=1#+FRAC#*(-.577191652#+FRAC#*(TEMP1#))
9330 TEMP2#=.482199394#+FRAC#*(-.193527818#+FRAC#*(.035868343#))
9340 GAMMA#=GAMMA#+FRAC#^5*(-.756704078#+FRAC#*TEMP2#)
9350 IF N%=0 THEN RETURN
9360 PROD#=1#
9370 FOR L%=1 TO N%: L#=L%: PROD#=PROD#*(FRAC#+L#): NEXT
9380 GAMMA#=GAMMA#*PROD#: RETURN
```

```
9500 REM
9510 REM Rename variables of interest for method of moments
9520 REM
9530 A=A/10: D1=D1/10: D21=D21/10: D22=D21^2        'getting centimeter classes
9540 RETURN

9600 REM
9610 REM Screen asking for patience while solving Weibull
9620 REM
9630 CLS: LOCATE 3,34: PRINT "GRANDIS";
9640 LOCATE 8,12: PRINT "I'm estimating the parameters of the distribution now"
9650 LOCATE 12,12: PRINT "Please be patient.     This takes quite a while.....
9660 RETURN

9800 REM
9810 REM Message about sum of Weibull frequencies smaller than s/ha alive
9820 REM
9830 CLS: LOCATE 5,9
9840 PRINT "Note that class frequencies less than 0.1 are disregarded and"
9850 LOCATE 7,14: PRINT "the sum of frequencies will be slightly less than"
9860 LOCATE 9,16: PRINT "the estimated stand density at clearfelling"
9870 LOCATE 25,22: PRINT "Press any key to continue."
9880 IF INKEY$="" GOTO 9880
9890 GOTO 8200
9900 END

10000 REM
10010 REM Printing the Weibull parameters upon request
10020 REM
10030 CLS: LOCATE 1,34: PRINT "GRANDIS";
10040 A=A*10: D1=D1*10 : D21=D21*10                'put moments back to mm
10050 LOCATE 3,20: PRINT "Input data and Weibull parameters";
10060 LOCATE 5,22: PRINT "S/ha";
10070 LOCATE 5,40: PRINT USING "####";TR
10080 LOCATE 7,22: PRINT "Minimum dbh";
10090 LOCATE 7,40: PRINT USING "###.##";A
10100 LOCATE 9,22: PRINT "Arithmetic dbh";
10110 LOCATE 9,40: PRINT USING "###.##";D1
10120 LOCATE 11,22: PRINT "Quadratic dbh   ";
10130 LOCATE 11,40: PRINT USING "###.##";D21
10140 LOCATE 13,22: PRINT "Scale parameter  ";
10150 LOCATE 13,40: PRINT USING "##.####";B
10160 LOCATE 15,22: PRINT "Shape parameter  ";
10170 LOCATE 15,40: PRINT USING "##.####";C
10180 LOCATE 25,22: PRINT "Press any key to continue"
10190 IF INKEY$="" GOTO 10190
10210 A$=INKEY$
10220 GOTO 9800
10230 END

10400 REM
10410 REM Screen kicking out because dbh or height too small for volume
10420 REM
10430 CLS: LOCATE 5,34: PRINT "GRANDIS": LOCATE 9,7
10440 PRINT "You have selected a regime which results in very small trees."
10450 LOCATE 11,7
10460 PRINT "The volume equation requires a minimum dbh of 70mm. Also, if"
10470 LOCATE 13,7: PRINT "mean height < 1.40m there is no dbh."
10480 LOCATE 25,26: PRINT "Press any key to continue";
10490 IF INKEY$="" GOTO 10490
10500 GOTO 8200                        'go to final closing screen
```

```
10600 REM
10610 REM Screen prompting user to switch printer in and adjust head
10620 REM
10630 CLS: LOCATE 5,34: PRINT "GRANDIS": LOCATE 9,24
10640 PRINT "Is your printer switched on?"
10650 LOCATE 11,12
10660 PRINT "Please use this opportunity to position the printer head";
10670 LOCATE 25,26: PRINT "Press any key to continue";
10680 IF INKEY$="" GOTO 10680
10690 RETURN                              'go to printing subroutine

10800 REM
10810 REM Error trap for thinning stems that have already died
10820 REM
10830 CLS: LOCATE 5,34: PRINT "GRANDIS": LOCATE 9,7
10840 PRINT "You have specified a thinning to a stocking level > estimated survival"
10850 LOCATE 25,22: PRINT "Press any key to continue"
10860 IF INKEY$="" GOTO 10860
10870 GOTO 8200                             'select another run/exit
10880 END

11000 REM
11010 REM Error trap for age of clearfelling before thinning
11020 REM
11030 CLS: LOCATE 5,34: PRINT "GRANDIS": LOCATE 9,7
11040 PRINT "You have specified a clearfelling age < age of first thinning "
11050 LOCATE 25,22: PRINT "Press any key to continue"
11060 IF INKEY$="" GOTO 11060
11070 GOTO 8200                             'select another run/exit
11080 END

11200 REM
11210 REM Error trap for extreme mortality in weighting stand
11220 REM
11230 CLS: LOCATE 5,34: PRINT "GRANDIS": LOCATE 9,7
11240 PRINT "You have specified an extremely low survival,  < 10% !! "
11250 LOCATE 25,22: PRINT "Press any key to continue"
11260 IF INKEY$="" GOTO 11260
11270 GOTO 8200                             'select another run/exit
11280 END

11400 REM
11410 REM Warning for thinning in excess of 50% of the stand
11420 REM
11430 CLS: LOCATE 5,34: PRINT "GRANDIS": LOCATE 9,14
11440 PRINT "You have specified a thinning in excess of 50% !! "
11450 LOCATE 12,12
11460 PRINT "This may involve extrapolation and dubious results."
11470 LOCATE 15,16
11480 PRINT "The simulation will proceed nevertheless."
11490 LOCATE 25,22: PRINT "Press any key to continue"
11500 IF INKEY$="" GOTO 11500
11510 RETURN
```

The vita has been removed from the scanned document