ACTA FORESTALIA FENNICA

230

JUSSI SARAMÄKI

A GROWTH AND YIELD PREDICTION MODEL OF *PINUS KESIYA* (ROYLE EX GORDON) IN ZAMBIA

*PINUS KESIYA*N KASVUN JA TUOTOKSEN ENNUSTEMALLI SAMBIASSA

THE SOCIETY OF FORESTRY IN FINLAND
THE FINNISH FOREST RESEARCH INSTITUTE

ACTA FORESTALIA FENNICA

Acta Forestalia Fennica was established in 1913 by the Society of Forestry in Finland. It was published by the Society alone until 1989, when it was merged with Communicationes Instituti Forestalis Fenniae, started in 1919 by the Finnish Forest Research Institute. In the merger, the Society and Forest Research Institute became co-publishers of Acta Forestalia Fennica.

Prior of the merger, 204 volumes had appeared in Acta Forestalia Fennica, and 145 volumes in Communicationes.

PUBLISHERS – JULKAISIJAT

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ACTA FORESTALIA FENNICA 230

A GROWTH AND YIELD PREDICTION MODEL OF *PINUS KESIYA* (ROYLE EX GORDON) IN ZAMBIA

*Pinus kesiya*n kasvun ja tuotoksen ennustemalli Sambiassa

Jussi Saramäki

To be presented, with the permission of the Faculty of Forestry of the University of Joensuu, for public criticism in Auditorium C2 in University of Joensuu on October 23th, at 12 o'clock noon.

The Society of Forestry in Finland — The Finnish Forest Research Institute

Helsinki 1992

Saramäki, J. 1992. A growth and yield prediction model of *Pinus kesiya* (Royle ex Gordon) in Zambia. Tiivistelmä: *Pinus kesiyan* kasvun ja tuotoksen ennustemalli Sambiassa. Acta Forestalia Fennica 230. 68 p.

The study presents a growth and yield prediction model for a *P. kesiya* stand by diameter classes. The material consists of temporary sample plots taken from a plantation inventory, of permanent sample plots established in commercial compartments and of an espacement trial. The mean basal area of the stand, variance and skewness of the diameter distribution are predicted. From these variables the parameters of the Weibull function are derived. Site class is assumed to be known or is calculated from measured information. Mortality is also predicted by estimating the number and mean size of dead trees. Thinnings are defined by the number of trees removed and by their relative size. If measured tree level data at the initial situation is available it can be utilized in the predictions, however, simulations can also be performed with stand level information. The minimum information needed for the prediction is planting density, site class as well as the times and removals of thinnings.

The calculations show that by decreasing the planting density of *P. kesiya* from the present 1330 stems/ha or by conducting early precommercial thinning both the relative and absolute amount of large sawlogs in the total production increase. An increase in the present planting density only slightly increases the total yield. It is obvious that the presently recommended rotation of 25 years is too short for producing large sawlogs, especially on poor sites. This rotation period is suitable for small sawlog production while for pulpwood regimes shorter rotation periods can be used. If thinnings are done before the maximum current annual growth is reached stands will react well, but later on the ability to respond to thinnings decreases rapidly. Thinning from below accelerates the production of large sawlogs more than thinning from above or systematic thinning. If all sawlog sizes are considered no great differences between thinning types exist. The study recommends different thinning regimes according to site class. Separate programs are recommended for the production of sawlogs and pulpwood.

The used thinning reaction model needs refinement and further studies with annually measured thinning trial material. However, conclusions drawn from the simulations do not substantially change even with the use of a more accurate model.

Tutkimuksessa esitetään malli, jolla metsikön kehitystä voidaan ennustaa läpimittaluokkittain. Aineistoina ovat Sambian viljelymetsien inventoinnin koealat, viljelymetsiin perustetut pysyvät koelat sekä yksi viidesti toistettu kasvatustiheyskoe. Menetelmässä ennustetaan puiden keskimääräistä pohjapinta-alaa, läpimittajakauman varianssia ja vinoutta, joiden avulla saadaan ennustettua Weibullin funktion parametrit. Kasvupaikkaluokka oletetaan tunnetuksi. Lisäksi ennustetaan luontaisesti kuolevien puiden määrä ja suhteellinen keskikoko. Harvennuksista tulee tietää poistuvien puiden lukumäärä sekä niiden suhteellinen koko. Menetelmällä voidaan hyödyntää mitattu läpimitta- ja pituustieto, mutta pelkillä metsikkötiedoillakin voidaan ennustaa läpimittajakauman kehitystä. Minimitietoina läpimittaluokittaiseen kehityksen ennustamiseen tarvitaan metsikön viljelytiheys ja kasvupaikkaluokka sekä harvennusten ajat ja poistumat.

Tutkimus osoittaa *Pinus kesiyan* reagoivan käytetyillä viljelytiheyksillä harvennuksiin hyvin, mikäli ne tehdään ennen vuotuisen juoksevan kasvun kulminaatiota. Vanhempana tehdyt harvennukset eivät paranna järeyskehitystä yhtä selvästi. Alaharvennus tuottaa selvästi enemmän järeitä tukkeja kuin systemaattinen- tai yläharvennus. Tukkien kokonaismäärissä ei ole suuria eroja eri harvennusohjelmissa. Tulosten mukaan nykyisin Sambiassa käytetty kiertoaikasuositus 25 vuotta on sopiva pienikokoisen tukkipuun mutta liian lyhyt järeän tukkipuun tuottamiseen erityisesti karuilla kasvupaikoilla. Sen sijaan ainespuun tuottamisessa voidaan käyttää suositusta lyhyempiä kiertoaikoja. Viljelytiheyden laskeminen tai aikainen taimikon harvennus nostavat järeiden tukkien määrää ja osuutta kokonaistuotoksesta. Viljelytiheyden nostaminen käytetystä 1330 rungosta/ha ei juurikaan nosta kokonaistuotosta. Tutkimuksessa suositellaan eri harvennusohjelmia eri kasvupaikoille ja erillisiä ohjelmia myös tukkipuun ja ainespuun kasvatukseen.

Harvennusreaktion tarkka mallittaminen edellyttää vuotuisia mittauksia järjestetyiltä harvennuskokeilta ja vaatii lisätutkimuksia, mutta ei oleellisesti muuta tutkimuksesta saatuja johtopäätöksiä.

Keywords: simulation models, diameter distribution, Weibull function, thinning reaction, *Pinus kesiya*.
FDC 56 + 174.7 *Pinus kesiya* + (689.4)

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ISBN 951-40-1234-8
ISSN 0001-5636

Tampere 1992. Tammer-Paino Oy

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Symbols and abbreviations

a,b,c	=	parameters of any function
b_r	=	calculated value of coefficient b
d	=	diameter at breast height (1.3 m), cm
D	=	arithmetic mean diameter of the stand at breast breast height, cm
g_m	=	mean basal area, cm^2,
h	=	height of the tree, m,
H_{dom}	=	dominant height, m,
ig_{diff}	=	difference in three year growth with Eqn. (24) predicted and actual mean basal area increments, cm^2,
I_v	=	volume increment of a stand (overbark), $m^3/ha/a$,
k0,k1,k2,k3,k4	=	parameters of function (21),
m0,m1,m2,m3	=	parameters of function (23).
mort	=	relative mortality (N_d/N_e),
N	=	number of observations
N_a	=	actual density, stems/ha,
N_b	=	stocking before thinning, stems/ha
N_d	=	number of dead trees, stems/ha,
N_e	=	stocking at establishment or immediately after thinning, stems/ha
N_n	=	nominal density or planting density, stems/ha
N_r	=	number of stems removed, stems/ha,
R_g	=	mean basal area of living trees or trees after thinning/mean basal area of all trees
R_m	=	relative mortality
R_r	=	relative removal (N_r/N_b)
s_e	=	relative standard error of the estimate $100 \cdot \sqrt{e^s - 1}$
Si	=	site index, dominant height at 15 years of age,
skew	=	$\Sigma(d-D)^3/var^{3/2}$
T	=	age, years
T_0	=	base age for site index curves, years
T_{diff}	=	0 if not thinned, otherwise time from latest thinning, years,
th	=	thinning percent ($100 \cdot V_r/V$) in latest thinning, if not thinning year th=0,
thr	=	thinning ratio (N_r/N_b),
v	=	volume of the tree, dm^3,
V	=	volume of the stand (overbark), m^3/ha,
V_a	=	volume of the stand after thinning (overbark), m^3/ha,
var	=	$\Sigma(d-D)^2/N$, cm^2
v_m	=	mean volume of trees, dm^3,
V_r	=	volume of the removal (overbark), m^3/ha,
V_{15}	=	volume to 15 cm top diameter in the stand (overbark), m^3/ha
$Weib_T$	=	Weibull function at age T
Y	=	yield (eg. volume or basal area).

Preface

This study is part of the Zambia Forest Research Project which was carried out during 1982—1988. The plans for growth and yield research within the project were prepared by my former head professor Yrjö Vuokila who visited Zambia in 1981. The main aim of the growth and yield part of the project was to produce reliable estimates of the growth and development of the main commercially planted species using existing data. The present study provides a growth and yield estimation method and results for the main pine species, *Pinus kesiya* which covers about two thirds of the plantation area. Published growth and yield tables already exist for the main eucalyptus species, *Eucalyptus grandis*.

The project has been financed by the Finnish Development Agency (FINNIDA), at first directly and then later via VTT Tech Inc. My stay as an employee of the afore mentioned organizations has made it possible to collect and partly analyze the present study material. I especially want to mention the late Dr J. Virtanen, Project Manager of the Zambian Forest Research Project, whose encouragement in my work was exemplary. The Finnish Forest Research Institute has the subject "The growth and yield study of Zambian exotic tree species" in the working program. This has facilitated my efforts in finalizing and publishing of the study.

The Zambian Government via its Department of Forestry has kindly accepted the use of this data in this publicaton as has ZAFFICO Ltd. Permission from the Chief Conservator of Forests to publish the results is greatly appreciated.

I am greatly indebted to my former colleagues in Zambia Mr. P.M. Sekeli, Mr. E.K. Kambilo, Mr. E.K. Kamwi, and Mr. E. Mundia for their help at different stages of the data collection and correction. I would also like to mention the many forest workers at Chati Forest Research Station who have participated in the field work during the last two decades.

During the data analyses stage I have had countless discussions about statistical and growth and yield problems with Mr. J. Heinonen MSc.(Pol.Sc.). His unrelentless help with statistical and computational problems has been unsurpassable.

In the final stages of compiling this manuscript, when I was about to lose hope that I would ever get the study finalized, the help and encouragement of my colleagues at Joensuu Forest Research Station gave me extra strength to get it finished. Especially the unselfish support by Ms. Leena Finér Lic.Sc.(For.) who took care of part of my duties as the Head of the Station during the last months of writing is heartfully acknowledged.

The manuscript was read by Ms. Leena Finér Lic.Sc.(For.), Mr. J. Heinonen MSc. (Pol.Sc.), Mr. T. Kolström Lic.Sc.(For.), Dr. J. Lappi, Dr. T. Pukkala, and Dr. R. Päivinen. Their valuable comments have been carefully considered and acknowledged. The English language was checked by Ms. Helen Ruhkala Lic.Sc.(For.).

The data capture was patiently and carefully done by Ms. Anja Saastamoinen and Ms. Heli Piiroinen. The figures and manuscript were technically finalized by Ms. Päivi Mäkkeli.

Last but not least I would like to thank my wife and children for their patience and understanding throughout.

Joensuu May 1992

Jussi Saramäki

1 Introduction

1.1 *P. kesiya* in Zambia

P. kesiya (Royle ex Gordon) was one of the first exotic species to be imported into Zambia. It was first planted in a species trial in 1937/38 planting season (Cooling & Endean 1967). It is a native species of South-East Asia, found both in the mainland and on the islands, and has been planted outside its natural range in Malagasy (Madagascar) on a commercial scale. *P. kesiya* tolerates quite a wide range of climatic and site variations (Cooling & Endean 1967). It also exhibits marked provenance differences in growth rate, stem form, and branching but survival and health are always good (Cooling & Endean 1967). It is thus not surprising that *P. kesiya* was selected as the main pine species for plantations in Zambia when plantings on a commercial scale were started during the 1960's (The Industrial... 1969). The seed originates from three main sources: Vietnam, The Philippines, and Malagasy, best seed being from the Philippines and Vietnam (Jones 1967). Jones (1967) mentions that the stem form of the Vietnamese source is better than that of the Philippine.

P. kesiya has remained a healthy and vigorous species and no major fungal or pest problems have occured in Zambia (A summary of... 1988). At the moment, all the seed can be collected from seed orchards established in the early 1960's at Chati and Ndola. Clonal seed orchards already produce viable seed (Mikkola 1989) also.

The total plantation area in Zambia at the beginning of 1985 was 49 950 ha, of which *P. kesiya* covered 28 100 ha (Saramäki et al. 1987). The stands are generally planted at 2.75 x 2.75 m (9' x 9') spacing giving 1330 stems/ha. All areas are deep ploughed before planting. Both mechanical and manual weeding of the area is supposed to take place 2—3 times during the first growing season. Weeding continues for 2—3 years thereafter. Initial pruning to a height of about 2.5 m is carried out when the trees are about 7 m high. A second pruning to a height of about 6 m is undertaken immediately after first thinning when trees are 12—14 m high. The recommendation for thinnings is as follows: first thinning to 720 stems/ha at the age of 10 years, second thinning to 450 stems/ha at the age of 14 years, and third thinning to 220 stems/ha at the age of 18 years. However, this thinning regime has not been followed in most cases and it is commonplace that first thinning has been neglected. The planned rotation period is 25 years.

For predicting the future performance of the plantations a network of permanent sample plots was established and measured regularly by the Division of Forest Research (The Industrial... 1969). However, the establishment of new permanent sample plots ended in the middle of the 1970's.

1.2 Yield prediction

1.2.1 General

The aim of yield prediction has been to provide reliable information for the forest manager about future cutting possibilities and the basis for species selection. With the development of mathematical methods, these predictions became more accurate and were based more on measurements. In Europe the first growth and yield estimates were produced in the middle of the nineteenth century (eg. Assmann 1970). In the tropics the study of growth and yield is at a much younger stage of development. Especially in exotic tropical plantations, growth and yield research is only a few decades old.

In southern Africa, growth and yield models for plantation trees have been largely based on the so called "Correlated Curve Trend" principle (CCT), first presented by O'Connors (1935) He was in the position to establish quite large experiments in order to test the hypothesis. O'Connors (1935) started with three principles:

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 espacement 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 espacement 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* (Bredenkamp 1984).

Later this hypothesis was extented by Marsh & Burgers (1973) to concern thinned stands too: "The increment of thinned stands is equivalent to that of unthinned stands of the same stocking (stems/ha) and density (m^2/ha or m^3/ha), but of younger age (i.e. the age at which they had the same basal area or volume per unit area)". This hypothesis has been validated with several subtropical species and appears to give accurate and unbiased estimates of growth after thinning, provided that growth is measured over at least three years (Alder 1980).

This principle means that when the results of the basic espacement trials are available no more thinning trials are needed. In Europe and North America this hypothesis has gained little attention (see Smith & Hafley 1987). This might be due to the use of much longer rotations in boreal forests than those used in the tropics, which makes it almost impossible to produce a basic series of espacement trials.

The traditional growth and yield study in even-aged stands consists of the following stand level parts:

- site classification
- development of growth functions for basal area or diameter increment
- development of growth functions for height increment
- description of form development
- modelling of thinning effect
- mortality development modelling.

If the model is based on the development of diameter distribution then the work follows the pattern:

- select the family of distributions
- estimate indexing parameters of distribution plot by plot
- fit regressions to predict the parameters of the selected distribution from characteristics like age, site index and stand density (Bailey 1980).

Site classification, thinning effect, and mortality modelling are also needed in the latter case.

Leech & Ferguson (1981) compared yield models for unthinned stands of radiata pine (*Pinus radiata*). They presented a wide list of models used in the yield prediction and compared Mitscherlich, Johnson-Schumacher, Bednarz and Gompertz models. The Mitscherlich model was regarded as the best because it has a limiting value of yield as age increases and it has an explicit mathematical form.

Growth modelling with functions has been used for a long time. Tennent (1982a) presented the trend in growth and yield modelling which is general throughout the world: first came stand functions based on simple linear regression, later more advanced functions were presented but these were of limited use because of inadequate base data. The third generation of models concentrates on developing models which are based on consistent theory and can describe the dynamic character of nature, keeping in mind the constraints found empirically during earlier decades.

Pienaar & Turnbull (1973) presented a proposal for a general growth theory in even-aged stands using the Chapman-Richards growth model as a base. The Chapman-Richards function is a very flexible four parameter function which had been used in animal population dynamic studies (Chapman 1961, 1967). Pienaar & Turnbull (1973) first analysed the relationship between yield and density, studied using agricultural crops by Kira et al. (1953) and Kira & Shinozaki (1956). These Japanese researchers state the "law of constant final yield" which in forestry terms can be read that independently of initial spacing, the total living yield in a given site will be equal. Pienaar & Turnbull (1973) used a South African espacement trial of slash pine (*Pinus elliottii*) to test this hypothesis and found it useful if initial spacings were not very low. They also found that within quite a wide range of initial densities, the age at which trees attain breast height at a given site is fairly stable. They also presented the hypothesis that: for a wide range of thinning regimes the growth rate in a thinned stand is identical to that of an unthinned stand of the same age and the same basal area as the thinned stand.

1.2.2 *Stand level prediction*

Two different approaches are available in yield prediction: the prediction for stand or tree development. An intermediate form between stand and tree level predictions is the prediction of distributions. Increased computing capacity has shifted the emphasis towards treewise prediction as it offers better possibilities to utilize gathered information. In many cases tree base models and stand base models produce incompatible results, causing problems for the users of the models. Bailey (1980) presented a diameter increment model which links tree level growth models and stand level diameter distribution models (see also Daniels & Burkhart 1988). Rennolls et al. (1985) compared Weibull diameter distribution models with the Forestry Commission's stand tables and found an improvement in accuracy compared to the use of stand tables only, which can be seen as one form of stand model. However, in many cases standwise prediction still dominates. Standwise prediction is simpler, does not presuppose so accurate measurements, and is adequate for most management purposes.

Hyink & Moser (1983) discussed the techniques for producing diameter distributions either by directly predicting the parameters of the distribution or by first predicting stand averages and using these averages to obtain the parameters of the diameter distribution. They suggested that a mathematical compatibility exists between diameter distribution models and stand average models.

In South Africa, New Zealand and Australia researchers (eg. Tennent 1982b, Clutter & Allison 1974, von Gadow 1983d) presented the first models for tropical pines.

The South African model development is largely based on "Correlated Curve Trend" trials. Von Gadow (1983d) created a model for the standwise development of unthinned stands of *Pinus patula* using these trials. Smith (1983) stressed the importance of compatibility of growth and yield models, so that predictions for longer periods remain within reasonable error limits. Long & Smith (1984) described stand development as a system where a fixed amount of foliage after the juvenile stage regulated the living volume and the density of unthinned forest stands. The system is explained by the general size-density model:

$$Y = Kp^A \qquad (1)$$

where Y = mean size,
p = number of plants/unit area,
A and K = constants.

This relation represents the combination of maximum average size and density that are possible in a plant community (White 1981). Long & Smith (1984) derive this model to a form where it can work as the site independent self-thinning boundary for forest stands. Knoebel et al. (1986) developed simultaneous growth and yield equations for predicting basal area growth and yield in thinned stands of yellow poplar (*Liriodendron tulipifera*). The estimates were analytically compatible. They also developed compatible diameter distributions using a parameter recovery technique for predicting parameters of the Weibull distribution. The algorithm for thinning removed a proportion of the basal area from each diameter class and produced stand and stock tables after thinning that were consistent with the situation before thinning.

1.2.3 *Tree level prediction*

The development of the models was fast and it soon became possible to predict the growth of individual trees and combine this treewise information to form stand level results. The first treewise growth models were developed soon after standwise models. In the beginning, these early models did not give, however, as accurate results as the stand models.

When a tree level model is estimated a decision must be made between distance dependent or independent functions. Distance dependent tree models need information about the spatial distribution of trees in a stand, however, distance independent models do not require such information (Pukkala 1988). The requirements of the measured information are, thus, much higher with distance dependent models, although spatial information can also be created if the spatial distribution function is known. In the case of forest plantations where the spatial pattern is regular, the knowledge of intertree distances does not improve the model greatly compared to the general measure of competitive stress (Martin & Ek 1984; Pukkala 1988). Pukkala & Kolström (1987) compared competition indices based on the sum of either vertical or horizontal angles between the subject tree and its competitors. In their study competition indices explained about 50 % of the total variation of radial growth in a Scots pine stand of medium age. However, competition indices accounted for 10...20 % of the variation which could not be explained without spatial data. Pukkala & Kolström (1987) assumed that size variation explains most of the growth variation in unthinned stands. Site variation may also explain part of the growth variation.

Mitchell (1975) presented a very detailed dynamic yield model for Douglas fir (*Pseudotzuga menziesii*) which consists of models for tree foliage development and its effect on volume growth. The model gives possibilities to simulate the effects of thinning, fertilization, animal browsing, and tree breeding on the yield of a stand.

Alder (1979) developed a distance-independent tree growth model for coniferous plantations in eastern Africa. He described the diameter increment as a function of dominant height, relative basal area and dominance ratio between trees. The relative basal area is the basal area of the stand related to the maximum basal area at that dominant height. Dominance ratio is the diameter of a tree in relation to dominant diameter in the stand.

Tennent (1982b) presented a distance-dependent growth model in which he used Hegyi's (1974) competition index to explain intertree relations. The initial stand was generated using the Weibull distribution. The parameters of the function were estimated using an inverse probability transformation where two percentile points of the diameter distribution were first estimated and then used to calculate actual function parameters.

1.2.4 *Diameter and basal area distributions*

Recently, yield prediction has concentrated on the presentation of stand information as diameter or basal area distributions of trees (eg. Munro 1974; Bailey & Dell 1973; Hafley & Schreuder 1977; Bliss & Reinker 1964; Clutter & Allison 1974; Schreuder et al. 1979; Bailey 1980; Kilkki & Päivinen 1986; Päivinen 1980; von Gadow 1983 b,c,d; Pukkala & Pohjonen 1989; Pikkarainen 1986). Even though the first attempts to use distributions were undertaken already at the beginning of this century (Cajanus 1914) the lack of calculating capacity prevented greater utilization. Distributions provide information of the amounts of different sized timber, which is essential for forest management planning.

Bailey & Dell (1973) proposed the Weibull probability function as a diameter distribution model and stated that it is simple and flexible. Von Gadow (1983b) compared beta, Johnson SB and Weibull functions in fitting diameter distributions for *Pinus patula*. He found the Weibull function to give the best fit, and Johnson SB to be also very suitable. Päivinen (1980) and Pukkala & Pohjonen (1989) used the beta function for describing the distribution of basal area or number of stems per hectare in diameter classes and presented a method which employs the distribution for the calculation of stand characteristics.

However, distributions can also be presented without any probability density function as fractions of the total, for example, as presented in Alder (1979). He divided the range of diameters into 10 equal size basal area probability classes. He then formed two vectors: one for diameters and one for the probabilities of the class with the probability vector known. Then he predicted the development of the diameters in each class as a function of dominant height, relative basal area and relative dominance of the class.

Another way to present the distribution is to use a transition matrix model to predict the growth of diameters by transition probabilities (e.g. Pukkala & Kolström 1988). The transition matrix model is useful in predicting the development of selection forest development, but it can also be used for even-aged forests.

The distribution function can also be presented as consisting of segments of different functions (Cao & Burkhart 1984). A segmented function is very flexible and could be useful for modelling irregular data.

Rustagi (1978) recommended the use of the diameter distribution of basal area because of the linear relationship between tree volume and its basal area in even-aged stands. He used a modified two parameter Weibull function to describe the distribution. Kilkki & Päivinen (1986) tested the usability of the Weibull function in describing the basal area diameter-distribution of small relascope sample plots. No major obstacles are envisaged in the use of the function, however, more research is needed for the determination of the minimum diameter.

Schreuder et al. (1979) presented equations to predict the number of trees, mean height and total volume over bark by diameter classes in unthinned natural stands of slash pine, when stand age, site index, and current number of trees are known. They used the Weibull distribution to fit diameter frequency data as well as height and volume data. When Weibull parameters for diameter distributions are known, the same parameters for height and volume distributions can be calculated using Stacy & Mihram's (1965) theorem.

1.3 Thinning reaction

The response of trees to thinning and possible shock immediately after thinning have caused problems for growth and yield modellers. Vuokila (1960, 1965) stated that the positive response to thinning at breast height can change to a negative reaction at a higher position along the bole of the tree. He also confirmed the earlier statement that thinnings can not improve the total production of forest stands. Marsch & Burgers (1973) solved the problem of thinning reaction by further developing the CCT theory. Harrington & Reukema (1983) found an occurrence of thinning shock in Douglas fir which reduced height growth. After 15 to 25 years at all thinning intensities this negative effect had changed to positive; the best height growth being at wider spacings. Diameter growth increased following thinning and the rates in diameter growth between spacings increased over time. Saramäki & Silander (1982) have also found a reduction in height growth immediately after heavy thinning.

In many growth models thinning is taken into account indirectly, as some measure of density is always included as an independent variable. Stand density changes with thinning and causes changes in the independent variables when post thinning growth is predicted. The type of thinning is often difficult to describe. However, inclusion of some measure of the relative size of removed trees compared to the size of remaining trees seems sufficient in describing the type of thinning (see e.g. Alder 1980). The effect of thinning is reflected in the competition index in distance-dependent treewise equations, eventhough a general competition measure like basal area provides almost the same information in plantations (Martin & Ek 1984; see also Pukkala 1988).

1.4 Mortality

One factor affecting forest productivity is mortality. Alder (1980) divides mortality into:

— establishment mortality
— density dependent mortality
— disease and pest mortality and
— windthrow and fire damage.

For establishment mortality function a multiple regression model with a few site, climatic, and establisment factors as independent variables are sufficient. Density dependent mortality can easily be omitted in models for stands planted at wide spacings and grown on short rotations or subject to adequate thinnings (Alder 1980). Density dependent mortality is also called regular mortality (Lee 1971). Models for regular mortality can be either treewise or standwise. The latter one uses age, site, and density as independent variables. In treewise mortality models Monserud (1976) found a generalized form of the logistic equation to provide the greatest discriminating capasity for predicting live and dead trees.

Somers et al. (1980) found the Weibull function adequate for predicting survival in even-aged young loblolly pine stands.

1.5 Site factors

The evaluation of forest site productivity is one of the main tasks in growth and yield studies. There are several different approaches to assess site productivity. Hägglund (1981) distinguishes three different types of expressions:

— site index. Height of a stand at a predetermined age
— mean annual increment, either at a fixed age or at the age when mean annual increment culminates
— other stand characteristics.

The variables used for indicating site properties can be stand variables, site variables, or a combination of both. In even-aged plantations site index is the most commonly used expression (e.g. Alder 1975; Curtis et al. 1974; Schönau 1976; Popham et al. 1979; Vuokila & Väliaho 1980). Also in naturally regenerated stands site index is used as long as the stands are even-aged (e.g. Gustavsen 1980). The selected age which corresponds to site index has often considerable importance (Heger 1973).

Mathematical functions used to describe the relationship between age and height vary but two basic properties can be distinguished. The relationship can be described either by anamorphic or polymorphic curves. Where anamorphic curves are concerned these are proportional so that the relative growth rates of different classes are constant at any age. With polymorphic curves the relative growth rates are nonproportional (Bailey & Clutter 1974). Hägglund (1981) recommended the use of polymorphic curves due to their flexibility (see also Boyer 1983). Recently, Lappi & Bailey (1988) presented a new height prediction method using random stand and tree parameters which is theoretically more advanced than methods used to date.

If a more general system for describing site properties is needed, site index curves must be related to other, not species specific, characteristics of soil and climate. Hägglund & Lundmark (1977) presented a site classification system based on site properties. They used the main features of ground vegetation and soil moisture for grouping stand data into site index classes. In Great Britain solar radiation, soil texture, and soil moisture content seemed to explain most of the variation in height growth in Scots pine stands (White 1982). In Zambia the plantation areas are selected according to the depth and texture of the soil (Endean 1966). Both these characters control the availability of soil moisture which seems to be the most important factor controlling growth in Zambia. Also the colour of the soil has some predicting value (Saramäki et al. 1987). Boyer (1983) also found site preparation before planting in longleaf pine (*Pinus palustris* Mill) plantations in Southern USA to be very important sources of variation in site index curves. He found seed source and stand density to be variables affecting early height growth. Both stand density and removal of competing vegetation affect the availability of moisture to the trees.

1.6 The aim of the study

Although *P. kesiya* is the major plantation species in Zambia its growth and yield is inadequately known. Growth predictions are based on experimental sample plots established and studied during 1960's and 1970's. The latest yield tables (Yield table... 1973) are only in stand table form and do not include information on size distribution. Also site classification has not been conducted. The assortments and their development are not studied.

The aim of the present study is to develop a growth and yield prediction model for *P. kesiya* plantations in Zambia. The model should,

1) be able to use all available information to make predictions more accurate;
2) give reliable estimates even when very little measured information exists;
3) make it possible to examine the effects of different thinning regimes on the growth and yield of *P. kesiya* ; and
4) be operationally usable in managing *P. kesiya* plantations in Zambia.

More specifically, the growth and yield prediction model must be able to produce predictions at the same level if:

a) only site index, age, and initial spacing of the stand are known;
b) apart from the previous characteristics more stand level information is available. For example, mean diameter, basal area, mean or dominant height etc;
c) treewise information is also available. For instance, diameter distribution, treewise heights etc.

2 Methods

2.1 Background

When growth and yield models are used, many types of information may be available. In some cases predictions must be done without any measured information. If this be the case, the model should be able to create starting values for the prediction. If stand level information is available the model must utilize that information to adjust the average values to the correct level. Furthermore, if treewise information is available the model should be able to utilize it.

For the growth and yield prediction model to be efficient it needs to be flexible. Apart from being flexible it also has to be compatible in such a way that results do not contradict when different level information is used. This can be achieved by solving tree and stand level equations simultaneously or validating them separately. The simultaneous solving of equations requires a great deal of computing capacity, especially if many functions are included. Stand level growth function is in most cases stable and simple enough to describe the growing process in plantation conditions.

Site index, age and initial spacing of the stand are always supposed to be known as the minimum information. Mean basal area is simple to measure and correlates well with the mean volume. It is also the second moment of the diameter distribution which helps in deriving parameters of diameter distribution function. By selecting mean basal area as the main characteristics to be predicted a strong link between stand characteristics and diameter distribution is obtained.

Information on tree diameter distributions is an important part of the yield model used in forest management planning. Information on the spatial distribution of the trees is regarded as useful when the effects of different treatments on the yield are studied. However, spatial distribution information is not so decisive where plantations are concerned because the original distribution is always known to be regular. The available study material, even though it includes spatial information, is not very suitable for spatial studies because of small sample sizes, the lack of thinning records, and small variation in spatial distribution. Because the main use of yield models is in forest management, diameter distribution models are regarded as necessary in the model building.

The height distribution and height development are important parts of the growth prediction system. Some assumptions about height development must be made. The most stable height variable is dominant height, as it is not greatly affected by thinnings from below. Site index is normally presented by height over age curves which describe the development of dominant height and give a basis for the height prediction. The distribution of heights can be described by a monotonic function with positive derivative which approaches zero when diameter increases and passes through the origin (e.g. Curtis 1967).

Mortality, even though it forms a minor part of the yield in treated stands, must form part of the system. However, the selection of mortality function is not so decisive for the whole system, as long as it behaves correctly within the used range of conditions. Modelling of thinning is another point where the effect on yield is not so great, but important, however.

The system must be interactive, to be able to incorporate all available information into the growth and yield prediction model and to be able to use the model without measured information. To incorporate necessary information into the system three input levels are needed (Fig. 1).

Independently of the amount of measurements, predictions will be produced at the same level. Of course the accuracy of yield predictions differs as it depends on the accuracy of measurements.

If measured information is available, its effect on the prediction must be highest near the time of measurement and diminish with increasing time.

The following components are needed for the system:

1) growth model for mean basal area;
2) models to derive the remaining characteristics from existing ones;
3) model for tree mortality;
4) thinning reaction model;
5) height curve functions;
6) models to recover distribution function parameters from stand characteristics;

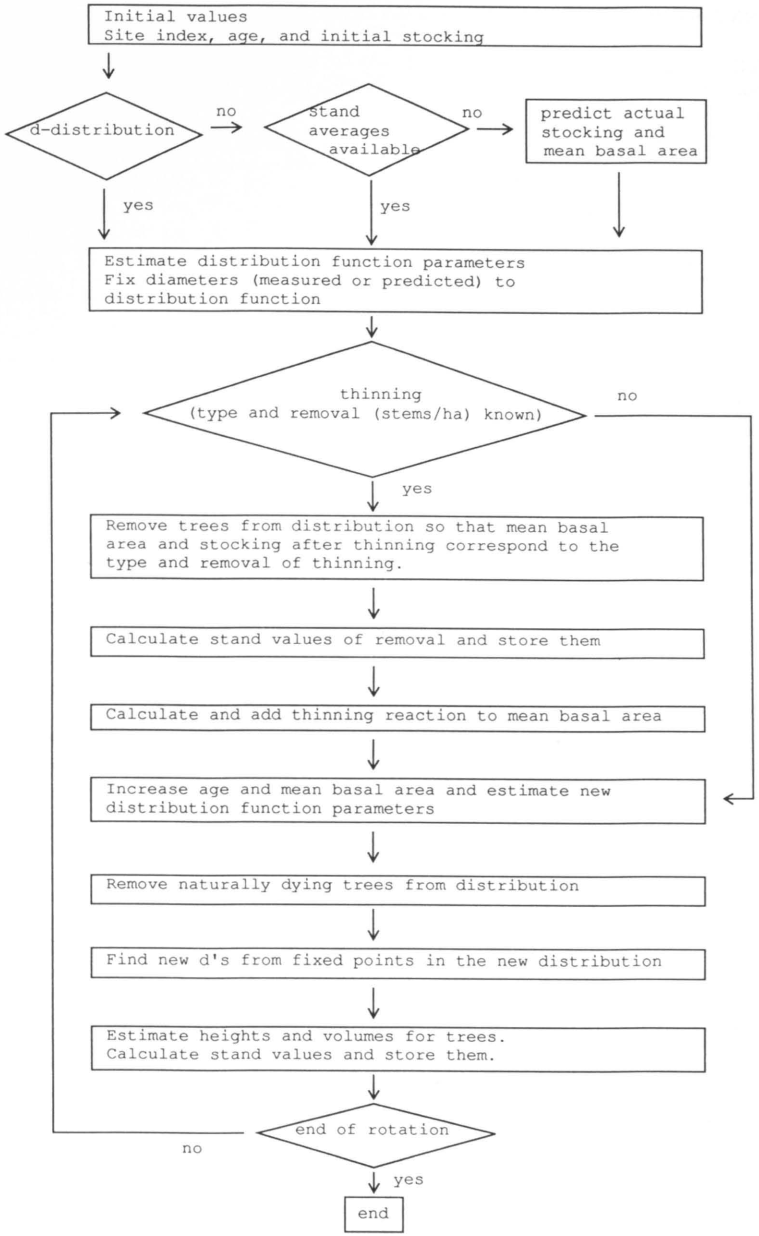

Figure 1. Schematic presentation of the system.

2.2 Growth functions

Apart from being flexible the growth function should be as simple as possible. It should also be able to predict both growth and yield by either integrating the growth function or by differentiating the yield function. Leech & Ferguson (1981) state that discriminating between families of models is difficult on the basis of ordinary or generalized least squares estimation of sampling variances and residual variances alone.

In this study the selection criterion was the simplicity of the function. A slightly modified Schumacher function (1939) was selected due to its simplicity and explicit mathematical form. The function described the relationship well in the data. The Schumacher function has been used for describing height development (Bailey & Clutter 1974; Ferguson & Leech 1976) but it also seems that a good fit is obtained for basal area development of tropical pines (Alder 1980). The yield function is monotonous and of the form:

$$Y = e^{(a-b/T)} \tag{2}$$

The function has the asymptote a. Both coefficients a and b can be regarded as functions of both stand and environmental factors. To obtain more flexibility a third parameter c was added as the power of age. The final form of the yield function was:

$$Y = e^{(a-b/T^{c})} \tag{3}$$

Parameter c can also be regarded as a function of stand factors.

2.3 Distribution function

Diameter or basal area distributions are usually described by beta and Weibull functions (e.g. Zöhrer 1969; Väliaho & Vuokila 1973; Bailey & Dell 1973; von Gadow 1983 a,b,c; Hyink & Moser 1983). Also normal (Pettersson 1955), gamma (Nelson 1964, lognormal (Bliss & Reinker 1964), Johnson's SB (Hafley & Schreuder 1977) and segmented (Cao & Burkhart 1984) distributions have been used. Good results have been achieved with beta, Johnson's SB and Weibull functions. Segmented distributions also seem to work well if some inherent problems are solved.

Beta and Johnson's SB both have four parameters whereas the Weibull function has three parameters. If both ends of the distribution are known the fitting procedure for beta and Johnson's SB functions is uncomplicated but the cumulative frequencies must be solved using numerical integration. The Weibull distribution has the advantage of having an analytical form for both cumulative distribution and probability density functions. The sample minimum and maximum do not represent the population maximum and minimum but limit the range of distribution if a beta function is used (Päivinen 1980; Kilkki & Päivinen 1986). The same applies to Johnson's SB function. When beta or Johnson's SB functions are used for consecutive years, they imply that the relative rate of diameter growth remains constant over age (Bailey 1980). When testing this hypothesis with data from a loblolly pine spacing study Bailey (1980) rejected the hypothesis. With Weibull the relative growth rate does not need to be constant over time (Bailey 1980).

Parameters of the distribution function can be solved either from weighted or unweighted distribution. Päivinen (1980) and later Kilkki & Päivinen (1986) and Kilkki et al. (1989) used basal area diameter distribution where the frequency of diameters is weighted by the square of the diameter or by the basal area of the tree. As basal area and volume of the tree are closely correlated, weighting in this way gives more weight to the most valuable parts of the distribution and is advantageous in static situations.

For the whole material parameters of beta probability density function,

$$f(d) = c(d - D_{min})^{a}(D_{max} - d)^{b} \tag{4}$$

where f(d) = frequency of diameter d
c = scaling factor to obtain a specified total number of stems
a,b = parameters

were calculated. The parameters of the Weibull cumulative frequency function,

$$F(x) = 1 - e^{-((x-a)/b)^{c}} \tag{5}$$

for $x,b,c > 0$

basal area diameter distribution were calculated as well. Their reliability was tested by comparing the calculated frequencies to the actual ones within the commercially most important diameter classes. The probability density function for Weibull is:

$$f(x) = c/b((x - a)/b^{(c-1)}\, e^{-((x-a)/b)^{c}} \tag{6}$$

Furthermore, reverse Weibull (see Maltamo 1988) was included in the comparisons. The reverse Weibull was calculated so that each diameter was subtracted from 50 cm. Differences between functions were not statistically significant. Visually, Weibull and reverse Weibull were close to each other (see Maltamo 1988, Kilkki et al. 1989) and beta seemed to differ a little more than the others (see Gadow 1983a). The weakness of the reverse Weibull is that parameter a, which in the reverse case describes the maximum diameter in a stand, is always very close to the sample plot maximum and causes bias when applied at stand level. The same also applies when the plot minimum and maximum are used as minimum and maximum diameters of the stand. The bias in reverse Weibull can be quite notable due to the large size of trees at that end of the distribution. The corresponding bias in normal Weibull is negligible due to the small diameters concerned. The normal Weibull function was selected because of its analytically clear form and relative simplicity in practical calculations, and because there were no clear indications of the superiority of the other tested functions.

In growth and yield studies all parts of the diameter distribution are equally important because the development of the whole distribution is of interest. This fact emphasizes the use of unweighted methods in the prediction, when change in the distribution over time must be known.

Even though basal area diameter distribution is better than the unweighted diameter distribution in static situations, its advantages are not so obvious when a change over time is concerned. For growth predicting purposes unweighted distribution seems more suitable. Comparisons were made between basal area diameter distribution and unweighted diameter distribution. No differences were seen to prove that one distribution type was better than the other. This led to the selection of the unweighted diameter distribution.

The expected frequency of the ith diameter class (n_i) with class width 2w, class midpoint x and total frecuency N in Weibull is:

$$n_i = N(e^{-((x-a-w)/b)^{c}} - e^{-((x-a+w)/b)^{c}}) \tag{7}$$

Parameter a is a so called location parameter and in forestry applications it is normally restricted to be equal to or above zero (eg. Bailey & Dell 1973; Rennolls et al. 1985) or some heuristic boundaries are set (Kilkki & Päivinen 1986, Maltamo 1988, Kilkki et al. 1989).

The parameters of Weibull diameter distribution function can be solved analytically if mean basal area, variance and skewness or the three first moments are known. This being so, it is possible that parameter a can obtain negative values, but a cumulative frequency below zero is negligible and can be added to the smallest positive diameters. All the three first mentioned variables have a clear meaning and are quite easily calculated from the measurements. This considerably reduces the calculation time. The parameters are approximated as follows (Heinonen, J., Finnish Forest Research Institute, Joensuu Research Station, pers. comm. 1990):

$$a = \sqrt{[(4 \cdot g_m)/\pi] - var} - \gamma \cdot \sqrt{(var)} \tag{8}$$

$$b = \sqrt{(var)} \cdot (3.60378 - 3.45238 \cdot skew + 2.96245 \cdot skew^2 - 3.35012 \cdot skew^3 + 3.42473 \cdot skew^4 - 1.85204 \cdot skew^5 + 0.37067 \cdot skew^6) \tag{9}$$

$$c = 3.60868 - 4.07287 \cdot skew + 3.87279 \cdot skew^2 - 4.32449 \cdot skew^3 + 4.37918 \cdot skew^4 - 2.36924 \cdot skew^5 + 0.47488 \cdot skew^6 \tag{10}$$

where $\gamma = 3.24799 - 3.30639 \cdot skew + 3.01856 \cdot skew^2 - 3.36202 \cdot skew^3 + 3.41416 \cdot skew^4 - 1.84851 \cdot skew^5 + 0.37052 \cdot skew^6$ (11)

Because the gamma function is also required in solving the parameters an approximation of gamma function was used (Heinonen, J., Finnish Forest Research Institute, Joensuu Research Station, pers. comm. 1990). As the values for parameter c varied in the data from 1.01 to 9 these values were set as limits for the function. Consequently, skewness values were restricted between −0.6 and +1.7. The values for variance and skewness are easiest derived from fixed size sample plots.

In Zambia the tradition has been to measure sample plots of fixed size. Diameter distributions are then available and calculation of needed variables is easy, as is solving the Weibull function parameters. For the purpose of the present study the method for solving the Weibull function from mean basal area, variance and skewness seems most suitable.

3 Materials

3.1 Location and quantity

All the commercial *P. kesiya* plantations are located in the Copperbelt province of Zambia (13° S, 28° E, 1200—1300 m a.s.l) (Fig. 2). The area has a mean annual rainfall of 1270 mm falling between November and April. Soils in the area vary from the sandy or clay sandy type to the heavy sandy clay type (The Industrial ... 1969). Within the soil a compacted hard layer exists at various depths, which restricts root penetration. Plantations have only been established on soils where the depth of the permeable layer is more than 1.8 m (6 feet).

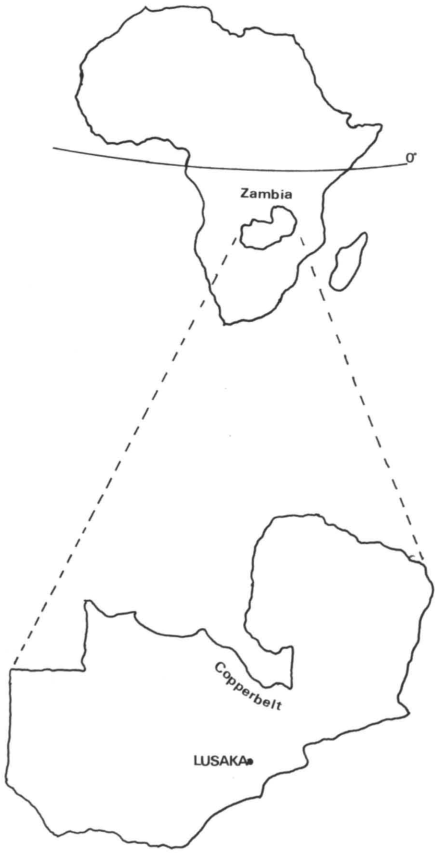

Figure 2. Location of the plantations and trials in the Copperbelt region.

The material used in this study was collected from three different sources and one source was divided into two sub materials according to the number of measurements.

Main data were collected from permanent sample plots established in the commercial compartments (Control plan 5/3/1, 1969) and measured from four to ten times. This material is later called *basic* or *original material.* 114 permanent sample plots were used including 766 assessments. Treatments of the compartments varied, but all were thinned at least once. The maximum number of thinnings was four. All the stands were pruned according to the pruning schedule. The seed origins were: Vietnam 74 plots, Philippines 36 plots and Malagasy 4 plots. The division of the assessments into age and site index classes is shown in Table 1 (see Chapter 4) and some basic data in Table 2.

Table 1. Age and site class distribution of the basic material by measurements.

Age class	Site index 18.00	21.00	24.00	27.00	Total
4.00		17	23		40
6.00	2	74	96	2	174
8.00		79	49	1	129
10.00	2	39	39	4	84
12.00	2	46	45	2	95
14.00	1	35	48	6	90
16.00	3	9	25	4	41
18.00	1	28	37	7	73
20.00	3	20	12	5	40
Total	14	347	374	31	766

Table 2. Description of basic and test material by measurements.

Variable	Mean	Std Dev	Minimum	Maximum	N
		Basic material			
Age (T),y	11.02	4.64	4.09	20.92	766
Stocking stems/ha (N)	866.63	312.95	179.31	1331.98	766
Volume (V), m^3	201.11	108.34	28.85	602.40	766
Site index (Si)	22.69	1.57	17.92	27.11	766
Dominant height (H_{dom}), m	17.43	5.88	7.08	31.50	766
Mean diameter (D_m), cm	20.96	5.85	9.23	36.85	766
Mean height (H_m), m	16.35	5.89	6.25	30.74	766
Variance of d-distr (var)	12.46	8.86	1.78	57.57	739
Skewness of d-distr (Skew)	−0.29	.50	−2.00	2.00	739
		Test material			
Age (T), y	11.28	2.76	7.76	16.99	360
Stocking stems/ha (N)	941.61	205.75	413.57	1360.00	360
Volume (V), m^3	251.98	85.42	78.70	491.35	360
Site index (Si)	22.67	1.68	16.34	28.26	360
Dominant height (H_{dom}), m	18.39	3.59	9.33	27.13	360
Mean diameter (D_m), cm	21.53	2.55	15.01	28.22	360
Mean height (H_m), m	17.15	3.56	9.39	27.12	360
Variance (var)	15.73	7.50	4.86	57.60	360
Skewness (Skew)	−0.32	.48	−1.80	.93	360

Table 3. Age and site class distribution of the test material by measurements.

Age class	Site index 15.00	18.00	21.00	24.00	27.00	Total
8.00		3	45	57	5	110
10.00		2	41	43	1	87
12.00			37	40		77
14.00		1	19	29	12	61
16.00	1	4	16	4		25
Total	1	10	158	173	18	360

These data were used to find the shape of mean basal area, variance, and skewness functions. They were also used to derive site index, mortality, thinning reaction, and all stand level functions. This material was used only, for finding shape of the main models functions and not for the calculation of parameter values, because the range was narrow compared to the inventory material. However, for site index, mortality and thinning reaction estimation this is the only material.

The second source material, later called *test material*, consisted of 125 permanent sample plots, which were measured only two or three times, making a total of 360 assessments. These stands were thinned once or were unthinned. However, all stands were pruned. The seed origins were: Vietnam 87 plots and Philippines 38 plots.

The division of these assessments into age and site index classes is shown in Table 3 (see chapter 4) and some basic data in Table 2. These data were used only for testing the equations and the whole model. The limited number of assessments prevented the use of this material for parameter estimation.

The third data source, later called *inventory material*, was from the plantation inventory data (Saramäki et al. 1987). It included 3260 temporary sample plots from 5 to 25 years of age. The plot size was 0.0314 ha for 5 to 10 years old stands and 0.05 ha for 11 to 25 years old stands. Plots having less than five trees and plots having a site index less than 15 or greater than 28 were excluded. The exclusion was based on the fact that plots with less than five trees are not any more eligible for growing and site indices outside the selected range are not suitable for growing *P. kesiya.* Plots were divided into site classes as follows:

Site class, H_{dom} at 15 years, m	% of total area
15	3,6
18	30,5
21	50,2
24	14,4
27	1,3

The seed origin was unknown for inventory material. In deriving height equations only a random sample of 4018 trees was used. Details of measurements are presented in Saramäki et al. (1987). Inventory data were used to derive final parameters for mean basal area, variance and skewness functions as well as for height equations. This material represents a statistically sound systematic sample for all plantations and thus, guarantees the usefulness of the model in an operational planning situation.

The fourth source material (Control plan 2P/7/6), later called *espacement trial material*, was a trial of nine spacings from 12048 stems/ha to 137 stems/ha with five replicates.

All the plots were kept unthinned apart from two spacings where the original spacings of 1076 stems/ha and 549 stems/ha were respaced to 269 stems/ha and 137 stems/ha respectively. The respacing was done before the assumed onset of competition. In this study measurements from four to 16 years of age were available. Plots only had 25 planting spots, but all trees were measured for both diameter and height ten times during the study period (Appendix 1). These data were used for finding the shape of mortality and mean basal area functions. This is the only material where the original density varies and it gives valuable information on the effect of density on the growth and yield.

3.2 Sample plots

Sampling intensity of basic and test material was 0.2 % Permanent sample plots were circular in shape and 391 m^2 (approx. 0.1 acres) in size. There was approximately one plot in every 20 ha. Plots were placed by random co-ordinates in the randomly selected compartments of a given stratum. The plots were established before first thinning and after first pruning if pruning occurred before thinning. In some cases the plot was established at times for normal first thinning. Remeasurements should be carried out at each thinning or at clear felling. One regular measurement took place once in three years, apart from the first established plots which were measured for a second time one year after establishment. The measurements were normally carried out in August-September during the onset of dormancy, however, if thinning was undertaken at other times in the year, measurements should have been taken at the time of thinning. Spacing (2.75 m x 2.75 m) in the plantations is very regular, thus every plot includes 52 planting spots.

Trees were numbered according to their location, thus the spatial distribution is exactly known. In order to keep the point for breast height diameter equal at subsequent assessments, a nail with a number tag was fitted exactly 1.83 m (6') above average ground level to avoid growth disturbance at 1.3 m level. While measuring the worker had a 53 cm long stick to reach from exactly 1.83 m to the breast height (1.3 m). Every living tree was measured for breast height diameter (mm) over bark using a diameter tape. Trees marked for thinning were distinguished on the assessment form. The four trees of largest diameter were always measured for height (dm) giving an estimate of mean top height (dominant height), mean height of the 100 largest trees per ha. Additionally , at least one tree in each one cm diameter class was measured for height (dm). Where possible, the total number of height measurements was not allowed to fall below 12. Due to the sample tree selection, trees measured for height once could not necessarily be measured in the next assessment. The details of establishment, measurement, data recording, compilation and filing are given in the Research Instruction Circular (Technical) No. 1 (Permanent... 1972).

3.3 Basic calculations

All plots were supposed to be measured at the time of thinning, however, this did not happen in every case. In calculations the plot was regarded as thinned if the number of stems had decreased more than 10 % from the previous assessment. The following stand characteristics were derived for every measurement:

- age, years;
- number of stems per ha;
- arithmetic mean diameter at breast height, cm;
- mean basal area, cm^2;
- mean diameter corresponding to mean basal area, cm;
- dominant diameter (mean of 100 largest trees per ha), cm;
- basal area, m^2/ha;
- mean height corresponding to the mean basal area tree, m;
- dominant height (mean of 100 largest trees per ha), m;
- mean over and under bark volume, m^3/ha;
- total volume overbark, m^3/ha;
- volume to 10 cm top diameter overbark, m^3/ha;

- volume to 15 cm top diameter overbark, m^3/ha;
- volume to 20 cm top diameter overbark, m^3/ha;
- site index class;
- parameters of the Weibull basal area distribution function;
- variance of the diameter distribution; and
- skewness of the diameter distribution

The mean height as well as the height of every tree was calculated from a plotwise height curve of the form:

$$h - 1.3 = a_0 + a_1 \cdot d + a_2 \cdot d^2 \qquad (12)$$

The volume functions are based on breast height diameter and height (Sekeli & Saramäki 1983). For the removal the same stand characteristics were calculated, except for those of dominant height, dominant diameter and Weibull parameters.

Each tree was given a height calculated from the height curve if it had not been measured for such. In the simulation stage volume functions of Sekeli & Saramäki (1983) were replaced by the new taper curve functions of Heinonen et al. (1991). As ZAFFICO Ltd would like the utilizable volumes underbark, the simulation system calculates total volume both over- and underbark and utilizable volumes underbark only.

4 Site classification

No site classification for forest plantations is available in Zambia. In earlier growth and yield predictions (Jones 1967; Yield table... 1973) only one average value was given for the plantations as a whole. Saramäki et al. (1987) developed site index curves for *P. kesiya* using temporary sample plots from the forest inventory. This function did not seem to follow the height growth pattern of the permanent sample plots although it fits well for the inventory data. As the permanent sample plot material was remeasured many times, the possibility existed to use more flexible functions.

Bailey & Clutter (1974) have presented ways to utilize either temporary or remeasured height observations to develop site index curves.

According to Bailey & Clutter (1974) the anamorphic model is

$$\log(h) = a_i + b(1/T)^c \qquad (13)$$

where a_i is the site-specific parameter of the model. This form can be further developed to form

$$h = Si \cdot 10^{b \cdot (T^{-c} - T_0^{-c})} \qquad (14)$$

where Si is site index when indices are based on dominant height at "base age" (T_0). Si can be solved from the above equation when the base age is fixed and dominant height and age of the stand are known. When b and c of Eqn. (14) are known the height-age curve can be determined for any combination of base age and site index.

The polymorphic model is

$$\log(h) = a + b_i \cdot (1/T)^c \qquad (15)$$

where a and c are constants and b_i is the site specific parameter. The site specific parameter b_i can be calculated if relative growth rate and age are known. Relative growth rate can only be calculated from repeated measurements as derivatives of the height-age curve are needed. Height can be expressed as a function of site index and age as follows,

$$h = 10^a \cdot (Si/10^a)^{(T_0/T)^c} \qquad (16)$$

where 10^a sets the asymptote to the height (Bailey & Clutter 1974). The parameters a and c can be solved by the method of Bailey & Clutter (1974).

Both anamorphic and polymorphic functions were tried as well as the function derived from inventory results (Saramäki et al. 1987). The anamorphic site function solved from the basic material using the method of Bailey & Clutter (1974) was

$$Si = H_{dom}/10^{-2.27552 \cdot (T^{-0.60241} - 15^{-0.60241})} \qquad (17)$$

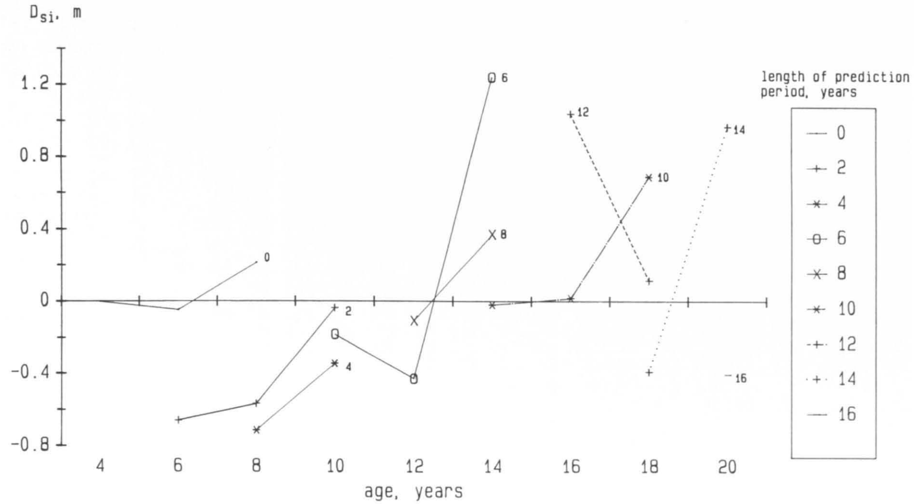

Figure 3. The mean residuals (D_{si}) of the site index equation (19) as a function of age and length of prediction period. Each sample plot has been compared to the site index from the first assessment.

The inventory function (Saramäki et al. 1987) was

$$Si = 10^{[(\log_{10}(H_{dom} - 1.80084)/(15/T^{0.74} + 1.80084]} \quad (18)$$

The parameters of the polymorphic site index function were calculated from the basic material with the method presented by Bailey & Clutter (1974). The function is

$$Si = 10^{(\log_{10}(H_{dom} - 1.79934/(15/T)^{0.60241} + 1.79934)} \quad (19)$$

Age 15 was chosen as the base age for *P. kesiya* as most sample plots had reached that age within the study period. Eqn. (19) was tested by examining the correlation between age and site index in the inventory material to see how well the equation fits in an independent material. A statistically significant positive correlation was observed. This means that young plots in the inventory material were on average smaller in height than in the permanent sample plot data which represents older stands. This correlation might be explained by differences in the intensity of early silvicultural operations (Boyer 1983). In the basic material a positive correlation was also seen between age and site index. However, the shift in the site index is on average only about 0.5 m and varies considerably. There were no correlations with the length of prediction period in the basic material and site index at each compared age (Fig. 3). This means that the used site index seems to be stable within a sample plot.

A steeper slope is seen with the inventory function than with the functions derived from permanent sample plot material. This indicates that the young and old stands in the inventory deviate in their development from the permanent sample plot material which consists of samples from the old inventory compartments. The means of ana- and polymorphic functions are very close but the standard deviation is smaller in the polymorphic case (Table 4). The stability of different site index values over time were compared (Fig. 4). Functions derived from permanent sample plot material remained stable, apart from at the very youngest ages. A good fit was obtained when derived functions were compared against test material. Ana- and polymorphic functions did not deviate from each other (Fig. 4) but site index value calculated from the inventory function seemed to increase with increasing age.

Table 4. Mean site indices for the basic material using different site index curves.

Site index curve	Mean	Std dev.	Min	Max	Cases
Anamorphic	22.73	2.01	16.31	28.38	766
Polymorphic	22.69	1.57	17.92	27.11	766
Inventory (Saramäki et al. 1987)	22.22	1.69	16.22	26.08	766

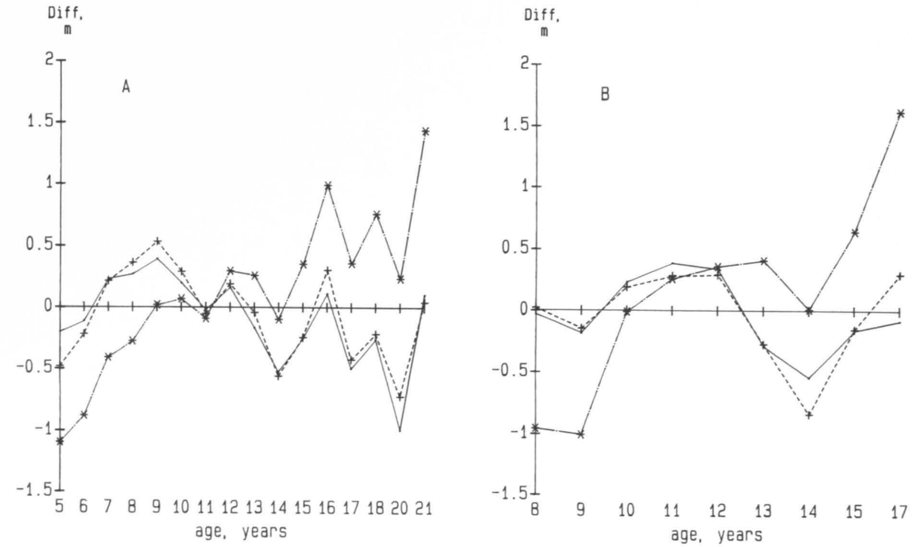

Figure 4. The stability of site index over age using different types of site indices. Diff = mean deviations per age class from the average site index of the plot; A = basic material; B = test material; ·—*—· = Inventory model (Saramäki et al. 1987); — = Anamorphic model (17) and —+— = Polymorphic model (19).

Furthermore, comparison of ana- and polymorphic curves at the sample plot level proved that variation within the sample plot is smaller when the polymorphic function is used. For these reasons the polymorphic curve was selected. Site index curves are presented in Fig. 5. When validating this function, the dependence of site index on age was tested and no trend could be found, however, an age of less than five years (one case only) gave an overestimate for site index. Site index seemed to be overestimated in stands where dominant heights were high. Because the initial density in all plots is equal, no density effect could be found. The material consists of three different seed sources. Mean site indices differed significantly between seed sources.

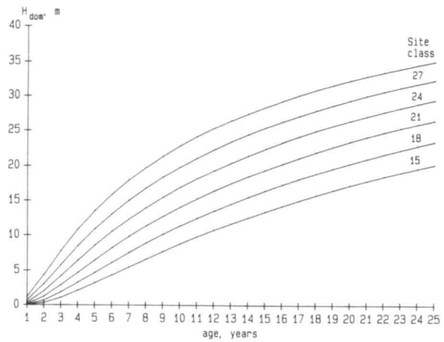

Figure 5. Site index curves for *Pinus kesiya*.

Provenance	Mean site index	Standard dev.	Number of observations
Vietnam	22.4	1.51	530
Philippines	23.5	1.34	212
Malagasy	20.8	1.04	24
Total material	22.7	1.57	766

At 5 % risk level the significant difference between Vietnam and Philippines is 0.28, between Vietnam and Malagasy 0.71 and between Philippines and Malagasy 0.74.

As no evidence exists of provenances being planted systematically on different soils or their ages or age distributions differing these deviations can be seen as a true effect of seed source.

5 Growth and yield equations

5.1 Mean basal area function

Mean basal area is defined as the arithmetic mean of tree basal areas. As stated earlier (Chapter 23) the selected function family is the modified Schumacher function:

$$\ln(g_m) = a + b/T^c \qquad (20)$$

As a measure of stocking, the number of stems per hectare was used because it is a commonly used characteristic in Zambia. It can be argued that basal area could have been a more effective measure. However, in a country where plantations of exotic trees have been established on very uniform sites, using extremely exact spacing the result, most probably, would have been almost equal to the presented one.

The first stage was to develop a common basal area model for cases where little is known about the actual stand.

The function is linear with respect of parameters a and b if coefficient c can be set as constant.

From the basic material it was found that parameter c is not dependent on site. To find the form of relationship between parameters a, b and c and stocking, data from the espacement trial (Control plan 2P/7/6) was used. Non-linear function,

$$\ln(g_m) = k0 \cdot N_a^{k1} + k2 \cdot N_a^{k3}/T^{(k4 \cdot \ln(N_a))} \qquad (21)$$

was solved. Parameter b in Eqn. (20) was found not to be dependent on stocking and the function was reduced to

$$\ln(g_m) = k0 \cdot N_a^{k1} + k2/T^{(k4 \cdot \ln(N_a))} \qquad (22)$$

Parameters k1 and k4 define the form of dependence, and were found to be −0.113 and 0.2 respectively. These parameters were set as constants in the final model. The other parameters were solved from the inventory data. As the site class was constant in the espacement trial material, it was included as a independent variable into the final model. The parameters can be solved using the least squares estimation from the function

$$\ln(g_m) = m0 \cdot si + m1 \cdot N_a^{(-0.113)} + m2/T^{(0.2 \cdot \ln(N_a))} + m3 \cdot Si/T^{(0.2 \cdot \ln(N_a))} \qquad (23)$$

because $N_a^{(-0.113)}$, $1/T^{(0.2 \cdot \ln(N))}$ and $Si/T^{(0.2 \cdot \ln(N))}$ can be seen as independent variables. $Ln(g_m)$ was found to be linearly dependent on site also.

The final function is

$$\ln(g_m) = a + b/T^c \qquad (24)$$

where $a = 0.04779 \cdot Si + 11.95430 \cdot N_a^{(-0.113)}$
$b = -23.54913 + 0.11086 \cdot Si$
$c = 0.2 \cdot \ln(N_a)$

Standard error (in logarithmic scale) of the function is 0.20796 (n = 3086), s_e = 14.78 %, and the degree of determination 0.998. This model was tested using the basic and test material. The mean deviation for basic material was 24.80 cm^2 and for test material 23.79 cm^2. The standard deviations of differences were 45.02 cm^2 and 48.23 cm^2 correspondingly. The model underestimates the mean basal areas of basic and test materials by 6.7 % and 6.4 % respectively. However, no trends can be seen when deviations are examined (Fig. 6). This is expected as the permanent sample plot material represents the older stands where silvicultural operations have been more intensive than in stands established later. Part of the difference can be explained by differences in the seed origin, which has also changed during the time of plantation establishment. However, this is only speculation as seed origin is known only for the permanent sample plot material. The model slightly overestimates the mean basal areas of very fertile soils (Fig. 7). The mean basal areas of large (over 35 cm diameter) trees were underestimated in the inventory material, however, only 18 observations of mean diameter larger than 35 cm were recorded.

Seed origin can cause some bias to the growth and yield prediction. This bias can be accounted for by changing height and diameter development. Buford & Burkhart

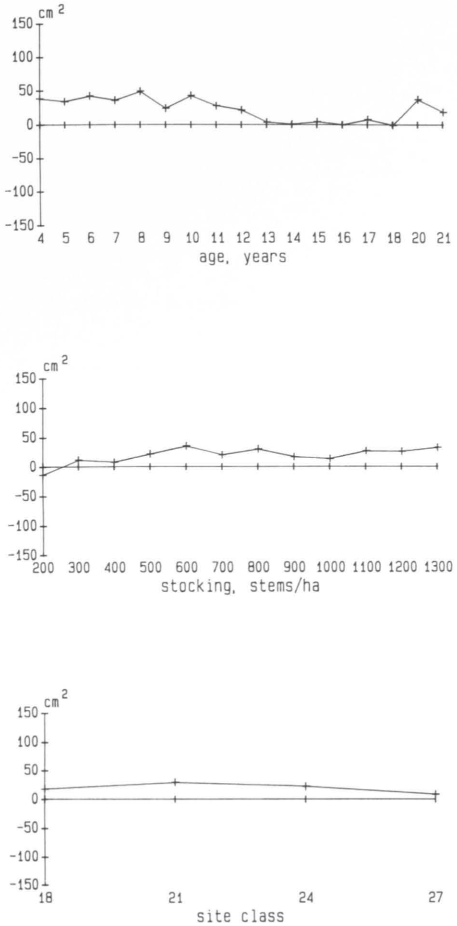

Figure 6. Mean residuals of the mean basal area model (24) in basic data.

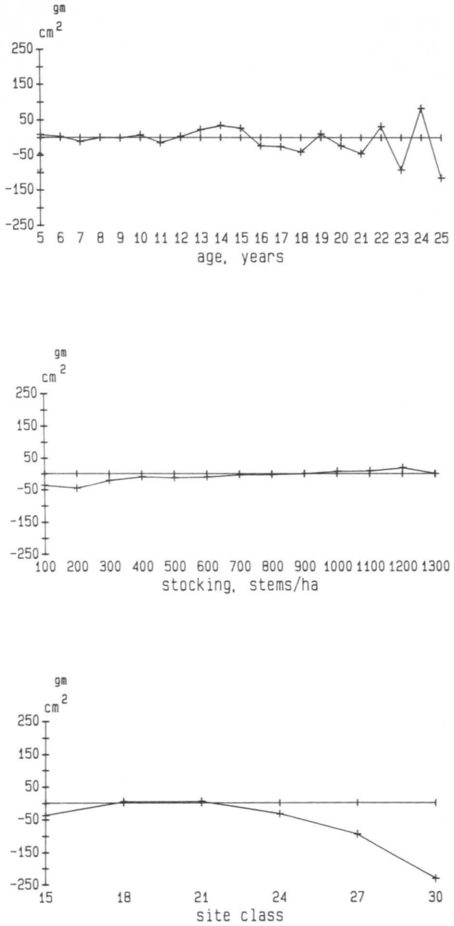

Figure 7. Mean residuals of mean basal area model (24) in inventory material.

(1987) found that by choosing the height curve carefully, differences in the development between seed sources can be modelled by altering the level of the height curve. In this study site index curves were developed without any consideration of seed stock. If differences in the height development of separate seed sources occur, they are partly hidden in the site index. To see if any effects of seed origin remain, the effect of the provenance was tested. Mean deviations by provenance in the basic material were:

Provenance	Deviation from estimated mean basal area, cm^2	Number of observations
Vietnam	33.92	530
Philippines	3.72	212
Malagasy	9.61	24

Seed source can be taken into account by inclusion of dummy variables into the model. By adding provenances as dummy variables into the model the deviations in the basic material vanished and in the test material the mean deviation was −1.83 cm^2. As this kind of correction, where the model parameters are derived from different material, includes also bias caused by the data it cannot be used in the final model. However, seed origin should be taken into account whenever it is possible.

This common model causes some bias to the mean basal area immediately after thinning, however, the bias disappears within three years. The direction of bias depends on the type of thinning. An underestimation of mean basal area is observed if thinning is from below, while an overestimation is seen if thinning is from above. The value of bias cannot be correctly estimated from the available material because the exact time of thinning was missing.

Measured information can be utilized as follows: if the mean basal area and stocking at a certain age are known, parameter b can be derived from Eqn. (20),

$$b_r = (\ln(g_m) - a) \cdot T^{(0.2 \cdot \ln(N_a))} \qquad (25)$$

This calculated coefficient (b_r) replaces estimated b in Eqn. (24). Parameters a and b, thus, remain unchanged up till the next thinning.

Furthermore, corrections of parameter a were tested but no decrease in the residual variation of diameter was seen. Therefore, the original assumption of parameter a (the asymptote of the function) being only dependent on stocking and site remained valid.

5.1.1 Inclusion of tree level information

Mean basal area can be converted to basal area of a tree if basal area or frequency distribution of diameter and the position of the tree in the distribution are known. The position of the tree can be expressed as 1) ordinal 2) percentage point or 3) distance from the mean. In the stand, the ordinal of a tree is very difficult to define. Definition of the percentage point is easier and the distance from the mean is always possible to calculate. Information on tree position can be used to define the distribution (see e.g. Dubey 1967). When two percentage points are known, estimators for parameters b and c in Weibull function can be obtained (Bailey & Dell 1973).

If diameter distribution is known at one point of time, the order of trees in the distribution can be assumed to remain the same as long as no treatments in the stand occur. Thinning causes changes in the order by releasing more resources to some trees than compared to others. However, within a quite short period after thinning the order stabilizes again. By studying only stable situations the position of the tree at a future point in time can be estimated. When the ordinal of the tree is assumed to remain unchanged, the only thing is to predict its percentile or change in percentile from one time to another.

Change in percentile was studied in the basic material by assuming that the percentage point remains unchanged from the beginning of each study period to the next thinning or final assesment. This assumption was based on results from the espacement trial where trial plots were not thinned. As one could expect, the greatest deviations from the assumption occured at both ends of the distributions. In practice, forest stands are normally thinned within shorter periods than 10 years, which makes it possible to use this material as test data.

The ability of growth prediction of both mean basal area function (24) and Weibull function was tested by comparing real diameter increments to calculated increments in different parts of the diameter distribution, using the previous assumption of a fixed percentage point. The increments were calculated by dividing the diameter difference between two consecutive measurements by the time between those two measurements. The classification was carried out using the percentage points at the earlier measurement.

A good prediction was seen for diameter increment in the basic material in different parts of the diameter distribution (Fig. 8).

When the test results were examined by diameter classes, greatest differences occurred at the extreme ends of distributions. The average estimation period was in this material 2.4 years which might explain the good fit. However, there was no significant correlation between deviations and the length of estimation period, although maximum lengths exceeded 10 years. The correlations were tested separately for the low and high end of the distribution. The estimation period was not correlated with the difference between percentage points at the beginning and end of the period.

The same tests were also carried out with test material. On average, the increment

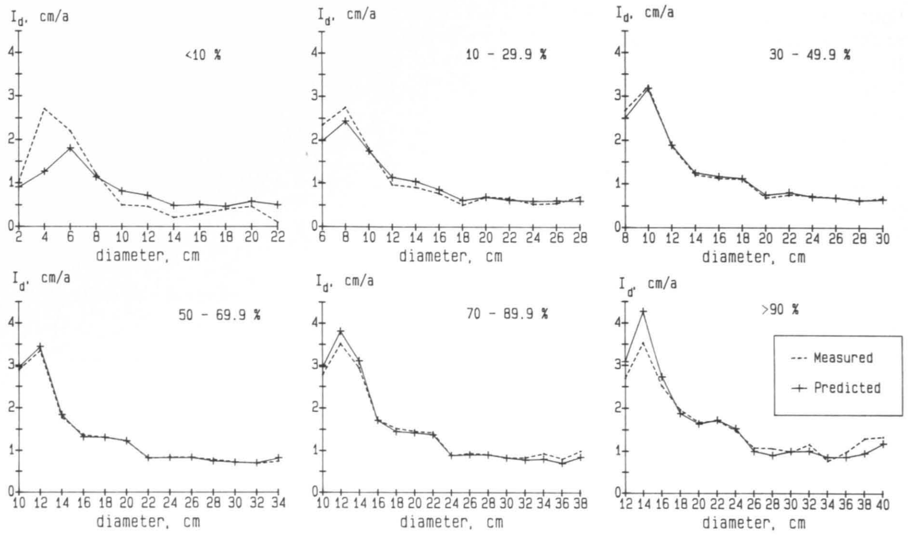

Figure 8. Measured and by Weibull function predicted diameter growth in different parts of the distribution in the basic material. Locations in the distribution are shown in each subfigure (e.g. 10—29.9 % means trees whose diameters are within these percentages in the distribution).

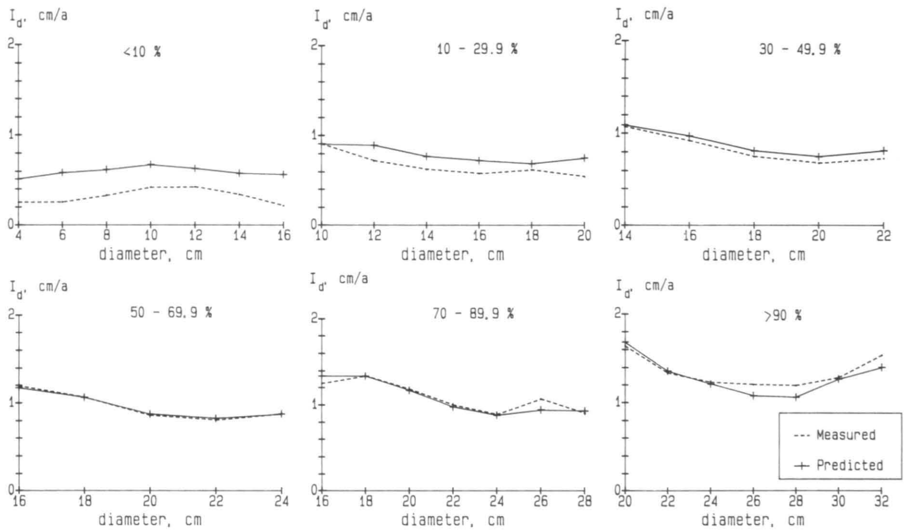

Figure 9. Measured and by Weibull function predicted diameter growth in different parts of the distribution in the test material. Percentage points are shown in each subfigure.

figures were smaller in the test material due mainly to delayed or non-existent thinnings. In the test material the estimated increments were too high at the low end of the distributions (Fig. 9).

This indicates that the estimated variance and skewness can not fully follow the slope of the real distribution. However, from a practical point of view, the overestimation was not alarming especially when the situation was the opposite in the basic material. As the estimation periods were longer with the test material (average 4.6 years) a greater possibility exists of making a wrong assumption.

The percentage point in the function seems to remain unchanged within the time limit found for the material. It was decided to use tree level information by fixing the measured tree diameter to the predicted Weibull cumulative frequency function. Keeping that percentage point (cumulative frequency point) constant until the next thinning or to the end of the rotation period, if a no thin policy was followed, the diameter of the tree can be predicted. As diameter distribution is available at each stage of the calculation, the 'real distribution' after thinning is calculated by removing trees from the diameter distribution before thinning. After thinning the trees are fixed again to the new predicted Weibull function.

5.2 Functions for distribution parameters

Weibull function can be described with moments or using the mean, variance, and skewness. In this study the mean basal area is known and variance and skewness are easily calculated. Regression analysis can then be used to find a relationship with moments and stand and site characteristics. The shape of dependence was found from the basic material, however, the values of the parameters were solved from the inventory material because the inventory material covered the whole range of variation found in the plantation.

The function for variance of the diameter distribution was

$$\mathrm{Ln(var)} = -3.03696 + 0.01007 \cdot \mathrm{Si} + 0.08207 \cdot \ln(N_a) + 0.87696 \cdot \ln(g_m) \quad (26)$$

Degree of determination of Eqn. (26) was 0.625, standard error 0.43911 (n = 3258), and $s_e = 31.81\ \%$. The factor to correct the bias caused by logarithmic transformation ($s^2/2$) was 0.09641. The residual picture (Fig. 10) shows that in old stands with large trees the model overestimates the variance, but on average the fit is acceptable.

The overestimation might be partly caused by the small sample plot size. Eqn. (26) was tested with basic and test material, too. The

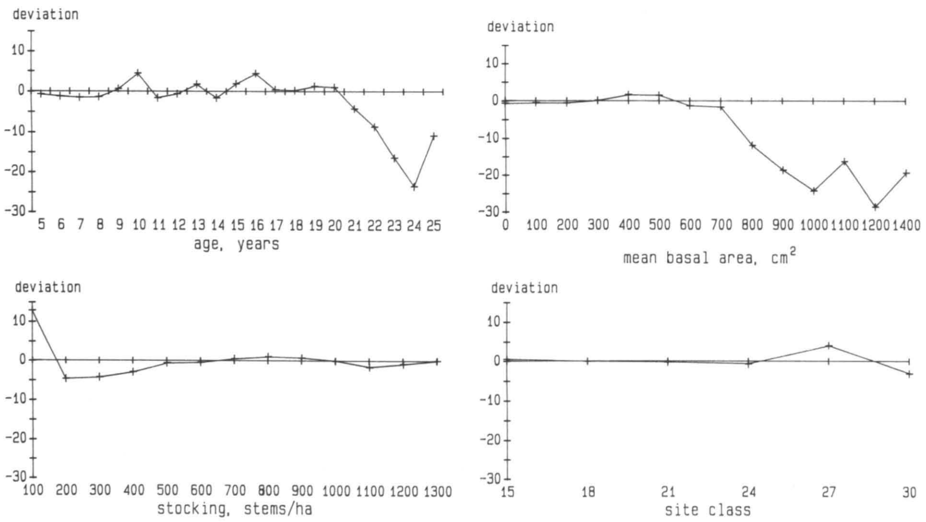

Figure 10. Mean residuals of the variance model (26) for the inventory material.

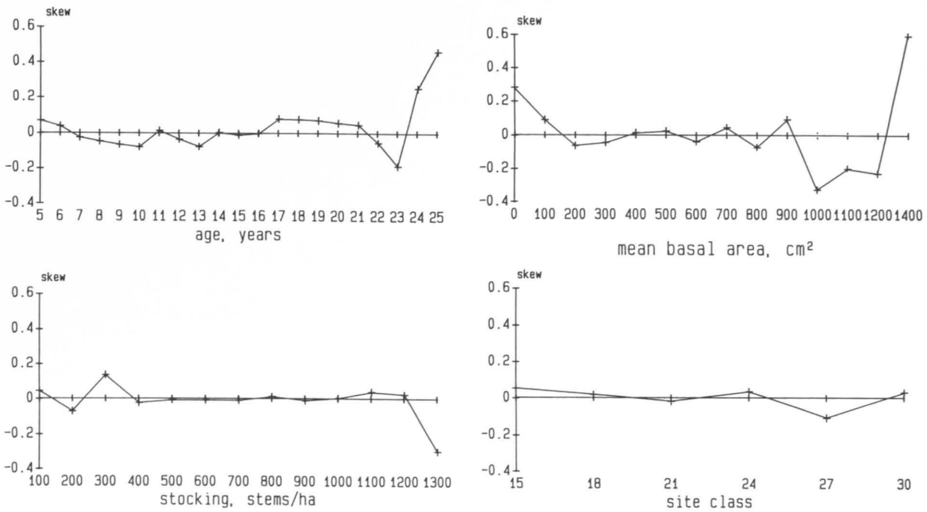

Figure 11. Mean residuals of the skewness prediction model (27) in the inventory material.

model overestimates the variance in both tested materials. The reason might be that the basic and test materials represent only part of the whole variance. The mean variance for inventory material was 19.09 as compared to 12.46 for basic material and 15.73 for test material. Changes in the intensity of silvicultural operations explain part of the differences, while part can be explained by seed source which can be seen when the deviations from the model value are examined by provenance:

Provenance	Deviation from Eqn. (26)
Vietnam	−9.8190
Philippines	−2.2092
Malagasy	−3.6419

The corresponding function for the skewness of the diameter distribution is

$$\mathrm{skew} = +0.03789 \cdot T^{0.5} - 0.000437684 \cdot N_a \quad (27)$$

The degree of determination is 0.170 and standard error 0.48344 (n = 3260). The model for skewness is very simple and the standard deviation of the model is more than double of the mean. The residual picture (Fig. 11) does not, however, show any trends. The model was proved to be unbiased by tests carried out with the basic and test material. The provenances did not affect the skewness significantly .

On average the skewness was larger in permanent sample plot material than in inventory material:

Variable	Mean	Std Dev
	Basic material	
Measured	−0.29	0.50
Predicted	−0.26	0.16
	Test material	
Measured	−0.32	0.48
Predicted	−0.29	0.10

The model diminishes the variation of skewness. It seems that the skewness is quite difficult to predict with the available variables. On the other hand, skewness is mainly changed by thinnings and the most important section for predicting skewness is carried out prior to first thinning. In normal cases skewness does not deviate greatly from zero and changes in skewness happen slowly and steadily. If heavy thinnings, either from below or above, are executed the recovery to a stable situation may last longer than that expected from the study.

5.2.1 Prediction when measured distribution is available

In many cases the distribution is assessed at the initial situation. This being so, the measured mean basal area, variance, and skewness can be used to derive parameters of

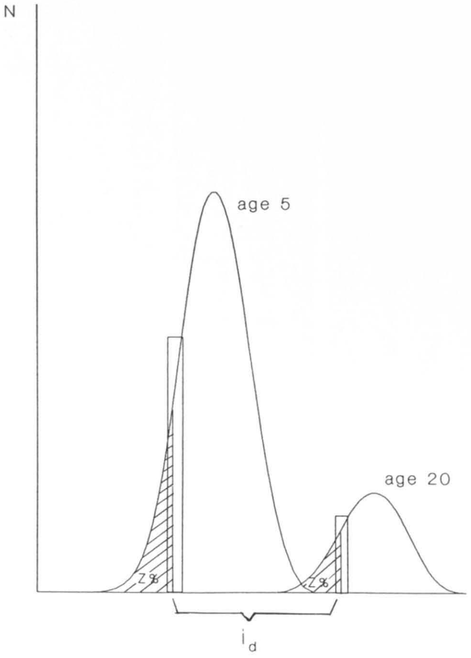

Figure 12. The principle of fixing diameter classes to predicted Weibull function. z = percentage point at measurement time.

the Weibull function. The percentage points of the trees can then be calculated from Weibull function and as explained earlier, (chapter 5.1.1) those percentage points can be used to locate the tree later in time in the predicted distribution (Fig. 12).

Another possibility is to use predicted variance and skewness for deriving parameters of the Weibull function. The procedure will then continue as explained above. However, the use of predicted variance and skewness may lead to an overestimation of the increment in small trees. On the other hand, the Weibull function must in the future, always be based on predicted values. Tree increment might be badly biased if in the first occasion, a measured Weibull is used and in the second a predicted Weibull. For this reason the measured diameters were fixed to the predicted Weibull and the percentage points were taken from the predicted Weibull function. As the percentage point is kept fixed, the original diameter classification changes with time. Because diameter distribution is presented in classes, the distribution was reclassified after growing by assuming the distribution within a class to follow Weibull function distribution at that point.

The type of thinning will automatically be taken into account in this system. If it is assumed that after thinning the trees grow the same as the trees having the same relative position in the new distribution as they had in the old, there will be no great increase in growth. If instead it is assumed that the distribution will reach the normal width in the future, the variation of increase will be greater, the bigger trees growing better and the smaller trees less than in the case of first assumption. As there was no information on the real development the more logical first assumption was selected.

If the distribution parameters are unbiased, stand development is reliably predicted. The predicted distributions also define, together with the assumption of nonmoving percentage point, the increment of trees in different diameter classes. The mean basal area function, which is increment function after derivation, together with the diameter distribution function can be seen as a distant independent tree model.

5.3 Mortality functions

When the stand is presented as a diameter distribution of trees, mortality should be taken into account to be able to change the distribution function according to changes in stocking. In treated stands mortality always plays a minor role and often it has been neglected. In order to explain mortality both the number of surviving or dying trees and their position in the distribution must be known. It can be assumed that part of mortality is random and part concentrates on the low end of the diameter distribution. The number of dying trees can be found from permanent sample plot information. Spacing trials best describe the dependence of mortality on the initial stocking. Thinning operations also cause some mortality which, in the present material, is difficult to describe. However, in reality thinning from below removes most of the smaller and suppressed trees and the actual mortality has only a marginal effect on the development.

The mortality process after stand establish-

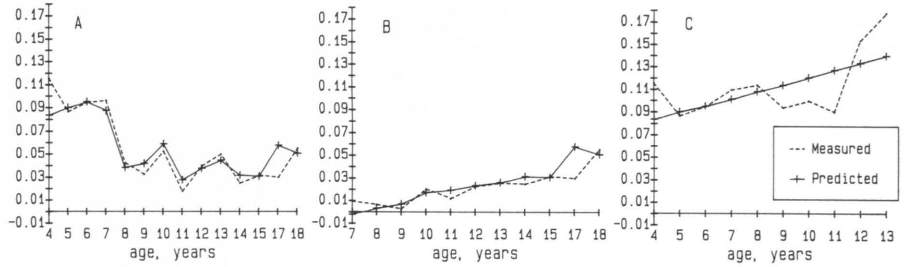

Figure 13. Comparison between measured and by Eqn. (28) predicted mortality (N_d/N_e) within A = all observations, B = observations of plots after thinning, C = observations of plots before thinnings.

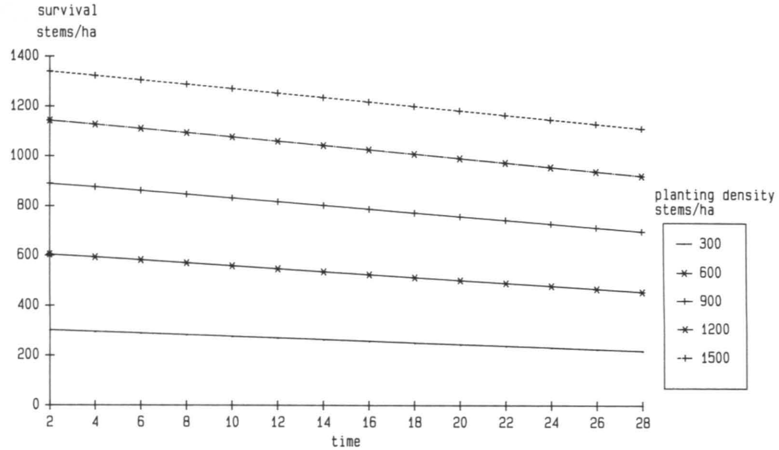

Figure 14. Number of living stems by age of stand according to model (28).

ment can be assumed to resemble the one after thinning. In this study wind damages were not observed and their effect was neglected. If thinnings are very heavy this assumption is no longer valid.

The mortality seemed to be, within the studied range, almost linearly dependent on age. Instead of the often used logistic function (Monserud 1976, Daniels & Burkhart 1988), normal linear regression analysis was used in fitting the relationship as it seemed to provide an adequate fit. The model of mortality is estimated from basic material when measurements at thinning are excluded. The model is:

$$\text{mort} = -4.06370 \cdot 10^{-6} \cdot N_e \cdot T - 8.36393 \cdot 10^{-3} \cdot T_{diff} + 1.181063 \cdot 10^{-7} \cdot N_e^2 + 0.01188 \cdot T - 1.14037 \cdot 10^{-4} \cdot N_e \quad (28)$$

The degree of determination of the model is 0.622 and standard error 0.05482 (n = 636). Variation in the mortality is quite large. However, the model predictions are close to the measured ones (Fig. 13). When this model was tested against espacement trial material, the fit was reasonable in the youngest stands but when trees were older than seven years of age there was a clear drop in the survival in espacement trial material. In the permanent sample plot material a few cases were observed where survival was as poor as in the espacement trial, however, in most cases the poor survival could be explained by the shallowness of the soil.

According to the model survival remains quite high in sparse stands and mortality increases steadily in denser stands (Fig. 14). As no data exists from old stands, the reality of these predictions cannot be confirmed, nevertheless, the figures are acceptable. In treated stands no unthinned periods longer than 15 years occur and in most cases periods are shorter than 10 years. Within this time limit the predictions do not greatly differ from reality in so far as there are no exceptional damages.

As well as the number of remaining trees in a stand the mean size of dead trees must also be known. The mean size was estimated as the ratio between the mean basal areas of remaining and all trees. The espacement trial material was used once again to discover the shape of the relationships. The ratio seems to increase slightly with age and decrease with decreasing planting density. In sparse stands the mortality seems to be almost random and in denser stands it concentrates on smaller stems. Before canopy closure the mortality is independent of stocking and age. It can be assumed that in general, trees which are bigger than average did not die naturally in the stand. The lower limit for the relation between mean basal areas can be set to one.

As naturally dead trees were not separated from other removed trees, thinning was assumed to be performed in cases where removal was greater than 105 stems/ha (more than four trees from one sample plot), and left for natural mortality in other cases. As dead trees removed in thinnings could not be counted, thinning occasions were excluded from mortality calculations. On this basis,

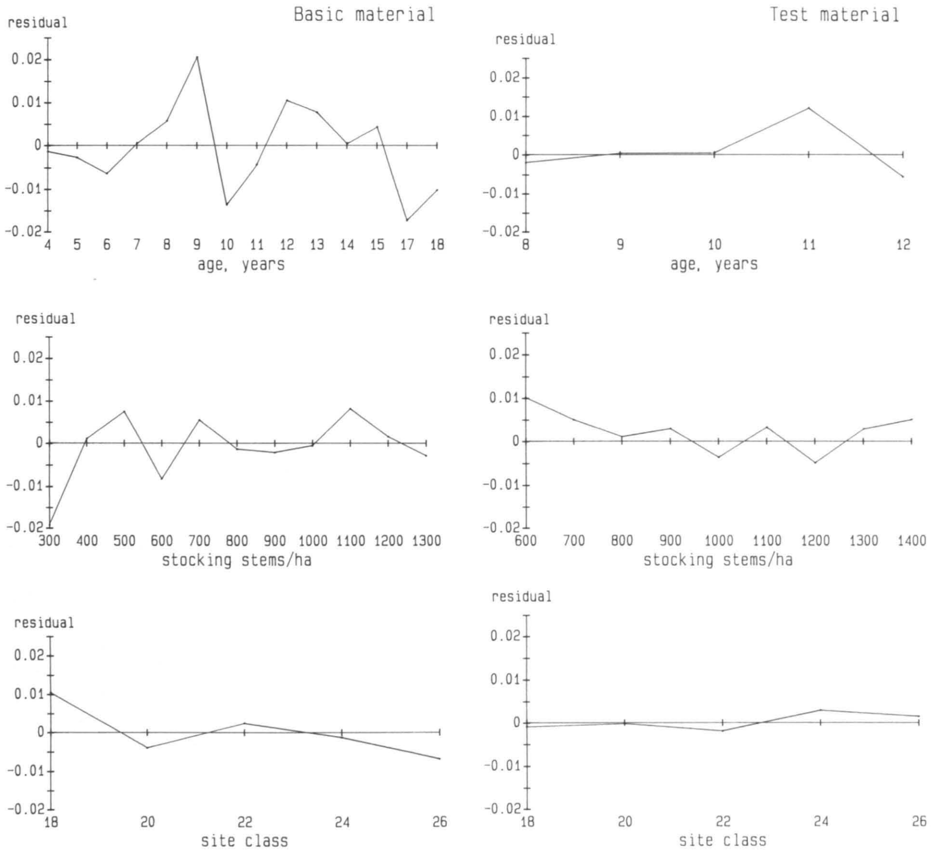

Figure 15. Mean residuals of the basal area ratio model (29).

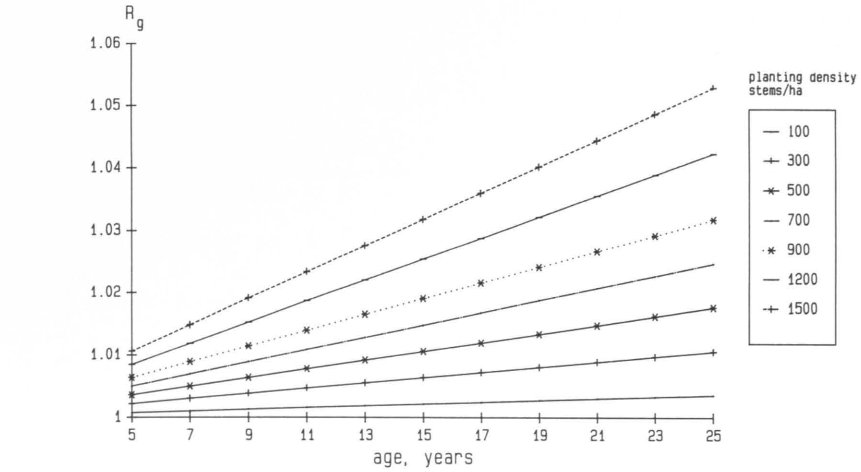

Figure 16. Development of the ratio between mean basal areas of living trees and all trees with stand age according to model (29).

132 cases of natural mortality were observed in the basic material and 86 cases in the test material.

A regression equation was developed to explain the ratio.

$$r_g - 1.0 = 1.414561 \cdot 10^{-6} \cdot N_c \cdot T \qquad (29)$$

The degree of determination was 0.344 and standard error of the estimate 0.01871 (n = 132). One was subtracted from the ratio to guarantee that the maximum mean size of dying trees does not exceed the mean size of the original stand. When testing against both basic material and test material the deviations did not show any trends (Fig. 15). However, the equation fulfils the conditions, that in sparse stands mortality is almost random and with increasing age and density greater mortality is seen with smaller diameters (Fig. 16).

With information of mean size and number of dead trees, the distribution for the remaining stand can be derived by removing the dead trees from the distribution so that the mean size of the remaining stand follows equation (29).

5.4 Thinning effect

Parameters of the basal area model were solved using observations where time from the latest thinning was not known. As in the basic material, measurements allowed a prediction interval of three years; the first three years after thinning were estimated separately. This was done by modelling the difference in basal area increment between the basic model and measured values in the basic material (Fig. 17). This difference is later called thinning reaction as it shows how much the increment deviates from the increment of an undisturbed stand with the same stocking.

All the stands are planted using the same stocking, 1330 stems/ha, thus competition

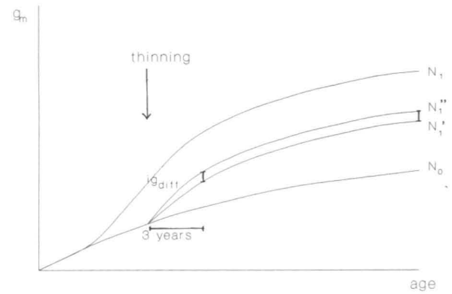

Figure 17. Schematic picture of the development of mean basal area after thinning from stocking N_0 to N_1. N_0 = development with stocking N_0 without thinning; N_1 = development with stocking N_1 without thinning; N_1' = development if no thinning reaction; N_1'' = development with thinning reaction; ig_{diff} = thinning reaction.

starts at the same time in all stands. The time at which competition starts also depends on the site. In this material site variation was so small that differences were insignificant. In young stands (age ≤ 7) no reaction to thinning is seen, instead, stands grow like stands which have grown from planting-out in the after-thinning stocking. Some signs that heavy early thinnings might diminish growth for a few years were observed. In all cases, heavy thinnings seem to cause very low thinning reaction if any at all.

As the material did not include information on thinnings from very old stands, the thinning reaction had to be partly estimated from heuristic values.

Thinning reaction was estimated in two steps. Firstly, the reaction was estimated for each thinning intensity separately, based on age only. The parameters a, b and c of the function

$$ig_{diff} = e^{(a+b\cdot \ln T + c\cdot (\ln T)^2)} \qquad (30)$$

are closely correlated and parameter b could be explained by relative removal (R_r). Parameters a and c were then found by regressing them against parameter b.

Relationships between parameters are partly based on assumptions, as not enough data were available at the older ages. Having fixed the relationships between parameters, the level of thinning reaction was scaled according to the data.

The functions after scaling for a, b and c are:

$$a = -53.14353 - 97.90727 \cdot (R_r)^4$$
$$b = 42.87249 + 82.71291 \cdot (R_r)^4$$
$$c = -8.16146 - 17.79403 \cdot (R_r)^4 \qquad (31)$$

It is not possible to give statistical characteristics for this equation, as part of the values used for estimation are heuristic. The model was only tested against the original material because no valid test material was available. On average, the model removes the systematic deviation caused by thinning but the residual variation is great (Fig. 18).

The mean basal area for the three first years after thinning is calculated by first using Eqn. (24) and then adding the value from Eqn. (30). If measured information is available, the difference between the logarithms of measured and predicted mean basal areas is added to asymptote a in Eqn. (24) to correct the equation at the right level.

The effect of thinning on mean basal area development was assumed to last three years, this being the length of time needed for the tree to change the whole foliage. It can be argued that especially in older stands the effect might last longer. This hypothesis was tested but the present material did not support this theory. As there were only a few observations at older stand ages, the function was forced to approach zero when stands were older than 20 years of age (Fig. 19).

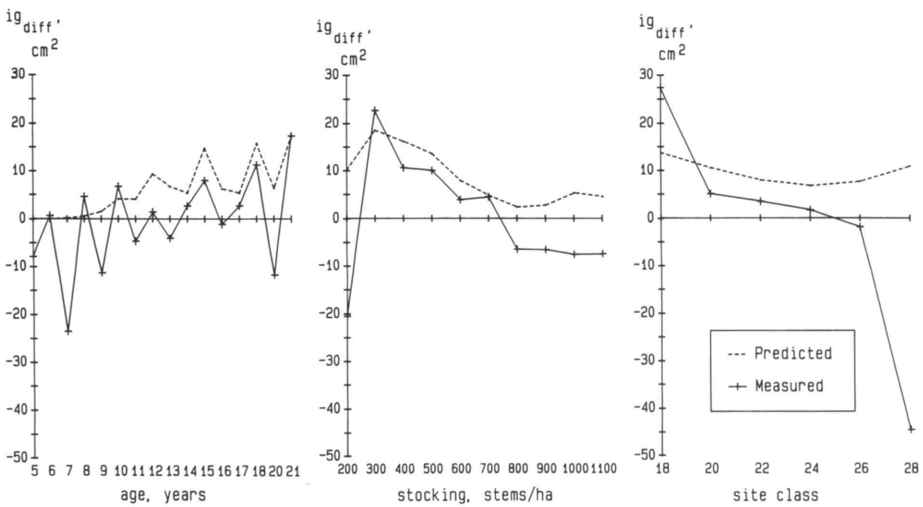

Figure 18. Comparison between predicted and measured thinning reaction.

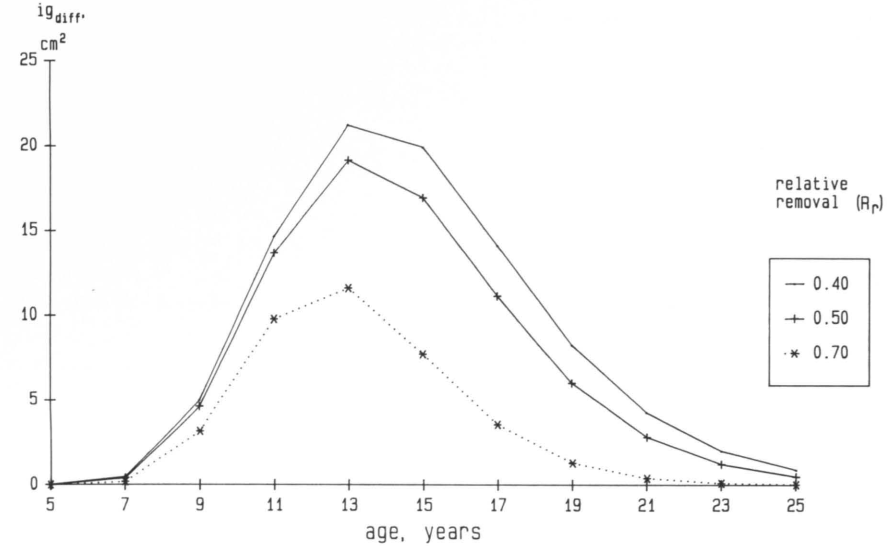

Figure 19. The shape of the thinning reaction model according to Eqns (30), (31).

The whole thinning reaction, as defined in this study, does not greatly affect the total growth within the rotation. The difference between treated and untreated stands arises mainly from differences in the growth rate at different densities.

In most thinnings there is a systematic as well as a selective component. The systematic component is a random sample from the diameter distribution and its proportion of total removal depends on the harvesting system. Thinning was assumed to be defined by the number of stems removed and by 'thinning type'. Thinning type means the ratio between mean basal area after and before thinning. If the ratio is one, thinning is random; if greater than one thinning is from below and if less than one thinning is from above. A regression equation was calculated in each case to give the relative removal from each diameter class. Because of the discrete nature of the diameter distribution, trees were removed or added to both ends of the removal in order to obtain the number of trees removed equal to the given values.

As no information was available about the rate of change of growth after thinning, the effect was set to last three years. The reaction was added to the basic curve so that mean basal area development was parallel with the original curve. When better data about thinning become available, the time taken to reach the basic curve and the shape of the approaching curve can be determined more accurately. However, the total effect can not deviate greatly from the assumed.

5.5 Tree height equations

It has been said that almost any monotonic function with positive derivative which approaches zero, when diameter increases and passes through the origin, can describe the distribution of heights (eg. Curtis 1967). For the derivation of height function the representative material from the inventory of the plantations was used (Saramäki et al. 1987). Due to the large amount of material, only a random sample of 4018 trees was selected. In this case the shape of functions was semi-logarithmic;

$$\ln(h - 1.3) = a + b/(d + 5)^2 + e$$

The final parameters of the function were:

$$a = 0.81349 \cdot \ln(T) + 0.04067 \cdot Si$$
$$b = -223.05280 + 5.97268 \cdot Si - 402.95493/T$$
$$c = 0.01227, \text{ correction due to the logarithmic transformation} \quad (32)$$

The type of function was selected according to Päivinen (1987). The standard error of estimate is 0.15665 ($n = 4018$), $s_e = 11.11$ %, and degree of determination 0.997.

If no measured information is available this function gives the best estimate of the height.

There are different ways of using existing height measurements for making height estimates more accurate. One way is to force the height curve to pass through the point defined by the mean of observed diameters and heights. This means only correcting the slope of the basic curve Eqn. (32). If a large number of height measurements are available then the normal least squares method can be used to calculate new parameters for the height curve. If the variance-covariance structure of height distributions is known, the random parameter approach (see Lappi 1986, Lappi & Bailey 1987, 1988) can be used as well. Because the model was derived from the inventory material it is a representative sample for the whole population and the needed variance-covariance structure can be calculated.

In the compartmentwise inventory which is currently going on in the ZAFFICO plantations in Zambia, only the largest tree in each sample plot is measured for height. When approximately 10 to 20 sample plots are measured in every compartment and measured trees represent the largest, the use of the ordinary least squares method is not recommended in height estimation. Both the random parameter approach method and correction of the level of basic curve method were tested using material from the compartmentwise inventory. Both methods gave equally good results. Because of the simplicity of the method based on the correction factor, the height curve was made to pass through the mean of observed heights and the corresponding diameter by only correcting the slope of the basic curve. Another reason for using the simple correction method was that height measurements are concentrated to the largest trees of the compartment.

Later, this corrected curve can either be made to approach the basic curve or to keep the difference between corrected and basic curve equal, either in absolute or relative terms. In this study the corrected curve defines the site index and later in the calculations that site index is kept constant, this in turn keeps the difference constant.

5.6 Stand models

For many practical purposes standwise estimation of growth is sufficient. Standwise models can also be used for examining predictions based on distribution.

In this study stand models were based on total volume and volume increment, both including bark. The stocking (stems/ha), age, and either site index or dominant height were assumed to be known. Stocking, if not given, was taken as the mean value of the corresponding site index and age class in the 1985 inventory (Saramäki et al. 1987). Thinnings were defined by age and the number of stems removed. As standwise models give only a rough estimate of the development, the type of thinning was taken as an average of thinnings in the permanent sample plot material. If only planting density is known, the mortality model Eqn. (28) can be used to estimate the situation at the starting point.

The model for total volume (overbark) is

$$V = \exp(3.49992 \cdot \ln(T) - 0.00674 \cdot N_a - 2.16568 \cdot \ln(N_a) + 0.59561 \cdot N_a^{0.5} + 0.10277 \cdot Si - 0.12328 \cdot T - 0.34614 \cdot \ln(Si) + 0.02522) \quad (33)$$

Degree of determination for the model is 0.998, standard error of estimate 0.22459 ($n = 951$), and $s_e = 15.98$ %.

The model for volume increment is

$$Iv = \exp(-0.60540 \cdot (\ln(T))^2 + 1.70174/(V_a \cdot T) - 0.42167 \cdot th + 0.06137 \cdot Si + 2.29363 \cdot \ln(T) + 0.04692) \quad (34)$$

The degree of determination is 0.992, standard error of estimate 0.30647 ($n = 648$), and $s_e = 21.93$ %.

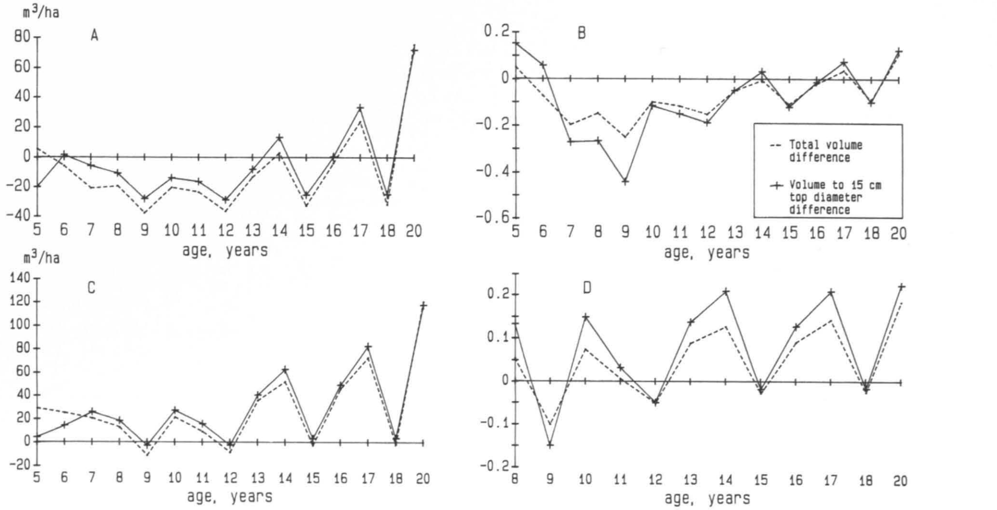

Figure 20. Absolute (A, C) and relative (B, D) differences of total volume and volume to 15 cm top diameter between measured values and those predicted by the stand models. A and B = Initial volumes measured and then Eqn. (34) used; C and D = Initial volumes predicted by Eqn. (33) and then Eqn. (34) used.

The volume of removal can be calculated from

$$V_r = -0.23741 \cdot v_m \cdot T^2 + 0.01489 \cdot N_r \cdot T + 36.70907 \cdot v_m + 453.65288 \cdot v_m \cdot thr - 76.76799 \cdot thr \quad (35)$$

Degree of determination is 0.985 and standard error of estimate 8.82634 ($n = 185$).

Apart from these volumes the amount of timber may also be needed. The volume to 15 cm top diameter (overbark) is calculated as the fraction of total volume.

$$V_{15} = V \cdot \exp(-9.71274 \cdot 10^{-6} \cdot N_a/v_m^2 + 7.10416 \cdot 10^{-9} \cdot N_a/v_m^4 + 6.89224 \cdot 10^{-5} \cdot N_a/v_m - 2.86385 \cdot 10^{-3} \cdot Si/v_m - 1.20259 \cdot 10^{-5}/v_m^4 + 1.07892 \cdot 10^{-6} \cdot T/v_m^4 + 2.42051 \cdot 10^{-7} \cdot Si/v_m^4 - 4.42949 \cdot T/v_m + 0.02001) \quad (36)$$

Degree of determination for this model is 0.970, standard error 0.20004 ($n = 951$), and $s_e = 14.22$ %.

Eqn. (19), presented in Chapter 4, can be used as a site index curve. Dominant height was taken directly from the site index curve.

The overall fit of the stand models was tested by simulating the development of permanent sample plots. The comparisons were performed in two ways. First, the initial stand characteristics (age, stocking, site index and volume) and age and number of stems removed in thinnings were given. The total production of both total volume and volume to 15 cm top diameter was compared at every measured point (Fig. 20 A, B). On average, the difference between measured and predicted volumes shows about 10 per cent overestimation, although the overestimation in relative terms diminishes with increasing age.

The same comparison was also done using given values only for age, stocking, and site index at the starting point (Fig. 20 C, D). When the initial volume is derived from Eqn. (33) the models seem to slightly underestimate total production. As Eqn. (33) underestimates the volumes of stands younger than six years, the underestimation is decreased if the simulation is started at ages above seven years. Also, in very sparsely stocked stands, the models seem to overestimate production. As expected there is a large variation in the production of timber above 15 cm top diameter during the years (7—9 y) when the first stems are reaching timber size. Although the average deviations at those age classes are not alarming, the standard deviations are large. Stand models can not describe the proportion of logs as accurately as distribution models.

6 Growth and yield simulation

6.1 Validation of the simultaion system

6.1.1 Validation against measured data

Although different submodels did not show any remarkable bias, a possibility exists that combined together the submodels may cause errors in the system. Alder (1979) used three types of validation on his model: 1) mass simulation of permanent sample plot material which contributed data to the model; 2) independent data set and 3) some detailed studies of thinning cases.

For this study the validity of the simulation system was tested in two ways. First, the difference between measured and predicted characteristics was calculated as the mean of differences of simulations starting from the first measured point and ending at the last measured point (Table 5, Appendix 2). The prediction time varied in the basic material from 7 to 16 years and in the test material from three to nine years. The system seems to slightly decrease the range of diameter distribution, however, on average, the decrease is not alarming. The tests were also made to see if the length of estimation period had any effect. The correlation between the difference in mean basal area and the length of prediction period was not significant although the mean difference increased slightly with increasing prediction period (Fig. 21). It seems probable that the length of prediction period does not cause bias.

The other test was to study how the total volume yield prediction differs from the measured one (Fig. 22). For this purpose the simulation was made from the age of the first measurement to the last measured age. The total volume yield was calculated as a sum of standing volume and removals. In the predictions, age, remaining number of stems, and type of thinning were taken from measured values. The differences were computed separately to site index classes to see if any trends exist. Average volume differences are well within one standard deviation from zero. Observations with selected sample plots did not show any clear trends, although there was considerable variation at sample plot level.

Table 5. Differences between measured and predicted values of different characteristics. Each plot is compared to prediction which start from first measurement.

Variable	Mean	Std dev	Minimum	Maximum	N
			Basic material		
Site index	−0.26	1.43	−6.70	3.20	114
%	−1.55	6.74	−35.26	12.21	114
Mean basal area (cm^2)	−26.13	62.82	−219.70	136.30	114
Mean DBH (cm)	−0.66	1.39	−4.60	2.70	114
Dominant height (m)	−0.12	1.360	−6.40	3.10	114
%e	−0.73	5.72	−28.19	11.27	114
Volume (m^3/ha)	−0.93	38.44	−121.40	104.00	114
%	−0.51	13.87	−55.76	23.39	114
Range of diameters (cm)	5.34	3.68	−6.20	13.90	114
Minimum diameter (cm)	−3.43	3.14	−11.00	4.00	114
Maximum diameter (cm)	1.91	2.50	−5.80	8.30	114
Prediction period, years	12.33	2.36	7.00	16.00	114
			Test material		
Site index	0.15	1.20	−3.40	3.80	123
%	0.30	5.21	−19.21	14.02	123
Mean basal area (cm^2)	−40.04	27.50	−136.00	32.40	123
Mean DBH (cm)	−1.05	0.70	−3.30	0.90	123
Dominant height (m)	0.16	1.13	−3.20	3.60	123
%	0.53	5.12	−17.20	14.40	123
Volume (m^3/ha)	−9.05	23.72	−70.30	53.60	123
%	−4.54	9.59	−39.31	19.69	123
Range of diameters (cm)	1.83	3.06	−10.00	12.70	123
Minimum diameter (cm)	−1.55	2.48	−8.00	9.00	123
Maximum diameter (cm)	0.28	1.59	−4.10	4.70	123
Prediction period, years	5.70	1.85	3.00	9.00	123

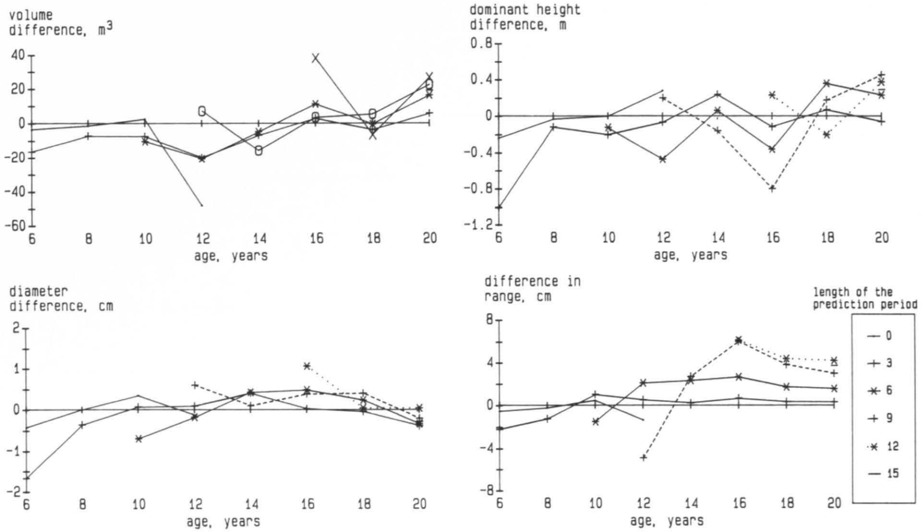

Figure 21. Dependence of standing volume, dominant height, range of distribution and mean diameter difference on stand age and the length of prediction period in the basic data.

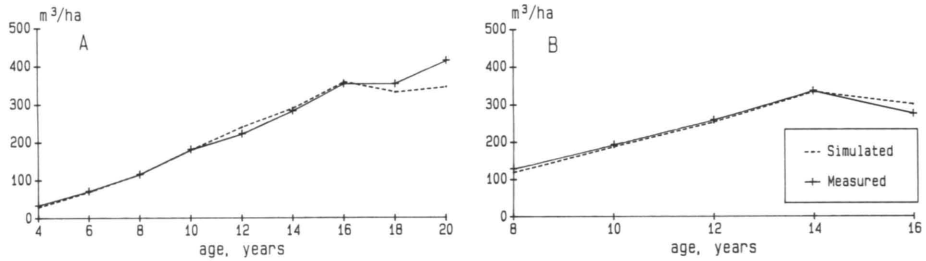

Figure 22. Comparison between simulated and measured total volume production in the basic (A) and test (B) material when simulation starts from measured values at the first assessment.

6.1.2 Sensitivity analysis

Sensitivity of the system was examined by comparing the errors in total volume production caused by errors in estimating the height and mean basal area. The real sample plot measurements were used as the starting point. Errors of ± 10, ± 20, and ± 30 % were induced in the first assessment, either in all diameters or in all heights at the age of about six years. The plot was thinned twice and had a site index of 22.

Greatest differences in stand volume occurred immediately after the production of errors in the diameters. However, towards the end of the rotation the differences diminished. Thinnings reduced the effect of errors. An error of 10 % in diameter caused in the predicted total volume, approximately an equal relative error at the end of the 25 year rotation , however, errors of 20 and 30 % altered the predicted volume production relatively less (Fig. 23). The greatest relative differences were caused to the production of large sawlogs of over 25 cm top diameter (Fig. 23 B). Underestimation of diameters caused greater differences in total volume and sawlog production than overestimation.

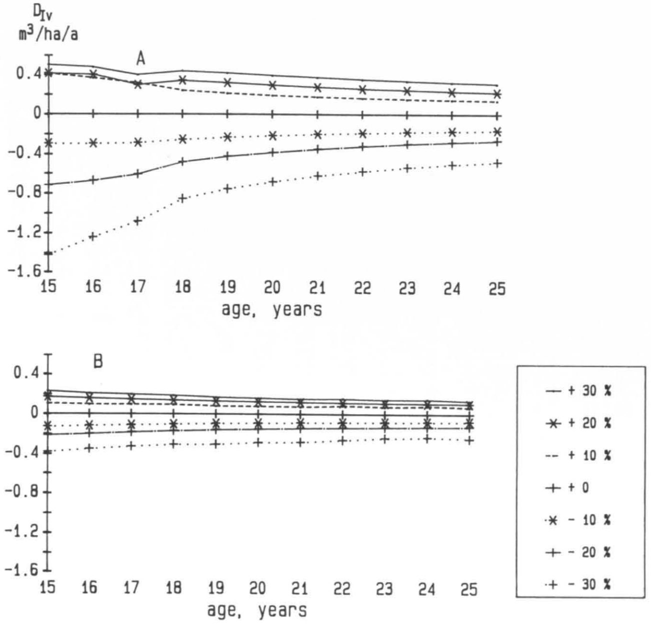

Figure 23. Relative yield differences in small (top diameter over 15 cm) (A) and large (top diameter over 25 cm) (B) sawlogs when errors of ±10 %, 20 %, 30 % are added to diameter measurements at the initial situation at the age of 6.5 years.

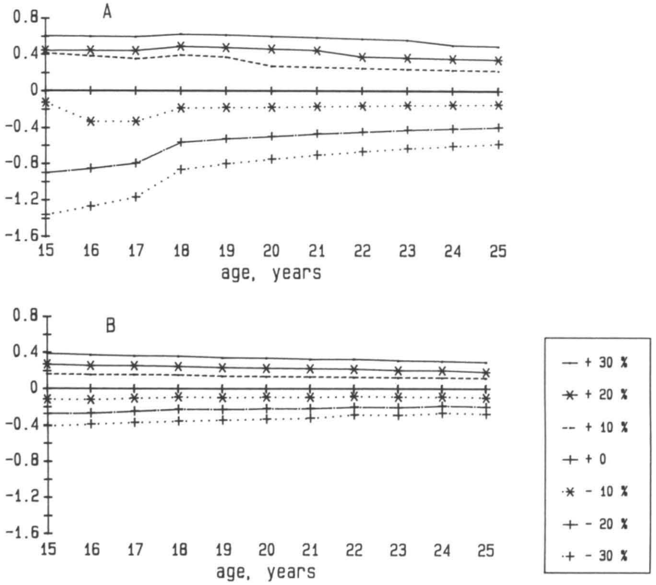

Figure 24. Relative yield differences in small (top diameter over 15 cm) (A) and large (top diameter over 25 cm) (B) sawlogs when errors of ±10 %, 20 %, 30 % are added to height measurements at the initial situation at the age of 6.5 years.

A given relative error in height produces greater differences in volume production prediction than error in diameter. Errors in height do not decrease as much with age as those in diameter (Figs. 23 and 24). Also, differences between error levels remain greater for height than compared to the diameter errors.

Height errors affect volume production in two ways: first by changing volumes directly, and second by changing the site index which affects basal area growth. Under- and overestimation of height produce almost equal relative errors in volume production (Fig. 24). Error in site class has a similar effect as the error in height.

6.2 Calculation system and initial values

For simulations a method is required to derive initial values for variables which are needed in the calculations. In the case of a planted forest stand, the initial density, time of planting and site class are assumed to be known in advance. For a new plantation there might be insufficient knowledge about the site, therefore, average site class can be used. Most growth and yield models are valid above ages of about five years. On most occasions the interest of forest planners increases with the size of trees. For simulation, early development must be predicted so that it joins smoothly with predictions where the models are valid. As very little information was available on early stand development, the decision was made that mean basal area development will follow Eqn. (24), mortality Eqn. (28), and variance above or equal to 1. The variance equation (26) was used if predictions above 1 were obtained. Skewness was predicted by Eqn. (27) using the conditions outlined in Chapter 24. Mean height development can be found from Eqn. (32). Mean basal area, variance, and skewness values were first calculated when trees reached breast height.

When density, age and site index are known the mean basal area can be predicted using Eqn. (24). Present density can be derived using Eqn. (28) and dominant height from site index by Eqn. (19). The variance and skewness of the diameter distribution are functions of density, age, site and mean basal area (see Chapter 42). Heights of trees in a certain diameter class are calculated using Eqn. (32). Having heights and diameters for all trees, volumes can be calculated using taper curve functions (Heinonen et al. 1991).

If the calculations start from measured stand values, the mean basal area development follows the model development, so that the difference is equal to the difference between measured and predicted mean basal areas at the time of measurement. Height development in the case of measured data is fixed to the measured site index. The calculation method is described in detail in the flow chart (Appendix 3).

6.3 Effects of site class, nominal density, thinnings, and rotation on the growth and yield

6.3.1 Site class

The effect of different site and management options on the growth and yield were studied to evaluate the simulation system. The following considerations are based on the assumption that all sawlog sized timber is sawable which is not the case in reality. However, the order of options remains valid.

Site fertility has a very pronounced effect on the yield. The most fertile site produces almost three times as much as the poorest site (Fig. 25) and relative differences increase when sawlog yield is examined (Fig. 25). As there are only a few plots on very fertile sites it is difficult to give an assurance whether predictions are correct. However, between the common site classes, yield differences are marked and affect the intensity and timing of thinnings as well as rotation. On the poorest sites production of large sawlogs is not possible with a reasonable rotation length. Planting density should be decreased and rotation extended, on poor sites, in order to obtain some yield of large sawlogs.

6.3.2 Nominal density

Planting density regulates the production of large sawlogs. The increase of planting density over 1300 stems/ha does not greatly increase total yield (Fig. 26).

According to the model, natural mortality increases with growing density, but the mortality as a whole is not a large portion of the total production. Differences in sawlog

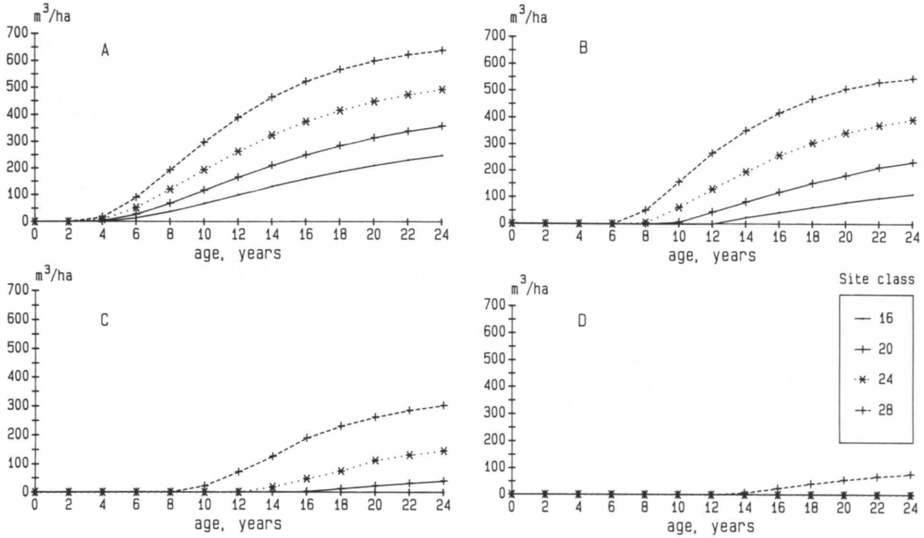

Figure 25. Effect of site class on the volume production. Stands are unthinned. Explanations: A = total volume yield, B = total yield of sawlogs over 15 cm top diameter, C = total yield of sawlogs over 20 cm top diameter, D = total yield of sawlogs over 25 cm top diameter.

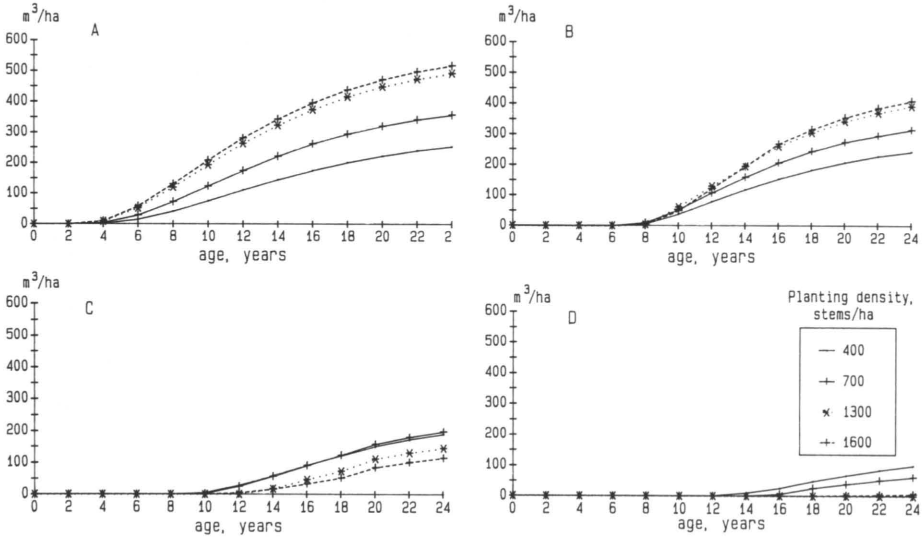

Figure 26. Effect of planting density on the volume production. Stands are unthinned. Site class 24. Explanations as in Fig. 25.

production at lower densities than 1300 stems/ha are clear and become clearer the larger the sawlogs which are examined. Density is taken into account in the model both via the mean basal area function and via variance and skewness functions. Density is also an independent variable in the mortality models.

6.3.3 Thinnings

Thinnings are the main practice by which to concentrate the growth potential of the site onto the selected trees. The effects of thinning were studied with the model by changing the timing, intensity, and type of thinning.

The start of thinnings was set to increase from seven years at three year intervals. Thinning intensity was kept constant at 45 % from stem number for every thinning. Thinnings were repeated after six years. Three thinnings in total were carried out when thinnings started at seven years of age. With the other cases only two thinnings were performed. As expected, the total volume yield was lowest with three thinnings, but large and medium sized sawlog production increased when thinnings had started early (Fig. 27). If thinnings are delayed the proportion of large sawlogs is minimal. Changing the first thinning age from 7 to 10 years already causes a clear difference in the sawlog production.

The effect of thinning intensity was studied by changing the removal percentage. The comparison was made between the thinning intensities of 30 %, 45 %, and 60 %. Thinnings were repeated at six year intervals as before. If thinnings start at an early age differences between thinning intensities become quite large (Fig. 28 A-D). Volume of thinnings at older ages does not greatly affect the production (Fig. 28 E-H). Late thinnings keep the total amount of large sawlogs low (Fig. 29). Light thinnings, if started early, produce a large amount of small sized sawlogs. The greatest amount of small sized sawlogs is produced when thinnings are delayed.

The effect of thinning type was studied by removing an equal number of stems either from below or above so that the thinning ratio (see chapter 4.4) changed from 1.4 to 0.6. The diameter distribution was such that in thinning ratios 1.4 and 1.2 and 0.6 and 0.8 respectively, the thinning removal was equal. In ordinary thinnings the ratio varies between 1.2 and 0.8.

Thinning type has only a minor effect on the total volume yield, but the production of larger sawlogs is strongly affected by the way thinnings are executed (Fig. 30). Thinning from above causes losses in the yield of the largest sawlogs. On the other hand, in site class 20, random thinning or mechanical thinning does not result in great differences in the yield of largest sawlogs compared to thinning from below. However, in site class 24 differences are notable.

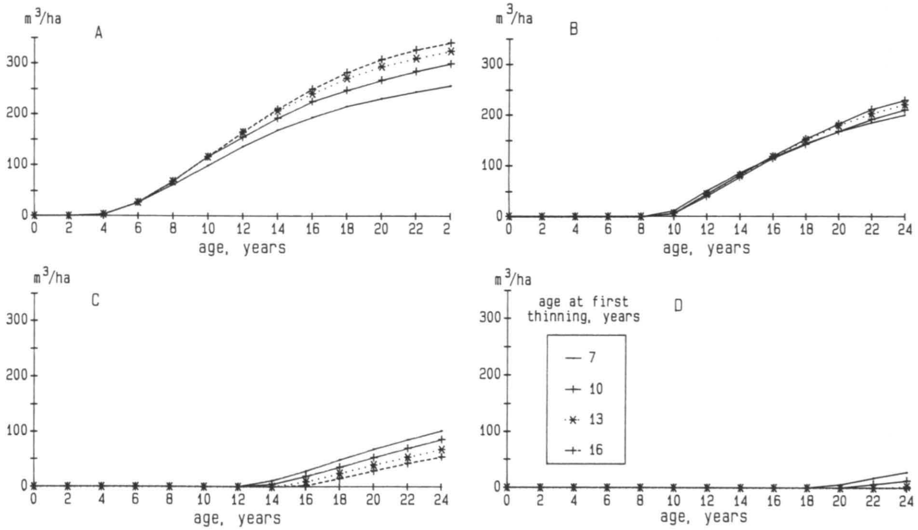

Figure 27. Effect of timing of first thinning on the volume production. Thinning removal was 45 % of the number of stems. Three thinnings are carried out if thinning starts at 7 years, otherwise there are two thinnings. Site class is 24. For other explanations see Fig. 25.

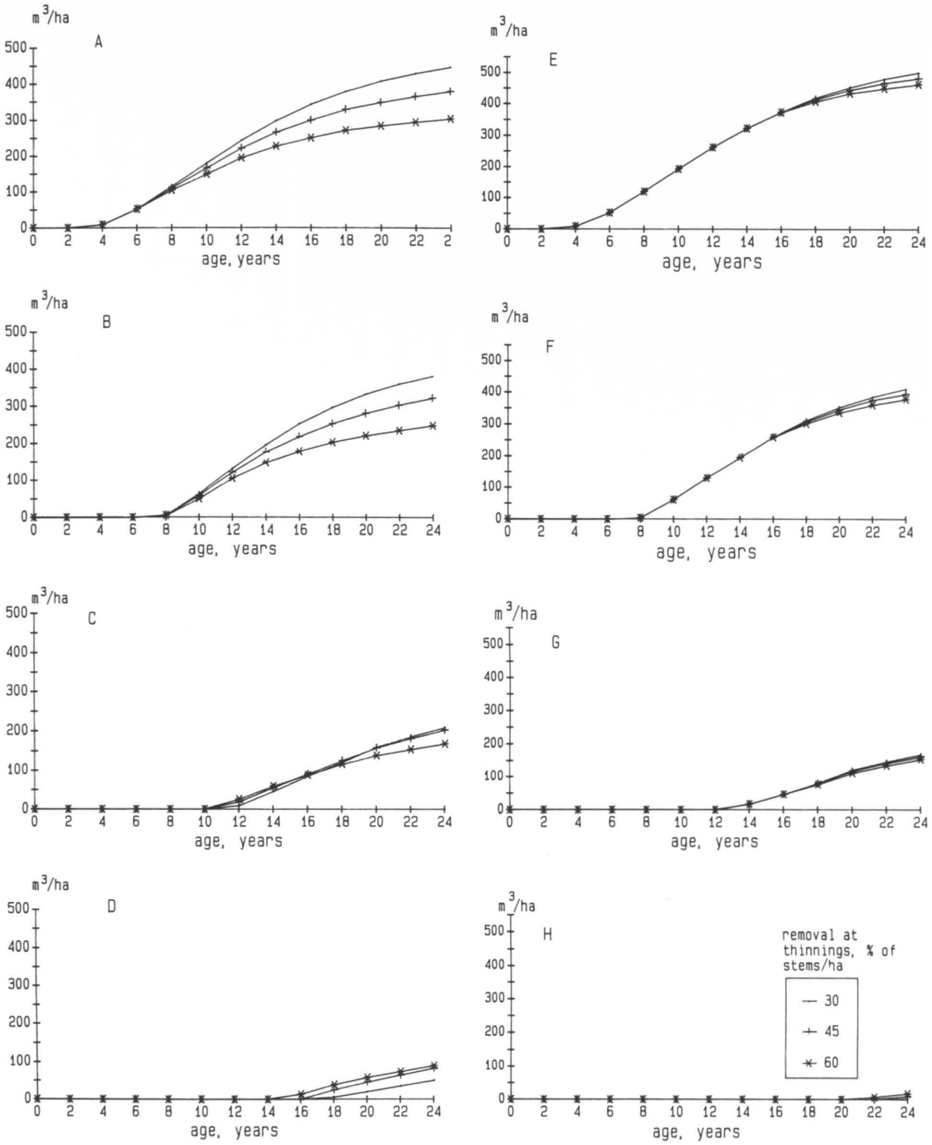

Figure 28. Volume production when first thinning is conducted at the age of seven years (A, B, C, D) or at the age of 16 years (E, F, G, H) and the intensity of thinning changes. Three thinnings occur in the first case and two in the second. Site class is 24. Explanations: A,E = total volume yield, B,F = total yield of sawlogs over 15 cm top diameter, C,G = total yield of sawlogs over 20 cm top diameter, D,H = total yield of sawlogs over 25 cm top diameter.

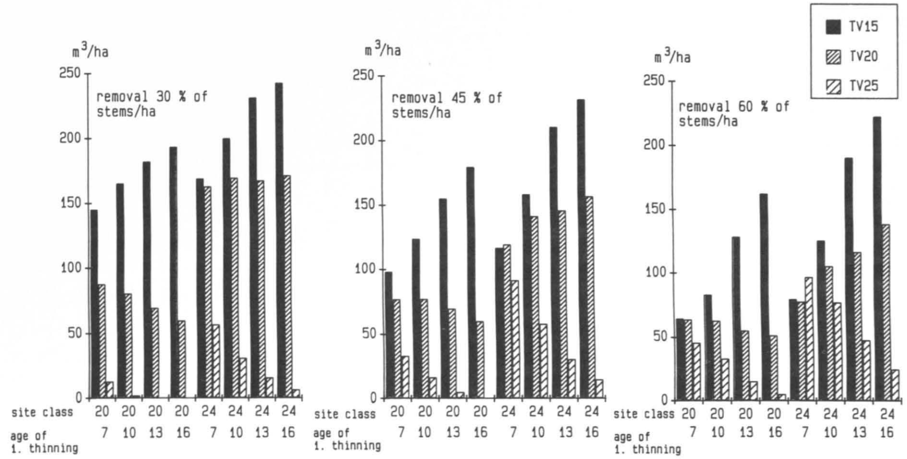

Figure 29. Production of different sized sawlogs with 25 year rotation at different site classes and with different thinning intensities. Three thinnings are carried out if thinning starts at 7 years, otherwise there are two thinnings. Explanations: TV15 = yield of sawlogs with top diameter between 15 and 19.9 cm, m^3/ha, TV20 = yield of sawlogs with top diameter between 20 and 24.9 cm , m^3/ha, TV25 = yield of sawlogs with top diameter over 24.9 cm, m^3/ha.

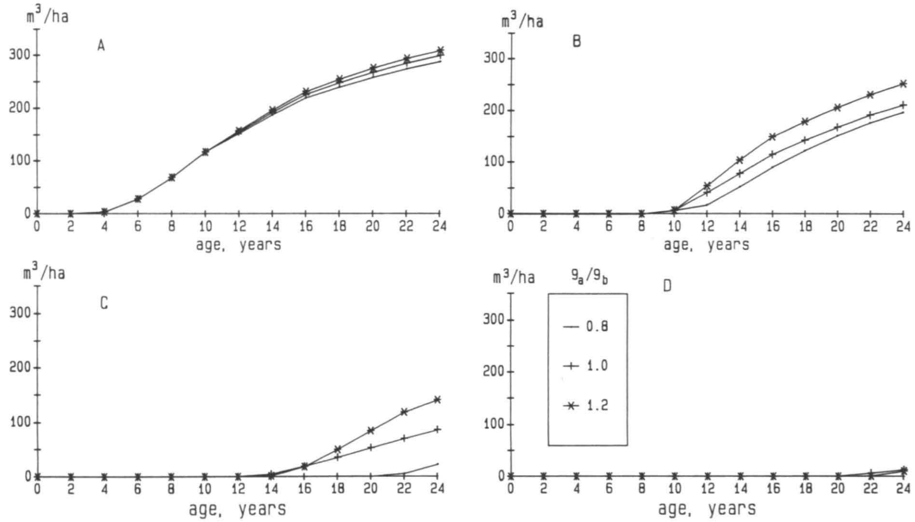

Figure 30. Effect of thinning type on the volume production. Thinning removal is 45 % of the number of stems, site class is 20, and two thinnings: first at 10 and the second at 16 years of age. Thinning type (g_a/g_b) is the ratio of mean basal areas before and after thinning. For other explanations see Fig. 25.

6.3.4 Rotation

The effect of rotation was studied by examining mean annual and total yields of medium (top diameter over 20 cm) and large (top diameter over 25 cm) sized sawlogs at different sites and using different thinning regimes. In all cases the planting density was 1300 stems/ha and the type of thinning systematic (Table 6).

On poor sites, the mean production of medium and large sawlogs increases with age in every thinning regime (Fig. 31). On the best sites, the mean annual yield of large sawlogs peaks at 30 years of age if the first thinning has been conducted before 10 years of age. If the first thinning is delayed beyond 14 years of age, the maximun mean yield of large sawlogs increases to the age of 35 years. On the best sites, the maximum mean annual production of medium sized sawlogs is almost independent of thinning regime and peaks between 20 and 25 years (Fig. 31). The earlier the thinnings are commenced the shorter the rotation can be, where the maximum production of medium and large sawlog is concerned. The best of the studied thinning regimes shows that the mean annual production of small (top diameter over 15 cm) sawlogs reaches a maximum on the best site before 20 years, on the medium site at about 20 years and on the poor site at about 25 years. The respective ages for medium sized sawlogs are 25, 25, 30 years and for large sawlogs 30, 35, and over 35 years.

Total volume production is greater the longer the rotation and the better the site. On poor sites, the production of large sawlogs is low even with the longest examined rotation and the best thinning regime, and form only 31 % or 69 m^3 of the total production. On the best sites, the respective figures are 24 % and 88 m^3 already at the 20 year rotation.

Marked differences are also seen between thinning regimes (Fig. 32). If the first thinning is delayed till 16 years of age the relative yields of large sawlogs are reduced to one third of that of the best regime. Omitting the first precommercial thinning (thinning regime 2) and then thinning heavily at 10 years, causes on poor sites with a 35 year rotation, about 10 % reduction in the large sawlog yield and about 5 % reduction in the medium sawlog yield. On average sites with a 25 year rotation reductions are 70 % for large sawlogs and 30 % for medium sawlogs, and on the best sites 55 % and 9 % respectively.

Table 6. Thinning regimes used in studying the effect of the length of rotation.

No	1st thinning Age	1st thinning Stems remaining	2nd thinning Age	2nd thinning Stems remaining	3rd thinning Age	3rd thinning Stems remaining
1	10	400	16	200	—	—
2	16	400	20	200	—	—
3	14	400	18	200	—	—
4	6	800	10	400	16	200

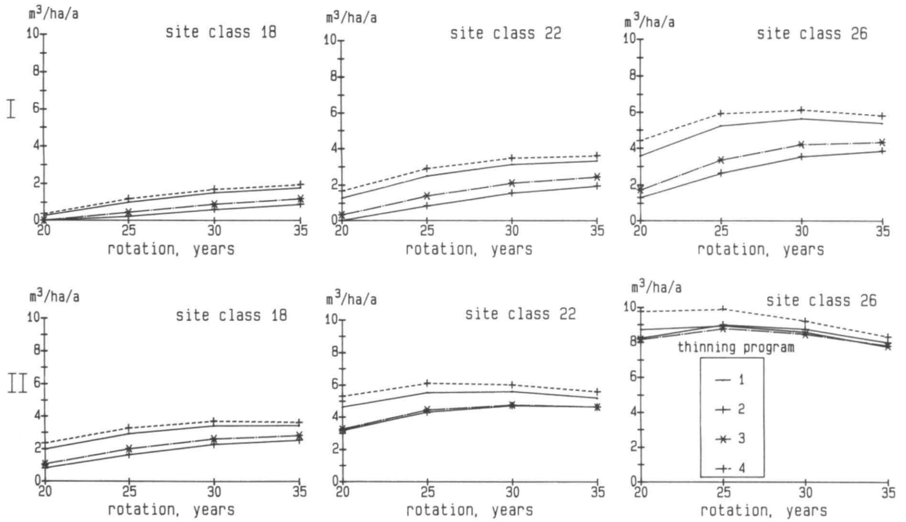

Figure 31. Effect of rotation length and thinning program on the mean annual sawlog production in different site classes. Thinning programs are presented in Table 6. Thinning type is random (g_a/g_b = 1.0) Explanations: I = mean annual production of sawlogs over 25 cm top diameter, II = mean annual production of sawlogs over 20 cm top diameter.

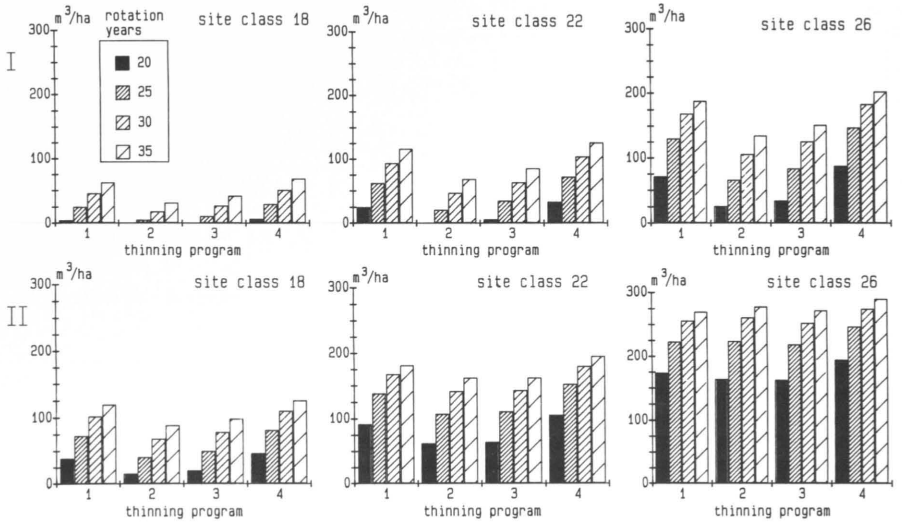

Figure 32. Effect of rotation length and thinning program on total sawlog production in different site classes. Thinning programs are presented in Table 6. Thinning type is random (g_b/g_a = 1.0). I = yield of sawlogs with top diameter over 25 cm. II = yield of sawlogs with top diameter over 20 cm.

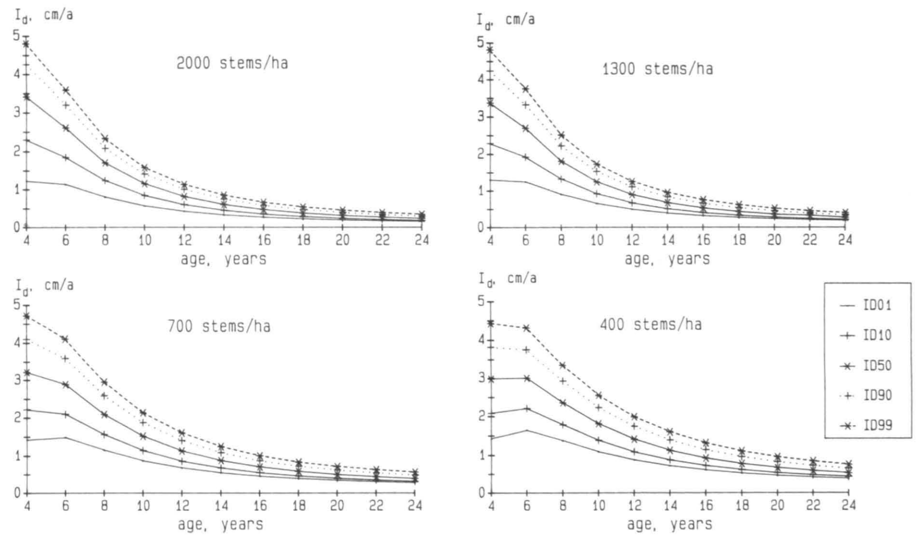

Figure 33. Development of the diameter increment in different parts of diameter distribution. Site class is 22. Explanations: ID01 = 1 %, ID10 = 10 %, ID50 = 50 %, ID90 = 90 %, and ID99 = 99 % percentage point of diameter distribution.

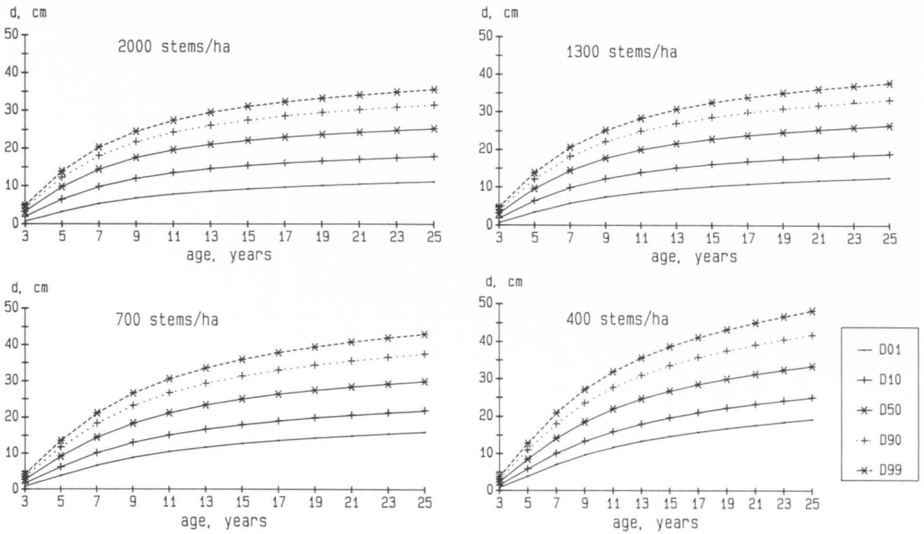

Figure 34. Development of diameter with different stocking. Site class is 22. Explanations: D01 = 1 %, D10 = 10 %, D50 = 50 %, D90 = 90 %, D99 = 99 % percentage point .

6.3.5 Distribution of diameter increment

The model makes some statements about the diameter increment in different parts of the diameter distribution. The reality of these statements was verified by producing distributions of diameter increment over age (Fig. 33). Furthermore, diameter distributions were created in the same way (Fig. 34).

The maximun annual diameter increment has already been passed at the age of five years, although at the lower densities trees are still growing at a maximum rate. At young ages the largest trees grow almost as well independently of stocking, but the smallest trees grow better the lower the stocking (Fig. 33). When stands get older increments in all parts of distribution increase with decreasing density.

The variation of increment is largest when the annual growth reaches maximum and then diminishes with age (Fig. 33). The range of variation of diameter increment is larger the higher the density in young stands and vica versa in old ones (eg. Fig. 33). On fertile sites, the range of increment is wider than on poor sites. The range of increment diminishes quite fast with age. In older stands the variation of increments almost levels out.

7 Discussion

General

The first aim of the study was to be able to use measured information to increase the accuracy of the predictions. Both stand and tree level information can be used in adjusting the predicted values, although the exact increase in accuracy can not be verified. The differences in height and diameter cause approximately equal difference in relative total and sawlog volume yield at the end of rotation if fixing of diameters is done at the age of about 6 years.

The inclusion of measured data provides more reliable estimates for short term

prediction. It is not known for how long the assumption of constant percentage point holds. After thinning the diameter distribution changes and causes also temporary irregularities in growth. In operational use it is recommended to measure diameter distribution after thinning and avoid the problems of increment prediction over thinning time. Thinning reaction is inadequately studied and needs more attention. The method used in this study, where thinning reaction is defined as deviation from the growth rate of an unthinned stand with the same stocking, seems to provide a good possibility for predicting total increment after thinning. The thinning reaction is only a small fraction of the total increment after thinning. The possible error remains small in all cases.

On the other hand, the predictions start unbiased if the starting age is over 5 years and apart from age, site class and stocking are known. If only planting density is known, the predictions are on the average unbiased but the variation of predictions is quite great due to variation in mortality. The measurement of actual stocking improves the precision of the predictions considerably. When simulating the development for the whole rotation, the seedling stage is adjusted so that it joins smoothly to the predictions at the age of 5 years. The early years of development are inadequate and need more research.

Although thinning reaction is not fully described in the study material, the simulation system makes it possible to simulate a large range of thinning regimes. The system as such allows both thinnings from above and below as well as systematic thinnings, but the data does not include thinnings from above. However, the model seems to work logically also in thinnings from above. The effects of thinning time, number of thinnings and thinning type can be studied with the system. The effect of the length of rotation can as well be studied. As the submodels in system are based on observations of less than 25 years of age, the results of simulations over the mentioned age must be examined with care.

The simulation system is built using standard programming language and it works in microcomputers with DOS-operating system. The system has an interactive version for studying the effects of different thinning regimes. For updating inventory data a special linking programme has been built.

For management purposes, the size distribution of trees is sufficient in most occasions. However, management also needs quality distribution. Quality distribution is quite difficult to model mathematically (see Smith et al. 1986) and to date it has been based on subjective classification (eg. Saramäki et.al. 1987) or on measurements of the length of clean bole or thickness of branches (eg. Uusvaara 1974, Kärkkäinen 1980), however, the length of the clean bole has no great explanatory value in pruned plantations. Temporal change of quality is even more difficult to predict. In plantations where records on pruning height are available, some estimates of the pruned proportion can be made. In this study quality was not predicted.

As the whole inventory material was used in the estimation of the parameters of the mean basal area and variance and skewness models, the models represent the present plantation conditions well. The new generation will be planted using improved seedlings from seed orchard seed. It is questionable how well the used functions can describe the development of these new generations.

The thinning and mortality functions had to be based on permanent sample plot material, however, this produced quite a representative result. As the observations in the thinning and mortality data are autocorrelated their error structure cannot be fully described. However, the data give unbiased and best estimates of the development.

Site classification

Site classification is always one of the key questions in plantation forestry, where little is known about the site potential before plantation establishment. Furthermore, the rate at which exotic species will deplete nutrient stores causes difficulties in obtaining a reliable site classification. This is because previous tree generation does not necessarily describe the present stand potential. Some soil characteristics have been used to predict site potential (The Industrial... 1969, Saramäki et al. 1987), but the variation found in site potential for one soil type is large. Site classification based on dominant height development was used in this study despite it being a weak predictor for successive tree generations (e.g. Kaumi 1983). It is not known to what extent the present site index curves can be used during the next generation. If these site curves will be used, further studies are needed about the stability of the site class during successive generations.

Mean basal area

The method of using mean basal area development as one of the basic equations in the simulation model, guarantees that stand level results remain within reasonable limits. The modified Schumacher equation as the base function was selected on the basis of its simplicity and analytically clear form. More flexible functions are available and can be used for the growth estimation (see Leech & Ferguson 1981). However, the advantages of these functions are not clear, while the Schumacher equation has been successfully used in growth and yield studies of tropical plantations (Alder 1980). Having only three parameters, the Schumacher function cannot exactly follow all growth patterns. Especially during the most accelerated increment period some bias can be found due to the inflexibility of the function.

Diameter distribution

The system for recovering the parameters of the Weibull function resembles that of Knoebel et al. (1986). Instead of using arithmetic mean diameter, mean basal area and minimum diameter, this study used mean basal area, variance and skewness for recovering parameters. In many studies (Kilkki & Päivinen 1986; Kilkki et al. 1989) the parameters have recovered by directly predicting the parameters with regression equations. By using the method of moments, common stand level forestry characteristics can be used in the recovery process.

The system used in the present study does not restrict the lower limit of the distribution from going below zero. As this study predicted the Weibull function from stand characteristics, only the minimum value could be verified. The simulation system starts from 5 years of age and negative values do not occur after this age in practice. In the case of starting from measured values, real diameters are fixed to the predicted Weibull function which does not cause any problems.

The equations for variance and skewness are simple. They cannot describe all the conditions found in the plantations, but on average they seem to give unbiased estimates. At the age class level, the estimates are still reasonably accurate and unbiased. If extreme treatments are used in the stands, the effects of the treatments can be estimated by fixing the measured percentage points to the predicted Weibull function and keeping the points constant to the end of the rotation. The form of the functions guarantees an assured behaviour of diameter increment in different parts of the diameter distribution.

Thinnings

Thinnings are simulated using quite a simple method. If simulated thinning types and intensities deviate greatly from practice, the output from simulations can be misleading especially where sawlog production is concerned. Thinning effect may also have been inadequately modelled, however, the influence on total yield is very small. Another practice would have been to use separate parameters after each thinning as presented in Knoebel et al. (1986). However, this requires many more equations and the whole variation in inventory material could not have been used. Although previous studies have experiences of the effect of thinning on height growth (eg. Saramäki & Silander 1982; Harrington & Reukema 1983) no corrections were made to the predicted height growth in this study. It was assumed that in ordinary thinnings the effect is small, causing no need for correction.

Most part of the increase in growth after thinning can be explained by changing stocking or density, nevertheless, detailed information of the type of thinning requires tree level data. By carefully selecting the tree increment function compatibility with the distribution level function (Daniels & Burkhart 1988) can be made. In tropical plantations the modelling of thinning reaction also requires annually measured data material, which was not available in this study.

Pukkala et al. (1990) define thinning removal in different diameter classes by removing a decreasing or increasing proportion from neighbouring diameter classes. The change in proportion defines the type of thinning. The specified thinning intensity is found iteratively. Knoebel et al. (1986) specified that a function estimates the amount of basal area to be removed from each diameter class. Parameters of the function were derived from empirical data and as such are dependent on the base material. The method used in this study is independent of the data and is a modification of the method of Pukkala et al. (1990). The method makes it possible to simulate both thinning from above and thinning from below as well as systematic thinning. It also guarantees that no contradiction exists between the diameter distributions before and after thinning. In many thinnings there is also a systematic portion. This can also be taken into account in the present system by defining in the thinning situation, the proportion of the systematic part which is removed first. The used system itself also allows extreme thinning types, but the mean basal area, variance, and skewness functions may cause bias in the predictions.

Mortality

Mortality, even though it forms a minor part of the yield in managed stands, has to be considered in simulation systems. To simplify the mortality process, the process was assumed to start after every thinning in the same way as from establishment, however, the rate of change was a little different. This might be an over-simplification but for material used in this study the assumption was valid. Mortality could also have been modelled with the Weibull distribution as Somers et al. (1980) propose. The use of Weibull function does not offer many advantages over the used regression model which is a stable monotonic function of time and density. The distribution of dead trees was treated in the same way as that of removal. When the mean size of dead trees is known, the same ratio as for the thinning type can be calculated and the same procedure used to remove trees from the distribution. An almost random distribution of dying trees in older treated stands was found in the model. Because there were no old untreated stands in which planting density was low, the validity of the model in this instance cannot be confirmed.

8 Conclusions

8.1 General

Management of tree plantations needs information on the development of stands as there is need to have updated data on stand condition. If the system is fully operational there will be a continuous forest inventory going on all the time. When a stand is thinned it will also be measured and this information replaces the old before-thinning information. By doing so no prediction about thinning removals in updating is needed and a continuous flow of measured information is available to make knowledge about the state of the forest more reliable. An ideal continuous inventory system would measure every stand only when the stand has stabilized after planting and subsequently after every thinning. The simulation system would take care of the rest.

The developed system provides a useful tool for the forest planner to compare future outputs from different thinning regimes. It also provides a means for utilizing existing inventory information in an efficient way by allowing updating of old inventory data and use of modern forest management planning methods. The system has been developed jointly with compartmentwise inventory methodology (Saramäki & Sekeli 1988) and together they form a continuous forest inventory system.

At present the simulation model is valid from the age of five years. If necessary, the early development of seedling stands can also be modelled using data from the planned seedling stand inventory (Saramäki 1988).

When new plantations of exotic species are planned, the future requirements of growth and yield information can and must be considered already in the beginning of the planning process. For reliable growth and yield prediction the following data material requirements must be met:

1) espacement trials to give information on the effect of initial stocking;
2) progeny trials to find out differences in the productivity and quality between seed sources;
3) thinning trials to predict the possible thinning reaction;
4) tree volume or taper curve equations for volume estimation; and
5) permanent sample plot network in the plantations to calibrate the yield figures at the right level.

Espacement, progeny, and thinning trials should be established so that most of the existing sites in the plantations are covered as interactions between site, spacing, and progeny (see eg. Zobel & van Buijtenen 1989) are known to occur. These trials should be established using the best available knowledge before large scale plantation establishment begins. When information from trials is gathered, the plantation establishment practices and seed sources can be changed according to the results. When the plantations get older growth and yield figures become more accurate.

8.2 Production possibilities of *P. kesiya* in Zambia

8.2.1 Treatment selection

The production possibilities of *P. kesiya* are examined using the developed models. The used rotation lengths are not based on economic calculations. If economic reasons are used for defining rotations, the used rate of interest would then play a decisive role. Furthermore, the rotation lengths could not be based on growing costs and incomes as they were not available in this study. The same applies to the selection of thinning regimes.

The plantations have an excess of small wood and a shortage of sawlogs — especially good quality sawlogs. The plantations have been established with the aim of producing raw material for both saw mills and the production of pulp and paper (The Industrial ... 1969). As there has been no market for small wood, apart from a small portion going to particle board and match manufacturing, most thinnings have been omitted (Saramäki et al. 1987). There is a need to study treatments where the sawlog proportion is as great as possible. Furthermore, studies on the effects of delayed thinning on the sawlog production are also needed. Plans are being made to start building a pulp mill in Zambia. For this reason it is also useful to study separate growing regimes for pulp wood and sawlog production. As *P. kesiya* stands need to be pruned to obtain first class sawn timber, the original planting density has little effect on the quality of the final product.

In order to achieve rapid tree growth the original density should be quite low. As nearly all *P. kesiya* plantations have been established with a 2.75 x 2.75 m spacing, the only possibility to maintain low level competition between trees is by means of heavy early — precommercial thinnings.

One growing regime to be studied has the first thinning already at an age of between five and seven years. The second thinning should be carried out between 11 and 15 years of age. At present, it is not economically feasible to thin more than twice during the rotation. Unfortunately, no information on heavy early thinnings is included in the data and the validity of the simulation results can not, thus, be guaranteed.

Delayed thinnings are common in the plantations. Thus, first thinning was set to take place between 10 and 18 years of age. The second thinning was planned to follow five to six years after this. Within this option an extented rotation was also studied, even though no inclusion of old stands is presented in the data.

The third option also includes the recommended old thinning regime where the first thinning is set at the age of 7 years, the second at 12 and third at 18 years of age. The present recommendation is that the first thinning should be at 7 years and the second one between the ages of 14 and 16 years.

As the mean site index for the whole plantation is 20, this was used as site index as well as site index 24 to represent the better sites. Only one planting density, 1330 stems/ha is used. Thinning programs are presented in Table 7.

Table 7. Examined old thinning programmes.

No	Age of thinning, years	Stems/ha remaining
1	10	720
	14	450
	18	220
	25	0
2	13	450
	20	220
	25	0
3	14	450
	18	220
	25	0
4	11	500
	18	300
	25	0
5	13	720
	18	450
	23	220
	30	0
6	6	720
	15	500
	22	250
	30	0
7	6	720
	14	450
	18	220
	25	0
8	6	720
	14	400
	25	0

8.2.2 Proposed thinning regimes for P. kesiya

The mean annual production of large sawlogs, which are the main product from the plantations, is still increasing at the age of 25 years (Fig. 35). This is presently used as the clear felling age. The total production of sawlogs of any size is greatest when thinnings start early (Fig. 36), although differences between regimes are not marked . If thinnings are delayed the proportion of small sawlogs increases compared to the proportion of large sawlogs. If the main aim of growing is maximizing the production of sawlogs over 20 cm top diameter, the rotation should be, on fertile sites, about 25 years, but on poorer sites the rotation should be extended to about 30 years. If the aim is to produce sawlogs larger than 25 cm top diameter the rotation should be extended even further by about five years. Early thinnings are clearly better for sawlog production than late ones.

Planting density could be decreased to avoid the first precommercial thinning. Decrease in planting density is more important on poorer sites. Even in the average site class it is uncertain with the present stocking whether sawlogs of over 25 cm top diameter can be produced. If the first thinning is delayed to ages over 13 years, only a small chance exists of obtaining sawlogs of over 25 cm top diameter using the 25 year rotation. Thinning reaction after 13 years of age is weak and different thinning regimes do not deviate greatly from each other (Fig. 37). If large logs are desired thinnings must be very heavy. The risk of wind damage increases when previously unthinned stands are heavily thinned. To prevent the area of delayed thinnings from increasing in the future, logging should concentrate on younger plantation areas where operations can be performed at the right time.

For sawlog production separate thinning regimes should be available for fertile (site index 24 and above), average (site index between 20 and 24), and poor (site index less than 20) sites. Planting density should be decreased to about 800 stems/ha on fertile and average sites. In areas already planted at 1330 stems/ha, precommercial thinning should be conducted to 700—800 stems/ha stocking at the age of 5—7 years. No losses in large sawlog production will be encounted if respacing is done at the right time. The only difference compared to 1330 stems/ha planting density is on the need of silvicultural operations at establishment and soon thereafter. On poor sites, planting density could even be 600—700 stems/ha.

Only two thinnings should be carried out, the first being at the age of 10—12 years and the second at the age of 15—18 years. In both thinnings about 50 % of stems are selectively removed leaving the final stocking at about 200 stems/ha. On poor sites, the final stocking could be even less than 200. On fertile sites, the ages of 10 and 15 years are used and on poor ones the ages of 12 and 18 years. On poor and average sites, the first ordinary thinning mainly produces pulpwood while on fertile sites small sawlogs are

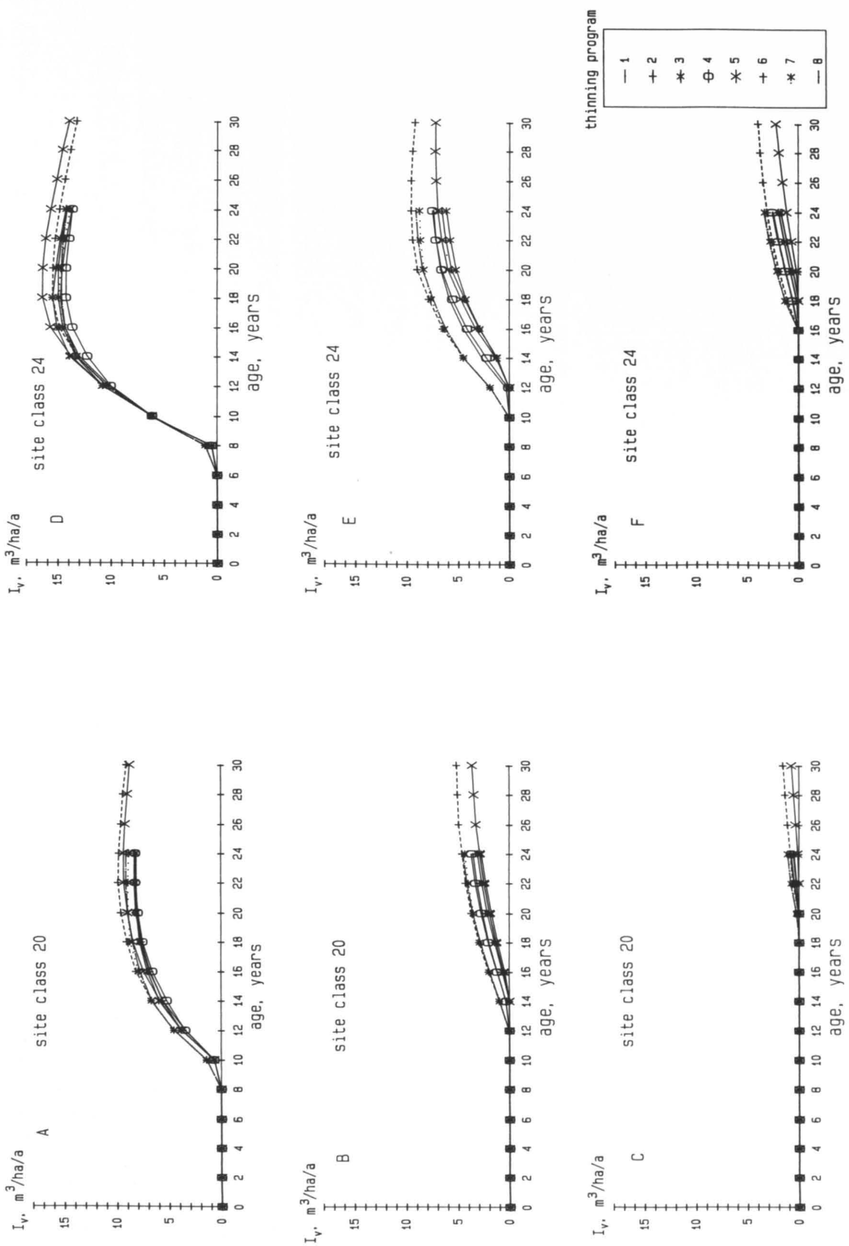

Figure 35. Development of mean annual yield of different sized sawlogs in site classes 20 and 24 in thinning programmes used and proposed in Zambia. Thinning programmes are presented in Table 7. Explanations: A,D = mean annual production of sawlogs of over 15 cm top diameter, m³/ha/a, B,E = mean annual production of sawlogs of over 20 cm top diameter, m³/ha/a, C,F = mean annual production of sawlogs of over 25 cm top diameter, m³/ha/a.

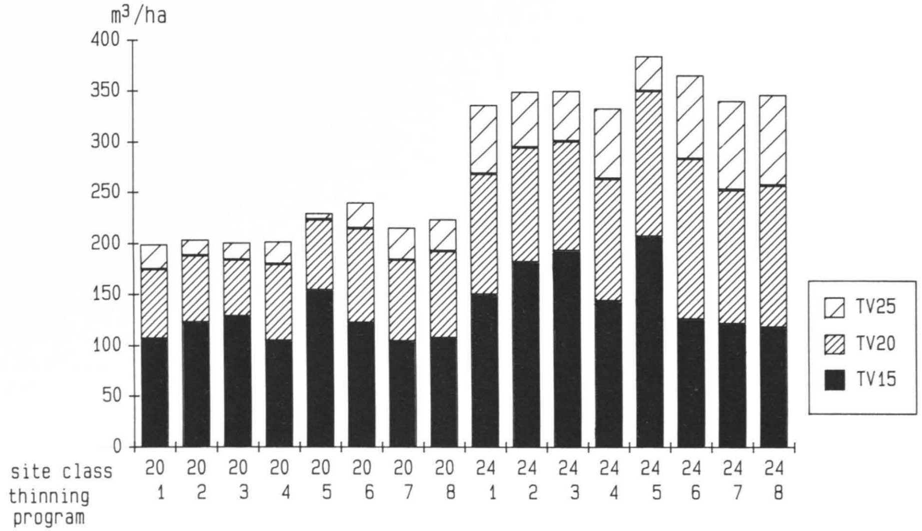

Figure 36. Total production of different sized sawlogs in site classes 20 and 24 and in thinning programs used and proposed in Zambia. Rotation 25 years. Thinning programs are presented in Table 7. For other explanations see Fig. 29.

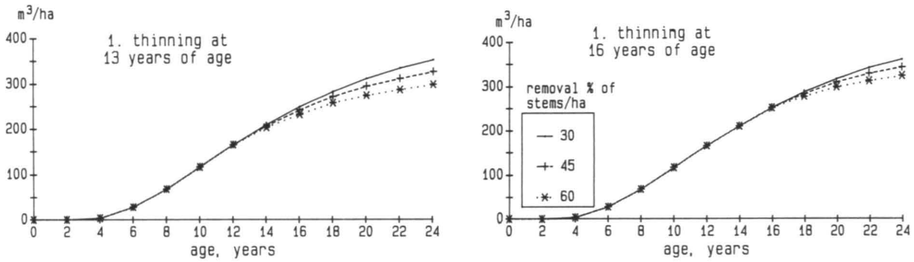

Figure 37. The effect of thinning intensity on the total volume production when thinnings are started late. Site class is 20; two thinnings at six years intervals.

produced. The main products of the second thinning are small and medium sized sawlogs. Large sawlogs are almost solely obtained from the final felling. As a whole, on poor sites about 40 % of the total yield is taken in thinnings. On fertile sites the respective portion is about 50 %.

On the basis of sawlog production a rotation period of 25 years is enough on fertile sites, while on average sites 28—30 years rotation seems suitable, and on poor sites 30—35 year rotation should be used (Fig. 38). These rotations approximately maximize the mean annual yield of large and medium sized sawlogs. Present signs show that an even longer rotation could maximize the mean annual yield of large sawlogs, but as the data used for the model estimation does not cover such old ages as needed, the conclusions cannot be verified.

If pulpwood production is the main aim of growing trees, thinnings do not seem necessary because the increase of utilizable timber by thinning is very small if any. Furthermore, the effect of natural mortality does not cause great losses. The rotation can be considerably shortened compared to the regime for sawlog production. To maximize the mean annual

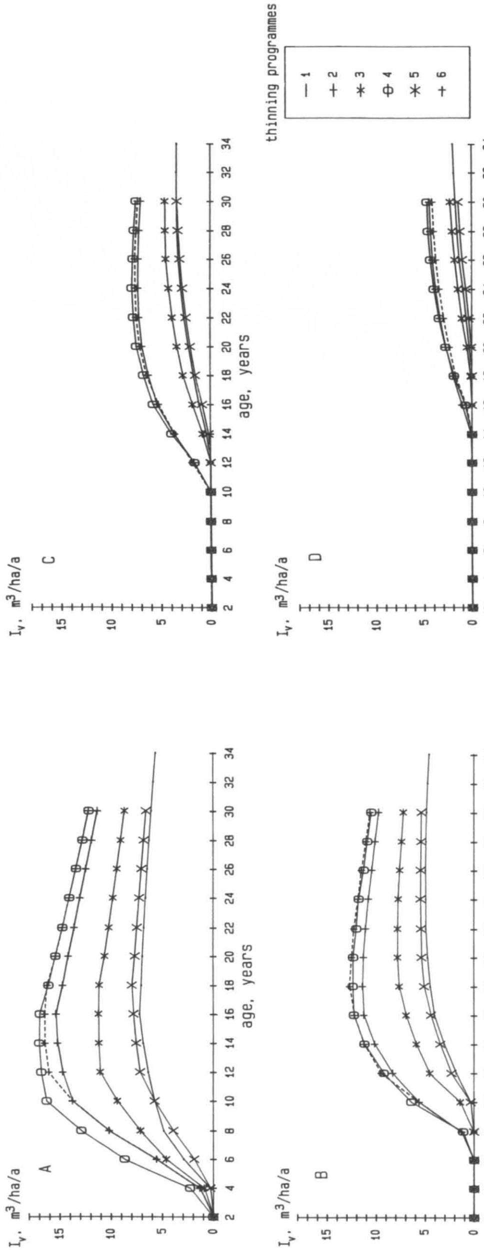

Figure 38. Development of mean annual production of total volume and different sized sawlogs in some thinning regimes recommended for Zambian plantations. Thinning removals 50 % of stems/ha at each thinning apart from precommercial thinnings. Thinning regimes are explained in Table 8. Explanations: A = mean annual volume increment, B = mean annual increment of sawlogs over 15 cm top diameter, C = mean annual increment of sawlogs over 20 cm top diameter, D = mean annual increment of sawlogs over 25 cm top diameter.

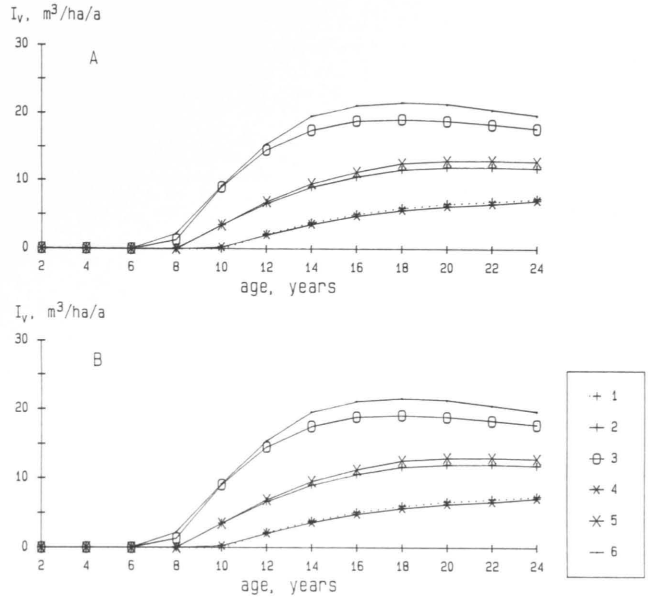

Figure 39. Development of mean annual total volume (A) and small (top diameter over 15 cm) sawlog (B) production by site class and planting density. No thinnings. Explanations: 1 = site class 18, nominal stocking 900 stems/ha, 2 = 22, 900 stems/ha, 3 = 26, 900 stems/ha, 4 = 18, 1300 stems/ha, 5 = 22, 1300 stems/ha, 6 = 26, 1300 stems/ha.

yield on fertile sites the rotation can be 15—18 years, on medium sites 18—20 years, and on poor sites 20—23 years (Fig. 39). Planting density changes the portion of natural deaths (Fig. 40) and the mean size of trees. Increasing planting density above 1300 stems/ha only minimally increases production (Fig. 41). Nominal densities less than 900 stems/ha decrease production so much that they are not recommended. To be effective, logging needs as large trees as possible. Minimum average stem size has often been set for economical reasons. This size depends on the method used in logging.

Table 8. Recommended growing regimes.

No	Site class	Planting density	1st thinning Age	Stems/ha remaining	2nd thinning Age	Stems/ha remaining	3rd thinning Age	Stems/ha remaining
1	18	700	10	350	16	175	—	—
2	24	800	10	400	16	200	—	—
3	20	1330	6	750	12	350	18	175
4	24	1330	6	800	10	400	16	200
5	18	700	12	350	18	175	—	—
6	24	800	12	400	18	200	—	—

If the minimum size is exceeded at 15 years when stocking is 900 stems/ha, the same limit is exceeded at 18 years with 1100 stems/ha stocking and at 21 years with 1300 stems/ha stocking. On average, trees are 1.5 cm larger at breast height at 15 years with a stocking of 900 stems/ha as compared to 1300 stems/ha. It seems that for pulpwood production, densities between 900 and 1300 are the best. The lower densities are for poor

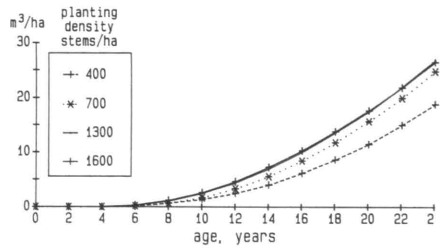

Figure 40. Development of total volume of natural mortality by age and nominal stocking. No thinnings, site class is 24.

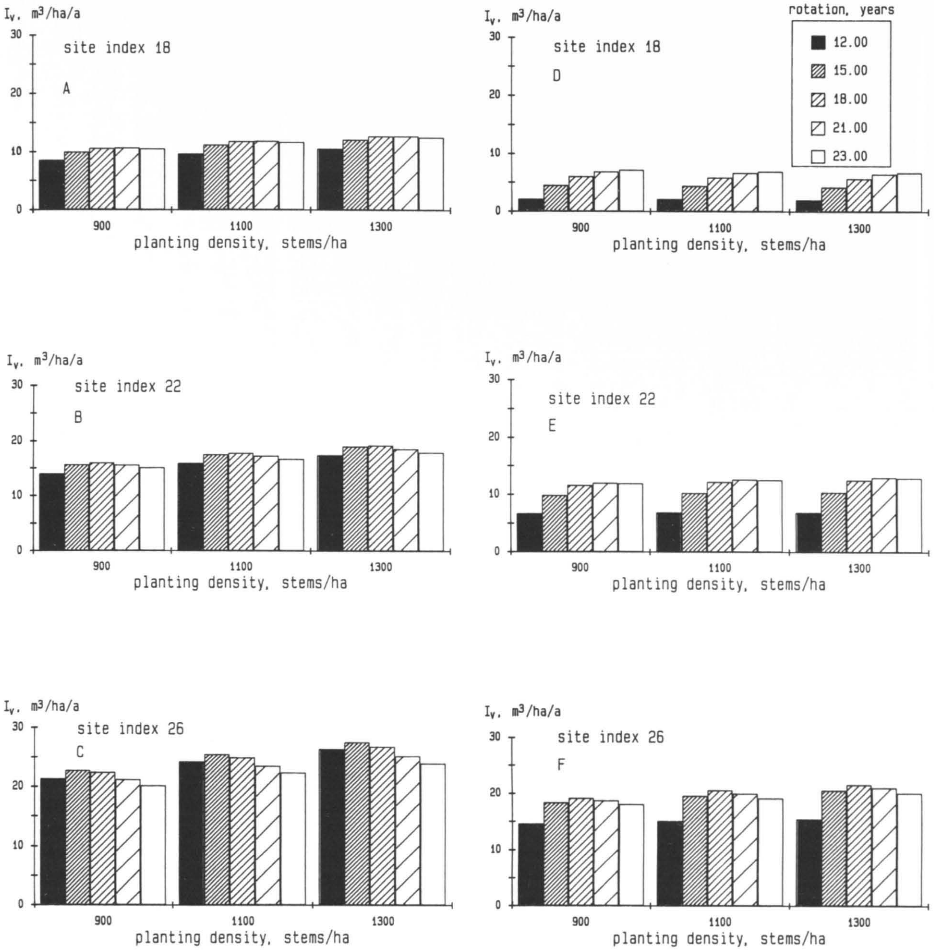

Figure 41. Mean annual total volume (A, B, C) and small sawlog production (D, E, F) by site class and planting density at different rotations. No thinnings.

sites and higher densities for fertile sites (Fig. 41). These densities are such that it is also possible to later change to the sawlog growing regime without great losses in production.

8.3 Future development of the Zambian application

In Zambia, all trials mentioned in Chapter 81 have been established, but only on a limited scale. The information on the effect of seed origin was inadequate and the thinning trial was too young to draw any conclusions. The system had to be built partly using temporary sample plots and partly assumptions. For this reason certain parts of the system are vulnerable to criticism. However, the most uncertain part — the thinning reaction estimation — does not change the conclusions drawn from the simulations. Another factor affecting the results is the possible bias caused by climatic fluctuations. Although the annual mean temperature in Zambia is stable, the precipitation changes considerably between years and is the main factor controlling growth. In the plantation area some measurements of precipitation are available, but unfortunately they do not form a continuous series. The value of the measurements as explaining factors for the changes in the annual increment is questionable due to missing data. Therefore, no corrections due to weather were made.

Although the system is ready for *P. kesiya* only, the same method is easily expanded to concern also other plantation species in Zambia. There is a special need for growth prediction systems for *Pinus oocarpa* and *Eucalyptus grandis*. A provisional yield prediction system already exists for *E. grandis* (Saramäki & Vesa 1989) and existing inventory material can be used to finalize the system. For *P. oocarpa* the provisional system can be created from existing inventory data, too. Unfortunately, no permanent sample plot material is available for *P. oocarpa* to produce thinning and mortality information. *P. kesiya* material may be used temporarily as complementary data.

Because material used for model building only covers the ages upto 25 years, predictions concerning older stands have to be interpreted with caution. Regimes where rotations over 25 years are used, are especially subject to uncertainty due to the lack of base information in the models. If, as is the present situation in Zambia, the main objective is to increase the production of large sawlog yield, the extension of rotations beyond the present recommendations seems to be one mean to achieve this target. However, the simulation model seems to slightly underestimate the production of older stands. Thus, the results of the over-25-year simulations are most probably conservative.

The first estimates for growth and yield of *P. kesiya* recommended 30 year rotations (The Industrial ... 1969, Yield Table... 1973). As the first trials were on fertile soils estimates of the growth rate were optimistic, approximating a mean annual growth of 21 m^3/ha (underbark) with a 30 year rotation (The Industrial... 1969). When more information was gathered the estimates were corrected to 16 m^3/ha (underbark) (Yield table... 1973) this being the level of the present study.

The main weakness of the system maybe that the base population represents the first tree generation. Nowadays planting is undertaken with seedlings raised from seed orchard seed. It is not known whether growth rates are better in the present plantings than in the older ones, but ocular investigations show that at least the quality has improved tremendously.

The genetic source of the seed seemed to have a clear effect on both the quality and growth characteristics of the tree. Seed source could have been taken account of in the model as a dummy variable, however, the source was not used in the simulations. Present day plantings are no longer conducted with the sources presented in the study material, but are the next generation of the seed coming from seed orchards. Generally, when new plantations are established in the tropics, using species which are not indigenous to the area, the seed source should always be taken as an explaining variable in models. The shape of the growth curve seems to be similar for different seed sources (Buford & Burkhart 1987), but even that is not always guaranteed.

As in this study prices and costs were not available, the economically optimal growing regimes were not, perhaps, produced. The next step in the study should be an economic analysis of different growing regimes. When making recommendations they can be based, apart from yield, also on knowledge of the local situation as well as on pure stand figures from simulations. Without economic analyses it seems obvious that by reducing density early enough the proportion of large and medium sized sawlogs can be increased and an improvement in the profitability of growing can be achieved. Decision for the extension of rotation needs economic analyses and more information about the price relations of different sized sawlogs. Clearly, there is a great need for further studies in this respect. The presented simulation system provides good background for these studies.

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Appendix 1. Data of spacing trial.

Trial has been assessed ten times at the ages of 3.81, 4.59, 5.53, 7.58, 8.56, 9.59, 10.56, 11.46, 14.48, 16.47 years

D1 = mean diameter at first assessment
H1 = mean height at first assessment
D2 = mean diameter at second assesment
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Count = number of surviving trees/plot.
The plot consists of 25 planting spots except spacing 8.53 × 8.53 m where plot is only 16 planting spots.

PLOT
3 Spacing 0.91 × 0.91 m

		Replicate				
		1	2	3	4	6
D1	Mean	·	5.9	·	6.3	6.4
H1	Mean	·	1.4	·	2.0	1.8
	Count		24		25	22
D2	Mean	·	13.7	·	7.8	7.9
H2	Mean	·	10.9	·	7.5	7.4
	Count		24		23	22
D3	Mean	·	14.7	·	8.3	8.8
H3	Mean	·	12.3	·	9.0	8.9
	Count		23		23	19
D4	Mean	·	16.5	·	10.3	11.1
H4	Mean	·	14.7	·	11.7	11.6
	Count		12		21	17
D5	Mean	·	11.1	·	10.3	11.2
H5	Mean	·	19.5	·	13.0	12.8
	Count		11		21	16
D6	Mean	·	10.6	·	9.9	10.5
H6	Mean	·	12.7	·	13.8	14.1
	Count		11		21	16
D7	Mean	·	11.8	·	10.3	10.9
H7	Mean	·	12.2	·	14.0	15.1
	Count		11		21	15
D8	Mean	·	12.3	·	10.5	11.1
H8	Mean	·	23.1	·	16.2	16.3
	Count		10		21	15
D9	Mean	·	13.1	·	10.9	11.3
H9	Mean	·	19.1	·	16.9	18.6
	Count		9		20	15
D10	Mean	·	13.5	·	11.1	11.5
H10	Mean	·	25.7	·	18.6	21.8
	Count		9		15	15

PLOT
6 Spacing 1.83 × 1.83 m

		Replicate				
		1	2	3	4	6
D1	Mean	7.9	·	8.7	8.6	8.4
H1	Mean	1.9	·	2.2	2.2	2.2
	Count	25		48	25	25
D2	Mean	10.8	·	11.5	11.0	11.0
H2	Mean	7.3	·	8.2	8.0	8.0
	Count	25		48	24	25
D3	Mean	12.4	·	12.5	12.0	12.5
H3	Mean	9.1	·	9.9	9.9	9.5
	Count	25		32	25	25
D4	Mean	15.5	·	15.2	14.7	15.2
H4	Mean	12.5	·	12.9	13.3	12.5
	Count	22		31	24	25
D5	Mean	15.2	·	15.3	14.7	15.4
H5	Mean	13.9	·	14.6	14.6	13.9
	Count	23		30	23	25
D6	Mean	15.9	·	15.7	15.1	15.9
H6	Mean	14.9	·	15.5	15.7	15.2
	Count	22		30	23	25
D7	Mean	16.4	·	16.1	15.6	15.8
H7	Mean	15.7	·	16.0	16.7	16.4
	Count	22		30	23	25
D8	Mean	16.9	·	16.5	16.0	16.1
H8	Mean	17.5	·	17.7	18.2	17.6
	Count	22		30	23	25
D9	Mean	18.0	·	17.4	16.9	16.6
H9	Mean	18.5	·	19.1	21.0	20.7
	Count	18		21	22	24
D10	Mean	18.5	·	17.8	17.2	16.6
H10	Mean	25.5	·	21.2	21.8	26.1
	Count	16		20	22	23

PLOT 8 Spacing 2.44 × 2.44 m

		Replicate				
		1	2	3	4	6
D1	Mean	8.2	6.9	9.4	8.5	8.6
H1	Mean	1.9	1.6	2.8	2.0	2.0
	Count	24	23	24	24	23
D2	Mean	11.4	9.8	12.7	11.9	12.5
H2	Mean	7.1	5.9	7.8	7.5	7.3
	Count	24	23	24	24	23
D3	Mean	13.2	11.6	14.3	13.4	14.6
H3	Mean	8.7	7.6	9.3	9.2	9.6
	Count	24	23	24	24	23
D4	Mean	17.1	15.2	17.7	17.0	16.4
H4	Mean	11.3	10.2	12.5	12.6	11.4
	Count	24	22	24	24	12
D5	Mean	17.2	15.4	18.1	17.2	16.5
H5	Mean	12.5	12.6	14.1	14.1	12.6
	Count	23	22	24	24	12
D6	Mean	18.1	16.0	18.6	18.0	18.6
H6	Mean	13.9	13.5	15.0	15.3	13.3
	Count	22	22	24	24	11
D7	Mean	18.3	16.7	19.1	18.4	20.0
H7	Mean	15.1	14.3	16.1	16.1	13.7
	Count	19	22	24	24	11
D8	Mean	19.4	17.3	19.6	19.0	21.0
H8	Mean	16.8	15.4	17.3	17.9	15.1
	Count	19	22	24	24	11
D9	Mean	20.8	18.6	21.9	20.5	25.4
H9	Mean	18.3	17.1	20.3	21.0	18.8
	Count	22	21	23	24	11
D10	Mean	21.4	18.7	22.6	20.9	25.8
H10	Mean	24.3	24.1	21.7	22.7	21.9
	Count	20	20	22	23	10

PLOT 9 Spacing 2.74 × 2.74 m

		Replicate				
		1	2	3	4	6
D1	Mean	8.1	8.2	8.4	9.5	8.5
H1	Mean	1.7	1.9	1.9	2.3	2.0
	Count	25	24	19	24	25
D2	Mean	10.9	11.8	12.2	13.1	11.9
H2	Mean	6.3	7.2	7.0	8.3	7.6
	Count	25	24	19	24	25
D3	Mean	12.8	13.8	14.4	14.8	14.3
H3	Mean	7.9	9.1	8.7	10.2	9.5
	Count	25	24	19	23	25
D4	Mean	16.8	17.7	18.8	18.8	18.0
H4	Mean	11.0	11.8	11.4	13.7	12.5
	Count	25	24	16	18	25
D5	Mean	17.1	17.8	19.9	19.3	18.0
H5	Mean	12.2	13.8	13.2	15.3	13.8
	Count	25	24	16	18	25
D6	Mean	18.1	18.6	21.0	20.7	19.0
H6	Mean	13.9	14.9	14.5	16.0	15.7
	Count	25	23	16	18	25
D7	Mean	18.9	19.3	22.0	21.7	19.8
H7	Mean	14.7	15.5	15.6	17.0	16.5
	Count	25	23	16	18	25
D8	Mean	19.4	20.1	22.9	22.6	20.4
H8	Mean	16.4	17.0	17.1	18.8	17.7
	Count	25	23	16	18	25
D9	Mean	21.3	21.6	25.0	24.5	21.9
H9	Mean	18.9	18.1	20.4	20.6	20.8
	Count	23	21	15	18	25
D10	Mean	22.1	22.1	25.8	25.3	22.9
H10	Mean	24.4	24.8	21.6	22.2	23.8
	Count	23	20	15	18	25

PLOT 12 Spacing 3.66 × 3.66 m

		Replicate				
		1	2	3	4	6
D1	Mean	8.8	8.7	9.5	9.5	8.4
H1	Mean	2.6	1.9	2.9	2.1	1.9
	Count	25	25	25	25	25
D2	Mean	12.1	12.4	13.9	13.4	13.6
H2	Mean	6.7	7.0	7.9	7.5	6.9
	Count	25	25	25	25	23
D3	Mean	14.2	14.9	16.3	15.6	14.9
H3	Mean	8.4	8.6	9.6	9.3	8.8
	Count	25	25	25	25	24
D4	Mean	19.5	19.3	21.0	20.2	19.5
H4	Mean	11.7	11.7	12.8	12.5	12.1
	Count	25	25	25	25	24
D5	Mean	20.2	19.9	21.5	20.7	19.6
H5	Mean	13.6	14.4	14.7	13.6	13.5
	Count	25	25	25	25	24
D6	Mean	21.8	21.0	22.9	21.8	21.0
H6	Mean	13.7	15.0	16.2	14.8	15.2
	Count	25	25	25	24	24
D7	Mean	22.9	22.0	23.7	23.1	22.0
H7	Mean	15.0	15.8	16.9	15.7	15.8
	Count	25	25	25	24	24
D8	Mean	24.1	23.0	24.7	24.2	22.8
H8	Mean	16.7	17.2	18.4	17.4	17.1
	Count	25	24	24	24	23
D9	Mean	26.7	25.1	26.9	26.5	24.8
H9	Mean	19.0	18.3	20.5	19.8	20.1
	Count	24	24	23	24	23
D10	Mean	27.7	26.1	28.1	27.4	25.8
H10	Mean	24.9	26.3	22.3	22.2	23.6
	Count	24	24	23	23	22

PLOT 16 Spacing 4.88 × 4.88 m

		Replicate				
		1	2	3	4	6
D1	Mean	9.7	9.4	10.1	9.3	9.3
H1	Mean	2.1	2.1	2.2	2.0	2.0
	Count	25	25	24	22	25
D2	Mean	14.4	13.5	14.8	13.6	13.6
H2	Mean	7.5	7.3	8.0	7.3	7.5
	Count	25	25	24	22	25
D3	Mean	17.4	16.3	17.5	16.5	16.6
H3	Mean	9.4	9.0	9.6	9.0	9.2
	Count	25	25	24	22	25
D4	Mean	23.1	21.8	22.8	22.0	21.4
H4	Mean	12.7	12.0	12.4	11.9	12.2
	Count	25	25	24	22	25
D5	Mean	23.4	22.6	23.6	22.9	21.7
H5	Mean	13.9	14.5	13.8	13.1	13.8
	Count	24	25	24	22	25
D6	Mean	25.5	24.2	25.4	24.3	23.8
H6	Mean	14.9	15.1	14.7	14.5	15.0
	Count	24	25	24	22	25
D7	Mean	27.0	25.8	26.5	26.3	25.1
H7	Mean	15.8	15.8	15.5	15.3	16.0
	Count	24	25	24	22	25
D8	Mean	28.3	27.0	27.7	27.8	26.4
H8	Mean	17.5	17.1	17.3	16.9	17.3
	Count	24	25	24	22	25
D9	Mean	29.9	29.7	30.5	31.3	29.1
H9	Mean	20.2	18.8	19.9	19.6	20.0
	Count	23	25	24	22	25
D10	Mean	31.0	30.5	31.7	·	30.5
H10	Mean	25.3	26.8	21.6	·	23.2
	Count	23	25	24		25

PLOT
18 Spacing 5.49 × 5.49 m

		Replicate				
		1	2	3	4	6
D1	Mean	9.7	9.9	9.9	9.5	9.2
H1	Mean	2.2	2.1	2.0	2.0	1.8
	Count	25	25	25	25	23
D2	Mean	14.4	13.8	14.4	13.9	13.5
H2	Mean	7.7	7.5	7.0	7.1	6.8
	Count	25	25	25	25	23
D3	Mean	17.2	17.2	17.4	16.8	17.1
H3	Mean	9.5	9.3	8.6	8.6	8.8
	Count	25	25	25	25	23
D4	Mean	22.7	22.7	23.0	22.5	23.2
H4	Mean	12.9	12.4	11.4	11.3	11.4
	Count	25	25	25	25	23
D5	Mean	23.0	23.8	24.1	23.1	23.6
H5	Mean	14.1	14.6	12.6	12.7	12.9
	Count	22	25	25	25	23
D6	Mean	25.2	25.6	26.1	25.0	25.8
H6	Mean	15.1	15.6	13.7	14.0	14.2
	Count	24	24	25	25	23
D7	Mean	26.7	27.4	27.6	26.4	27.4
H7	Mean	16.0	16.2	14.4	15.1	15.1
	Count	23	24	25	25	23
D8	Mean	28.0	28.7	29.2	27.9	28.3
H8	Mean	17.7	17.5	16.3	16.3	16.3
	Count	22	24	25	25	23
D9	Mean	30.7	32.3	32.8	31.8	31.8
H9	Mean	20.8	19.4	18.6	19.4	18.2
	Count	24	24	25	25	23
D10	Mean	32.6	33.5	35.2	32.9	33.3
H10	Mean	26.2	24.2	20.7	21.6	21.9
	Count	24	24	25	25	23

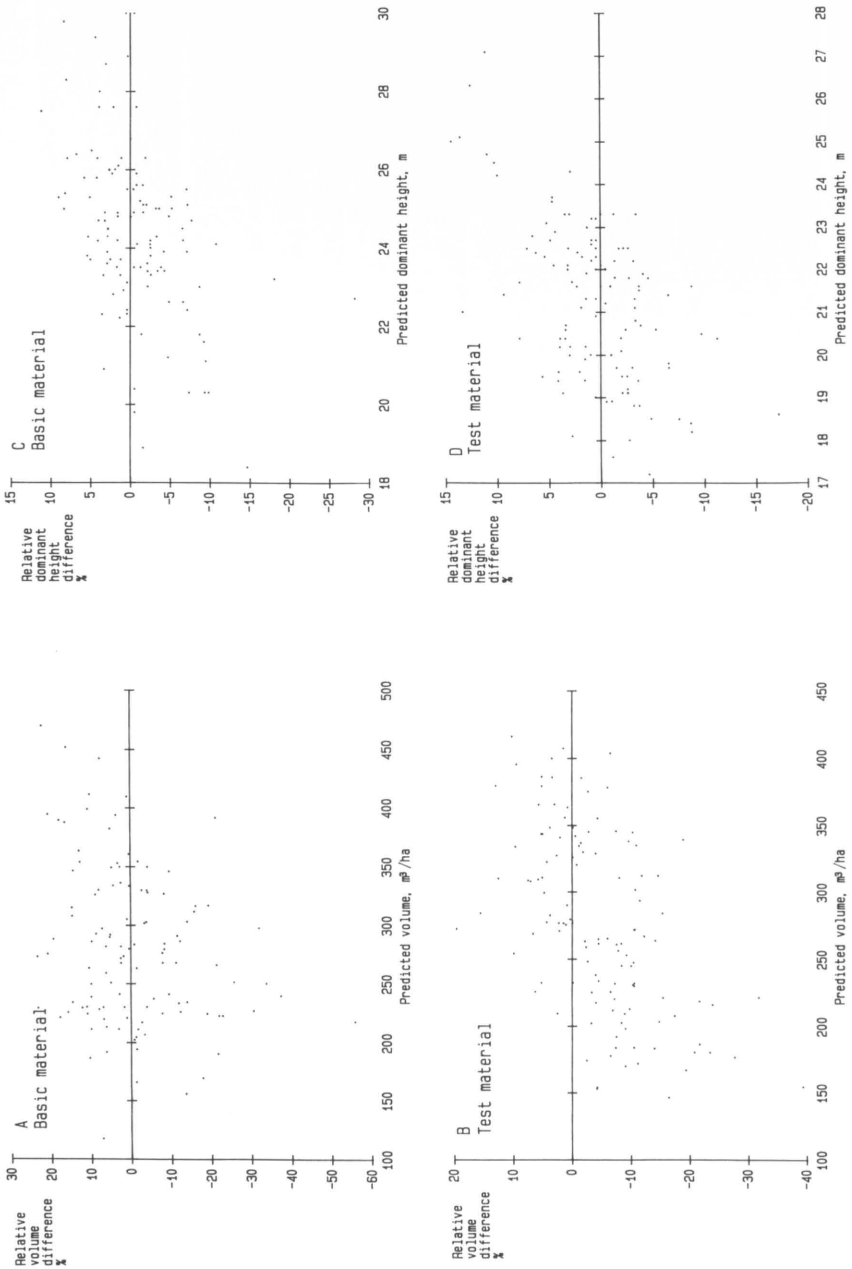
PLOT
20 Spacing 6.10 × 6.10 m

		Replicate				
		1	2	3	4	6
D1	Mean	9.1	8.5	9.6	·	8.4
H1	Mean	2.1	1.9	2.1	·	1.9
	Count	24	25	24	10	24
D2	Mean	12.4	13.4	14.5	·	12.0
H2	Mean	6.7	7.7	7.8	·	7.1
	Count	6	4	5	3	4
D3	Mean	16.4	16.0	17.3	·	16.9
H3	Mean	9.0	8.4	9.5	·	8.9
	Count	24	25	22	7	15
D4	Mean	22.7	22.0	23.7	·	23.8
H4	Mean	11.9	11.3	12.3	·	11.9
	Count	24	24	22	7	15
D5	Mean	23.2	23.5	24.9	·	24.3
H5	Mean	13.1	13.5	13.8	·	13.3
	Count	22	23	22	6	15
D6	Mean	25.9	25.2	27.7	·	26.7
H6	Mean	14.4	14.4	14.8	·	13.9
	Count	23	22	22		15
D7	Mean	28.1	27.3	29.4	·	28.7
H7	Mean	15.2	15.1	15.5	·	14.8
	Count	22	22	22		15
D8	Mean	29.6	28.7	30.9	·	30.3
H8	Mean	16.9	16.3	16.8	·	16.2
	Count	22	22	22		15
D9	Mean	33.6	33.3	35.2	·	34.2
H9	Mean	20.3	18.4	20.4	·	18.4
	Count	22	22	21		15
D10	Mean	35.8	35.3	36.9	·	36.2
H10	Mean	25.4	24.9	21.5	·	21.7
	Count	22	22	21		15

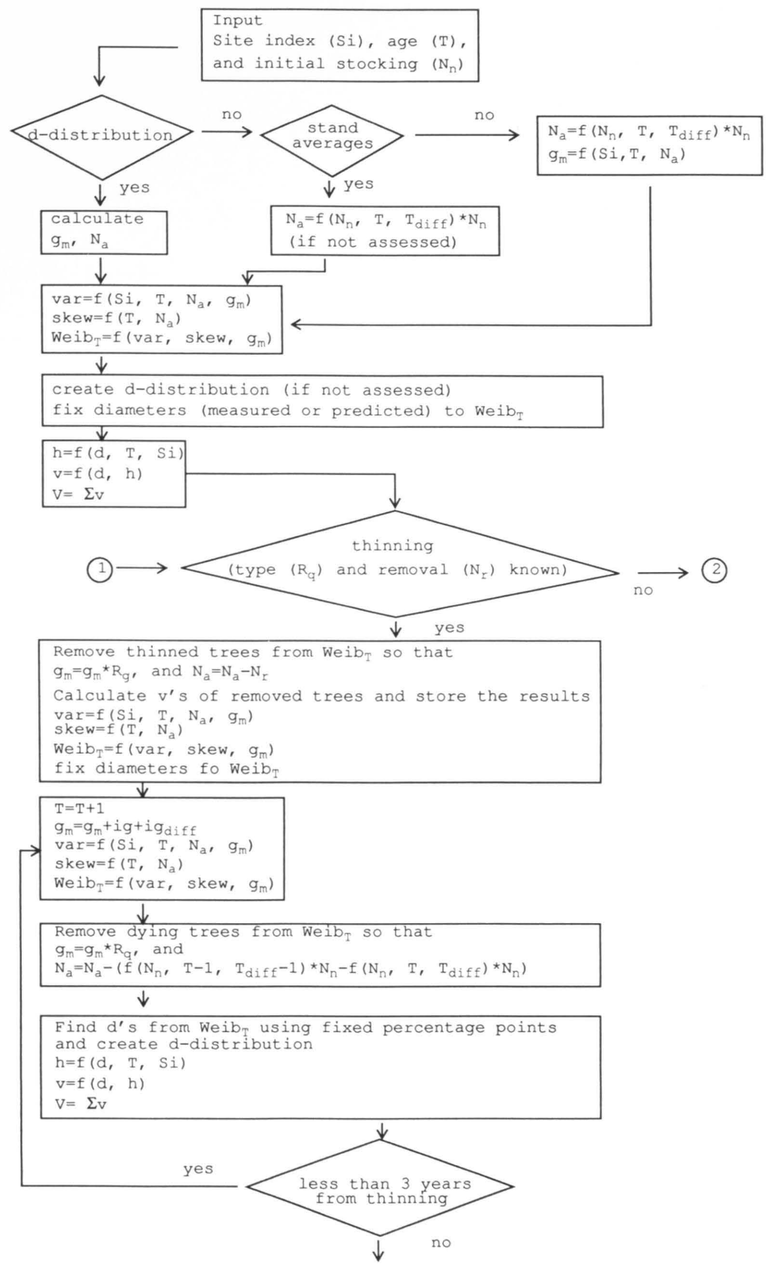
PLOT
28 Spacing 8.53 × 8.53 m

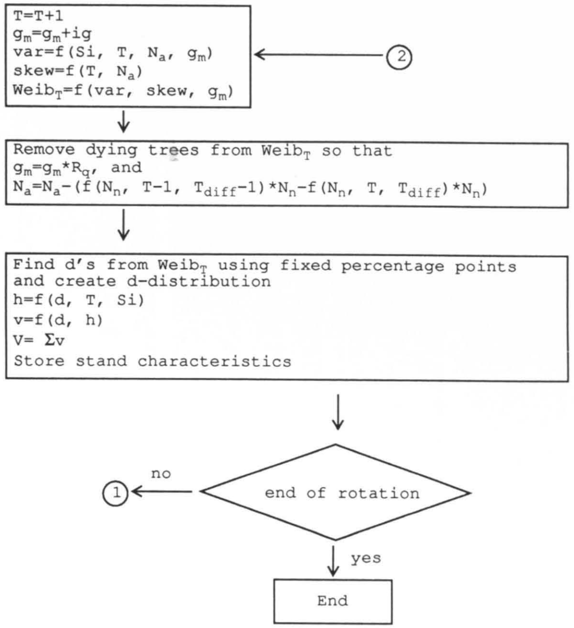
		Replicate				
		1	2	3	4	6
D1	Mean	8.5	9.3	10.0	9.8	9.2
H1	Mean	2.0	2.0	2.1	2.1	2.1
	Count	24	25	20	25	23
D2	Mean	12.1	13.4	14.4	14.1	13.7
H2	Mean	7.1	7.0	7.9	7.6	7.5
	Count	24	25	21	25	23
D3	Mean	17.5	16.0	16.6	17.2	16.6
H3	Mean	9.5	8.2	9.5	9.3	8.7
	Count	15	15	15	16	16
D4	Mean	25.5	23.3	23.3	24.7	23.9
H4	Mean	12.3	10.7	12.2	11.5	11.4
	Count	15	15	14	16	16
D5	Mean	26.9	25.3	24.9	25.7	24.8
H5	Mean	13.6	12.9	13.8	12.7	12.7
	Count	13	15	14	16	16
D6	Mean	30.3	28.2	28.5	29.3	28.1
H6	Mean	14.3	13.7	14.3	13.8	13.5
	Count	13	15	14	16	16
D7	Mean	32.7	30.6	30.9	31.7	30.2
H7	Mean	15.0	14.1	15.3	14.8	14.1
	Count	13	15	14	16	16
D8	Mean	35.0	32.2	32.7	33.7	32.0
H8	Mean	16.4	15.2	16.6	16.2	15.7
	Count	13	15	14	16	16
D9	Mean	40.5	37.8	39.0	39.5	34.4
H9	Mean	18.6	17.9	19.9	18.8	17.7
	Count	13	15	14	16	15
D10	Mean	43.2	40.4	41.1	41.8	39.1
H10	Mean	24.3	24.4	21.3	21.4	21.3
	Count	13	15	14	16	15

Appendix 2. Relative differences between measured and predicted volume (A, B) and dominant height (C, D). Each plot is compared at the last assessment when prediction has started from first assessment.



Appendix 3. Flow chart of simulation.





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Acta Forestalia Fennica 230 — Saramäki

ISBN 951-40-1234-8
ISSN 0001-5636