GROWTH, YIELD AND SILVICULTURAL MANAGEMENT OF

EXOTIC TIMBER SPECIES IN KENYA

by

WINSTON JOSHUA KAMURU MATHU
B.Sc.F. University of new Brunswick, Canada 1971
M.Sc.F. University of Das-Es-Salaam, Tanzania 1977

A THESIS SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

in the

FACULTY OF GRADUATE STUDIES

Department of Forestry

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA
©March, 1983

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the library shall make it freely available for reference and study. I further agree that permission for extensive copying of the thesis for scholarly purposes may be granted by the Head of my Department or by his representatives. It is understood that copying or publication of this thesis for financial gains shall not be allowed without my written permission.

Department of Forestry
The University of British Columbia
2357 Main Mall
Vancouver, B.C. Canada
V6T 1W5

March 18, 1983

ABSTRACT

Supervisor: D.D. MUNRO

This study presents the growth, yield and the silvicultural manage-
ment of Cupressus lusitanica, Pinus patula and Pinus radiata, the three
most important timber species growing in the Kenya highlands. The study
is based on 163, 176 and 164 permanent sample plots for the three
species respectively.

The stand dominant height development was predicted as a function
of stand age and site index, defined as dominant height at reference age
of 15 years. The Chapman-Richard's growth function was used for
C. lusitanica and P. radiata while a linear quadratic equation was used
to describe dominant height development for P. patula by geographical
regions. Height development for the two pine species was found to be
significantly different (up to age 20 years) in the Shamba and grassland
establishment sites.

Stand basal area before thinning was predicted as a function of
stand age, dominant height and number of stems using a Weibull-type
growth equation. In thinned stands basal area was predicted through a
basal area increment nonlinear equation. For P. radiata, basal area
increment was predicted as a function of basal area at the beginning of
the growth period (1 year) and age. For C. lusitanica and P. patula, a
third term-stand density index, defined as the percent ratio of average
spacing between trees to stand dominant height was included. The
Weibull probability density function was used to characterize stand

diameter distribution with the Weibull parameters predicted as a function of stand parameters. Stand volumes were determined from tree volume equations for the respective species while the mean DBH of stems removed in thinnings was predicted from mean stand DBH before thinning and weight of thinning.

Using the above functions, a growth and yield simulation model EXOTICS was constructed. Written in FORTRAN IV G-level which is compatible with IBM System/360 and System/370, EXOTICS is an interactive whole-stand/distance independent model with an added capability for providing diameter distribution (by 3 cm diameter classes) to give final main stand yield by size classes. The model is intended to facilitate silvicultural management of the three species in the Kenya highlands. On validation, EXOTICS was found to have no bias within the range of validation data, and 95% confidence limits of 16%, 20% and 17% for C. lusitanica, P. patula and P. radiata respectively.

Using EXOTICS, the current silvicultural management schedules in Kenya were studied. The thinning regimes were found to have marked effects on the current annual volume increment. It was therefore concluded that at the present level of silvicultural management, Moller's theory that thinning has no appreciable effects on total volume yield does not hold for the three species in Kenya. The current thinning policy aimed at production of large-sized sawlog crop in as short a rotation as possible at the expense of some loss in total yield is discussed and found to have been overtaken by events. A policy based on the concept of maximum volume production is advocated. A thinning experiment (using C. lusitanica) demonstrated that total merchantable

volume could be increased by between 5 and 10% (using 20% thinning

intensity) depending on site quality class. Within the range of

stockings maintained in plantations in Kenya, thinning intensity was

found to be the most important consideration, with stocking before

thinning having very little effect on both mean annual volume increment

and total merchantable volume yield up to age 40 years.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

DEDICATION

I dedicate this thesis to my wife - Nellie Muthoni Mathu. Nellie gave up her career in teaching in order to come and minister to me during my study here in Canada. Her dedicated love and encouragement have been my main source of strength.

Also to my children - Muthoni, Mwihaki and Mathu who provided most welcome distraction from the rigours of my study, especially in the evenings.

INTRODUCTION

The total forest land in Kenya consists of about 2 million hectares or 3% of the total land area of the country, all of which is publicly owned and administered by the Kenya Forest Department. Of this land, about two thirds is designated protection forest, leaving about 660,000 hectares for timber production. To date, over 150,000 hectares have been converted to exotic softwood plantations, mainly Cupressus lusitanica Miller, Pinus patula Schlecht and Cham and Pinus radiata D. Don. These species are grown primarily for the supply of sawtimber and pulpwood to privately owned forest industries.

The demand for timber and timber products in Kenya has been rising and will continue to rise in the foreseeable future. This is as a result of two components: increasing population estimated at an annual rate of 4% and increasing per capita consumption of wood and wood products, a result of a rising standard of living. To meet this rising demand for wood and wood products within the constraint of a fixed forest land base, one of the options open to the government is more intensive forest management to maximize yield from the available forest land through silvicultural manipulation of the stand. To do this effectively requires a good knowledge of the growth and yield of the candidate species under the various physical, edaphic and silvicultural conditions prevailing in the country. When available, this knowledge forms a basis for the formulation of alternative management strategies to meet the desired goals and objectives. This can best be achieved if a reliable means of forecasting growth and yield under the relevant

physical, edaphic and silvicultural constraints is available to provide the necessary quantitative information.

Since large scale plantation forestry started in Kenya around 1936 (C. lusitanica) and 1946 (P. patula and P. radiata), several studies on growth and yield of plantation species have been undertaken. Some of these, including Wimbush (1945), Griffith and Howland (1961) and Paterson (1967) were limited in scope, either because they were based on limited data or were for specific regions. However, since the setting up of a permanent sample plots program in 1964, three important studies based on data from these plots have been undertaken:

1. Wanene (1975, 1976) and Wanene and Wachiuri (1975) constructed variable density yield tables for P. patula, P. radiata and C. lusitanica, respectively. These tables were of particular significance as they were the first tables of their kind for yield estimation. However, they were based on simple regression methods and so could not represent the dynamic processes of stand growth very well. Shortcomings in these yield tables were discussed by Mathu (1977).

2. Mathu (1977) studied the growth and yield of C. lusitanica in Kenya as part requirement of an M.Sc. study program. This study improved on the methodology used by Wanene and Wachiuri by casting the principal growth function as a rate of change of the stand basal area. However, this study was limited in that it only considered growth for an average site in Kenya. Two major areas for future research were identified.

(a) Need for further investigation of basal area increment in overstocked and understocked stands and in different site classes.

(b) Need to investigate further the height development in the different regions in the country.

3. Alder (1977) developed a single stand yield prediction model – the VYTL-2 – as a subroutine in the PYMOD forest management program as part of the requirements in a Ph.D. study program. VYTL-2 presents the stand state as a list of diameters (derived from a diameter probability density function), stand growth is driven by a site index curve while a tree diameter increment equation (a function of site index, stand basal area and dominance ratio – a measure of competitive stress) effects diameter growth for diameter classes as percentiles of a cumulative distribution function. This, therefore, is a single tree distance independent model although growth is for diameter classes rather than the individual tree (see Chapter 3 Section 2).

The VYTL-2 was designed to simulate yields for single stands of C. lusitanica, P. patula and P. radiata and, according to Alder (1977), it is also capable of simulating different thinning treatments and so can be used as a silvicultural tool. However, two main factors mitigate against use of this model as a silvicultural tool:

1. On validation at 95% confidence level, the output from this model ranged from 40% underestimate to 20% overestimate of total volume yield (Alder 1978). According to the author,

these errors appeared to be associated with a variety of factors: genetic, biotic and climatic; and not with any structural flaw in the model. Whatever the cause, the effects of these systematic errors is to reduce the confidence of the model especially as a tool for silvicultural research.

2. The thinning algorithms in the model are based on purely hypothetical assumptions such as low thinning, mechanical thinning, etc. which imply a fixed distribution of the removed stems in the stand. These assumptions which amount to accepting the concept of an "ideal" thinning type are unrealistic in practice. In addition, the model allows only one thinning option within a single simulation run. In practice however, different thinning criteria may be required at different points in the life of the stand, necessitating use of more than one thinning option within a single simulation run. This flexibility is lacking in the VYTL-2 model.

The PYMOD model of which VYTL-2 is a subroutine was intended as a long-term forecasting and feasibility analysis system for entire forests. For given initial planting intensities, several plantations and their site indices, the model simulates species mix, product mix and yields using satisfying (as opposed to optimizing) criteria. This model is similar to the Australian model FORSIM which simulates the growth of many stands comprising a total forest estate at one time and summarizes yields by various size classes from all compartments (Gibson et al. 1970). However, unlike the Australian situation, the present East

African scene for which PYMOD was designed lacks forest planning systems capable of defining all the constraints - economic, product mix, species mix, etc. that are required to utilize PYMOD capability. This may partly explain why the model has received so little attention in East Africa.

The growth conditions under which the three species are managed in Kenya vary considerably in terms of site qualities (including site factors such as rainfall distribution and intensity, soils, elevation above sea level, etc.), establishment sites (defined later) and silvicultural regimes. From a review of past studies, it is apparent that the growth and yield of these species under the prevailing conditions has not been adequately addressed; neither has the possibility of the adoption of alternative silvicultural regimes been considered as a means of increasing growth and yield of the stand. It is also apparent that there is no reliable means of forecasting growth and yield that can be used to facilitate silvicultural manipulation of the stand towards the desired goals and objectives. These problems gave rise to the three objectives of this study:

1. To study growth and yield of the three species: $\underline{C}$. $\underline{lusitanica}$, $\underline{P}$. $\underline{patula}$ and $\underline{P}$. $\underline{radiata}$ under the variety of sites, establishment sites, stand structures and silvicultural practices found in Kenya.

2. To construct a stand growth and yield model as a means for yield prediction and as an aid to silviculture for evaluation of different management strategies.

3. To evaluate the impact of the present and alternative management schedules on stand development for different management objectives.

CHAPTER 1

BACKGROUND INFORMATION

1.   Species Nomenclature and Distribution

Cypressus lusitanica Miller (1768) also called Mexican cypress,

Portuguese cypress, Cedar of Goa or just cypress is of the family

Cupressaceae and genus Cupressus.   In nature, it occurs naturally

between latitude 15-45° North and is widespread in Central and Southern

Mexico, Guatemala, Honduras and El Salvador, where it grows to a height

of 30 meters at 1800-2400 meters elevation (Dyson 1968).   Outside its

natural range, this species is planted extensively in the South and West

of France, Japan, Portugal, Spain and East Africa.   In New Zealand,

South Africa and Malawi, it is planted as a minor plantation species.

Cupressus lusitanica was introduced to Kenya in 1905 but large scale

planting did not begin until 1936 (Wimbush 1945).   Figures for distribu-

tion by area are only available for Kenya as shown in Table 1.

Pinus patula Schlecht and Cham also called Patula pine or spreading-

leaved pine occurs naturally in a comparatively restricted range in the

States of Queretaro, Hildalgo, Pueblo, Mexico and Vera Cruz in Central

Mexico at an elevation of 1500-3000 meters elevation with annual average

rainfall of 1200 mm (Mirov 1967).   Outside its range, P. patula is

planted mostly in Africa where South Africa pioneered its use. It was

introduced to Kenya in 1910 but large scale planting did not start until

1946 (Pudden 1957).   P. patula is grown mainly for pulpwood and saw-

timber but the wood can be used for other purposes, e.g. veneer as in

TABLE 1: Distribution of the species by area in the major countries
in which the species are grown.

Species	Country	Area in hectare	Source of data
C. lusitanica	Kenya	66,000	Kenya Forest Department (1981) (Per. Comm.)
P. patula	South Africa	174,000	Crowe (1967)
	Kenya	50,000	Kenya Forest Department (1981) (Per. Comm.)
	Malawi	23,000	Marshall and Foot (1969)
P. radiata	New Zealand	307,000	Grut (1970)
	Chile	261,000	" "
	Australia	185,000	" "
	Spain	173,000	" "
	South Africa	35,000	" "
	Kenya	18,000	Kenya Forest Department (1981) (Per. Comm.)

Kenya. Table 1 shows the distribution of the species in South Africa, Kenya and Malawi.

Pinus radiata D. Don also known as radiata pine, insignis pine, Monterey pine or remarkable pine belongs to a group of pines known as closed-cone pines believed to have been widespread along the coast of California in prehistoric times (Forde 1966). The present distribution of P. radiata is the coastal region of central California and Mexico, where it grows naturally on some 4,050 hectares (Scott 1960). It exists in two varieties; two needles and three needles.

In its natural habitat, P. radiata is a small to medium sized bushy tree which grows quickly and bears cones at an early age - 6 years. Cones are hard and persist for many years on the stems and branches and may remain closed for many years after maturity. In this form, the tree is of little economic value.

The climate in central California and Mexico where P. radiata grows is a special type of mediterranean climate with little summer rain but adequate summer moisture from frequent sea fogs and mists. It grows on gentle to moderate slopes from the coastline to 10 kilometers inland, on deep sandy soil types (sandy loam soils) with rainfall ranging between 500 to 1050 mm per annum. 70 to 75% of the rain falls in winter.

P. radiata is the most widely planted species outside its natural habitat.

As with P. patula, it was introduced to Kenya in 1910 and large scale planting started in 1946 (Pudden 1957). The distribution of this species by area in the major countries where it has been introduced is shown in Table 1.

2. Climate and Soils

The bulk of softwood plantations in Kenya are found in the Kenya highlands between 1800 to 2750 meters above sea level. Within the highland zone, variations in relief do occur, of which the most significant is the Great Rift Valley which transects the central highlands in a North/South direction, as shown on Figure 1. This variation in relief results in great variation in climate and vegetation.

As shown on Figure 1, the highland zone lies right across the equator. One would therefore expect an equatorial type of climate characterized by high insolation, high rainfall and high evaporation rates. However, the combination of altitude and the relief variation modifies the climate so that no single climatic type can characterize the climate of this zone.

According to Gilead and Roseman (1958), the most important elements of climate for plant growth are warmth (temperature) and water (rainfall). Using these two elements, several procedures have been used to characterize the water loss from evapotranspiration and water gain from rainfall in relation to plant growth. These include the Thornthwaite system of climatic classification (Thornthwaite 1948), Penmans method (Penman 1948) and the Gaussens method (Gaussen 1954). Of these three, the Gaussens method has been adopted in this study mainly because it utilizes the only two climatic data available - rainfall and temperature measurements.

Basically the Gaussen procedure consists of constructing ombrothermic diagrams as follows:

FIGURE 1

KENYA FOREST BLOCKS AND WEATHER STATIONS

WEATHER STATIONS

1 = Eldoret
2 = Molo
3 = Kericho
4 = Kimakia
5 = Muguga
6 = Nanyuki
×—×—×—× Encloses the highland zone.
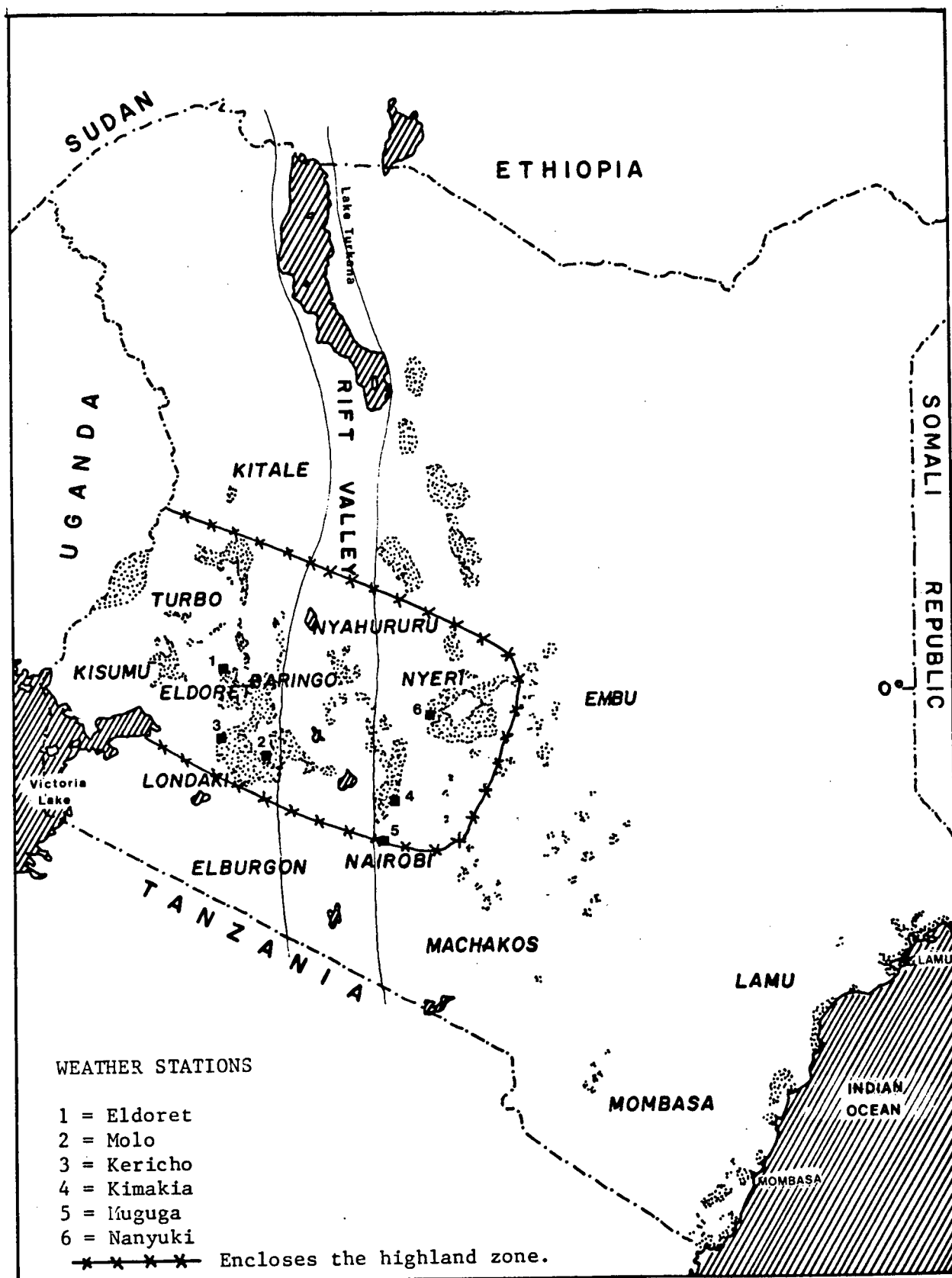
1. On the abscissa scale, plot the months of the year.

2. On the ordinate scale, label the right axis with monthly precipitation in mm and the left axis with monthly average temperatures in degrees centrigrade to a scale double that of precipitation.

3. Join all the levels of monthly temperature to get the thermic curve, join all the levels of monthly rainfall to get the ombrographic curve.

When the ombrographic curve sinks below the thermic curve, precipitation < 2 temperature. The space enclosed by the two curves indicates the duration and severity of the dry season. This criteria for dry season is based on a rule of thumb but the results are consistent with those obtained using other procedures (FAO 1974).

Figure 2 shows the ombrothermic diagrams for weather stations representative of the highland zone (see also Figure 1) while Table 2 gives the rainfall summary, altitude and an indication of the dry months for each station. Data was obtained from the East African Meteorological Department (1973, 1975).

Figure 2 shows that of the three stations representing the highlands west of the Rift (Eldoret, Molo and Kericho), there is no dry season as defined by the ombrothermic diagrams. In general the diagrams for these stations indicate one long rainy season between March to September and one season with minimum rainfall between October to February.

FIGURE 2

OMBROTHERMIC DIAGRAMS FOR WEATHER STATIONS REPRESENTATIVE OF THE HIGHLAND
ZONE IN KENYA

FIGURE 2 con't

KERICHO

KIMAKIA

14
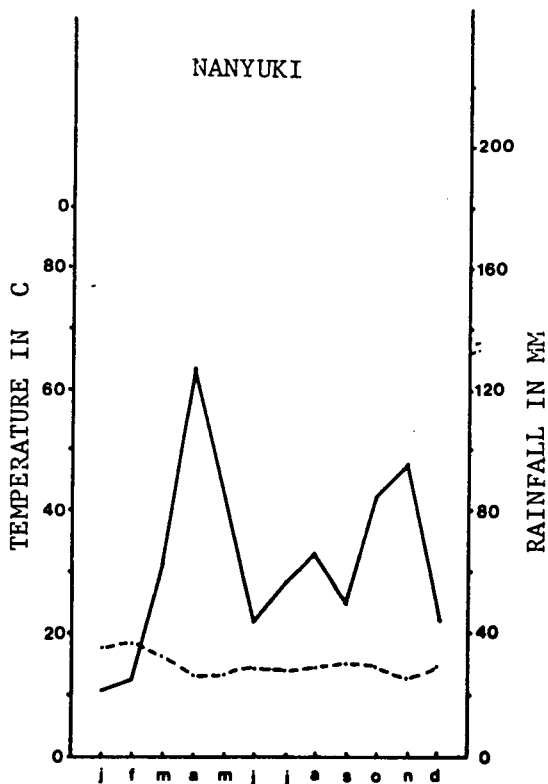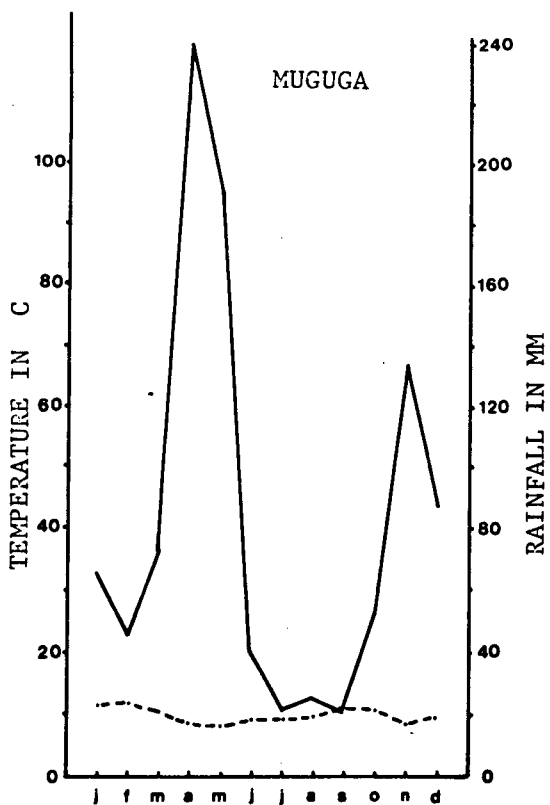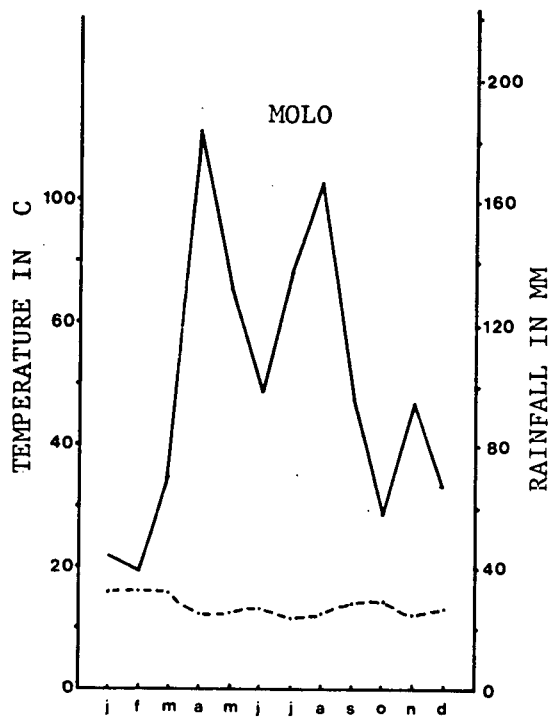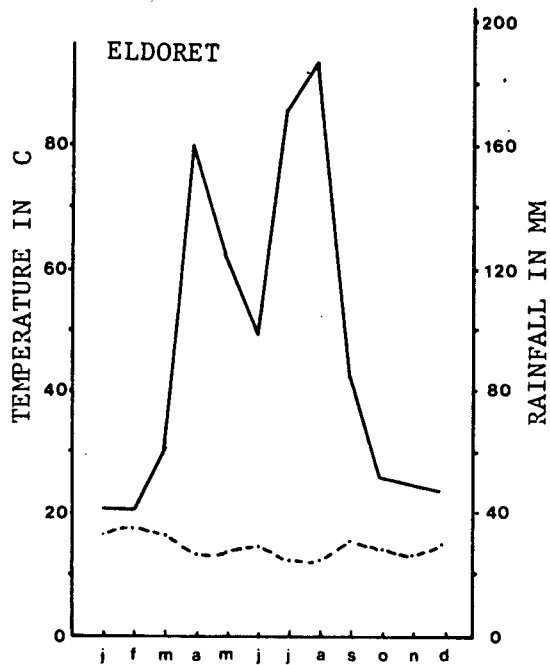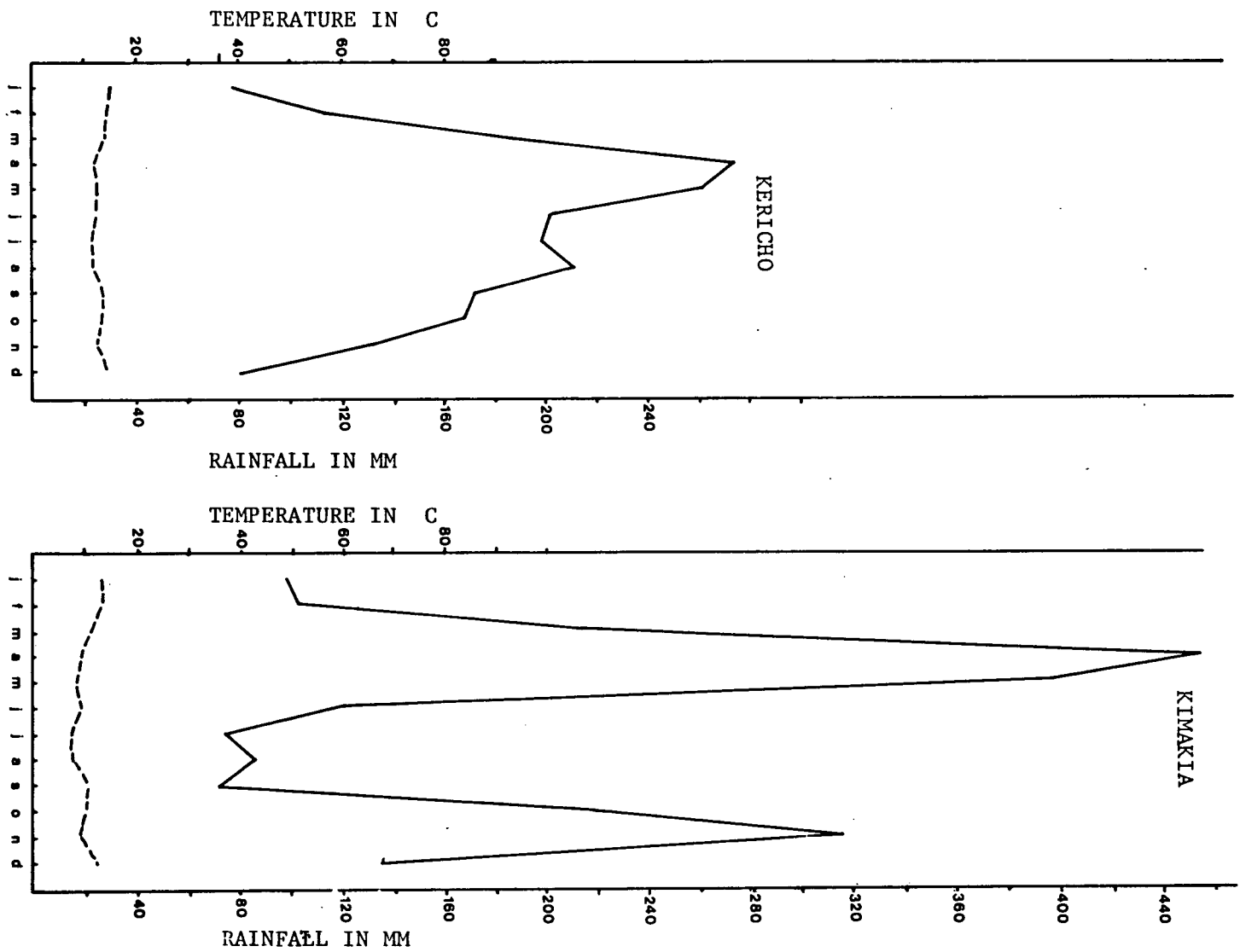
TABLE 2:   Summary of rainfall and altitude for weather stations
           representative of the highland zone.

Weather station	Elevation in meters above sea leavel	Rainfall in mm per annum	Dry season
Edoret	2084	1124 (24)	no dry season
Molo	2477	1177 (28)	" " "
Kericho	2134	2081 (7)	" " "
Kimakia	2439	2288 (14)	" " "
Muguga	2096	995 (20)	September
Nanyuki	1947	759 (32)	January & February

Number in bracket indicate number of years of record.

Of the three stations representing the highlands east of the Rift (Kimakia, Muguga and Nanyuki), Kimakia has the highest total annual rainfall followed by Muguga, with Namyuki having the least. Muguga has a one month dry season (September) while Nanyuki has two months (January and February) of dry season. In general, the diagrams for these stations indicate one long rain season between March and May with a peak in April and a short rainy season between October to December with a peak in November. January/February and July/August/September are seasons of minimum rainfall.

In general the highland sites where plantations are established are overlaid with volcanic loam soils, usually of great depth. They are usually well drained so that there is rarely any water table within reach of tree roots. However, there are exceptions and in some places where drainage is impeded, pans of laterite may be found which in some cases act as barrier to tree root penetration to lower soil strata. Volcanic loams are generally very suitable for tree growth.

3. Silvicultural Forest Management in Kenya

In discussing forest management in Kenya, there are two possible approaches: the technical approach whereby the success of a given management activity is measured on the basis of biological criteria, e.g. highest volume production; and the economic approach whereby the criteria for success is based on economic evaluation. To date, the economic evaluation of management practices have never been attempted in Kenya, mainly because of lack of a basis for assessing the quantitative

impact of the silvicultural practices. Only technical aspects of forest management will be discussed in this section.

Nursery practice

Artificial regeneration through planting is the standard practice in Kenya. Nursery practice is a highly developed technology. Seed is usually sown in level, shaded beds which are usually netted to protect the seedlings from birds and small mammals. The soil mixture consists mostly of sand with no humus material. Seed pretreatment is not required for any of the three species. Table 3 shows the number of seed per kilogram and the germinative capacity for each of the species under normal nursery practice.

TABLE 3*: Seeds per kilogram and germinative capacity for C. lusitanica P. patula and P. radiata in Kenya.

Species	Seeds per kg	Germinative capacity %	No. seedlings per kg
C. lusitanica	236,000	30%	70,000 to 75,000
P. patula	180,000	30%	50,000 to 60,000
P. radiata	35,000	40%	15,000 to 20,000

*Data obtained from the respective technical reports.

As soon as the seeds have germinated and before any side roots are developed, the seedlings are pricked out into trays of size 38 x 40 cm and 10 cm high containing soil to 8 cm depth or rarely into transplant beds raised 8 cm above the ground level. For C. lusitanica, ordinary

forest soil is used, while pine soil is required for the pine species, as the later contains a mycorrhiza species necessary for the survival of the pine seedlings. Each box contains 49 plants so that each seedling enjoys approximately 250 cu.cm of soil. Use of fertilizers in the nursery is standard practice. Seedlings are considered mature for planting out in the field when they are approximately 20-30 cm high.

Plantation establishment methods

There are two systems of plantation establishment in Kenya:

1. Shamba System: This is a highly developed taungya system whereby the land earmarked for tree planting is issued to permanent forest employees for crop cultivation. After one or two years of crop growing, trees are planted and the employees continue growing their crops until the trees are too tall for agricultural crops. Under this system, the employees gain from the agricultural crops while the trees are planted in culti- vated ground and get free weeding the first few seasons of their life.

2. Grassland Planting: Forest glades and open grasslands are rarely suitable for agricultural crops. Tree planting in these sites is preceded by minimum land preparation consisting of strip ploughing or simply digging pits where the trees will be planted.

Experience with C. lusitanica has shown it to be very intolerant of weed competition, especially from grass. As such it is never planted on grassland sites. Pine species on the other hand can be established

under either system as their survival on grassland sites is quite acceptable.

Initial spacing and early tending in plantations

The objective of stand establishment in Kenya is similar to that of South Africa: to grow trees to merchantable size in as short a time as possible. Thus, the stand establishment is characterized by wide spacing accompanied by heavy thinning and pruning to insure high quality stems. Presently, the initial spacing is 2.5 x 2.5 meters (1600 stems per hectare) and, as indicated in the 1981 revised Technical Order for P. patula there is a move to even wider spacing (3.0 x 3.0 meters = 1110 stems per hectare). This is very wide spacing compared to central Europe where spacing is 1.4 x 1.4 meters = 5000 seedlings per hectare for 2+2 year old spruce seedlings or Britain where spacing ranges between 2.2 x 2.2 meters to 2.0 x 2.0 meters (2000 to 2300 seedlings per hectare) (Kuusela 1968). For the latter countries, the objectives of stand establishment are to obtain sufficiently dense stands to utilize fully the site productivity and to improve the quality of the tree stems by self pruning. These and the slower growth rates explain the closer initial spacing.

An important consideration in adopting a specific initial spacing policy is the cost of raising the seedling in the nursery and planting out in the field. Wide initial spacing may be justified in Kenya, firstly because it means fewer seedlings to be raised and therefore less nursery and planting expenses and, secondly because the intensive ground

preparation and subsequent tending especially under the Shamba system, ensures higher survival of seedlings.

Pruning

By definition, pruning involves removal of live branches so as to ensure production of timber free of dead knots. The wide initial spacings accompanied by heavy thinnings as practiced in Kenya imply an increase in size of branches and delay in natural pruning. Pruning is therefore a standard practice. Table 4 shows the current pruning schedules for the three species.

Thinning

Under traditional forestry practices as practiced in Europe and Britain, the objective of thinning is to harvest those trees which would be wasted as mortality and to better the quality of standing stock. Thinnings are therefore very light so that the density of standing stock is kept as high as is necessary for maximum volume production. The thinning practices in Kenya on the other hand are based on Craib's (1939, 1947) thinning policy which advocated very heavy thinnings so as to promote tree diameter growth. This policy is not consistent with the objective of maximum volume production but aims at production of larger sized material in as short a rotation as possible at the expense of some loss in total yield.

Craib's revolutionary ideas on thinning went against traditional thinning policies, especially with regard to the recommendation for more severe thinnings on poor sites. As a result this policy has received varied comments, some against (Hawley and Smith 1954, Johnston 1962) but

TABLE 4: Pruning schedules for C. lusitanica, P. patula and P. radiata
in Kenya as per relevant technical orders.

Species	Age/dominant height in meters	Pruning height from ground level	Number of stems/ha to be pruned	
			Sawtimber/ plywood	Pulp- wood
C. lusitanica	2 years	1/2 height but not over 2 meters	All stems	All stems
	4 years	1/2 height but not over 4 meters	All stems	All stems
	9.25 meters	2/3 tree height	533 stems	All
	11.25 meters	2/3 tree height	533 stems	N/A
	13.75 meters	2/3 tree height Minimum 9 meters Maximum 11 meters	533 stems	N/A
P. patula	3 years	1/2 height + 1 whorl	All	N/A
	4 years	1/2 height + 1 whorl	N/A	All
	8 meters	1/2 height + 1 whorl	600	N/A
	12 meters	1/2 height + 1 whorl	600	N/A
	16 meters	10 meters	600	N/A
P. radiata	3 years	1/2 height + 1 whorl	All	All
	12.0 meters	1/2 height + 1 whorl	426	All
	17.5 meters	1/2 height + 1 whorl	426	N/A
	24.5 meters	1/2 height + 1 whorl	213	N/A

mostly in support (De Villiers et al., 1961, Hiley 1959, Fenton 1972, Lewis 1964). Due to changing management objectives, Craib's management recommendations have been revised in South Africa to suit specific objectives, such as production of pulpwood or to improve on timber quality. For further discussion on these, the reader is referred to Kotze (1960) and De Villiers et al. (1961).

The thinning regimes adopted in Kenya compare closely with those of South Africa. However, while thinning regimes for the latter are tied down to specific site quality classes, those for Kenya are for an average site consequent on the lack of a means of assessing site quality classes. Thinning regimes for Kenya can therefore be considered as a compromise between the thinning regimes for the poorest and best site quality classes in South Africa, with some adjustments for the higher rates of growth in Kenya. These are shown on Table 5 for sawtimber and plywood and Table 6 for pulpwood.

In general, sawtimber crop is considered mature for clearfelling when the mean stand DBH is 48 cm while for plywood, final mean stand DBH is 51 cm. Rotation age for pulpwood plantations varies but is usually between 15 to 20 years.

4. Silvicultural Problems Related to Ecological Features of Exotic Plantations in Kenya

Before the silvicultural problems of stand management in Kenya can be discussed, it is worthwhile to mention a few ecological features which are peculiar to these plantations as these have a direct bearing on the problems:

TABLE 5*: Basic thinning schedules for sawtimber and plywood crops for the
three major plantation species in Kenya.

Species	Treatment	Dominant height or age at thinning	Stem/ha after thinning	
			No.	% of planting
C. lusitanica	Planting		1,600	
	1st thinning	11.25 meters but not before age 6 years	888	55.5
	2nd thinning	5 years after 1st thinning	533	33.3
	3rd thinning	10 years after 1st thinning	355	22.2
	4th thinning	15 years after 1st thinning	266	16.6
P. patula		Before 1981	1,600	
	Planting	After 1981	1,110	
	1st thinning	16 meters	600	54.0
	2nd thinning	5 years after 1st thinning	400	36.0
	3rd thinning	10 years after 1st thinning	250	22.5
	4th thinning	15 years after 1st thinning (plywood planta- tions only)	170	15.3
P. radiata	Planting		1,600	
	1st thinning	12 meters	853	53.3
	2nd thinning	17.5 meters	426	26.6
	3rd thinning	7 years after 2nd thinning	266	16.6
	4th thinning	13 years after 2nd thinning	213	13.3

*Data from the respective technical orders.

TABLE 6: Basic thinning schedules for pulpwood crops for the three major plantation species in Kenya.

Species	Treatment	Age or dominant height at thinning	Stems per hectare after thinning	
			No.	% of planting
C. lusitanica	Planting	–	1,322	
	clearfelling	15-20 years	–	–
	or			
	thinning	15 years	840	63.5
P. patula	Planting:			
	before 1981		1,322	
	after 1981		1,110	
	1st thinning (old plantations)	12 years	980	74.1
	New plantations	–	No thinning	
P. radiata	Planting	–	1,322	
	Clearfelling	15-20 years		
	or			
	Thinning	15 years	880	66.6

1. The plantations are monocultures, meaning there is only one
   species in a given stand.

2. The species have only recently been introduced to Kenya, so
   that they have not yet fully adapted themselves to the new
   environment.

3. The stands are even-aged, so that there is only one stratum in
   terms of spatial distribution.

4. The species are usually very fast growing so that the rate of
   nutrient impoverization through tree harvest may be very
   rapid.

The above ecological features implies that these man-made ecosystems
are very fragile and ecologically immature so that they are very
susceptible to pest outbreaks. In particular, the following problems
have been identified in Kenya.

Diseases: Two important fungal diseases have been identified in
Kenya plantations:

1. Cypress canker disease, caused by a parasitic fungus
   Monochaetia unicornis (Cook and Ellis) Sacc. It is not known
   if this fungus was present in Kenya or if it was introduced.
   The fungus causes lesions on the stem of cypress trees,
   especially Cupressus macrocarpa Hartw. but has been known to
   affect C. lusitanica to a smaller degree. This disease was
   responsible for stoppage of any further planting of
   C. macrocarpa despite the fact that it was the more superior
   species in terms of tree growth.

2. Dothistroma pini species, another parasitic fungus, was responsible for the cessation of all planting of P. radiata in 1961 when the fungus was discovered, apparently having been introduced into Kenya from elsewhere. This disease is known to weaken the trees and sometimes kill them at a young age between 5 to 15 years. After that age, most trees not already killed recover and start to grow normally again. Attempts to control the disease are still in progress in Kenya.

Another fungus of minor economic importance is the universal Armillaria mellea in both C. lusitanica and pine plantations.

Insect: Among the important insect pests is the newly introduced woolly aphid, a Pineus species which attacks mostly pines. This insect attacks young twigs and needles, weakening the trees and eventually killing them. Another important insect is the Oemida gahani Distant which enters heartwood of living C. lusitanica trees through pruning or injury scars, thus degrading the quality of the logs.

Rodents and big game damage: Rodents, including moles and rats find the bark of the young softwood plants especially palatable. Similarly, big game such as elephants, buffaloes and Sykes monkeys are a continuous problem in forest plantations, either by pushing over the trees or by feeding on the succulent bark.

Fire problems: As indicated on the ombrothermic diagrams of Figure 2, January and February are usually the driest months of the year in most areas of the highlands. Numerous forest fires do occur, mostly

originating from honey hunters and causing considerable damage to forest plantations.

Soil degradation: Although no study has been done to determine if soil fertility will decrease in successive rotations, evidence from Southern Australia on P. radiata (Keeves 1965) and from Swaziland on P. patula (Evans 1975) indicate that yield in successive rotations can be expected to be lower. This is as expected due to the fact that a large quantity of organic matter and mineral nutrients are removed when harvesting the trees.

All the above problems presents a very difficult challenge to forest management, especially as new problems are continuously arising. Nonetheless, the advantages of even-aged monoculture plantations mitigate, the problems. In view of the limited forest area in Kenya, the very high yield obtainable from plantations makes the investments in forest protection worthwhile.

5.   Permanent Sample Plots

5.1   The permanent sample plot program in Kenya

Objective

The permanent sample plots (hereafter refereed to as p.s.p's) establishment program was initiated in Kenya in 1964 for all three species: C. lusitanica, P. patula and P. radiata. The main objectives of the program were:

1. To obtain information on growth rates of these species under the climatic and edaphic conditions prevailing in Kenya.

2. To obtain information on the yield of these species under the silvicultural practices obtaining in Kenya.

3. To provide a basis for the development of plantation management guide.

Plots distribution and layout in the field

All the p.s.p's are located in the major geographical regions where these species are planted in Kenya. In order to give a clear picture of the growth pattern, the original p.s.p's were established in 5, 10, 15, 20, 25, 30 and 35 year old plantations. The number of plots in each age class was proportional to the total area of that class so that the larger the area for a given age class, the higher the number of plots. Similarly, the larger the area for a given species, the higher the number of plots allocated to it. The whole idea of distributing plots in 5 year age intervals was that after 5 years of continuous measurements, the growth pattern for the whole rotation would be known. Within a given age class, the distribution of the plots was based primarily on the basis of plantation stratification into site types, geographical regions and climatic factors: mainly rainfall distribution.

Due to technical and financial problems, the initial sampling intensity within a given age class was 2 plots per 50 hectares. Within the selected plantation, the location of the plot was subjective. The plots size was 0.04 hectare (.25 acre) and circular in shape. Since the

initial establishment, many more plots have been established using the same procedures (see Table 7).

Ideally the p.s.p's should be marked as inconspicuously as possible so that they do not receive preferential treatments during thinning or pruning operations. For practical purposes however, and ease of reloca- tion, the plots are clearly marked on the ground. This may point to a possibility that the plots may be receiving different treatments from the rest of the plantation. However, this possibility is minimum since treatments in the plantations are supervised by the forest officer-in- charge of the forest district.

Plot measurements and preliminary data analyses

Two main plot parameters are measured annually:

1. Diameter at 1.3 meters above ground, referred to as diameter at breast height or DBH. This is measured for all trees on the plot to the nearest 0.1 cm with a diameter tape.

2. Stand dominant height, defined as the mean height of the 100 largest diameter trees per hectare, is measured for each plot. This is accomplished by measuring the height of the four largest diameter trees on the plot. In the past, such instru- ments as Haga and Blume-Leiss hyposometers have been used but currently, the Suunto clinometer is in use.

The measuring of p.s.p's is usually timed for just before the thin- ning operations start. This timing is crucial since the measurements of trees removed in a thinning are taken as those at their previous years measurement.

Under an agreement between the Kenya government and the Common-wealth Forestry Institute, Oxford University, all the basic p.s.p. data is sent to the latter for further calculation, processing and storage on computer tapes. The following information on p.s.p's is available for up to and including 1979:

1. **For Main Crop**:

    (a) Age at time of thinning

    (b) Number of stems per hectare

    (c) Mean DBH of the stand (in cm)

    (d) Dominant height of the stand (in meters)

    (e) Basal area per hectare (in square meters/hectare)

    (f) Stand density indices

    (g) Volume of the stand in cubic meters per hectare. This is obtained using the tree volume equations for the respective species (see Chapter 3).

2. **For Thinnings**:

    (a) Number of stems removed per hectare

    (b) Basal area removed (in square meters/hectare)

    (c) Volume removed (in cu.meters per hectare) calculated as for main crop.

3. **For Total Production**:

    (a) Total basal area production in sq.meters per hectare

    (b) Total volume production in cu.meters/hectare

    (c) Current annual volume increment

    (d) Mean annual volume increment.

Table 7 shows a summary of the basic p.s.p. data for up to 1979.

TABLE 7: Summary of the permanent sample plot data

| | | S P E C I E S | | |
		C. lusitanica	P. patula	P. radiata
No. Plots		163	176	164
Remeasurements		1,413	1,452	1,625
	Minimum	4.7	3.6	5.5
Age in Years	Mean	17.4	12.5	13.6
	Maximum	43.6	27.7	34.6
	Standard deviation	8.6	4.9	5.4
	Minimum	4.3	3.8	5.3
Dom. Height	Mean	20.2	19.0	24.2
in m.	Maximum	39.4	37.3	51.2
	Standard deviation	7.2	6.7	8.8
	Minimum	12.1	8.4	7.9
Hart's Density	Mean	21.4	20.2	16.6
Index	Maximum	74.9	57.0	168.8
	Standard deviation	5.0	6.8	9.7

5.2 Permanent sample plots data as a basis for growth and yield studies

In general, growth and yield studies are based on data obtained

from either permanent sample plots (cf. continuous forest inventory),

temporary sample plots, or on a combination of both. When temporary

sample plots are used, greater error can be expected since the effects

of past stand treatments and variation in growth over time are not taken

into account. In regions where annual growth rings are a standard

feature of tree growth, the problems of temporary samples are overcome

through stem analysis procedure. Growth rings in the exotic species in

Kenya are usually a reflection of seasonal fluctuations in rainfall

rather than annual growth and so are unreliable as a guide to past tree

growth. Permanent sample plots are therefore the only suitable source

of data for growth and yield studies in these plantations.

5.3 Problems associated with permanent sample plot data

General problems

The problems associated with p.s.p. data have been discussed by

several authors, including Vuokila (1965) and Adlard (1974). These can

be summarized as follows:

1. Mensurational errors (also common to all sample plot systems).
    These include sampling errors in terms of plot distribution by
    age classes, site classes, etc. and measuring errors that may
    occur due to use of faulty measuring equipment or techniques.

2. Problems associated with plot management. These include
    failure to relocate the plots in the field, to re-identify
    individual trees in the plot or differential treatment of the

plots in relation to the rest of the plantations (see 5.1 above).

3. Problems inherent in the p.s.p. system itself. The main problems inherent in the p.s.p. system arises from accidental damage to the plot or elements in the plots e.g., damage to individual trees from game, diseases or insects.

These problems results in errors of varying magnitude in the final parameters estimated from the data. Barring the possibility of sampling errors, the results of measuring errors are in general minimal,and in the long run,of a random nature. Similarly, possibility of failure to relocate plots in the field is very remote in Kenya as the plots are clearly mapped on the plantation maps, while differential treatment of p.s.p's is minimized through staff supervision.

The problem of autocorrelation in p.s.p. data

One of the important assumption underlying the use of regression analysis – the principle data analysis precedure in this study – is that the residuals are independent. For example in the usual regression model:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \ldots\ldots \beta_p X_{ip} + \epsilon_i \ldots\ldots\ldots\ldots\ldots\ldots \quad 1.1$$

where

Y_i = Dependent variable

$X_{i1}, X_{i2} \ldots X_{ip}$ = Independent variables

$\beta_0, \beta_2 \ldots \beta_p$ = Regression parameters to be estimated

ϵ_i = A normally distributed error with mean zero and variance = σ^2,

it is assumed that the individual error (ε_i) for a given observation is independent and not predictable from the error of any other observation. When this assumption is violated, autocorrelation is said to exist. This problem often occurs with permanent sample plots data due to repeated measurements being taken on the same sample plot.

The general theory on the problem of autocorrelation has been discussed in detail by Durbin and Watson (1950) and Johnston (1960). With respect to application in forestry, the problem has been recognized and handled in different ways by different researchers working on growth and yield studies. For example, Buckman (1962) working on growth and yield of red pine (Pinus resinosa Ait) in Minnesota recognized the problem but went ahead and used ordinary least squares regression method in the hope that the error involved was not large. Similarly, Curtis (1967) recognised this problem with Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) volume measurements from permanent sample plots. He went ahead and used ordinary least-squares procedure but took care of the problem through an ad hoc procedure involving testing for significant correlation between any two contiguous observation on each plot.

A more detailed study on correlated errors was carried out by Sullivan and Clutter (1972). Using permanent sample plot data for Loblolly pine (Pinus taeda L.), they compared two yield models, one developed by the ordinary least-squares procedure and the other by the maximum likelihood estimating procedure, the latter being one of the possible methods of overcoming the weaknesses of ordinary least squares procedure when autocorrelation exists. The results of this comparison

indicated that for all practical purposes, the two models were the same. Because of the difficulty involved in estimating parameters using the maximum likelihood procedure (using iterative procedures), Sullivan and Clutter wondered if it was worth the effort. These sentiments agreed with those of Swindel (1968) who had addressed the same problem and come to the conclusion that ordinary least-squares should be given due consideration for parameter estimation because of its simplicity, especially when parameter estimates rather than confidence intervals are the main interest.

A more recent example of the application of the maximum likelihood estimators of parameters for linear models when the error components are correlated due to having repeated measurement on plots is provided by Seagrist and Stanford (1980). This example serves to demonstrate the difficulty involved in using this procedure for parameter estimation. From a review of the literature, it may be stated that, to date, there is no simple procedure for handling the problem of autocorrelation in linear regression models and that further research is required in this area. The view adopted in this study is that the problem of autocorrelation may exist in the permanent sample plots data but no effort will be expended to resolve it because of the simplicity of the ordinary least-squares procedure.

6. Study Methods

The basic procedure in growth and yield studies involve derivation of the growth or yield function. The principle tool adopted for parameter estimation for the functions in this study is the ordinary

least-squares procedure for both linear and nonlinear regressions.
Wherever possible, nonlinear models were preferred to linear models for
reasons given later in Chapter 2).

The ordinary least-squares method for the estimation of the regres-
sion parameters for the linear models are detailed in many books on
mathematics and statistics. In particular, Draper and Smith (1981, 2nd
edition) have given detailed procedures for fitting linear and nonlinear
regression models. Wherever linear models are used in this study,
rigorous regression analysis and study of residuals have been performed
to ensure that regression analysis assumptions are met and that the
model was appropriate for the data. However, not all details of the
analysis are shown and in most cases, only the relevant statistics are
presented.

In addition to regression analysis, tests of regression bias were
performed and individual functions validated using independent data
(data not used in deriving the functions) wherever possible. These
independent data were created by setting aside 20 randomly selected
plots for each species. Finally, in nearly all cases, graphical or
tabular presentation of the results from the derived function were
studied to ensure that the function performance is consistent with
expectation. It should be mentioned here that the major criteria in the
choice of variables entering a given function was their having a
biological meaning in the function.

In this study, nonlinear equations were fitted using the nonlinear
least-squares subroutine P:3R of the BMDP developed by the University of
California in Los Angeles. The routine estimates the model parameters

iteratively by minimizing the sums of the squared error of prediction using the Gauss-Newton iterative procedure. The subroutine requires that the function and the first partial derivatives (with respect to the parameters to be estimated) be specified and the initial estimates of the parameters be supplied. Further details on BMDP are contained in the BMDP manual. The simulation procedure used for model construction is discussed in Chapter 3.

CHAPTER 2

STAND DEVELOPMENT AND GROWTH FUNCTIONS

1. Height Development and Site Index Curve Construction

1.1 Introduction

Site in forestry terminology refers to the interaction of both the physical and biological factors determining the productive capacity of an area for a given tree species (or its provenance or variety). Because of the large number of combinations of physical factors and biological factors of a species, there is therefore almost an infinite number of sites. In practice however, sites are recognised for a given tree species (and or its provenance or variety) within a given area within which the environmental conditions are considered more or less homogeneous.

Over the years, several methods of quantifying site have been developed. Spurr (1952), Husch et al. (1972) and many other authors have detailed the different methods, all of which can be grouped into two categories:

1. Those based on site factors considered closely associated with yield: examples are the indicator plant approach developed by Cajander in Finland (Ilvessalo 1927) and the environmental factors approach, using climatic factors, soil factors, fauna and vegetation (Spurr (1952), Husch et al. (1972) and others).

2. Those using stand characteristics as phytometers. Examples are use of volume yield or the expected mean annual volume

increment at a predetermined reference age (Hamilton and
Christie 1971) and the use of stand dominant height with or
without reference to a predetermined age.

In general, the second category has been the most widely used.
This can be attributed to the widely accepted assumption that the
various site factors affecting the growth of a given tree species can be
quantified in their influence on stand characteristics.

Between the two stand characteristics most widely used to quantify
site, volume appears the most logical in that it is usually the primary
interest in forest management. Its main drawback is that volume yield
can be influenced by silvicultural treatments such as thinning and
initial spacing. As a result, the most widely used procedure in growth
and yield studies has been to derive the height over age and age over
total volume yield relationships for various sites. When this relation-
ship is known, height may be used to estimate total volume yield (Crawe
1967). The objective of this section is to investigate the height over
age relationship for the three species: C. lusitanica, P. patula and
P. radiata in Kenya.

The stand dominant height as used in this study is defined as the
mean height of the 100 largest diameter trees per hectare (Hummel 1953).
This is preferred to stand mean height as it is little affected by stand
treatment, especially low thinning. However, it should be noted that
this assumption may not always hold, for example in the case of high
thinning (an exception in Kenya thinning practice) and in situations
where the dominant trees might die of disease or insect attack or other
factors.

The basic assumption underlying use of dominant height over age relationship for site classification is that a stand of a given age and height will always yield the same total volume on a given site if the site remains unchanged. This assumption will be valid provided that the supposition that total volume yield is not affected by the degree of thinning (Moller 1947) holds. However, it is not known if this supposition holds for Kenya thinning practices.

1.2 Site Index Curve Construction

Procedure

The dominant height attained by a given forest stand at a predetermined reference age is the most widely used index of site quality and will be used in this study. To facilitate objective application of this approach, a system of height over age curves, called the site index curves is developed.

Over the years, two main methods for construction of height over age and site index curves have evolved:

1. Anamorphic curves procedure: This procedure consists of fitting one guiding curve to the height over age data, either graphically or using statistical methods, and then fitting a family of anamorphic curves above and below the guide curves at arbitrarily defined intervals. These curves assume:

(a) Constant proportionality between growth curves for all sites and stand conditions.

(b) Site quality is independent of age.

These assumptions are consistent with theory which suggests that all other factors being equal, stands on poor sites develop at a slower rate than those on better sites. Because of its simplicity, this procedure was the first to be developed and nearly all earlier site index curves were based on it. Nonetheless, these assumptions have been proven false for several species, e.g. Stage (1963), Beck and Trousdell (1973), Spurr (1955), Powers (1972), Carmean (1956), King (1966) and others. This has given rise to the second procedure:

2. <u>Polymorphic curve procedure</u>: According to Stage (1963), the polymorphic site index curve approach is a generalization of the assumption that site index is independent of age. It recognises that height over age curves for a particular species may vary in shape for different climatic regions, vegetation types, soils and other factors. For example, according to Beck and Trousdell (1973), height growth for red pine (<u>Pinus resinosa</u> Ait) on high-quality sites is rapid at first but the curve flattens while stands are still young, while height growth on low-quality sites is sustained at a slower rate for a longer period, thus justifying polymorphic curves.

From the above discussion it would appear that the discussion of anamorphic curve procedure is purely academic since it is now a well established fact that site index curves are essentially polymorphic, which vary in shape from one site to another (Rawat and Franz 1974). In practice however, the issue is not so simple. For example, the procedure used to estimate the individual plot site index in this study (discussed below) dictated that the resulting curves would be inherently anamorphic, thus necessitating further testing to support the fact.

This was especially necessary since two main factors may be expected to introduce polymorphism to height over age curves in Kenya.

1. Differences in rainfall (distribution and quantity) in different parts of the country. As mentioned in Chapter 1 Section 2, the western part of the country has one rainy season and one dry season; while the East of the Rift valley has two rainy seasons and two dry seasons during the year. This may cause differences in growth rates.

2. Differences in soil types in the different parts of the country may cause differences in growth rates.

Estimating Plot Site Index

The permanent sample plot data for site index curve construction consisted of an n by 2 matrix for each plot where n was the number of plot remeasurements for the two variable entries, age and stand dominant height. A third variable, site index for each plot was therefore required for the final site index curve equation. Figures 3, 4 and 5 shows the height over age data used in this study.

By definition, site index refers to the dominant height attained by a given stand at some arbitrarily predetermined reference age. Several factors affect the choice of this age. For example according to Curtis et al. (1974), index age should approximate the rotation age since the main interest is usually the total production over the rotation. According to Trousdell et al. (1974) however, index age should be chosen such that the period of rapid growth is completed, and should preferably

FIGURE 3

HEIGHT/AGE RELATIONSHIP FOR C. LUSITANICA PLOTS
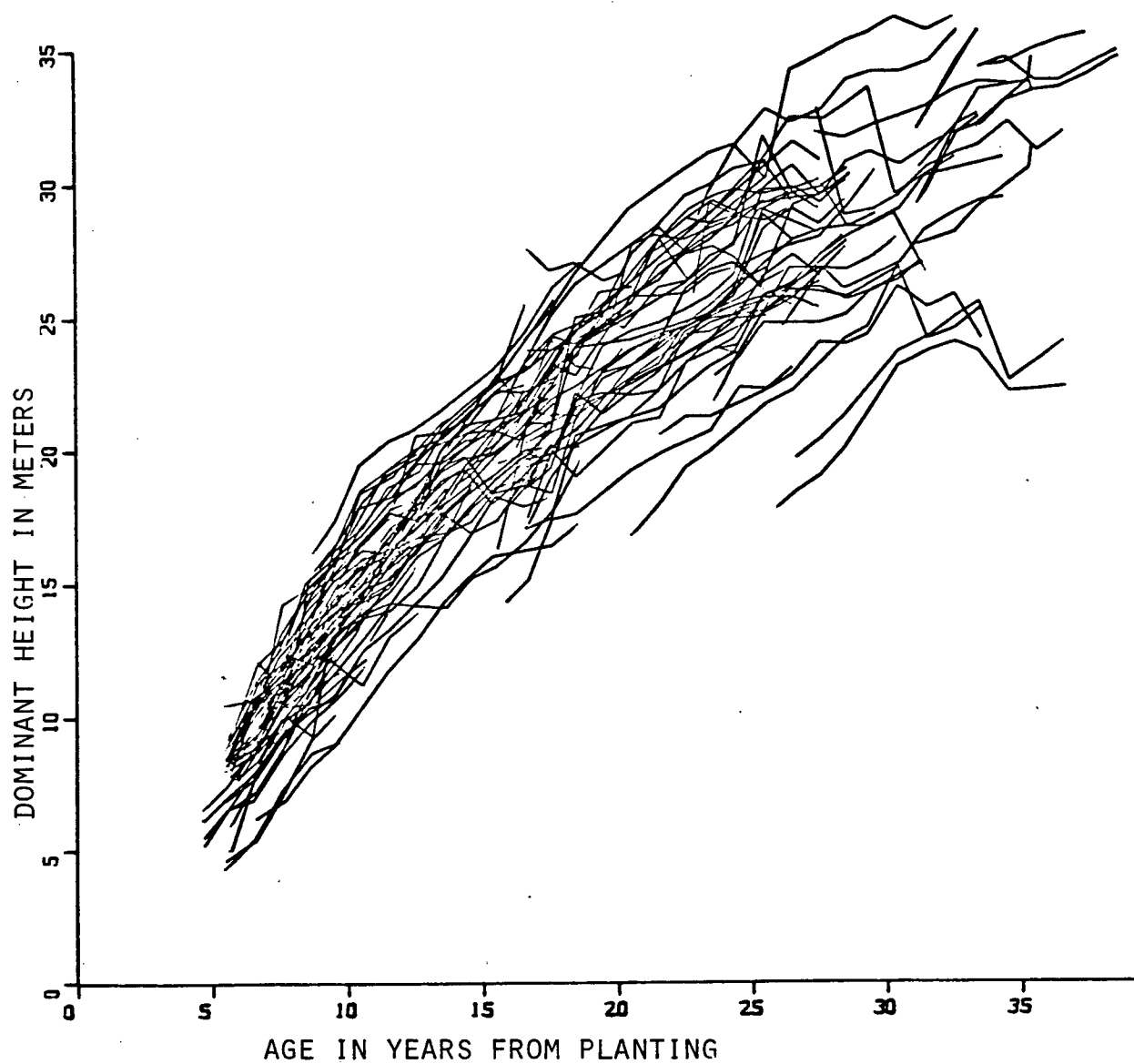
FIGURE 4

HEIGHT/AGE RELATIONSHIP FOR P. PATULA PLOTS
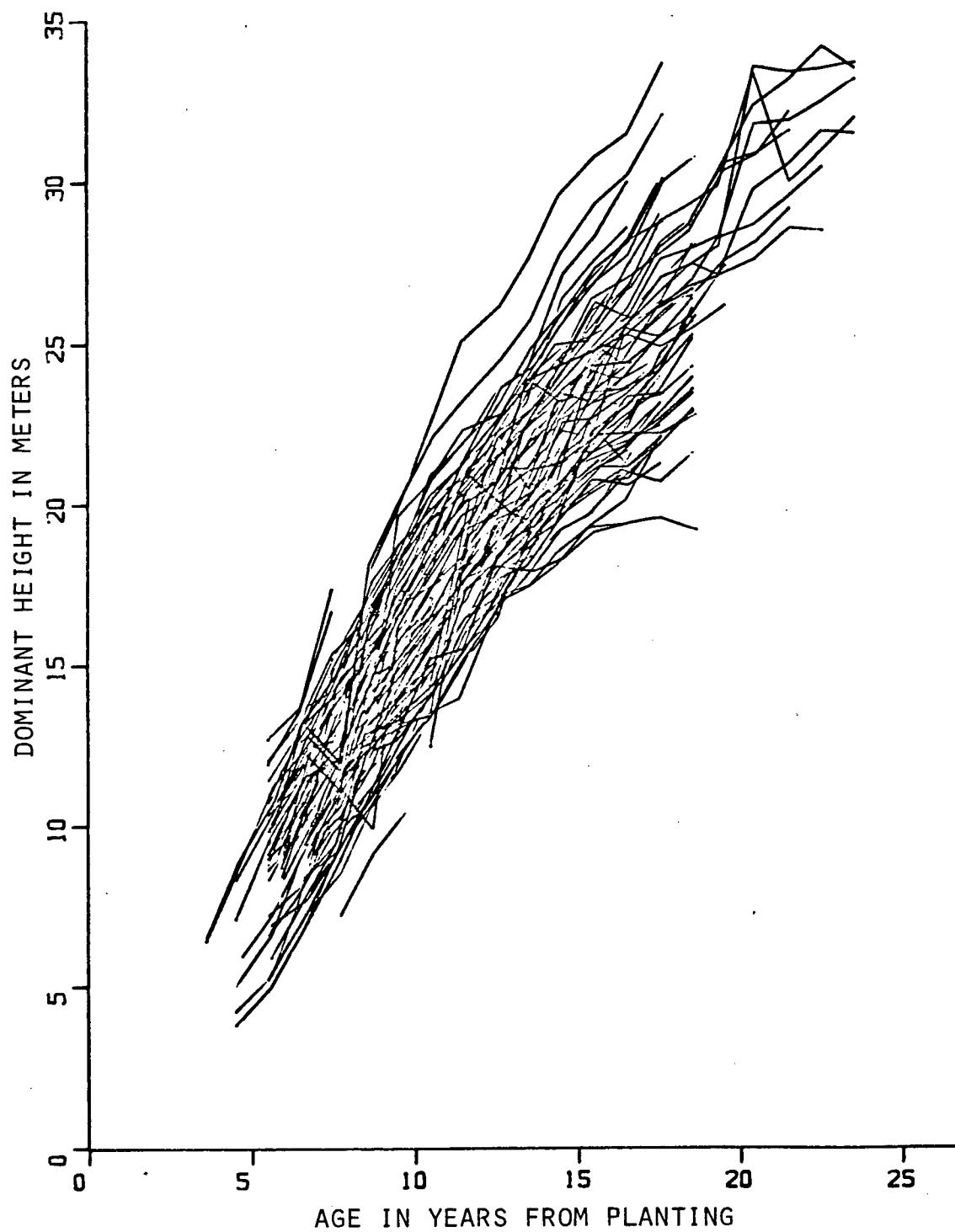
FIGURE 5

HEIGHT/AGE RELATIONSHIP FOR P. RADIATA PLOTS
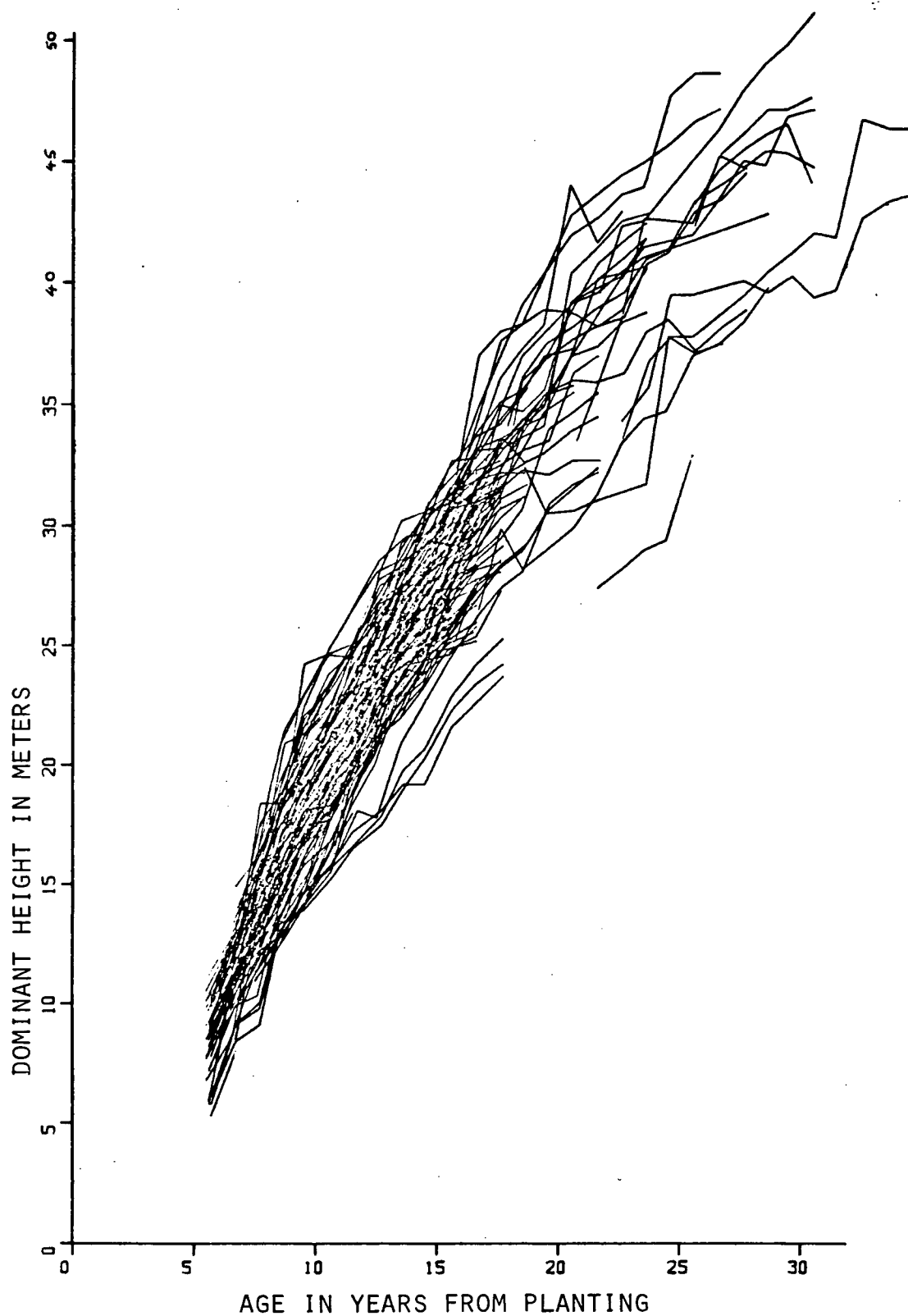
be somewhat less than the usual rotation age for the species. They recommended an index age near the average age of the stands to be predicted so as to generate the most accurate predictions.

In Kenya, the rotation age for the species covered in this study ranges between 15 years for pulpwood plantations to about 30 years for sawlog and peelerlog plantations. From the point of view of management therefore, choice of 15 years as reference age is logical as it includes the rotation age for pulpwood plantations. Other factors in favour of this choice are that at this age, the stands are high enough to have passed the juvenile stage and the age is central enough to the range of data covered in this study (Alder 1977). Site index in this study therefore refers to the dominant height attained by the stand at age 15 years.

The first step in the estimation of the individual plot site index was to fit the best linear model to the dominant height over age data for each species, with the dominant height as the dependent variable. Table 8 gives the equations, the estimated coefficients and other relevant statistics for each species.

The above equations provided the guide curve, representing the general growth trend for the respective species. Using these guide curves, the individual plot site index was estimated as follows:

TABLE 8. Coefficients for the dominant height (m) over age (yrs) linear equations

	C. lusitanica	P. patula	P. radiata
	$H_{dom} = b_0 + b_1 \log_{10} A$	$H_{dom} = b_0 + b_1 A + b_2 A^2$	
b_0	-16.0380	-1.0064	-4.5323
b_1	30.5460	1.8909	2.6424
b_2	-	-0.0205	-0.03337
n	1413	1452	1625
r^2 or R^2	.90	.88	.92
SEE	2.29	2.35	2.54
H(15)	19.9	22.8	27.6

At any given age, the plot site index, relative to the mean dominant height at age 15 years (H(15)) is given by:

$$S' = \frac{H_i \times \hat{H}(15)}{\hat{H}_i} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.1$$

where S' = Estimated site index corresponding to height H_i.

H_i = Plot dominant height at the given age in meters.

$\hat{H}_i$ = Dominant height in meters (corresponding to H_i) estimated from the guide curve equation.

From these estimates, the average plot site index S, is estimated as follows:

$$S = \frac{\sum\limits_{i=1}^{n} S'}{n} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.2$$

where n = number of plot remeasurements.

The resulting dataset for each plot is an n by 3 matrix:

Age	Height	Site Index
a_1	h_1	S
a_2	h_2	S
.	.	.
.	.	.
.	.	.
a_n	h_n	S

where column 3 is the same number for each plot. Figure 6 illustrates this procedure diagrammatically using the equation for C. lusitanica.

FIGURE 6

SITE INDEX ESTIMATION PROCEDURE FOR <u>C. LUSITANICA</u>
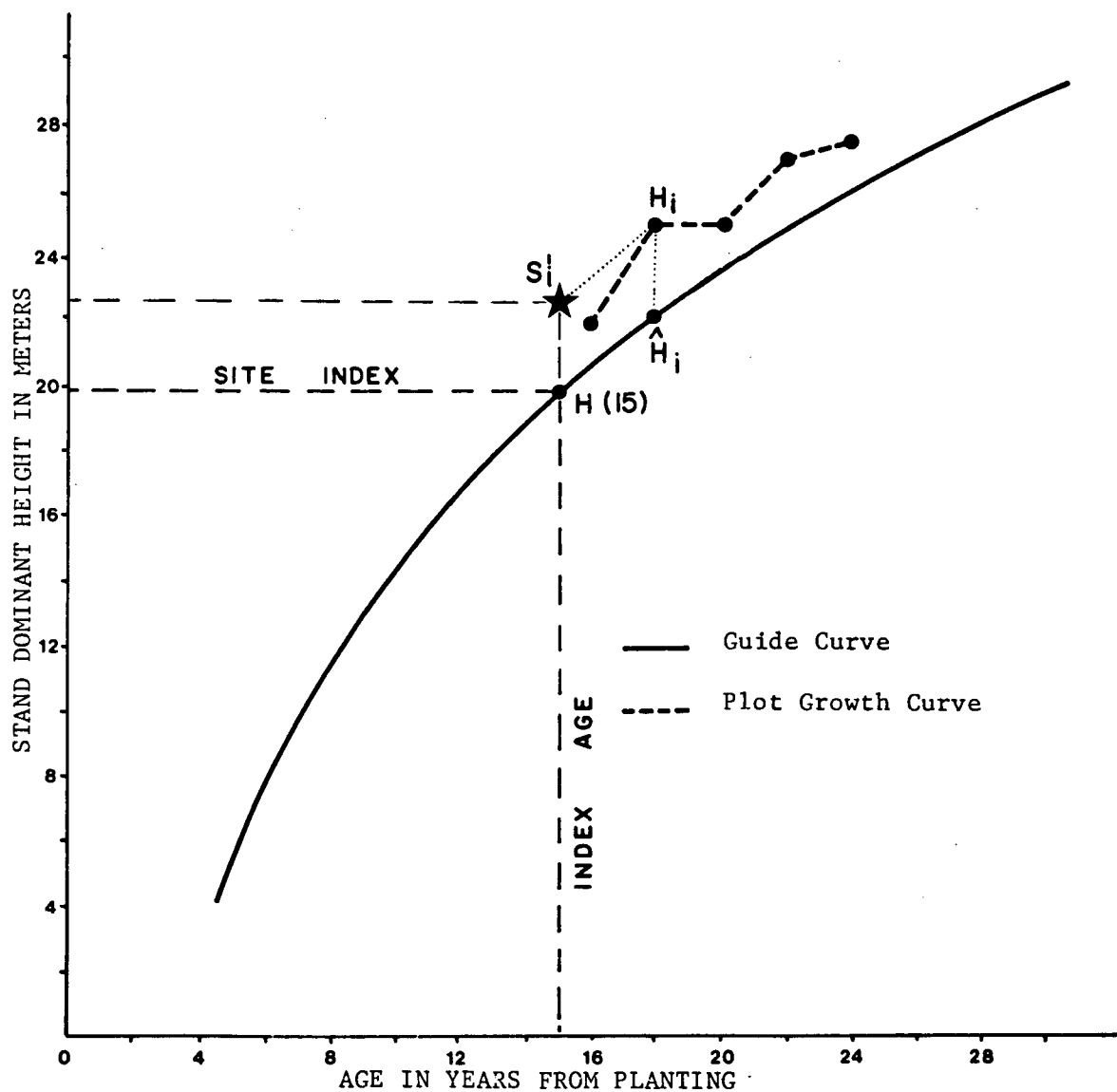
Choice of the Height Over Age Model

Forestry literature has numerous examples of height over age growth

models, both linear and nonlinear. The linear models are of the general

form:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 \ldots \beta_p X_p + \varepsilon_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.3$$

where Y = dependent variable.

X_1, $X_2 \ldots X_p$ = Independent variables.

β_0, $\beta_1 \ldots \beta_p$ = Regression parameters to be estimated.

ε_i = A normally distributed error with mean zero and variance σ^2.

The term linear implies that the model is linear in parameters.

This family of models has been widely employed in the past to describe

height over age relationships. Examples are provided by Meyers (1940),

Schumacher (1939), Trorey (1932) and others. Schumacher's equation was

used for height over age relationships for the exotic timber species in

East Africa (Alder 1977).

In general, the linear models are easy to develop and to apply and

often fit the data best. However, they are not always the most appro-

priate. For example, the height over age curve of an individual tree or

a forest stand is known to be a typical biological growth curve: Sigmoid

in shape, starting at the origin and increasing monotonically to an

inflection point, and then approaching the asymptote, determined by the

genetic constitution of the individual tree or stand and site factors.

From a theoretical standpoint therefore, linear models are inappropriate

since they do not satisfy the biological principles of the growth

process.

One example of nonlinear models has general form:

$$Y = e^{(\beta_0 + \beta_1 X^{\beta_2} + \varepsilon)} \quad \dotfill \quad 2.4$$

where β_0, β_1 and β_2 are the parameters to be estimated.

X is the predictor variable.

The term nonlinear implies that the function (2.4) is nonlinear in parameters and cannot be linearized through transformations. In general, most nonlinear models used in growth and yield studies conform to the theoretical laws of biological growth and are flexible, thus permitting changes in shape, form and scale of the curves to fit the data of interest. In addition, they provide a basis for formulation of general hypotheses that express the underlying laws of growth. This, according to Pienaar and Turnbull (1973) provides a justification for extrapolation beyond the range of conditions represented by the data.

For height over age curves, the most popular nonlinear model has been the Chapman-Richard's equation in the form:

$$H = b_0(1 - e^{-b_1 A})^{b_2} \quad \dotfill \quad 2.5$$

where H = Stand height.

A = Age of the stand.

b_0, b_1 and b_2 are the coefficients to be estimated.

This function is a generalization of Von Bertalanffy's growth model (Richards 1959) where some of the parameters have a physiological interpretation such that b_0 represents the biological site potential or maximum height attainable on a given site, while b_1 represents the stand growth rate, b_2 is related to b_1 value such that

$$\frac{b_1}{|\ln b_2|} = \text{culmination age of the current annual increment.}$$

The application of this model to forestry was popularized through the work of Pienaar and Turnbull (1973), when they demonstrated its application to basal area growth. It now forms the basis for most height over age curves in North America. Examples are Hegyi et al. (1979), Trousdell et al (1974), Beck (1971), Brickel (1968) and others.

Another nonlinear model that is increasingly attracting interest in growth and yield studies is the modified Weibull function in the form:

$$H = b_0(1 - e^{-b_1 A^{b_2}}) \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad 2.6$$

where H = Stand height.

A = Age of the stand.

b_0, b_1 and b_2 are coefficients to be estimated.

The coefficients b_0, b_1 and b_2 have the same interpretation as for Chapman-Richard's equation. This function was developed by Weibull (1939, 1951) as a probability distribution function of the form:

$$F = 1 - e^{-(\frac{x}{\sigma})^{\lambda}} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad 2.7$$

where F = Frequency for a given class of interest.

   X = Class size.

   σ = A scale parameter.

   λ = A shape parameter.

As a probability distribution function, this model has been used in forestry to model tree diameter distribution, basal area, surface area etc. By introducing an expanding factor (α) to the model, Yang et al. (1978) demonstrated that the modified form:

$$F = \alpha (1 - e^{-(\frac{x}{\sigma})^{\lambda}}) \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad 2.8$$

performed as a highly flexible, monotomically increasing sigmoid curve with very desirable growth characteristics such as passing through origin when age is zero, having an inflection point and tending to an asymptote as age increases. For height over age curves in this study, both the Chapman-Richard's equation 2.5 and the modified Weibull equation 2.6 were tested to determine the most appropriate.

Comparing the Two Models

Both equations 2.5 and 2.6 were applied to the height over age data for each of the three species.

The results are given on Table 9a, b and c which shows:

   1.   The estimated parameters for each model.

TABLE 9. Comparison of the Modified Weibull and Chapman-Richard models for height over age curves

Equation	Coefficients			r^2	SEE	Mean bias in meters by age classes		
	b_0	b_1	b_2			<10 years	10-20 years	>20 years
C. lusitanica								
a) Chapman-Richards (2.5)	36.1960	-.06092	1.2005	.89	2.40	-.14	.11	-.05
Weibull (2.6)	36.4873	-.03905	1.0978	.89	2.40	-.23	.17	-.05
n = 1201						(802)	(448)	(451)
P. patula								
b) Chapman-Richards (2.5)	54.9478	-.04249	1.1650	.89	2.36	-.07	-.02	.37
Weibull (2.6)	51.1519	-.02707	1.1399	.89	2.36	-.04	-.02	.41
n = 1231						(457)	(680)	(94)
P. radiata								
c) Chapman-Richards (2.5)	55.2035	-.06871	1.5531	.92	2.56	.14	-.15	.27
Weibull (2.6)	52.3892	-.01997	1.3414	.92	2.56	.09	-.10	.23
n =						(406)	(843)	(170)

2. Number of remeasurements on which the parameters are based.

3. The standard error of estimate defined as:

$$SEE = \sqrt{\frac{\sum\limits_{i=1}^{n} (H_i - \hat{H}_i)^2}{n - p}} \qquad \dotso \qquad 2.9$$

where p = Number of parameters estimated in the model.

n = Total number of observations.

H_i and $\hat{H}_i$ are the observed and predicted dominant heights.

4. Coefficient of determination for each model, estimated as:

$$r^2 = \frac{TSS - RSS}{TSS} \qquad \dotso \qquad 2.10$$

where TSS = Total sums of squares

$$= \sum\limits_{i=1}^{n} (H_i - \bar{H})^2$$

RSS = Residual sums of squares

$$= \sum\limits_{i=1}^{n} (H_i - \hat{H}_i)^2$$

where H_i, $\hat{H}_i$ and $\bar{H}$ are the observed, predicted and the

mean of observed stand dominant height.

5. The mean bias by arbitrarily defined age classes:

<10 years, 10-20 years and >20 years. The mean bias was

calculated as:

$$B = \sum_{i=1}^{n} (H_i - \hat{H}_i)/n_j \quad \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \quad 2.11$$

where n_j = Number of observations in age class j,

H_i and $\hat{H}_i$ are as above.

Number of remeasurements within each age class are shown

in brackets.

As seen from Table 9, both models gave identical results for each species, based on coefficient of determination or standard error of estimate. Similarly, mean bias of age classes was negligible for both models for all three species. However, a look at the coefficient b_0 shows that for C. lusitanica, both models gave identical values. This is as expected since for both models this parameter estimates the maximum attainable height for the species. For the two pine species however, the model gave different values of b_0, that for Chapman-Richard being higher than that estimated by the Weibull function in both cases. The explanation for this is that for these two species, the data did not cover the asymptotic phase of growth and so the estimated value of b_0 cannot be very reliable. This is further confirmed by Table 10 which shows the asymptotic standard deviation for the estimated coefficients. For C. lusitanica, the asymptotic standard deviation for b_0 is much lower compared to that for P. patula and P. radiata for both models. It is worth noting that between the two pine species, the asymptotic standard deviation for b_0 is lower (for both models) for P. radiata whose data cover higher age classes than that for P. patula (35

years $\underline{P}$. $\underline{radiata}$, 25 years $\underline{P}$. $\underline{patula}$ upper age limit); see also Figures

3, 4 and 5.

Table 10 also shows that for b_0 and b_2, the Chapman-Richards

model gave lower asymptotic standard deviation than the Weibull model,

while for b_1, Chapman-Richards gave a slightly higher value for all

three species. Based on these results therefore, Chapman-Richards

equation (2.5) was selected for the height over age relationships in

this study.

TABLE 10. Asymptotic standard deviations for the estimated coefficients
          of Table 9

| Coefficient | b_0 | | b_1 | | b_2 | |
function	2.5	2.6	2.5	2.6	2.5	2.6
$\underline{C}$. $\underline{lusitanica}$	0.5737	0.9808	0.002100	0.001827	0.007812	0.02981
$\underline{P}$. $\underline{patula}$	2.7884	4.2858	0.003013	0.001032	0.004198	0.03933
$\underline{P}$. $\underline{radiata}$	0.9137	2.2989	0.001697	0.000047	0.005463	0.01084

2.5 = Chapman-Richards function.
2.6 = Modified Weibull function.

Introducing Site Index to Height Over Age Model

Having decided on the general height over age model, the next step

was to introduce site index as the second independent variable in the

equation. From theoretical considerations, one would expect that the

better the site quality, the higher would be the height growth rate.

Similarly, one would expect that the better the site quality, the higher

the expected maximum attainable dominant height. Site index was therefore introduced as a linear function of the coefficients b_0 and b_1, the coefficients associated with maximum attainable height and growth rate respectively in equation 2.5. Three equations were tested:

$$H_{dom} = b_0 S (1 - e^{-b_1 A})^{b_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.12$$

$$H_{dom} = b_0 (1 - e^{-b_1 AS})^{b_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.13$$

$$H_{dom} = b_0 S (1 - e^{-b_1 AS})^{b_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.14$$

where S = plot site index. All other symbols are as before.

For all species, equation 2.13 gave the best results in terms of mean bias by age classes and standard error of estimate, suggesting that site quality expressed itself best in its effect on growth rate. This was unexpected since as mentioned above, one would expect that site quality should also be associated with coefficient b_0 for maximum attainable dominant height, thus favouring equation 2.14. This could partly be explained as being due to lack of sufficient data in the asymptotic phase of growth, more so for the two pine species, as shown on Figures 3, 4 and 5.

Table 11 shows the parameter estimates and other relevant statistics (calculated as for Table 9) from equation 2.13 for each of the species while Table 12 gives the asymptotic standard deviations for the estimated parameters.

TABLE 11. Coefficient estimates and other statistics for the height
over age and site index equation 2.13

Species	Coefficients			R^2	SEE	Mean bias by age classes		
	b_0	b_1	b_2			<10	10-20	>20
C. lusitania	41.9764	−0.002153	1.0481	0.97	1.24	−0.04	0.26	−0.23
P. patula	52.6155	−0.002038	1.2048	0.97	1.14	−0.02	0.04	−0.31
P. radiata	61.6871	−0.001941	1.3583	0.98	1.22	−0.07	0.03	−0.15

TABLE 12. Asymptotic standard deviations for the estimated coefficients
of Table 11

Species	Coefficients		
	b_0	b_1	b_2
C. lusitanica	0.4891	0.000054	0.00253
P. patula	1.0308	0.00010	0.00190
P. radiata	0.7352	0.000092	0.001753

The estimated parameters (Table 11) appear both logical and consistent with expectation. For example, the value of coefficients b_0 and b_1 are highest for P. radiata followed by P. patula and C. lusitanica, in that order as expected. Similarly, the magnitude of estimated b_0 appear reasonable as indicated by the plot growth trends on Figures 3, 4 and 5.

The estimated coefficients of determination are very high for the three species with a standard error of estimate in the order of 1.2

meters. The mean bias by age classes is negligible for P. radiata,
while the model for C. lusitanica gives a positive bias of .26 meters
between ages 10-20 years and a negative biases of .23 meters above age
20 years. For practical purposes, these biases can be considered
insignificant. For P. patula, the bias up to age 20 years is negligible
while above age 20 years, the model gives a bias of .31 meters, which
could also be considered insignificant. The overall fit of equation
2.13 to the data therefore appeared quite satisfactory for all three
species, except for the minor biases.

Validating the Site Index Model

The site index estimation procedure used in this study was based on
a guide curve, thus presuming that height development on a given site is
proportional to height development on other sites. This implied there-
fore that the dominant height development was inherently anamorphic.

In theory, if the site index model is correct and the principle of
anamorphic height development holds, one would expect the dominant
height of a given stand to develop along the same site index curve
throughout the rotation. In other words, for a given plot, if the
proposed growth model is adequate, there should be no correlation be-
tween site index and age. In practice however, random shifts in site
index may be expected from year to year due to:

1. Climatic fluctuations from year to year.

2. Measurement errors.

3. Interruptions in dominant height development arising from:

(a) rare cases of high thinning, resulting in removal of
    dominant trees.

(b) death of dominant trees due to diseases, insect attack or
    windthrow.

In addition, if a species is composed of different provenances or
varieties, one would expect some plots to have positive and others nega-
tive correlation of site index to age, depending on the growth rate of
the particular provenance or variety in relation to the general growth
model for the species. In general, we would expect these correlation
trends to be random with respect to age and site index, while systematic
trends would indicate that the model was inadequate for the particular
species. The latter would be indicated by:

1. Plots in specific site classes showing specific correlation
   trends.

2. Plots in a given age group showing a particular correlation
   trend.

3. Plots from a given region or with a specific characteristic,
   e.g. establishment method or an identified provenance or
   variety showing a particular correlation trend.

To test for these trends, the following procedure was followed:

1. For each plot, predicted site index at each remeasurement was
   calculated by solving for S in equation 2.13 to get:

$$S = \ln(1 - (\frac{H}{b_0})^{\frac{1}{b_2}})/-b_1 A \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad 2.15$$

where ln refer to natural logarithm.

2.   For each plot, a simple linear regression of the calculated

site index on age (using standardized variables) was fitted.

The regression coefficients obtained at step 2 above for each plot

are beta weights, which are measures of the correlation coefficient be-

tween site index and age. These were studied as the index of fit for

the model for each species. Table 13 gives the total number of plots

and the number and percentage of plots which showed significant correla-

tions at .05 level.

TABLE 13.   Distribution of plots showing site index over age correlation
at .05 probability level for the three species

	Total no. plots	Total no. plots with significant correla- tion at .05 level		Correlation sign	
		No.	%	+	−
C. lusitanica	139	41	29.5	22	19
P. patula	144	54	37.5	18	36
P. radiata	148	42	28.4	19	23

Table 13 shows that of the 41 (29.5%) C. lusitanica plots with

significant correlations at .05 probability level, 22 had positive and

19 had negative correlations. A study of the distribution of these

plots with respect to site index and age showed no particular trend and

therefore these shifts could be considered random, arising from any of

the causes mentioned above. The site index model 2.13 was therefore considered satisfactory for C. lusitanica.

Similarly, of the 42 (28.4%) P. radiata plots with significant correlations, 19 had positive and 23 had negative correlations, while a study of their distribution showed no particular trend with respect to site index or age. Site index model 2.13 was therefore also considered adequate for this species.

For P. patula however, the results from the above test indicated problems. Not only did it have the highest number of plots with significant correlations; 54 (37.5%); but of these, 18 were positive and 36 negative. This raised doubts regarding the applicability of the model. Further investigation of these plots indicated the following discrepancies.

1. All the plots with significant correlations showed a definite regional bias. For example, all plots from Nabkoi group (Nabkoi, Buret, Cengalo and Timboroa) had positive correlations, while all plots from Elburgon and Kiandongoro groups had negative correlations, etc.

2. Of all the 10 plots from grassland planting sites that had significant correlations, 9 of them, all coming from the Nabkoi group had positive correlations. The lone plot with a negative correlation came from the Nanyuki group.

These discrepancies indicated the possibility of variability of height over age relationships in the different regions of the country and according to establishment methods. This called for further investigation.

Height Development On Different Establishment Sites

As mentioned in Chapter 1 Section 3 the two pine species are established on either of the two site types:

1. Grassland planting. Planting on grassland sites is done with minimum land preparation other than digging pits into which seedlings are planted.

2. Shamba planting, a highly developed taungya system which results in well cultivated fields for tree planting and ensures care of the young trees in their initial one or two years of life in the field.

On all sites previously occupied by high forest, shamba planting is the only method of plantation establishment. Grassland sites on the other hand can either be converted to shambas before tree planting or planted as grasslands. However, the current practice is to plant grassland sites simply as grasslands. To date, the effects of establishment site on the growth and yield of plantations are not known although the general opinion is that they affects growth only in the first few years of the plantation life. This section of the study examines the effects of establishment site on height development for the two pine species between ages 5 to 20 years (the age range covered by grassland plots).

Data Analysis and Procedure

All the grassland plots for P. patula except one came from Nabkoi and Turbo regions. Analysis for this species was therefore limited to plots from these two regions. Grassland plots for P. radiata were

distributed over the whole range where the species is grown. The number of plots and total number of remeasurements for each species are shown on Table 14.

For data from each establishment site, the best height over age linear equation:

$$H_{dom} = b_0 + b_1A + b_2A^2 \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad 2.16$$

where H_{dom} = Plot dominant height in meters.

A = Stand age from planting in years.

b_0, b_1 and b_2 are regression coefficients to be estimated.

was computed and covariance analysis carried out to determine whether the differences in the regression coefficients between the two establishment sites could be ascribed to sampling error or to real differences between the establishment sites. This was accomplished using the U.B.C. S:SLTEST routine (Chinh 1980) to test the hypothesis that the regression coefficients b_1 and b_2 are identical among the two establishment sites and if not rejected, to test the hypothesis that a common equation can be used. The latter tests whether the intercepts (b_0) are equal, given that the regression coefficients are equal. Table 14 gives the results of this analysis while Figure 7 shows the height over age curves for each species by establishment site. For statistical theory on the tests, the reader is referred to Chinh (1980) and Kozak (1970).

TABLE 14. Covariance analysis for slope test for height over age equations for $\underline{P}$. $\underline{patula}$ and $\underline{P}$. $\underline{radiata}$ for different establishment sites

	P. patula (Nabkoi and Turbo)			P. radiata (whole country)		
	Shamba	Grassland	Common slope	Shamba	Grassland	Common slope
b_0	0.6275	-0.9087	–	-3.230	-4.5390	–
b_1	1.7560	1.8400	1.6420	2.7140	2.5940	2.7130
b_2	-0.01494	-0.02365	-0.012	-0.03779	-0.03256	-0.03800
n	137	145	282	532	878	1410
No. plots	23	25	48	38	106	144

Equation $H_{dom} = b_0 + b_1 A + b_2 A^2$

TEST HYPOTHESIS OF A COMMON SLOPE

F	1.92	0.56
F(.05)	3.00	3.00
DF(1)	2	2
DF(2)	276	1404
Probability	0.1489	0.5721

TEST HYPOTHESIS OF A COMMON EQUATION

F	49.87	171.37
F(.05)	3.84	3.84
DF(1)	1	1
DF(2)	278	1406
Probability	0.0000	0.0000

FIGURE 7

HEIGHT OVER AGE CURVES FOR DIFFERENT
STAND ESTABLISHMENT SITES
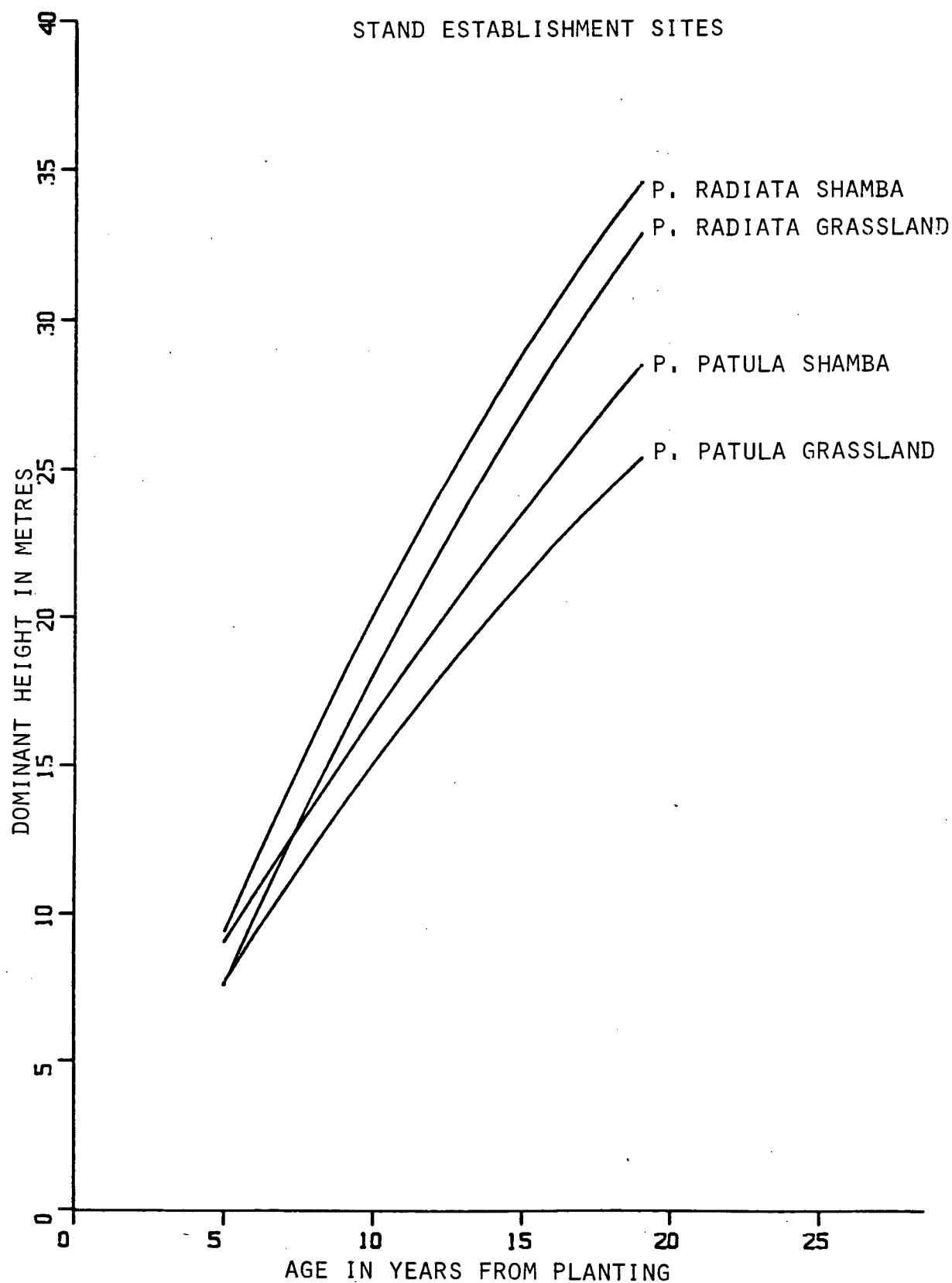
Results and Discussion

For both species, the common slope hypothesis (Table 14) is not rejected at the .05 level since the calculated F-values are less than the critical F-values. Thus, the regression surfaces for the two establishment sites may be assumed parallel for the two species. Despite this result, Figure 7 shows that while the curves for P. radiata are a constant distance from one another, the distance between the P. patula curves tend to increase with age.

The test for a common equation led to rejection of the hypothesis that the intercepts are the same for both establishment sites for both species since the calculated F-values were much higher than the critical F-values. This meant that the coefficient b_0 in equation 2.16 cannot be assumed equal for the two establishment sites, thus precluding use of a common equation.

The above results suggest that the growth rate for the two establishment sites can be assumed to be the same. For P. radiata, the growth curve for grassland sites remain about 2 meters below that for shambas for the whole period covered by the data i.e. up to age 20 years. For P. patula, the curve for grassland sites remains below that for shamba but the distance between them increases with age, though not significantly so at .05 level. This distance worked out to be 0.156 of age up to age 20 years.

The above observations that the effects of establishment sites remain throughout the life of the plantation (as suggested by the growth trend up to age 20 years) were unexpected. For example, while the initial differences can be expected due to the competition for nutrients

and moisture between the young trees and grass on grassland sites, if all other factors remained the same, one would expect that the effects would diminish with age. The unexpected results therefore point to two possibilities both of which could be operative:

1. Grassland sites may be intrinsically poorer than high forest sites.

2. There may be a factor of growth, e.g. mycorrhiza, which may be lacking or is less effective under grassland conditions.

Further investigation on the true cause of the differences in growth between the two establishment sites is needed. For example if the differences are entirely due to the initial competition, it may indicate a need to cultivate the grasslands before tree planting and subsequent weeding.

Conclusion

The most important finding from this investigation was that grassland planting results in slower height development compared to shamba planting for P. patula and P. radiata. The effects of establishment site are continued up to age 20 years. The immediate practical significance of this finding are:

1. Where the forest manager has a choice over establishment site for the two pine species, shamba planting is to be preferred.

2. Any growth and yield model for the two pine species should have establishment site as one of the input variables.

Height Development by Geographical Regions for P. patula

For this investigation, the P. patula plots were stratified into 8

groups according to the geographical regions in which they are located.

These regions conform to the inventory zones already recognized by the

Kenya Forest Department. For data from each region, equation 2.16 was

computed and the covariance analysis and F-tests performed to test the

hypotheses of common slope and common equation, as in the previous

section. Table 15 gives the results of this analysis while Figure 8

shows the resulting height over age curves for each region.

The results on Table 15 indicated an F value of 8.65 which is

significant at .05 level. This led to the rejection of the hypothesis

of a common slope, which implied that at least one of the regression

surface was not parallel to one other. This result could have been

anticipated from a study of Figure 8 which shows the curves from differ-

ent geographical regions crossing each other and growing in different

directions. Use of a single set of site index curves was therefore

considered inappropriate for this species. Because of the small number

of plots in regions 4 and 8, these regions were eliminated from further

analyses so that only six regions were considered. For the time being

however, the equation for region 3 (Elburgon) can be used to approximate

growth in region 4 (Likia) while the equation for region 1 (Nabkoi

region) can be used to approximate growth in region 8 (Timboroa), based

on geographical proximity of the regions. Table 16 shows the six

regions, their mean annual rainfall and the elevation above sea level of

the weather station.

TABLE 15. Covariance analysis for slope test for height over age equations for <u>P</u>. <u>patula</u> in different regions in Kenya

| | Geographical region | | | | | | | | Common slope |
	1	2	3	4	5	6	7	8	
b_0	−7.3550	−11.6800	−1.395	−2.4440	−7.6360	−1.8870	−3.9060	−5.9540	−
b_1	2.5250	3.9930	2.0180	1.9440	3.0950	2.0870	2.9160	2.2330	1.9720
b_2	−0.03391	−0.1063	−0.03106	−0.03127	−0.06403	−0.02598	−0.08390	−0.03160	−0.0230
n	124	108	395	16	75	175	140	35	1072
No. plots	15	9	40	2	10	22	34	4	136

Equation: $H_{dom} = b_0 + b_1A + b_2A^2$

TEST HYPOTHESIS OF COMMON SLOPE

F	=	8.65
F(.05)	=	1.70
DF(1)	=	14
DF(2)	=	1048
Probability	=	0.000

where Region 1 = Nabkoi
2 = Nanyuki
3 = Elburgon
4 = Likia
5 = Kiandongoro
6 = Kinale
7 = Turbo
8 = Timboroa

FIGURE 8

HEIGHT/AGE RELATIONSHIP FOR P. PATULA BY
GEOGRAPHICAL REGION

1 = NABKOI

2 = NANYUKI

3 = ELBURGON

4 = LIKIA

5 = KIANDONGORO

6 = KINALE

7 = TURBO

8 = TIMBOROA
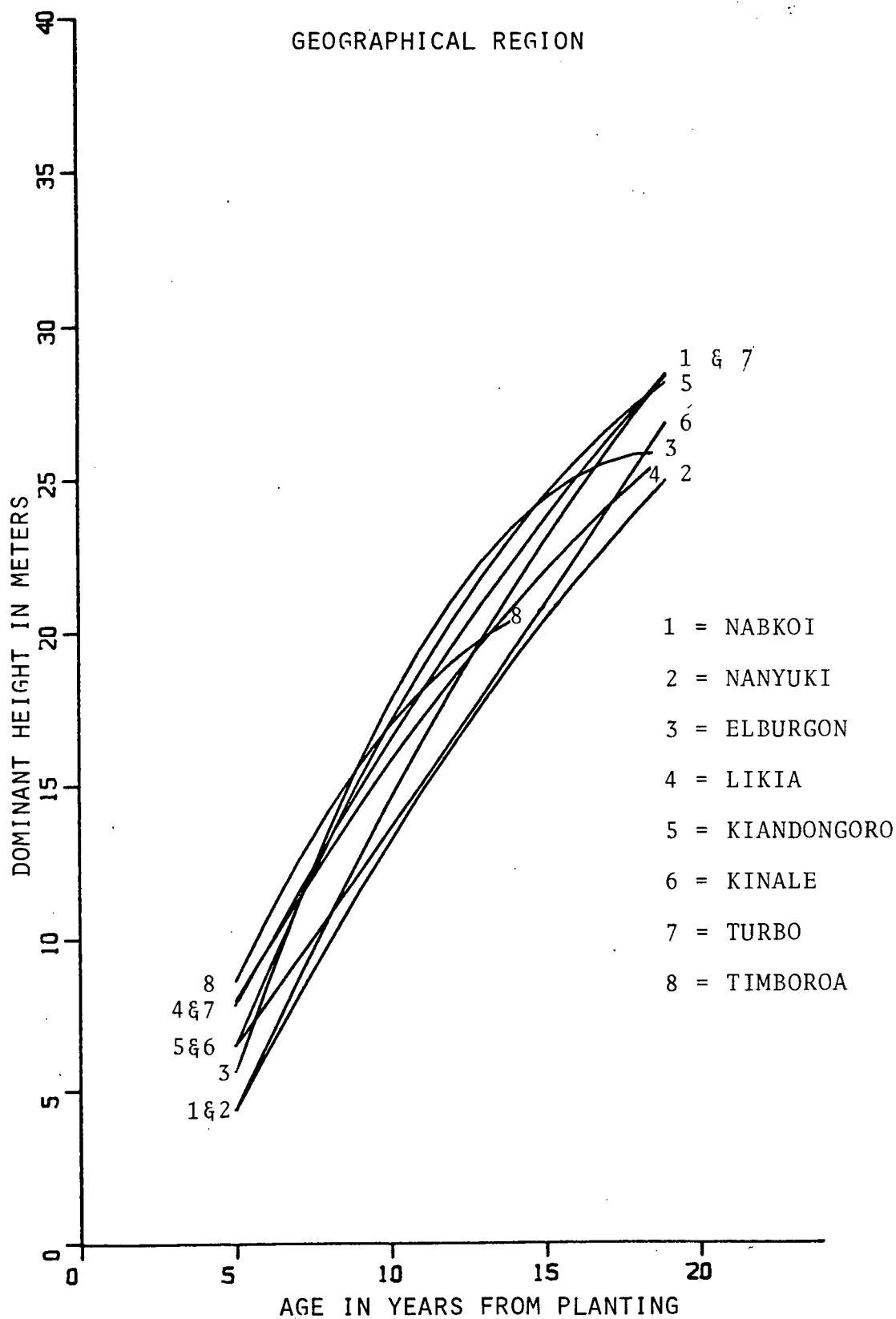
TABLE 16. Rainfall data and elevation for geographical regions recognized for separate site index curves

Zone	Region	Forest district	Mean annual rainfall mm	Average elevation m	Weather station
1	Nabkoi	Buret Cengalo Nabkoi	1160.6 (26)	2592	Nabkoi FS
2	Nanyuki	Ontulili	908.3 (23)	2256	Ontulili FS
		Nanyuki	1001.0 (25)	2317	Nanyuki FS
		Gathiuru	954.0 (10)	2287	Gathiuru FS
3	Elburgon	Elburgon West	1093.6 (56)	2378	Elburgon FS
		Elburgon East	1094.6 (23)	2439	Nessuit FS
4	Kiandongoro	Kiandongoro	1670.0 (24)	2378	Kiandongoro FS
		Kabage	1373.8 (14)	2287	Kabage FS
5	Kinale	Kamae Kimakia Kinale Kieni	1465.5 (14)	2591	Kamae FS
6	Turbo	Turbo	1170.0 (26)	1890	Turbo FS

Number in brackets refer to record years.
FS = Forest Station.

The recognition that height development trends differs from one region to another in Kenya is a new finding. For example Alder (1977) and Wanene (1975) developed a single system of site index curves for the whole country. As can be seen from Table 16 the variability in height development in the different regions cannot be wholly attributed to differences in rainfall and elevation. For example Nanyuki region and Elburgon region are almost similar in terms of mean annual rainfall and elevation. Yet their height development (curves 2 and 3 on Figure 11) are quite different. This suggests that there may be other factors affecting growth, for example soils, rainfall distribution, interactions of these with rainfall (quantity) and altitude and genetics. Further investigations are needed to determine what factors are most important in respect to this variability.

Site Index Curves for P. patula

For the permanent sample plots from each region, site index was recalculated using equation 2.1 and 2.2 and the appropriate equation for the region (Table 15) to obtain $\hat{H}(15)$ and $\hat{H}_i$. However, an attempt to fit the Chapman-Richards model (2.5) or the modified Weibull function (2.6) to the height over age data for each region separately failed for some, due to the short range of ages covered by the data, as shown on Table 17 which gives the range of data for each region. The best linear model for the data, equation 2.16 was therefore used and site index introduced:

TABLE 17. Height and age data for $\underline{P}$. $\underline{patula}$ by geographical regions

Region	H_{dom}		Age		No. of plots	No. of remeasurements
	Min.	Max.	Min.	Max.		
1. Nabkoi	5.2	34.2	5.5	23.6	15	124
2. Nanyuki	8.3	33.7	5.6	18.7	9	108
3. Elburgon	6.4	30.5	3.6	22.6	40	394
4. Kiandongoro	7.2	30.8	6.7	18.7	10	74
5. Kinale	5.9	32.2	4.7	21.6	22	179
6. Turbo	5.0	21.1	4.5	13.6	34	140

$$H = b_0 + b_1S + b_2AS + b_3A + b_4A^2 + b_5A^2S \ \dots\dots\dots\dots\dots \quad 2.17$$

where variable labels are as before.

For convenience and ease of regression analysis, a nested regression equation was fitted, using dummy variables to differentiate between the regions. Table 18 gives the coefficients for the regression equation 2.17 and the predicted heights at ages 10 and 15 years for each region.

The nested regression 2.17 gave a lower standard error of estimate (.81 meters) compared to that given by the nonlinear equation 2.13 for P. patula (1.14 meters). Thus, stratification of data by geographical regions led to higher precision. The predicted dominant height at age 15 years for site index 20 was about 20 meters for all regions (Table 18) except for Turbo whose data did not cover this age. This is as expected from the definition of site index. However, the predicted dominant height for the same site index at age 10 years varies between 12.7 meters for Nabkoi to 16.9 meters for Turbo. This underscores the essence of polymorphic growth, that plots may be of the same site index but have different growth curves, depending on the environmental conditions under which the plots are growing. It should be noted here that the quadratic model used for this species shows very rapid decrease beyond the range covered by the data and so extrapolation should be avoided.

TABLE 18. Regression Coefficients for site index curves for P. patula by regions

Region	b_0	S b_1	AS b_2	A b_3	A^2 b_4	A^2S b_5	Predicted values for S.I. 20 H_{15}	H_{10}
1. Nabkoi	0.1831	-0.3322	0.1298	-0.3148	0.01663	-0.002545	20.0	12.7
1. Nanyuki	-13.0639	-0.1388	0.01763	3.1635	-0.1616	0.003034	19.8	14.8
3. Elburgon	-9.5594	0.2714	0.05252	1.2761	-0.03566	-0.0005576	20.2	14.4
4. Kiandongoro	-21.0919	0.8502	-0.8114	4.2404	-0.1863	0.006048	20.5	15.6
5. Kinale	-1.6231	-0.03267	0.07984	0.2728	-0.007494	-0.0009530	19.8	13.8
6. Turbo	2.2528	-0.2011	0.1762	-1.2576	0.1199	-0.007974	-	16.9

R^2 = .98

SEE = .81 meters

Validating Site Index Curves for P. patula

A similar procedure as used to validate equation 2.13 was used to validate equation 2.17 by solving for S and regressing predicted site index against age for each plot:

$$S = (H_{dom} - b_0 - b_3A - b_4A^2)/(b_1 + b_2A + b_5A^2) \quad \dots\dots\dots\dots \quad 2.18$$

Table 19 gives the results.

TABLE 19. Distribution of plots showing significant site index over age correlation at .05 level for P. patula by geographical regions

Region	Total No. plots	Plots with significant correlation		Correlation significant	
		No.	%	+	−
Nabkoi	15	3	20.0	1	2
Namyuki	9	1	11.1	0	1
Elburgon	40	17	42.5	10	7
Kiandongoro	10	1	10.0	1	0
Kinele	22	5	22.7	2	3
Turbo	34	2	5.9	1	1
	130	29	18.7	15	14

The results of Table 19 indicates almost an equal number of plots showing both negative and positive correlation for all regions. The

total number of plots with significant correlations is also quite

reasonable, the percentage for all regions being lower than that

obtained on Table 13, except for Elburgon region. A plot of the site

index on age for the 17 plots from Elburgon with significant correlation

at .05 probability level showed no apparent trend. Thus, these correla-

tions appeared random and therefore could be attributed either to

measurement errors or interruption of dominant height development

discussed earlier. Site index curves for P. patula as defined by

equation (2.17) for each region were therefore accepted.

The Final Curves

As mentioned earlier, the definition of site index requires that at

reference age, site index equals stand dominant height. However, due to

the statistical nature of the curve fitting procedure, this condition

was found to be not satisfied. For example Table 18 above shows that

the predicted dominant height at reference age 15 years as used in this

study varied between 19.8 to 20.5 meters for site index 20 for P. patula.

Similar variation existed for C. lusitanica and P. radiata. This result

was not surprising since the least squares procedure used to fit the

curves assumed dominant height and site index to be independent, which

is not the case. In other words, there was no built in procedure to

guarantee that dominant height will equal site index at reference age.

To insure that this condition was satisfied, the following conditioning

procedure was used:

For $\underline{C}$. $\underline{lusitanica}$ and $\underline{P}$. $\underline{radiata}$:

At age 15 years we require that:

$$H_{dom} = S = b*_0(1 - e^{-b_1AS})^{b_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 2.19$$

where $b*_0 = b_0$ coefficient that satisfies the condition:

$H_{dom} = S$ at age 15 years.

$$\text{Thus} \quad b*_0 = \frac{S}{(1 - e^{-b_1AS})^{b_2}}$$

$$= \frac{S}{(1 - c^S)^{b_2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.20$$

where $c = e^{-15b_1}$

Thus the final equation for $\underline{C}$. $\underline{lusitanica}$ and $\underline{P}$. $\underline{radiata}$ site index curves was:

$$H_{dom} = \frac{S}{(1 - c^S)^{b_2}} \left(1 - e^{b_1AS}\right)^{b_2} \quad \ldots\ldots\ldots\ldots \quad 2.21$$

where all variables are as before.

This conditioning could only be done numerically since this equation cannot be solved by least squares method. Figures 9 and 10 shows the final curves for $\underline{C}$. $\underline{lusitanica}$ and $\underline{P}$. $\underline{radiata}$ using equation 2.21.

FIGURE 9

SITE INDEX CURVES FOR C. LUSITANICA IN KENYA
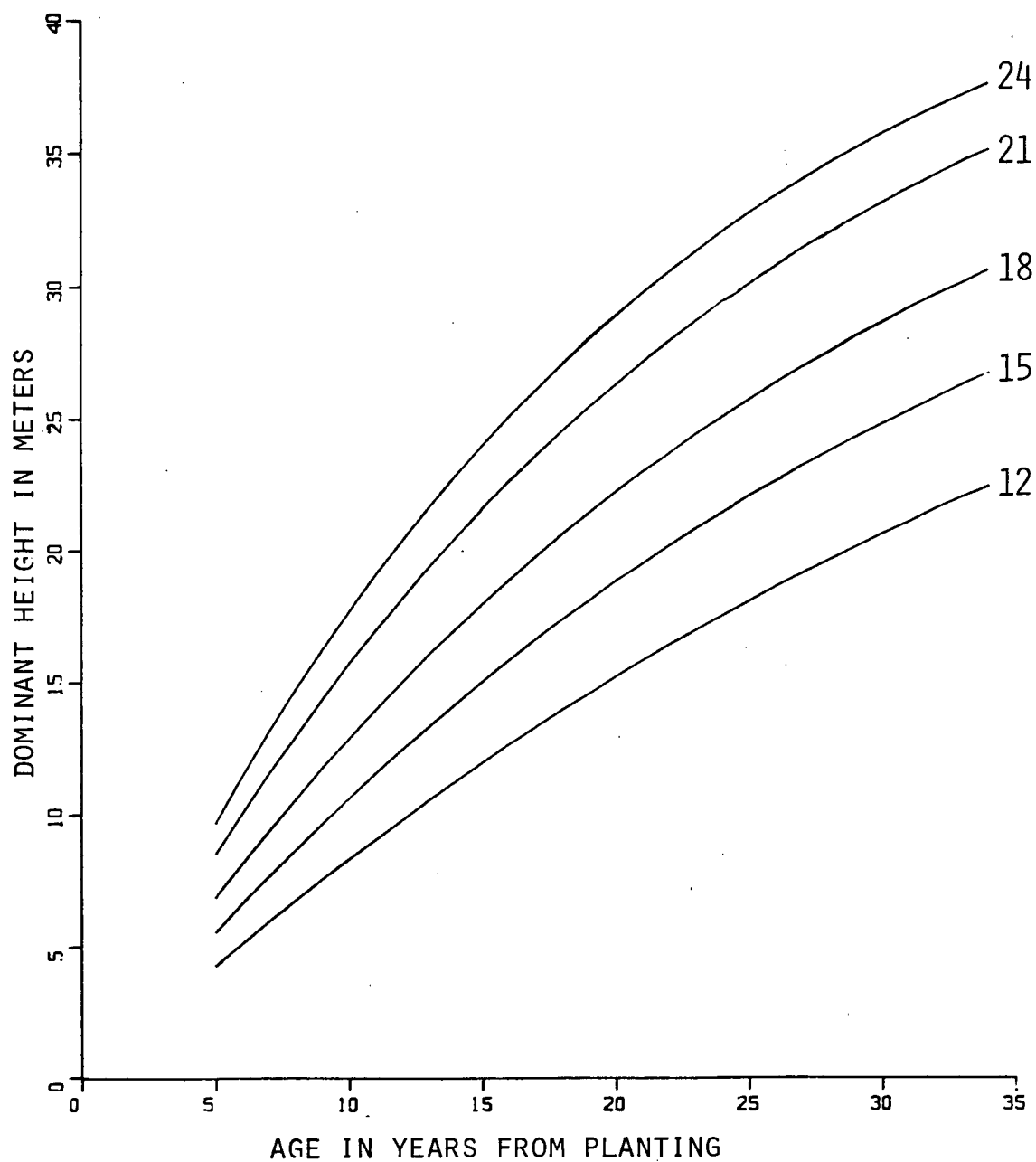
FIGURE 10

SITE INDEX CURVES FOR P. RADIATA IN KENYA
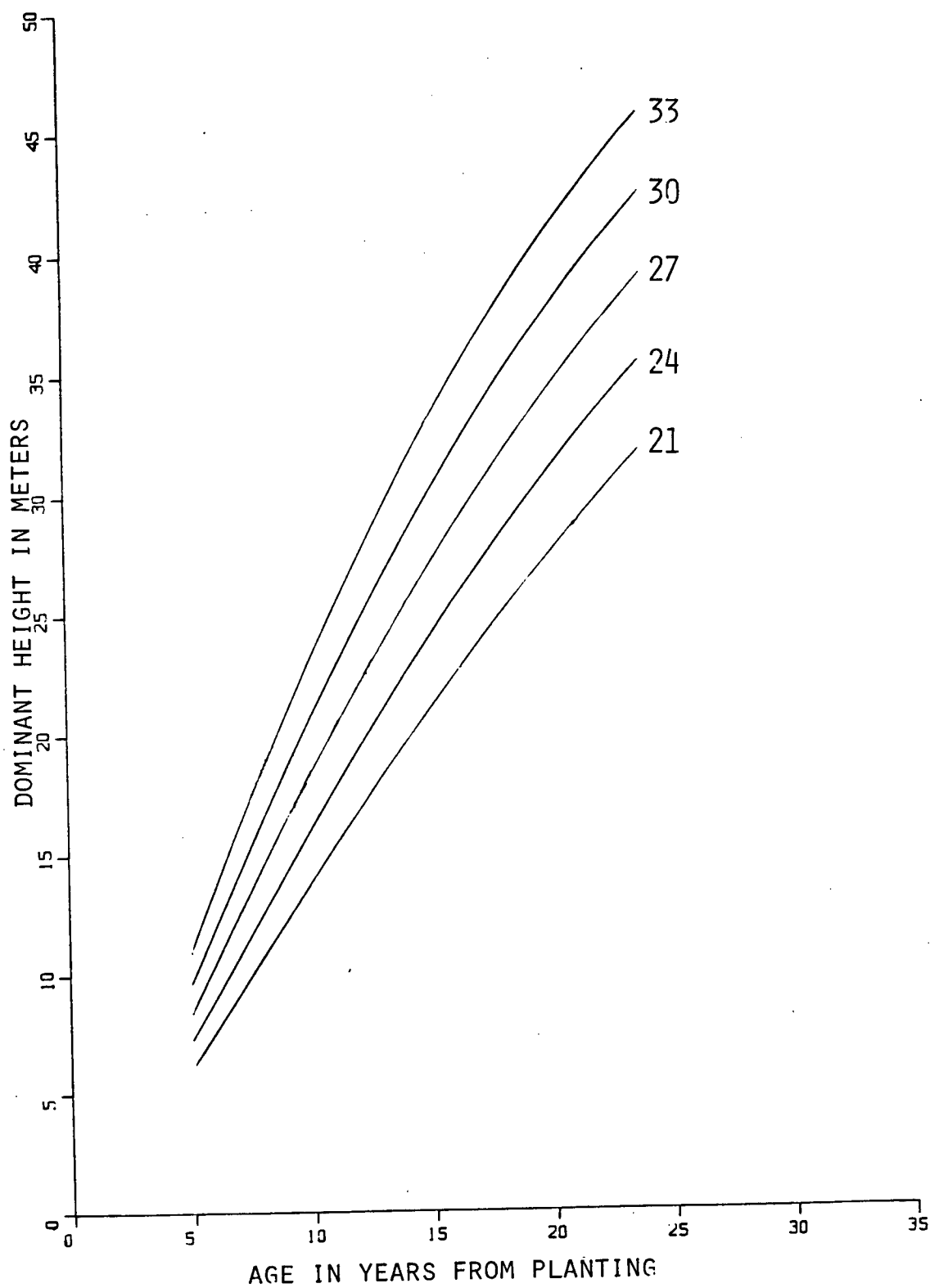
For P. patula:

The conditioning of equation 2.17 was accomplished through equation 2.18 as follows:

Let S* be the site index defined by the model.

Let S be the site index that will insure that site index =

dominant height at age 15 years.

Then at age 15 years:

$$H_{dom} = S^* = S(b_1 + b_2A + b_5A^2) + (b_0 + b_3A + b_4A^2) \quad \dots\dots\dots \quad 2.22$$

$$\therefore \quad S = \frac{S^* - (b_0 + b_3A + b_4A^2)}{(b_1 + b_2A + b_5 A^2)} \quad \dots\dots\dots\dots\dots\dots\dots \quad 2.23$$

$$= \frac{S^* - c_1}{c_2} \qquad \text{where } c_1 = b_0 + b_3(15) + b_4(15)^2$$
$$c_2 = b_1 + b_2(15) + b_5(15)^2$$

Thus, the conditioning of the site index model for P. patula was through numerical adjustment of the site index of interest. Figure 11 gives the site index curves for P. patula for Nabkoi region only.

FIGURE 11

SITE INDEX CURVES FOR P. PATULA IN KENYA

NABKOI GROUP
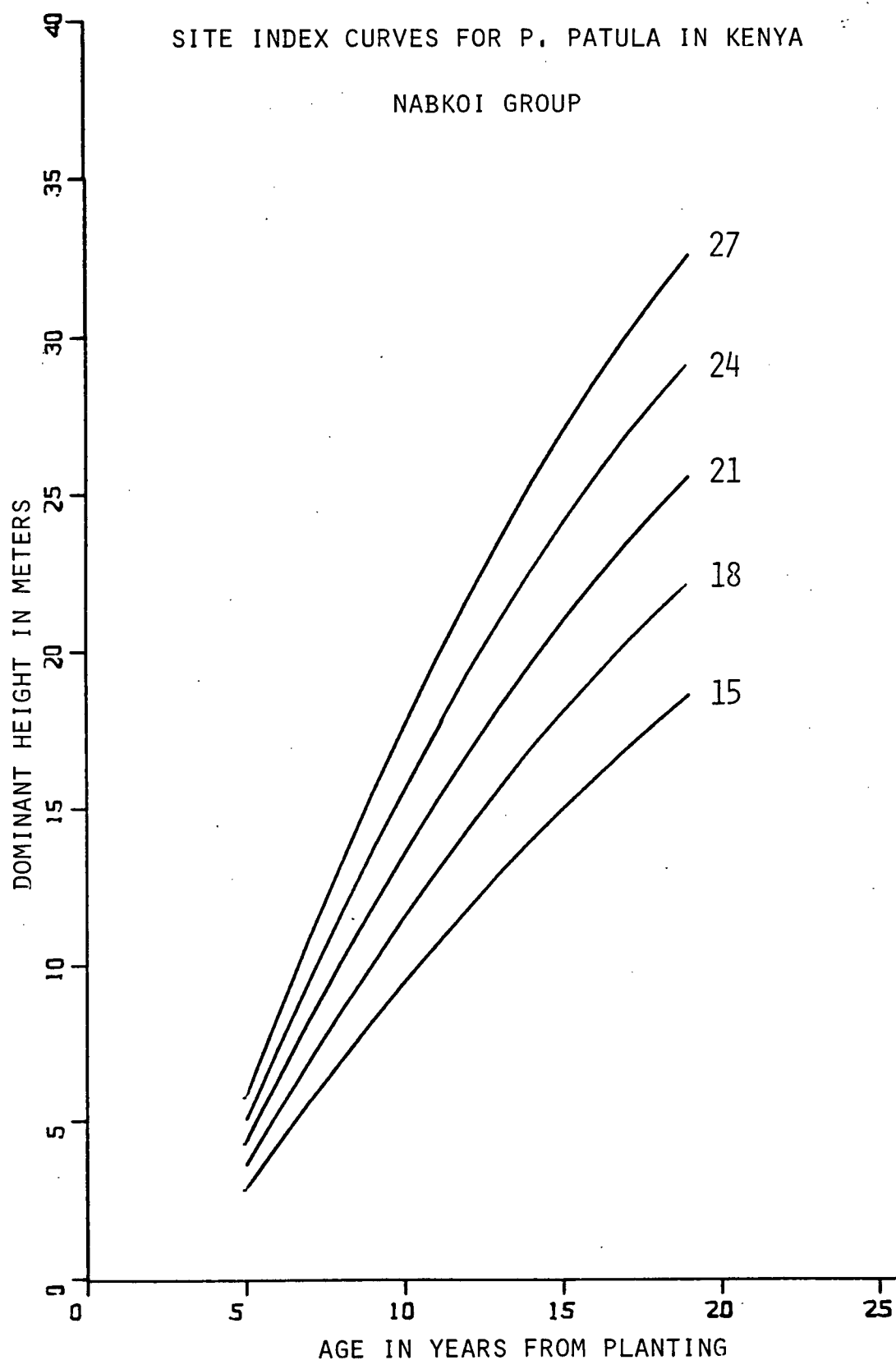
2.0 Mortality, Stand Density Development, and Thinning Practices in Kenya Plantations

2.1 Mortality

As defined by Husch et al., 1972, mortality is the number or volume of trees periodically rendered unusable through natural causes such as old age, competition, insect and diseases, wind, etc. From this defini-tion, two types of stand mortality can be identified; that arising from natural mortality as a result of competition and the irregular type arising from unnatural causes; diseases and insect attack, fire, wind-throws, etc. The latter category can range from insignificant to catas-trophic, occurring at intermittent intervals during the life of a stand.

Natural mortality is central to stand dynamic and simulation studies procedures for dealing with this type of mortality in growth and yield models have been discussed by Smith and Williams (1980), Hamilton (1980), Lee (1974) and others. Irregular mortality on the other hand is very little understood and very difficult to predict. According to Lee (1974), statistical procedures are available for treating this type of mortality, e.g. treating it as an overall probability or stochastic process for a given area. The major problem however is related to availability of adequate data needed to develop the models. For example, windthrow may be related not only to the regional weather patterns and the root systems of the species but also to the silvicultural treatments that the stands have received.

Because of the intensive level of plantation management in Kenya, natural mortality arising out of competition may be considered non-existant after first thinning. This is because the first thinning is designed to remove dead, dying, diseased, wolfed and suppressed stems so that the remaining stems are healthy and therefore able to withstand any competition that may occur before the next thinning. Before first thinning however, mortality might occur, especially if thinning is delayed beyond the prescribed stage. However, there was no evidence of mortality in the available p.s.p. data.

Irregular mortality on the other hand is a constant threat to plantation management, as mentioned earlier in Chapter 1. Although lack of data may be cited as the reason why this problem is not addressed in this study, the view is also taken that this effort would not be worthwhile. This is because forest managers are constantly improving forest protection procedures such as fire protection, game damage and insect and disease control so that any mortality model may well be invalid before it is ready for use.

2.2 Stand Density Development

Definition and Importance of Stand Density

The growth rate of an individual tree is determined by its genetic characteristics, the site quality and the amount of growing space available to it. Stand density refers to the measure of the aggregate degree to which a given tree species utilizes the growing space. The genetic character of an individual tree and site quality can be manipulated

through tree breeding techniques and through use of fertilizers and site

preparation techniques respectively. However, it is through density

control; initial spacing, thinning and other silvicultural techniques

that the forest manager has the best chance of directing growth towards

the desired goals and objectives. This is one of the reasons why the

effects of stand density on stand development has been so extensively

studied. Some of the important studies include: Braathe (1957),

Beekhuis (1966), Marsh (1957), Cromer and Pawsey (1957), Adlard (1957),

Newnham and Mucha (1971), Smith and Williams (1980), Hummel (1947) and

Baskerville (1965).

Measures of Stand Densities

Several measures of stand density have evolved over the years, the

basic ones being volume per unit area, basal area per unit area and

number of stems per unit area. These measures have been very widely

used mainly because they are simple and easily understood. However,

they are related to age and site quality, which is a disadvantage when

the stand density is required to express the degree of site occupancy.

Stand density expressions that are independent of age and site, referred

to as stand density indices; have therefore come into general use.

Examples of these are Reineke's stand density index (Reineke 1933),

Chisman and Schumacher's tree area equation (Chisman and Schumacher

1940) and Schumacher and Coile's stocking per cent (Schumacher and Coile

1960). For full details on these, see Husch, Miller and Beers (1972)

Chapter 17-2, Curtis (1970), Crowe (1966), etc. Among the stand density

indices mentioned above is the spacing between trees expressed in terms

of stand dominant height, referred to in some forestry literature as Hart's density index and in others as Hart-Becking stand density index (Crowe 1967, Wilson 1979). This stand density index has been very widely used in thinning research in Europe (Braathe 1957), South Africa (Crowe 1967) and North America (Wilson 1979) and is of particular interest in this study. It is therefore discussed below in greater details.

Hart's Stand Density Index

This stand density index was first proposed by Hart (1928) but according to Wilson (1979), the concept of spacing had been used in Denmark as far back as 1851 where it may have been formulated as:

$$\text{Relative distance of trees} = \frac{\sqrt{\dfrac{\text{Area}}{\text{No. of trees}}}}{\text{Height}} \quad \cdots\cdots\cdots\cdots \quad 2.24$$

The present definition of this index can take any of the two forms:

1. For square spacing:

$$S\% = \frac{\sqrt{\dfrac{10,000}{\text{No. trees/ha}}}}{H_{dom}} \cdot 100 \quad \cdots\cdots\cdots\cdots \quad 2.25$$

2.   For triangular spacing:

$$S\% = \frac{\sqrt{\dfrac{10{,}000 \times \text{Sin } 60°}{\text{No. trees/ha}}}}{H_{dom}} \cdot 100 \quad \ldots\ldots\ldots \quad 2.26$$

where $S\%$ = Stand density index.

Between these two forms, the square spacing formula has received a much wider acceptance, mainly because it is free of the constant (Sin 60°) and therefore much easier to apply. However, one problem associated with use of this index is that it assumes a regular spacing in the stand, even after repeated thinning. This may not always be true. Its main advantages are that it is largely independent of stand age, site quality and species, besides being simple and easy to apply.

One of the desirable characteristics of a stand density index expression is that it should give an idea of the degree to which an area is being utilized by trees. As it stands, Hart's density index does not fully account for the degree of site utilization. For example, consider two stands of the same stand dominant height and the same spacing. According to this index, the two would have the same density index. Yet if one had been thinned to the present density earlier than the other, it would have a considerably higher basal area. This shortcoming is especially important in intensively managed plantations where the history of stand treatment is an important consideration in growth and yield determination. It should also be noted that stand dominant height is used instead of stand mean height, because the former is little affected by stand treatments, especially thinning.

Stand Density Development for the Plantation Species in Kenya (based on
Harts Density Index)

The opinion over whether stands should be managed at constant stand
density index or not differs among foresters. For example, Hummel and
Christie (1953) favoured maintenance of constant index throughout the
rotation period, while Becking (according to Braathe 1957) recommended
constant index for Douglas-fir and poplars and a decreasing (with age)
index for beech and larch in Holland. Another strong proponent of
thinning to a constant stand density index is Wilson (1979) who recom-
mended leaving a spacing of 20.6% of dominant height after each thinning
at Star Lake, Minnesota. Although not explicitly defined in terms of
S%, thinning schedules for P. patula and P. radiata in South Africa and
New Zealand respectively are defined in terms of number of stems per
hectare to be left at a given stand dominant height (Crowe 1967, Fenton
1972), which translates to thinning to a constant density index. In
general, thinning to a constant density index is favoured, if only
because it provides an objective criteria for deciding when a stand is
due for thinning.

As shown on Table 5 of Chapter 1 on silviculture, the first thin-
ning for all the three species in Kenya is defined in terms of number of
stems to be left at a specified stand dominant height. This translates
to an S% of about 30%, 25.5% and 27.7% for C. lusitanica, P. patula and
P. radiata respectively after first thinning. For P. radiata, 2nd
thinning is defined similarly and translates to the same S% after

thinning. The 2nd and subsequent thinning for C. lusitanica and

P. patula and also subsequent thinnings for P. radiata are defined in

terms of number of stems to be left after each thinning while the

thinnings are spaced at constant time intervals. The effects of this

practice on S% development in the different site index classes are shown

on Figure 12a,b and c for C. lusitanica, P. patula and P. radiata

respectively. The figure shows:

1. For C. lusitanica S% varies between 18-30% while for P. patula

    and P. radiata, it varies between 15-25%.

2. Stand density index (S%) varies for the different site

    qualities for each species, with wide spacing developing on

    poor site and overcrowing on good sites. For example for

    C. lusitanica, S% for final thinning on site index 12 is 30%

    while that for site index 24 is 20%.

The practical implications of this practice are that it is likely

that the full site capacity on poor sites is not fully exploited while

overcrowding on very good sites may be affecting growth. In addition,

this practice ignores the effects of spacing (S%) on stand development,

thus depriving the management of one of the basic tools for control of

tree diameter development. This is especially critical from a utiliza-

tion point of view. To date, the effects of the present schedules on

growth and yield are not known and it is hoped that results from this

study will provide some knowledge on the magnitude of these effects.

FIGURE 12
NO. STEMS/HEIGHT/S% RELATIONSHIP BY SPECIES AND SITE INDEX CLASSES IN KENYA

(a)
C. LUSITANICA

(b)
P. PATULA (Nabkoi)

(c)
P. RADIATA
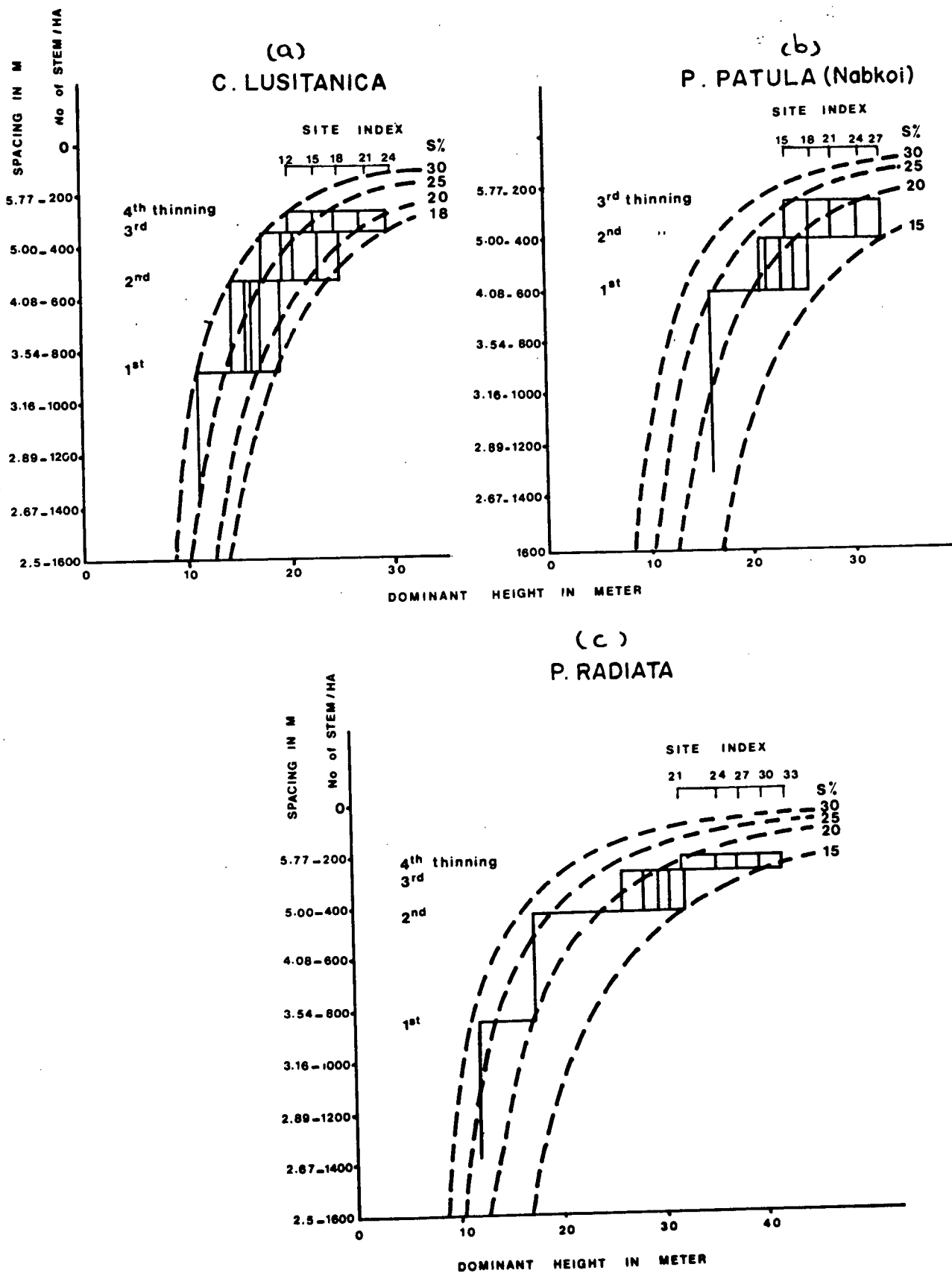
2.3 Thinning

Definition: Braathe (1957) defined thinning as the act of removing some of the stems in an immature stand of trees in order to give the remaining trees better conditions for growing and producing wood of high quality. However, this definition is inadequate without further qualification as to:

1. Type of thinning

This qualification describes the trees to be removed; based on the position of the trees with respect to either spatial distribution or tree sizes. For example low thinning which ideally implies removal of the smallest trees, starting with the suppressed ones or high thinning, which ideally removes trees from the dominant and codominant categories.

The definition of types of thinnings is well documented in most texts on silviculture e.g. Smith (1962) pages 90-94. However, it should be noted that in practice, most thinnings are a combination of two or three types at the same time or in sequence. This is because the thinning objectives change as the stand structure changes and the individual stand develops.

2. Thinning intensity

This refers to the proportion of the stand removed in thinning as a function of the stand before thinning. Several measures of thinning intensity have been used.

(a) The ratio d/D attributed to Eide and Langsaeter (Braathe 1957) where:

    d = Mean DBH of trees removed in a thinning

    D = Mean DBH of trees before thinning.

This ratio basically measures the type of thinning carried out. Thus according to the above authors, thinning types can be defined according to the value of the ratio d/D:

    ≤ 0.70 = Low thinning

    0.70 to .85 = No definite low or crown thinning

    0.85 to 1.0 = Crown thinning

    > 1 = Selection thinning

This ratio has been used by Reukema and Bruce (1977) to define the recommended thinning type for Douglas-fir.

(b) The number of trees to be removed at each thinning, expressed either as a pure number or as a proportion of initial stand density; such as is presently practiced in Kenya.

(c) Basal area (or volume) removed as a proportion of basal area (or volume) before thinning. For example Reukema and Bruce (1977) defined the intensity of thinning for Douglas-fir in terms of the minimum recommended residual basal area to be maintained in the stand after each thinning. The Forest Management Tables (Metric) for Great Britain use the same principle by defining the

marginal thinning intensity in terms of the annual rate
of volume removal equivalent to 70% of the maximum mean
annual increment. This proportion represents the maximum
thinning intensity which can be maintained without loss
of volume production (Hamilton and Christie 1971).

3. Thinning cycle: which refers to the periodicity of thinning.
Choice of thinning cycle is a function of both economic and bio-
logical considerations. For example, frequent but light thinnings
are preferred from yield and biological considerations while fewer
(longer cycles) but heavier thinnings are attractive from an
economic point of view. The biological considerations often
override the economic considerations mainly because the main
concern is the growth conditions of the remaining stand. Thus,
although not implicitly stated, the thinning cycle for Douglas-fir
(Reukema and Bruce 1977) is defined by the growth rate of the
stand, the time it takes for the basal area to grow from the recom-
mended residual level to the maximum basal area, where maximum is
defined as the approximate maximum basal area to which a given
number of merchantable trees should be grown in a managed stand.
The concept of maximum size-density advocated by Drew and
Flewelling (1979) for control of plantation density for Douglas-fir
in New Zealand reinforces the importance of biological considera-
tion in determining the thinning cycle. It should however be noted
that the thinning type, thinning intensity and thinning cycle are
very closely interrelated and choice of one influences the other.

Thus the forest manager has to compromise between the biological desirability of a thinning and the economic considerations when determining both the thinning intensity and thinning cycles, since choice of one affects the other.

Thinning Type and Intensity for Plantation Species in Kenya

So far, the thinning schedules for the three species have been described in terms of thinning cycle (time intervals between thinnings) and intensity (in terms of number of stems and spacing (S%). It remains to describe the thinning type and the thinning intensity in terms that will reveal both the size and the proportion of the stand removed in terms of mean DBH and basal area of stand before thinning. The summary of data for this study is shown on Table 20 by species and basic variables as measured on the permanent sample plots. From these variables, other descriptive variables, the ratios of the basal area, DBH and number of stems were derived. In addition, each thinning was categorized as precommercial (those which took place at ages $\leq$ 13.5 years) or commercial.

1. Mean DBH of thinning/mean DBH before thinning ratio

Table 21 shows the ratios of the mean DBH of thinnings to mean DBH of stand before thinning for precommercial, commercial and combined thinnings for each species.

The following observations can be noted from this table.

1. ' That for all three species the ratio $\frac{DBH(T)}{DBH(BT)}$ for precommercial and commercial thinnings are almost equal although those for

TABLE 20. Summary of thinning data by species and relevant variables

Variable	Species	n	Mean	Mininum	Maximum	Standard deviation
Age of thinning (years)	C. lusitanica	117	12.1	5.6	30.4	5.6
	P. patula	139	11.0	5.7	24.5	4.2
	P. radiata	121	11.5	5.5	30.4	4.8
Dominant height (m)	C. lusitanica	117	16.0	7.6	30.2	5.6
	P. patula	139	17.2	8.0	35.4	6.5
	P. radiata	121	20.6	5.9	44.2	8.3
No. stems thinned	C. lusitanica	117	289	74	791	195
	P. patula	139	278	74	1161	185
	P. radiata	121	2706	49	988	196
No. stems before thinning	C. lusitanica	117	1007	198	1631	400
	P. patula	139	908	222	1680	347
	P. radiata	121	959	99	2001	422
DBH of thinning (cm)	C. lusitanica	117	18.4	6.2	51.0	8.4
	P. patula	139	17.5	7.2	35.7	5.8
	P. radiata	121	15.5	3.2	45.8	8.1
DBH before thinning	C. lusitanica	117	21.3	10.2	45.1	8.4
	P. patula	139	19.9	8.6	37.0	5.9
	P. radiata	121	18.9	7.6	47.9	7.9
Basal area of thinning	C. lusitanica	117	6.5	0.3	22.5	4.2
	P. patula	139	6.3	0.4	21.5	4.2
	P. radiata	121	4.6	0.1	15.1	3.4
Basal area before thinning	C. lusitanica	117	29.9	7.6	53.0	10.0
	P. patula	139	25.9	2.4	57.4	9.7
	P. radiata	121	22.5	7.4	45.8	9.1

TABLE 21. Mean DBH of thinning/mean DBH before thinning relationship

	Mean $\frac{DBH}{DBH}(T)$ (BT)	Minimum	Maximum	Standard deviation	n
		Precommercial			
C. lusitanica	.84	.53	1.0	.11	75
P. patula	.87	.59	1.1	.09	91
P. radiata	.77	.30	1.0	.15	82
		Commercial			
C. lusitanica	.88	.54	1.13	.11	42
P. patula	.89	.66	1.05	.07	48
P. radiata	.86	.45	1.10	.14	39
		Combined			
C. lusitanica	.85	.53	1.13	.11	117
P. patula	.88	.59	1.10	.09	139
P. radiata	.80	.30	1.10	.15	121

precommercial are slightly lower. In general, a bigger difference was expected between these two types of thinnings since with commercial thinnings, there is a tendency towards a systematic type of thinning so as to remove some stems of economic value to offset cost of thinning, while precommercial thinnings are aimed at stand hygiene, removing trees mostly from the lower diameter classes. This difference may have been partly reduced by the presence of wolfed trees which are usually removed during precommercial thinnings.

2. The combined ratio for C. lusitanica and that for P. patula are almost equal while that for P. radiata is slightly lower. This may reflect the effects of dothistroma pine disease mentioned in Chapter 1 since thinning, especially precommercial, removes diseased trees as a priority.

3. Based on the classification of Eide and Langsaeter (according to Braathe 1957) the ratio $\frac{DBH(T)}{DBH(BT)}$ for P. radiata (0.80) corresponds to no definite low or crown thinning while that for C. lusitanica and P. patula (0.85 and 0.88 respectively) borders on the lower side of crown thinning.

2. <u>Basal area of thinning/basal area before thinning ratio and number of stems thinned/number of stems before thinning ratio</u>

Both of these ratios followed exactly the same pattern as for the $\frac{DBH(T)}{DBH(BT)}$ ratio, except for the magnitude. Table 22 shows the magnitude for the basal area ratio for the precommercial, commercial and combined data by species. The table indicates that the average level of basal area removal is between 20-25% of the basal area before thinning although it can be as low as 1% and as high as 70%.

3. <u>Mean DBH of thinning</u>

The mean DBH of stems removed in a thinning can be expected to be a function of:

(1) Mean diameter of stand before thinning.

(2) Thinning type: For example, mean DBH of thinnings in low-thinning can be expected to be lower than mean stand DBH before thinning, mean DBH of thinnings in selection thinning would be higher than mean stand DBH before thinning.

(3) Weight of thinnings: In low, crown or in selection thinning, the heavier the thinning, the closer would their mean DBH approach the mean stand DBH before thinning.

Other variables that can affect the mean DBH of thinnings include stand dominant height and age. Preliminary investigations however indicated the stand mean DBH before thinning as the variable best correlated with mean DBH of thinnings.

TABLE 22. Basal area of thinning/basal area before thinning ratios

	Mean ratio	Minimum	Maximum	Standard deviation	n
			Precommercial		
Cypress	.22	.02	.56	.12	75
P. patula	.24	.03	.70	.12	91
P. radiate	.19	.01	.56	.13	82
			Commercial		
Cypress	.22	.06	.61	.11	42
P. patula	.25	.05	.71	.14	48
P. radiate	.23	.02	.68	.13	39
			Combined		
Cypress	.22	.02	.61	.12	117
P. patula	.24	.03	.71	.13	139
P. radiata	.20	.01	.68	.13	121

As a measure of weight of thinning the ratio $\frac{BA(T)}{BA(BT)}$ was better

correlated to mean DBH of thinnings than the ratio $\frac{N(T)}{N(BT)}$. This is as

expected since basal area is a better measure of stand density than

number of stems. Both ratios showed significant correlation at .05

probability level except for the ratio of number of stems for

C. lusitanica. For this study, one thinning option in the envisaged

yield model required that thinnings be defined in terms of number of

stems to be left after the thinning. For this option therefore, the

appropriate measure of weight of thinning in the DBH of thinning

equation was $\frac{N(T)}{N(BT)}$. The following multiple linear equation was

formulated:

$$DBH(T) = b_0 + b_1\ DBH(BT) + b_2\ \frac{N(T)}{N(BT)} \qquad \dots\dots\dots\dots\dots\dots \quad 2.27$$

Table 23 shows the estimated parameters and other relevant

statistics for the respective equations for each species. All the

independent variables were significant at .05 probability level,

including those for C. lusitanica while the study of residuals indicated

no systematic trends.

TABLE 23. Parameter estimates and other statistics for the DBH of
thinning equation 2.27

	Species		
	C. lusitanica	P. patula	P. radiata
b_0	-3.3840	-2.1596	-4.5192
b_1	.9508	.9262	.9637
b_2	5.2153	4.0669	6.1003
n	117	139	121
R^2	.92	.92	.91
SEE	2.37 cm	1.64 cm	2.42 cm
	(12.9%)	(9.4%)	(15.6%)

The other thinning option in the envisaged model required that
thinning be defined in terms of proportion of basal area to be removed
at each thinning. Thus if basal area before thinning is known, basal
area to be removed is completely defined. The problem with this
procedure was how to determine the number of stems removed in thinning
since only basal area removed is known. This was accomplished by first
calculating the mean diameter of thinned stems using the equation:

$$DBH(T) = b_0 + b_1 \, DBH(BT) + b_2 \frac{BA(T)}{BA(BT)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad 2.28$$

Table 24 shows the estimated parameters and other statistics for
equation 2.28 for each species.

TABLE 24. Parameter estimates and other statistics for the DBH of
thinning equation 2.28

| | Species | | |
	C. lusitanica	P. patula	P. radiata
b_0	−4.0099	−2.4008	−4.4723
b_1	.9316	.9129	.9274
b_2	11.6300	7.2044	11.9780
n	117	139	121
R^2	.94	.94	.93
SEE	2.06 (11.2%)	1.46 (8.3%)	2.14 (13.8%)

All the independent variables were significant at .05 probability
level and the study of residuals indicated no systematic trends.

3. Basal Area Growth before First Thinning

3.1 Introduction

Basal area is one of the most important stand characteristics in
that it is one of the directly measurable independent variable in the
stand volume equation. There is also no doubt that basal area is the
simplest and most widely accepted measure of stocking density (Rawal and
Franz 1973). Thus, in intensively managed plantations, basal area is
often used as one of the criterion for determining when the stand is due
for first and subsequent thinnings. It is also one of the variables

often used for initializing the stand for growth and yield in whole stand, diameter free models (Smith and Williams, 1980).

Basal area development in managed stands can be considered in two phases, before and after first thinning. Before first thinning the development is mostly a function of stand density, site quality and stand age. After first thinning, the basal area of the stand is a function of not only these factors but also of the intensity and frequency of thinnings. This section of the study investigates the development of basal area before first thinning for the three species.

3.2 Data for Basal Area Development

Data for basal area development were derived from plots established when stands were 3 to 8 years old and had number of stems higher than 1,000 stems per hectare. Table 25 shows a summary of the data. A preliminary study of the basal area growth for P. patula had shown that for Kinale region, basal area development was markedly different from that of the rest of the country. For example, the mean basal area at age 7 years was 28.6 m^2 compared to 19.7 m^2 for the rest of the country. This explains why data for this species were treated as two different groups.

3.3 Choice of the Regression Model

The growth of the individual tree basal area is described by Spurr (1952). He further stated that the growth curve for basal area of the

TABLE 25. Summary of the basal area before thinning data

Species	Variable	n	Mean	Standard deviation	Mininum	Maximum
C. lusitanica	Age (years)	112	7.1	1.29	4.7	11.5
	No. stems/ha	112	1337	177.28	1013	1656
	Height (dom) m	112	10.2	2.32	5.0	15.8
	Basal area m^2	112	19.5	6.66	4.2	38.2
P. patula rest of country	Age (years)	172	7.2	2.02	3.6	16.5
	No. stem/ha	172	1300	162.22	1012	1631
	Height (dom) m	172	11.9	3.47	3.8	26.3
	Basal area m^2	172	19.7	8.52	1.1	49.1
P. patula Kinale Group	Age (years)	45	7.0	.87	5.5	8.5
	No. stem/ha	46	1296	119.71	1038	1532
	Height (dom) m	46	12.0	1.86	8.2	16.4
	Basal area m^2	46	28.6	5.81	14.7	40.8
P. radiata	Age (years)	95	7.2	1.10	5.5	9.5
	No. stem/ha	95	1342	178.29	1038	1705
	Height (dom) m	95	12.8	2.89	6.1	20.0
	Basal area m^2	95	15.3	3.84	5.7	24.4

stand is similar, especially for managed stands where mortality is negligible. Spurr was referring to the sigmoid growth curve.

Pienaar and Turnbull (1973) used Chapman-Richards growth model for basal area growth of a stand for different stand densities. In their study, the authors fitted this equation to data from different stocking densities from controlled experiments in South Africa (CCT experiments worked upon by Marsh (1957)). They demonstrated that the magnitude of the asymptote parameter may be density dependent, but within certain limits could be considered constant for different densities, thus supporting the hypothesis of constant yield.

The above study indicated that the basal area growth curve is sigmoid, starting at the origin and tending to an asymptote as age increases. However, in their study of asympotic growth curves, Rawat and Franz (1973) noticed that for some species like pine (Pinus silvestris, L.), basal area per acre over age curves were not asymptotic but bend downwards after reaching the maximum value. They explained this as due to the fact that the site is not capable of supporting optimum number of stems per unit area at higher ages. They therefore recommended derivation of stand basal area from basal area over age curve of mean tree and number of trees per unit area over age curves. For this study however, the data did not cover the higher ages. Basal area per hectare was retained as the dependent variable as it is the variable of direct interest.

From experimentation with the Chapman-Richard's and modified Weibull function; the latter was selected as most suited to the data:

$$BA = b_0 \left(1 - e^{-b_1 A^{b_2} H^{b_3} N^{b_4}} \right) \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad 2.29$$

Where   BA = Stand basal area in m^2/ha

A = Stand age in years

H = Stand dominant height (includes effects of site quality)

N = Number of stems per hectare

b_0; $b_1 \dots b_4$ are coefficients to be estimated

where b_0 = The asymptote.

b_1 = The rate at which basal area approaches the asymptote

b_2; b_3 and b_4 are scale parameters.

This model assumed constant asymptote for all site qualities and stand densities. Both assumptions appear justified because of the narrow range of densities covered by the data and because the data does not cover the asymptotic phase of growth. In other words, the estimated asymptotes are mainly a reflection of the rate at which the plots are growing in the early ages. Table 26 shows the estimated parameters and other relevant statistics from equation 2.29 for all the species. SEE and R^2 values were estimated using equations 2.9 and 2.10 respectively with BA substituted for H. Table 27 gives the asymptotic standard deviations for the estimated coefficients of Table 26 while Figure 13 shows the basal area over age curves for various site index classes at stand density of 1200 stems per hectare.

TABLE 26. Parameter estimates and relevant statistics for basal area
before thinning: Equation 2.29

	Species			
	C. lusitanica	P. patula*	P. patula(k)	P. radiata
b_0	39.6342	53.1844	87.7894	22.1194
b_1	-0.00001426	-0.0000003329	-0.000006209	-0.00000727
b_2	1.2418	0.9381	1.2788	0.2540
b_3	1.1797	1.1033	0.5626	1.7142
b_4	0.7807	1.3367	-	-
n	112	172	46	95
R^2	.85	.91	.91	.63
SEE	2.61 m^2 or 13.35%	2.58 m^2 or 13.1%	1.79 m^2 or 6.26%	2.36 m^2 or 15.4%

*   P. patula rest of the country.

(k) P. patula Kinale region.

TABLE 27. Asymptotic standard deviations of the estimated coefficients of Table 26

Species	b_0	b_1	b_2	b_3	b_4
C. lusitanica	4.6935	0.000000	0.2540	0.1662	0.1657
P. patula*	4.6404	0.000000	0.1292	0.1082	0.1394
P. patula(k)	38.8152	0.000000	0.2091	0.1311	-
P. radiata	2.1430	0.000000	0.4698	0.3400	-

* P. patula rest of the country.

(k) P. patula from Kinale group.

FIGURE 13

BASAL AREA OVER AGE CURVES FOR VARIOUS SITE INDEX CLASSES AT STAND DENSITY OF 1200 S.P.H.

C . LUSITANICA

P . RADIATA
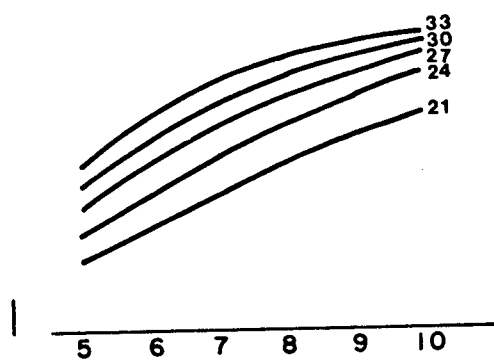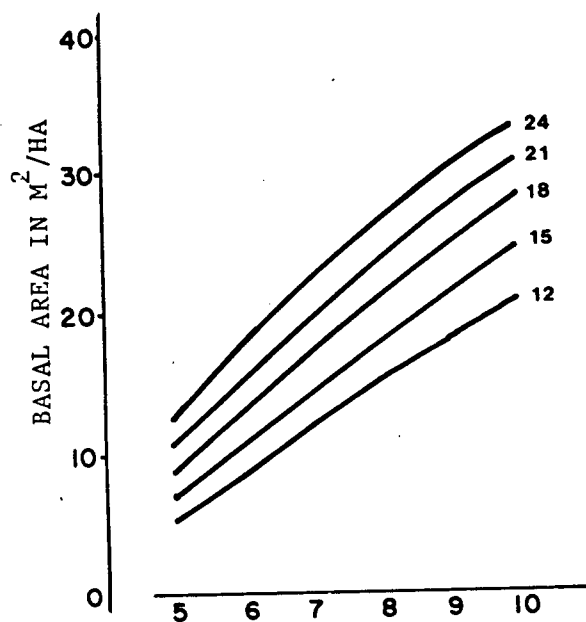
P. PATULA (REST OF THE COUNTRY)
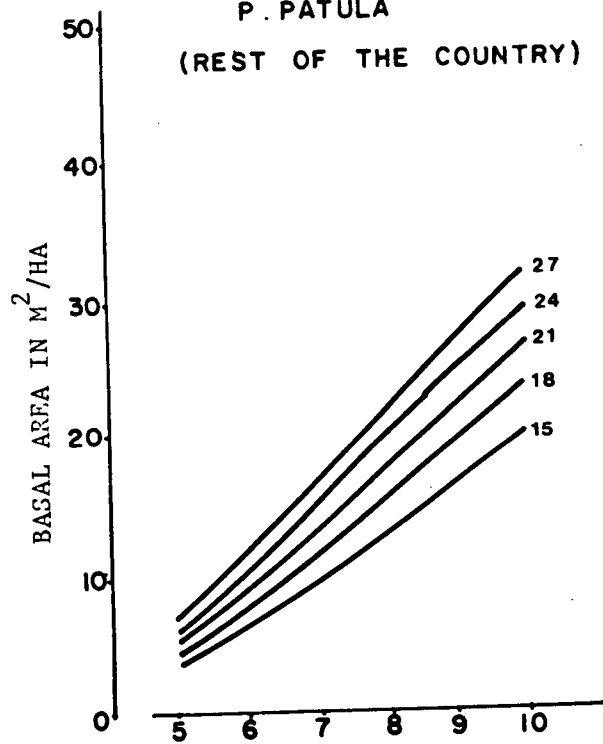
P. PATULA (KINALE)
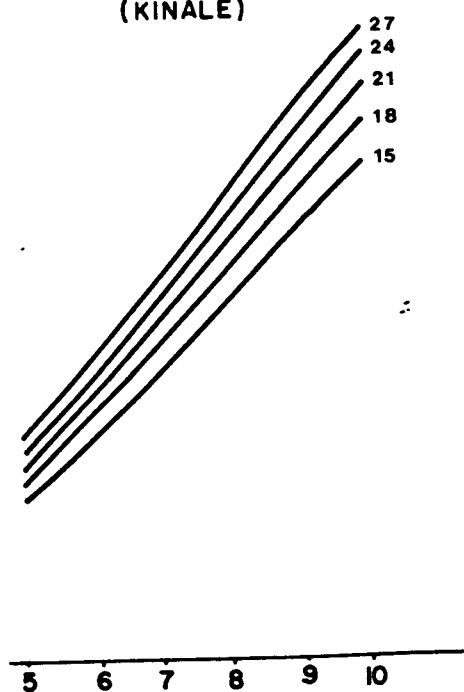
AGE IN YEARS FROM PLANTING

3.4 Validation and Discussion of the Basal Area before Thinning Equation 2.29

Equation 2.29 was accepted on the basis of the high coefficient of determination and the good fit indicated by a study of the residuals for the individual species equations. However it remained to see how well these equations predicted basal area development of permanent sample plots not used to formulate the equations. Unthinned plots from the 20 permanent sample plots set aside for each species as test data were used for this. Figure 14a,b,c,d shows the observed and predicted basal area for C. lusitanica, P. radiata, P. patula (rest of the country) and P. patula (Kinale) plots respectively.

The figure indicates very accurate prediction for some of the plots, e.g. plots 348 for C. lusitanica, and plots 391 and 276 for P. patula from the rest of the country and from Kinale respectively. For the other plots, the growth rate appears very accurately modeled but the predicted curves are shifted either above or below the observed curve. The shift for C. lusitanica and P. patula (both groups) is within +2 sq. meters of basal area, with no indication of bias.

The shift for P. radiata plot 289 is of the order of 4 sq. meters at age 8.5 years but this reduces to 2.5 sq. meters at age 11.5 years. For plot 164, the shift is almost nil at age 7.5 years but the curves diverges towards age 9.5 years. This trend is reversed for plot 373. In general, the variability is expected to be higher for this species as indicated by the lower coefficient of determination (.63) compared to that of the other species (Table 26). This could be the effects of

FIGURE 14

OBSERVED AND PREDICTED BASAL AREA FOR UNTHINNED PLOTS NOT USED IN FORMULATING THE BASAL AREA EQUATION

C . LUSITANICA
(a)

P. RADIATA
(b)

AGE IN YEARS FROM PLANTING
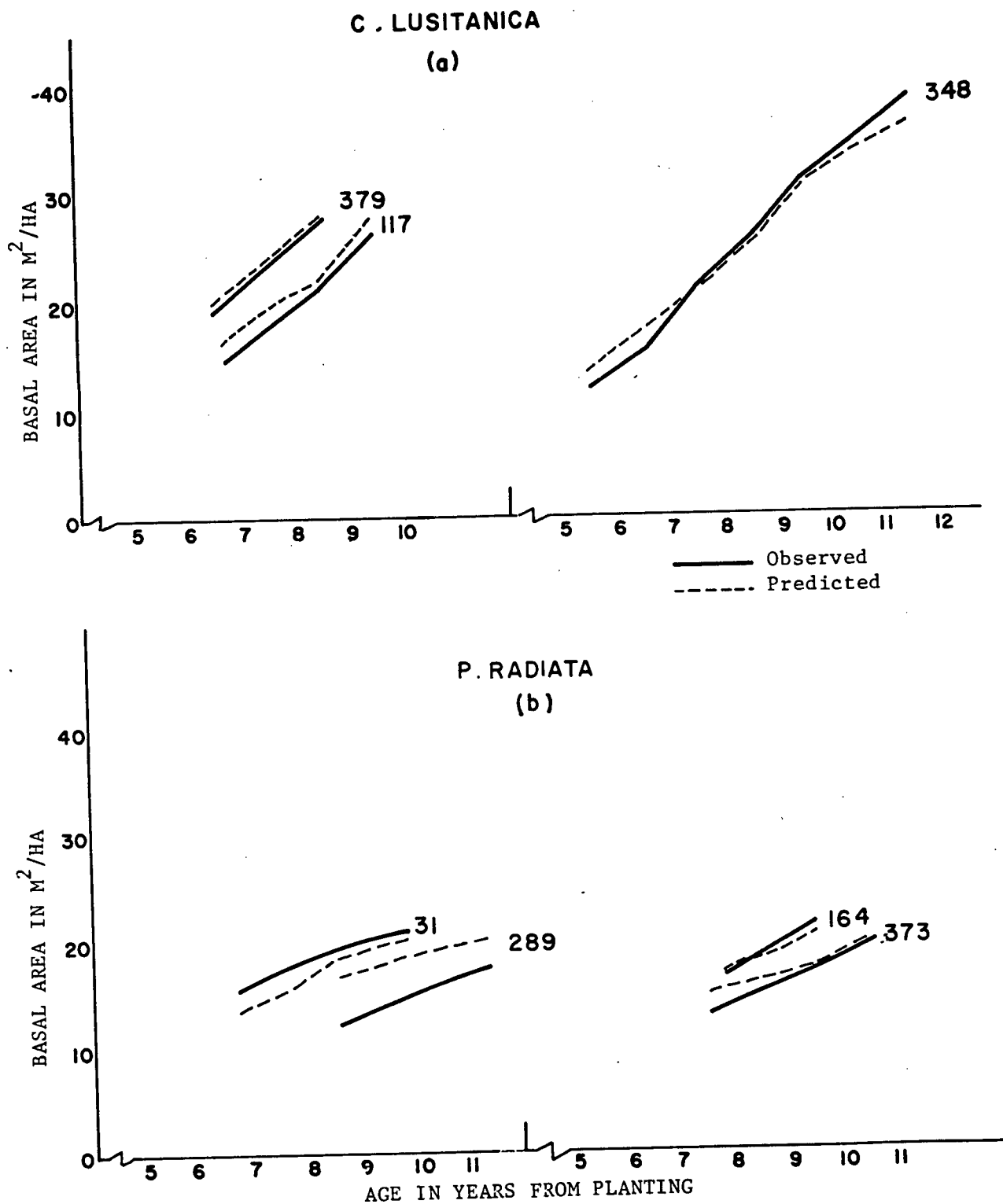
FIGURE 14 con't

P. PATULA (Rest of the country)

(c)

P. PATULA (KINALE)

(d)

AGE IN YEARS FROM PLANTING
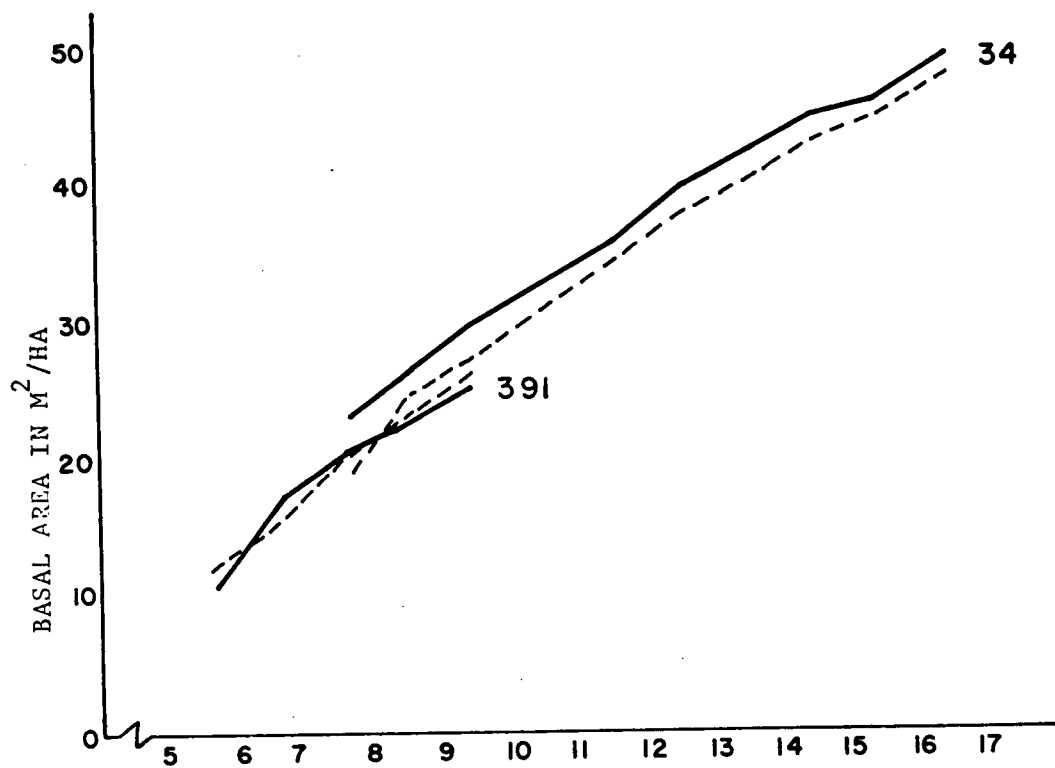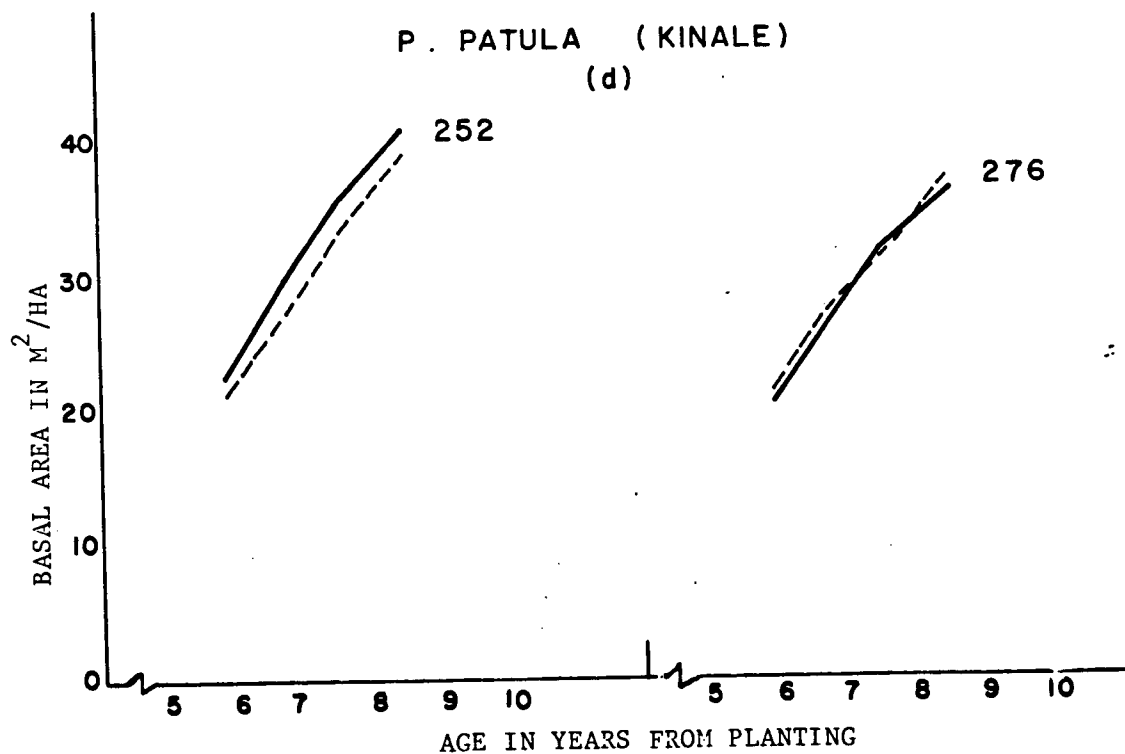
dothistroma pine disease which attacks this species in the early age, between 3 to 15 years. Surprisingly, this variability was not noticed for height development, which would suggest that probably the effects of this disease on stand development are expressed mainly on basal area development. There is however no indication of bias or inconsistency in these predictions.

The higher rate of basal area development for P. patula plots from Kinale region was unexpected. For example from the study on height development, there was no indication that this region had better site quality than the others (see Figure 8 curve No. 6) Also from Table 16 we see that this region has the second highest rainfall to Kiandongoro region, while Table 25 for the basal area data does not indicate differences in stand density for plots from Kinale and those from the rest of the country. This leaves two possible explanation:

1. That there are site factors possibly associated with soils which expresses themselves through basal area development for P. patula. This would be contrary to the general growth theory which holds that effects of site factor are expressed mainly through stand height development.

2. That the P. patula grown in Kinale region is of a different provenance or variety from that grown in the rest of the country. To date, there has been no evidence of this possibilty.

The implication here is that P. patula trees from Kinale region are of different form from that of trees from the rest of the country.

This phenomenon needs further investigation as the findings are of both economic and biological importance.

4. Basal Area Development in Thinned Stands

4.1 Introduction

As mentioned in the previous section, basal area development in plantations can be viewed in two phases, before and after first thinning. This section deals with the second phase in which the effects of thinning are a factor.

Thinning influences stand development through two changes in stand conditions:

1. It reduces the standing basal area by removing some of the trees, the basic units on which growth occur.

2. It reduces competition for light and nutrients, thus creating conditions condusive to faster rate of growth of the remaining trees in the stand.

The first effect results in an instant reduction in total basal area per unit area and an instant change in mean stand DBH, whose magnitudes depend on type of thinning. For example thinning (as practiced in Kenya) results in the remaining stand having a higher mean DBH than before thinning. This effect has been termed mechanical or statistical growth (Grut 1970).

The second effect affects the subsequent rate of stand basal area growth or mean stand DBH increment. Most studies on basal area

development in thinned stands have considered basal area increment as the variable of interest rather than basal area itself. Examples are Crowe (1967), Grut (1970), Curtis 91967), Clutter (1963), Sullivan and Clutter (1972), Clutter and Allison (1974) and others.

In studying basal area increment of a stand, an important consideration is the period of growth. In general, a longer period, e.g. 5 or 10 years has the advantage of evening out the year to year climatic variations. This would result in an apparent higher precision in the prediction equation. In predicting periodic growth however, an assumption is made that within that period, annual growth rates are the same. This could result in serious errors especially for fast growing tropical species such as are the subject of this study. For this reason and because permanent sample plots in Kenya are measured annually, annual growth interval was used.

4.2 Choice of Dependent and Independent Variables

As mentioned above, the variable of interest in basal area development after first thinning is usually basal area increment. The possibility existed of using either basal area increment per hectare or basal area increment of the tree of mean basal area in the stand. The former was selected as it is more directly related to stand basal area, one of the main driving variables of the envisaged growth and yield model.

For independent variables in the basal area increment equation, the following variables were considered:

1. Basal area in square meters per hectare at the beginning of the growth period. This variable forms the basic unit from which basal area increment is formed and on which it is accumulated. Basal area is also one of the most easily obtainable and widely accepted measure of stocking density. It was therefore an obvious candidate as an independent variable in the basal area increment equation.

2. Stand age: For a given standing basal area, one would expect that the older the stand, the lower the basal area increment.

3. Interaction of number of stems per hectare and stand dominant height. The effects of number of stems on basal area increment are accounted for largely by basal area. Similarly, some of the effects of site quality are absorbed by the basal area since the better the site quality, the higher the basal area, provided competition is not limiting. However it should be noted that the better the site quality, the higher the dominant height of the stand and therefore for a fixed number of stems per hectare, the higher the competition and therefore lower basal area increment.

In the preliminary study of the basal area increment equation, the third independent variable (interaction) was introduced as the stand density index - S%, calculated from equation 2.25:

$$S\% = \frac{\sqrt{\dfrac{10,100}{\text{No. trees/ha}}}}{H_{dom}} \cdot 100$$

S = Harts stand density index (see also Section 2.2).

Thus, this stand density index acted as a measure of the interaction between number of stems and stand dominant height, an equivalent of competition index measuring the effect of average spacing on basal area increment on a per unit area basis. For C. lusitanica and P. patula, this variable proved significant at the .05 level but non-significant for P. radiata in the preliminary linear equations. Table 28 gives the summary of data used for basal area increment study.

4.3 Basal Area Increment Equation

In the preliminary study of the relationship of the basal area increment to the independent variables, the following curve shapes were observed:

1. With age: an exponential decay curve; all three species.

2. With initial basal area: also an exponential decay curve, approximating a hyperbola: all three species.

3. With S%: an approximate linear relationship for C. lusitanica and P. patula; no relationship indicated for P. radiata.

From literature review and preliminary trial with nonlinear models, the final equation adopted was an extension and more generalized model

TABLE 28. Summary of basal area increment data

Species	Variable	Mean	Standard deviation	Minimum	Maximum	n
C. lusitanica	Age	20.3	8.43	7.5	43.6	
	BA	34.6	10.34	8.5	67.9	658
	S	21.2	3.95	12.6	35.9	
	BAI	2.2	1.10	0.1	5.9	
P. patula	Age	14.3	4.56	7.4	27.7	
	BA	28.0	10.64	5.2	62.2	638
	S	19.6	5.70	8.4	57.0	
	BAI	2.4	1.29	0.1	7.7	
P. radiata	Age	15.2	5.44	7.5	34.6	
	BA	25.6	10.15	4.7	57.0	723
	S	–	–	–	–	
	BAI	2.1	0.79	0.2	4.7	

for basal area increment for P. radiata in New Zealand (Clutter and Allison 1974):

$$BAI = e^{\left(b_1 A^{b_2} + b_3 B^{b_4}\right)} \quad \dots\dots\dots\dots\dots\dots\dots\dots \quad 2.30$$

Where: A = Initial age

B = Initial per acre basal area

BAI = Predicted basal area increment during the next year

b_1, b_2, b_3 and b_4 are regression coefficients.

In their equation, Clutter and Allison had $b_4 = -1$ which was generalized in this study. The extension consisted of inclusion of a third independent variable, S% (Hart's stand density index), to account for the interaction between stocking and stand dominant height. Preliminary investigations with this variable however proved nonsignificant for P. radiata and so the extended form of the equation was used only for C. lusitanica and P. patula:

$$BAI = e^{\left(b_1 A^{b_2} + b_3 B^{b_4} + b_5 S\right)} \quad \dots\dots\dots\dots\dots\dots\dots \quad 2.31$$

Where: BAI = Basal area increment in m^2/ha

B = Basal area in m^2/ha at beginning of the growth period

A = Age at end of growth period

S = Harts stand density index at end of growth period

b_1, $b_2 \dots b_5$ are regression coefficients.

Equation 2.31 (and similarly 2.30) can be rewritten as:

$$BAI = e^{b_1 A^{b_2}} \cdot e^{b_3 B^{b_4}} \cdot e^{b_5 S} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.32$$

so that e^{bi} indicate the rate of growth of the basal area increment

due to the respective independent variable, while b_2 and b_4 are

scale parameters related to the shape of the relationship of the respec-

tive variable sto basal area increment. Table 29 gives the estimated

parameters from equation 2.31 (C. lusitanica and P. patula) and equation

2.30 (P. radiata) and their relevant statistics. The parameters for the

New Zealand P. radiata equation are also given for comparison purposes.

Table 30 gives the asymptotic standard deviations of the estimated para-

meters from equations 2.30 and 2.31.

4.5 Results and Discussion

The equations for all three species show moderate to low coeffi-

cient of determination: 0.61, 0.69 and 0.31 for C. lusitanica,

P. patula and P. radiata respectively. The coefficient for P. radiata

is especially low compared to that for New Zealand. However it should

be noted that the data for New Zealand came from a relatively restricted

area – the New Zealand Forest Products Limited forests, while that for

Kenya came from the whole country. This and the dothistroma disease

problem in Kenya may partly explain the high variability in Kenya data.

In general, high variability in basal area increment may be

expected since the increment is a function of several other factors not

included in the model:

1.   Climatic variation from year to year.

TABLE 29. Parameter estimates and other relevant statistics for the basal area increment equation for $\underline{C}$. lusitanice, $\underline{P}$. patula and $\underline{P}$. radiata (Kenya and New Zealand)

Coefficients	$\underline{C}$. lusitanica	$\underline{P}$. patula	$\underline{P}$. radiata (Kenya)	$\underline{P}$. radiata (N.Z.)
b_1	7.7226	11.1362	5.9090	5.978
b_2	-0.3836	-0.2327	-0.6218	-0.2941
b_3	-4.7451	-7.1706	-11.1983	-21.663
b_4	-0.2227	-0.07970	-1.0632	-1
b_5	0.01653	0.01282	–	–
n	658	638	723	
R^2	.61	.69	.31	.76
SEE	.68 m^1 or 31%	.72 m^2 or 30%	.66 m^2 or 32%	18.2%

TABLE 30. Asymptotic standard deviations for the parameters on Table 29

Coefficients	$\underline{C}$. lusitanica	$\underline{P}$. patula	$\underline{P}$. radiata (Kenya)
b_1	0.2864	3.5863	0.5602
b_2	0.1362	0.1691	0.05722
b_3	0.8785	4.4411	5.3622
b_4	0.0948	0.0666	0.2440
b_5	0.0043	0.0036	–

2. Stand disturbances during cultural operations. For example in
a study of basal area increment for P. radiata, Grut (1970)
found that during approximately the first year after a
thinning, the increment was lower than that normal for the
particular age, site quality and number of stems. This, he
stated, could partly be explained by the fact that a portion
of the growing stock had been removed and the remaining crop
had not yet adjusted itself to the new conditions. After a
year, the basal area increment rose above that which is normal
for the particular age, site quality and number of stems.
This could partly be explained as due to the manurial effects
of the released slash and roots left in the ground.

Although climatic factors can be measured for inclusion in the
basal area increment equation, they are not useful for practical pur-
poses since it is not possible to project accurately what these factors
will be in future. The effects of silvicultural disturbances on the
other hand can only be measured for controlled experiments: information
that was not available for this study.

The signs for all the predicted parameters are consistent with
theory. For example, the positive sign associated with b_1 for age
implies that basal area increment will be decreasing as age increases
because of the negative value of b_2, while the negative sign
associated with b_3 for basal area implies that basal area increment
will be increasing as basal area increases, all other factors being held
constant, because of the negative value associated with b_4. The

positive sign associated with coefficient b_5 for density index for

C. lusitanica and P. patula means that basal area increment will

increase as density index of the stand increases. This can result from:

1. Increasing spacing as a result of heavier thinnings.

2. For fixed spacing, lower site quality means higher stand density index.

In either case, the result is less crowding of the remaining stand, less competition and therefore higher basal area increment for the remaining stand. Similarly, stands with a higher number of stems per unit area or on high quality sites means higher crowding: more competition and therefore lower basal area increment. Thus this sign is consistent with growth theory.

An important observation in Table 29 is that the parameter b_1 which is associated with growth rate with respect to age is almost the same for both the Kenyan equation and the New Zealand equation for P. radiata. The parameter b_4 associated with shape of the basal area increment to basal area relationship is also almost the same; thus confirming the hyperbolic relationship, while the other parameters differ by almost twice each other. However, the comparison of the magnitude of these parameters is invalidated by the fact that the equations are not based on the same units.

It is also significant that for P. radiata in Kenya, the interaction between number of stems and stand dominant height as measured by stand density index (S%) failed to be significant. As mentioned earlier, this variable measures the effects of competition on basal area

increment per unit area. Thus for this species, stand density index, within the range maintained in plantations in Kenya, has no significant effect on basal area increment on a unit area basis. This may well explain why Clutter and Allison (1973) used only basal area and age in their basal area increment equation for this species in New Zealand.

Figure 15a and b shows the predicted basal increment for various densities for P. radiata in Kenya and New Zealand, using equation 2.30. The range of densities is within the range covered by the data for Kenya. Two main observations are worth of note:

1. For any given basal area, basal area increment is much higher for Kenya than for New Zealand. This could be a result of site factors in Kenya being more favourable to the growth of this species.

2. For Kenya, basal area increment is much more affected by stand density (as measured by basal area) than in New Zealand, especially for basal area under 30 m^2/ha. Thus, the theory that basal area increment is not affected by changes in stand density does not hold for Kenya at the present range of densities. For P. radiata in New Zealand, the theory appears to hold closely. This may be a reflection of the difference in site quality, suggesting that for Kenya, site quality is much higher so that the present stand densities do not entirely utilize the site potential, especially below 30 m^2 per hectare.

FIGURE 15

BASAL AREA INCREMENT CURVES

(a)

P. RADIATA (KENYA)

(b)

P. RADIATA (NEW ZEALAND)
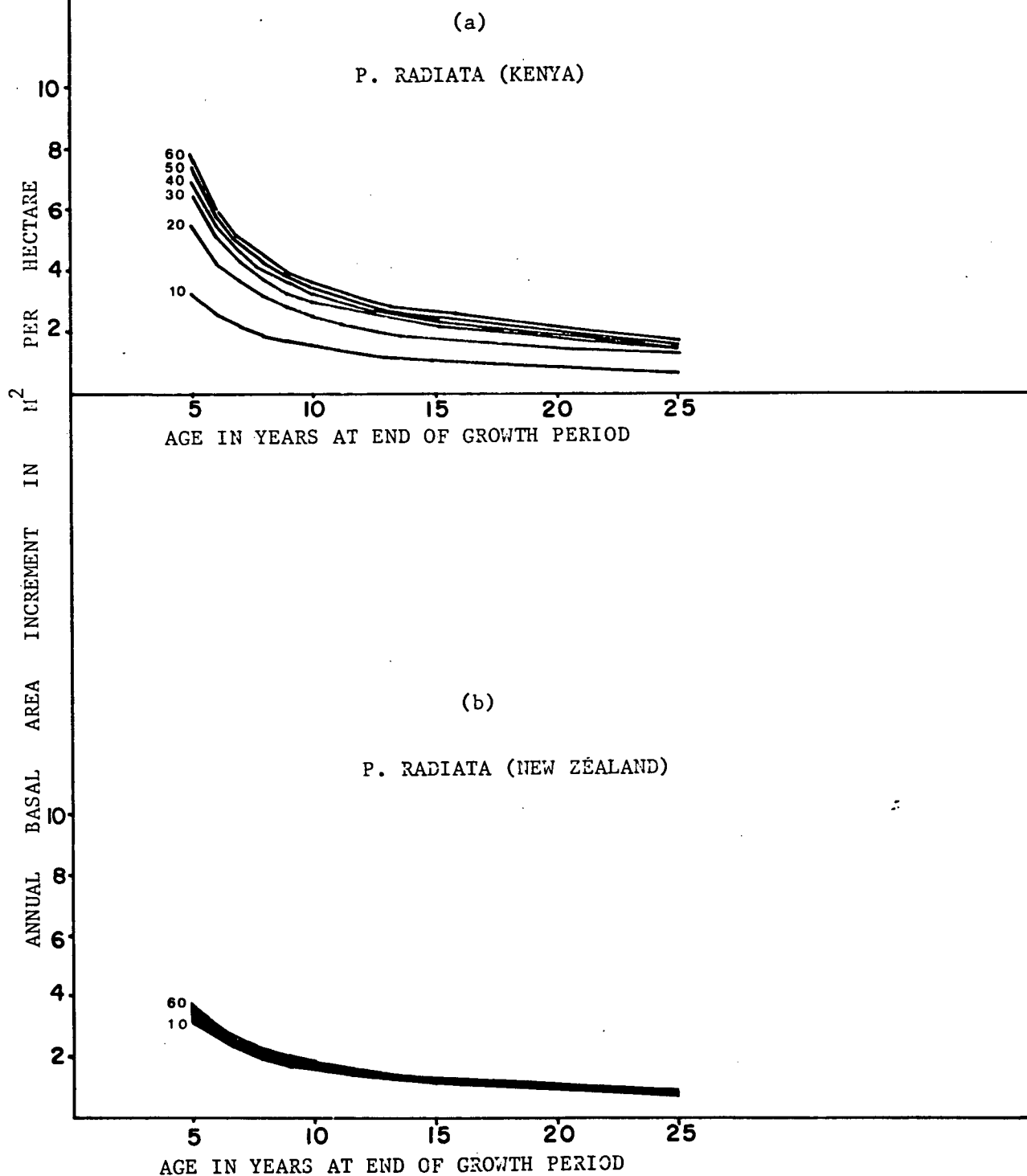
Figure 16a and b shows the predicted basal area increment for

various stand densities for C. lusitanica and P. patula, using equation

2.31. These curves are for the average stand density index (21.2 and

19.6 respectively) within the range of densities covered by the data.

For a given basal area, the curve would be higher for higher value of S%

and vice versa. The figure indicates the same pattern as for P.

radiata. Thus, basal area increment for these species varies with stand

density within the range of densities maintained in Kenya plantations.

5.   Stand Diameter Distribution

The information on stand structure and diameter distribution is

central to forest stand management. Besides forming the basis for the

stand table construction, this knowledge is especially important in

stands managed for sawtimber and veneer production since the final yield

in these plantations is closely related to the size of the logs.

Knowledge of the volume distribution by size classes forms the basis for

decision making as to when a stand can be economically harvested for a

given end product.

According to Hyink (1980), three basic approaches have been

employed in modelling growth and yield attributes by size classes:

1.   Approaches employing Markov chains and systems of differential

     equations. According to Moser (1980), this approach uses a

     square matrix of conditional probabilities that correspond to

     the probability of going from state i to state j after one

FIGURE 16

BASAL AREA INCREMENT CURVES

(a)

C. LUSITANICA

S% = 21

(b)

P. PATULA

S% = 20

AGE IN YEARS AT END OF GROWTH PERIOD
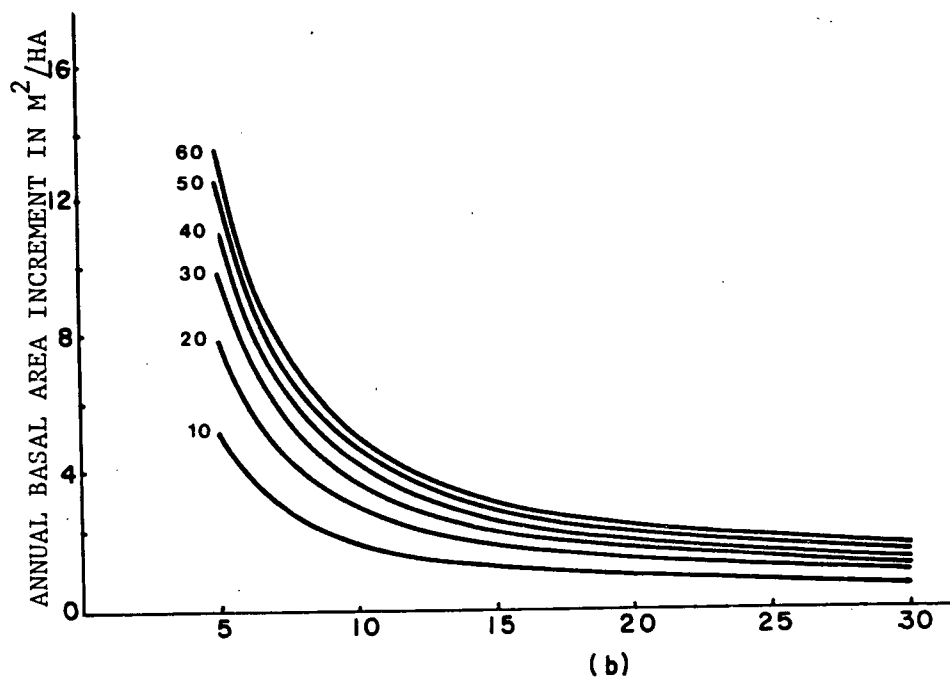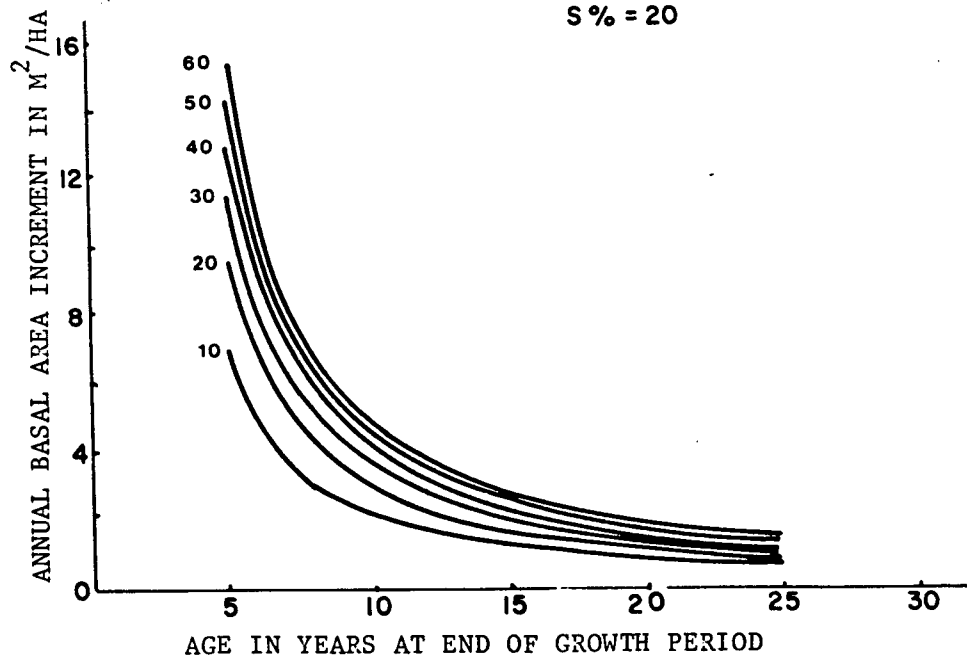
step or transition. In practice, this approach corresponds to the updating of a stand table.

2. Individual tree model approach: By their nature, individual tree models, pioneered by Newnham (1964), provide growth and yield attributes for individual trees.

3. Diameter distribution approach based on probability theory.

The first two approaches place no restriction on the form or shape of the underlying diameter distribution (Hyink 1980), an advantage over the third approach. It should however be noted that these approaches are inherent to the modelling strategy and so are not alternatives for the third approach in the whole stand, diameter free models. It is this third approach which is of interest in this study.

5.1 Theoretical Considerations

The basic assumption underlying the probability distribution approach to stand diameter distribution is that the latter can be adequately characterized by a given probability density function (pdf). In particular, even-aged stands tend to have unimodal shape and form, which has lead to the wide use of continuous unimodal probability density function to characterize their diameter distribution.

In general, the probability density function has the property:

$$\int f(x;\theta)\, dx = 1 \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad 2.33$$

Where θ = a vector containing the parameters of the particular pdf.

Put in another form:

$$p(x_1 \leq X \leq x_2) = \int_{x_1}^{x_2} f(x;\theta)\, dx \qquad \dots\dots\dots\dots\dots\dots\dots \quad 2.34$$

which reads that the probability of the random variable X assuming a value between x_1 and x_2 is given by the integral of the probability density function between the two values (x_1 and x_2). The problem therefore in applying this theory to forestry is one of finding the appropriate pdf and estimating its parameters.

5.2 Choosing the Appropriate pdf

As mentioned above, even-aged stands in general have diameter distribution with unimodal shape and form. Over the years, several mathematical functions have been used to model this distribution. Examples including the normal curve (e.g. Crowe 1967), Gram-charlier Series (e.g. Meyer 1930, Crowe 1967), Pearl-Reed population growth curve (Osborne and Schumacher 1935, Nelson 1964, Crowe 1967), Beta distribution (Clutter and Bennett 1965, McGee and Della Bianca 1967, Lenhart and Clutter 1971), the Gamma distribution (Nelson 1964) and the Weibull function (e.g. Bailey and Dell 1973, Clutter and Allison 1974, Alder 1977,

Rustagi 1978 and Hyink 1980, Schreuder and Swank 1974). In an analyses

of the suitability of most of these function for characterizing diameter

distribution, Bailey and Dell (1973) concluded that no other diameter

distribution function exhibits as many desirable features as the Weibull

function. These include the simplicity of algebraic manipulation and

its ability to assume a variety of curve shapes. This explains why most

of the recent work on diameter distribution and stand structure has used

this function, as evidenced by the examples quoted above. This function

was chosen for this study for the above reasons and because preliminary

investigations indicated that it would adequately characterize the

diameter distribution of the permanent sample plots available for this

study.

The Weibull probability density function has already been discussed

in Section 1.2 of this chapter in connection with height over age growth

function. For diameter distribution, the usual procedure is to work

with the cumulative distribution form of the function, defined as:

$$F(x) = 1 - e^{-\left(\frac{x-x_0}{b}\right)^c} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad 2.35$$

for $x > x_0$

$$0 \leq F(x) \leq 1$$

where $F(x)$ measures the area under the curve between $X = x_0$ and

$X = x$. Thus in terms of diameter distribution,

$$F(x) = p \ (X \leq d) \quad \text{or} \quad p(d_1 \leq X \leq d_2) = F(d_2) - F(d_1) \ \ldots\ldots \ 2.36$$

This equation is equivalent to equation 2.34.

5.3 Fitting the Weibull Model to Diameter Distribution Data

The data for the diameter distribution study consisted of 58

permanent sample plots made up of all three species: 30 for P. patula,

18 of C. lusitanica and 10 of P. radiata. The number of stems per plot

ranged between 4 to 70 stems on which tree DBH had been measured to one

decimal place of a cm. For consistency with timber measurement

practices in Kenya, the tree diameters for each plot were stratified

into 3 cm diameter classes. Of the 58 plots, 8 were selected at random

and set aside as test data. Data summary for the 50 remaining plots are

given on Table 31.

TABLE 31. Summary of the DBH distribution data

Variable	n	Minimum	Maximum	Mean	Standard deviation
Age	50	9.700	41.700	18.568	6.5781
Height	50	16.100	39.000	24.754	6.0117
Stems	50	74.000	1160.0	523.08	278.37

The first step was to fit the Weibull cumulative distribution

function to the 50 diameter distribution histograms to obtain an

estimate of the parameter:

$$F(D) = 1 - e^{-b^*D^{*c}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.37$$

where $\quad b^* = \dfrac{1}{b^c}$

$D^* = D - (DL + 3)$

DL = Minimum diameter class on the histogram

D = A given diameter class

b and c are Weibull parameters

F(D) = Observed probability of trees having a DBH $\leq$ D.

The parameters b and c were estimated using BMDP:3R nonlinear sub-routine. Figure 17 shows the histogram for plot 135 and the curve resulting from the estimated parameters.

The next step was to test how well the Weibull function character-ized the diameter frequency distribution of the 50 plots. For each plot, the expected frequency per diameter class was calculated using the estimated parameters and a Chi-square test of goodness of fit performed using the following equation:

$$\chi^2 = \sum_{i=1}^{K} \frac{(N_i - N_i)^2}{N_i} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.38$$

where $\quad N_i$ = Observed number of trees in a diameter class i

N_i = Expected number of trees in a diameter class i predicted using the estimated parameters

k = Total number of diameter classes

χ^2 = Calculated Chi-square value.

FIGURE 17

DIAMETER DISTRIBUTION HISTOGRAM AND THE FREQUENCY CURVE RESULTING FROM THE FITTED WEIBULL PROBABILITY DENSITY FUNCTION

Plot no 135
N = 716 Sph
n = 39
D_L = 18
b = 10.6246
c = 1.9257
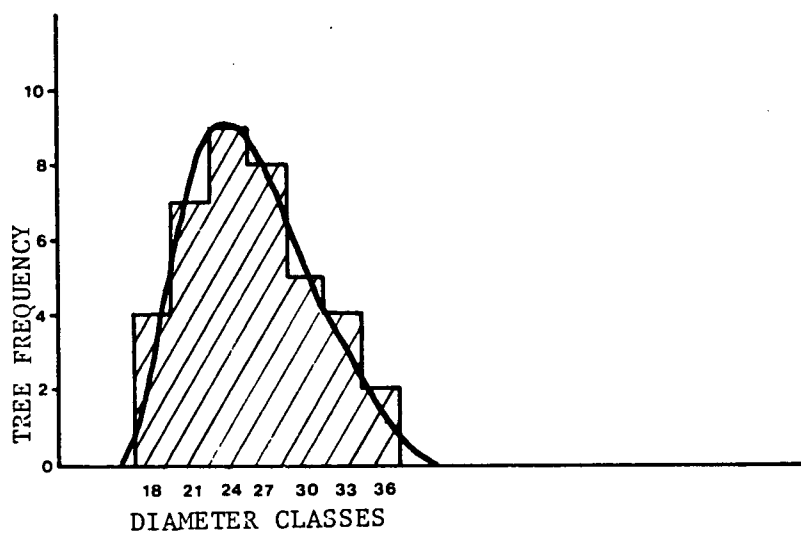
DIAMETER CLASSES

The calculated χ^2 values were then compared with the tabulated χ^2 values for .05 probability level of significance and k-3 degrees of freedom.

Out of the 50 plots, χ^2 values could not be calculated for 8 plots as they had 3 or fewer diameter classes. Of the remaining 42 plots, only 4 showed a lack of fit, either because they had very long tails or had sharply truncated data. On basis of this test therefore, the hypothesis that the diameter distribution follows the Weibull distribution was accepted.

5.4 Estimating the Parameters and Validation of the Estimating Model

The Weibull parameters estimated for each individual plot define the shape and form of the frequency distribution by diameter classes of the particular plot. As is expected, these parameters differ from plot to plot due to differing stand conditions. In order to be able to predict the appropriate D_L and Weibull function parameters for given stand conditions, the linear and curvilinear correlation of D_L and the estimated parameters with stand variables was studied (Table 32).

Table 32 indicates that the minimum diameter in a stand is best correlated with the stand mean dbh, age, stand dominant height and the $\log_{10}$ number of stems per hectare in that order. The high correlation of D_L with age and dominant height could be explained as largely due to the high correlation between the stand mean dbh, age and stand dominant height and so any one of these could be used as the predictor variable without loss of precision in the estimation of this variable.

TABLE 32. Linear and curvilinear correlation of the D_L and estimated Weibull parameters with other stand variables

n = 50	DF = 48	r @ .05 = 0.28	r @ .01 = 0.36

Stand variables	D_L	b	c
Age	0.92	0.34	−0.46
Height	0.80	0.28	−0.43
No. stem	−0.76	−0.10	0.40
DBH	0.94	0.37	−0.43
D_L	1.00	0.04	−0.43
DBH − D_L	−0.02	0.94	0.13
$\dfrac{D_L}{DBH}$	0.66	−0.54	−0.44
$\dfrac{1}{No.\ stem}$	0.77	−0.04	−0.42
Log Age	0.91	0.29	−0.50
Log Height	0.76	0.26	−0.44
Log No. stems	−0.81	−0.07	0.42
Log (DBH−D_L)	−0.14	0.90	0.15
Log $\dfrac{D_L}{DBH}$	0.63	−0.50	−0.42
Log DBH	0.93	0.35	−0.46
Log D_L	0.95	0.01	−0.52

DBH = Mean stand DBH in cm ($\bar{D}$)

Height = Stand dominant height in meters

D_L = Minimum stand DBH in cm

No. stems = Number of stems per hectare

b & c = Estimated Weibull parameters.

On the other hand, the number of stems per hectare is not so closely correlated with the stand mean DBH. These two variables were therefore selected as predictors of the minimum stand diameter or the x_0 parameter. The inverse of number of stems was used instead of the logarithm$_{10}$ of the number of stems because the former resulted in a regression equation with a higher coefficient of determination. The final equation was:

$$D_L = -3.2048 + .7472\bar{D} + 691.14(\frac{1}{N}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.39$$

where D_L = Minimum stand dbh

   $\bar{D}$ = Stand mean dbh

   N = Number of stem/ha

   n = 50

   R^2 = .90

   SEE = 3.1 cm = 15% of the mean

all the predictor variables were significant at .05 level.

The scale parameter b was very strongly correlated with the difference between the stand mean DBH and the minimum stand DBH, followed by the ratio of the two. This was not surprising since this parameter is defined in terms of its position on the x-axis, on which both D_L and $\bar{D}$ are located (Bailey and Dell 1973). A regression for this parameter with these two variables as predictors gave the following equation:

$$b = -3.6207 + 1.2263(\bar{D} - D_L) + 5.7910\left(\frac{D_L}{\bar{D}}\right) \quad \ldots\ldots\ldots\ldots\ldots \quad 2.40$$

$n = 50$

$R^2 = .91$

$SE = 1.24 = 11\%$ of mean

Both predictor variables were significant at .05 probability level.

The parameter c on the other hand did not have any stand attribute with which it was strongly correlated. Trials with several combinations of predictor variables produced the following best equation:

$$c = 4.6585 - 2.0635\left(\frac{D_L}{\bar{D}}\right) - .02360\bar{D} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2.41$$

$n = 50$

$R^2 = .27$

$SE = .68 = 27\%$ of mean

Both predictor variables were significant at .05 probability level.

5.5 Model Validation

Equations 2.39 and 2.40 proved quite satisfactory based on their coefficient of determination and the study of their residuals plotted against the predicted values. Equation 2.41 proved the best possible with satisfactory distribution of residuals. However, it still remained to see how well these equations would predict the respective Weibull

parameters for independent data from the same population as used to derive the equations. Table 33 gives the predicted parameters and the observed parameter obtained by fitting the Weibull function to the frequency distributions of the 8 plots set aside for this purpose.

In terms of mean bias the equations for D_L indicate no bias. Similarly, the equation for c indicates, no overall bias. However, the model is only moderately sensitive to changes in stand attributes, so that high values of c are associated with positive residuals and low values with negative residuals. Parameter b, on the other hand, has one large positive residual, that of plot 327, which has largely contributed to the positive bias for this parameter. Otherwise, the other residuals range between ±3.6, which is within the expected variability as indicated by equation 2.40. Equation 2.40 can therefore be considered unbiased since, as seen from Figure 18, plot 327 represents an outlier.

In terms of precision, the standard errors of estimate for all parameters, are in general higher than those obtained in the derivation of their equations. This can be explained partly by the lower degrees of freedom associated with the test sample. In addition the standard error for parameters b and c can be expected to depart even farther from that of their equation since their variability includes the variability in D_L (as a predictor variable which is itself a predicted variable).

Figure 18 shows the histograms of the diameter frequency distributions of the test plots, the observed distribution (solid curve) obtained by fitting the Weibull function to the individual plot cumulative probability data, and the predicted distribution (dotted curve) obtained from Weibull parameters predicted from equations 2.39, 2.40 and 2.41.

TABLE 33. Comparison of predicted and observed Weibull parameters for the test plots

Plot #	D_L			b			c		
	Observed	Predicted	Residual	Observed	Predicted	Residual	Observed	Predicted	Residual
210	11.7	14.8	-3.1	13.6583	10.0550	3.6033	3.6882	2.7844	0.8538
327	26.6	33.3	-6.7	21.5330	14.1089	7.4241	3.3244	2.0608	1.2636
128	18.4	19.9	-1.5	14.2300	11.2948	2.9352	2.4216	2.5530	-0.1314
147	19.3	16.4	2.9	8.7052	10.4026	-1.6974	2.8789	2.7055	0.1734
189	26.8	23.2	3.6	9.0294	12.7995	-3.7701	1.7225	2.4350	-0.7125
202	14.8	15.1	-0.3	10.4126	9.7630	0.6496	4.0712	2.7574	1.3138
221	25.1	23.6	1.5	10.4964	11.1698	-0.6734	1.4104	2.3862	-0.9758
238	18.8	14.7	4.1	5.9215	9.5166	-3.5951	1.8959	2.7720	-0.8761

SE = 4.41 cm   SE = 4.64 cm   SE = 1.1248

or 21.8%   or 39%   or 42%

Mean bias = 0.0625   Mean bias = 0.6095   Mean bias = 0.1136

FIGURE 18

DIAMETER DISTRIBUTION HISTOGRAMS, FITTED WEIBULL P.D.F. AND THE PREDICTED WEIBULL P.D.F. FOR THE EIGHT TEST PLOTS
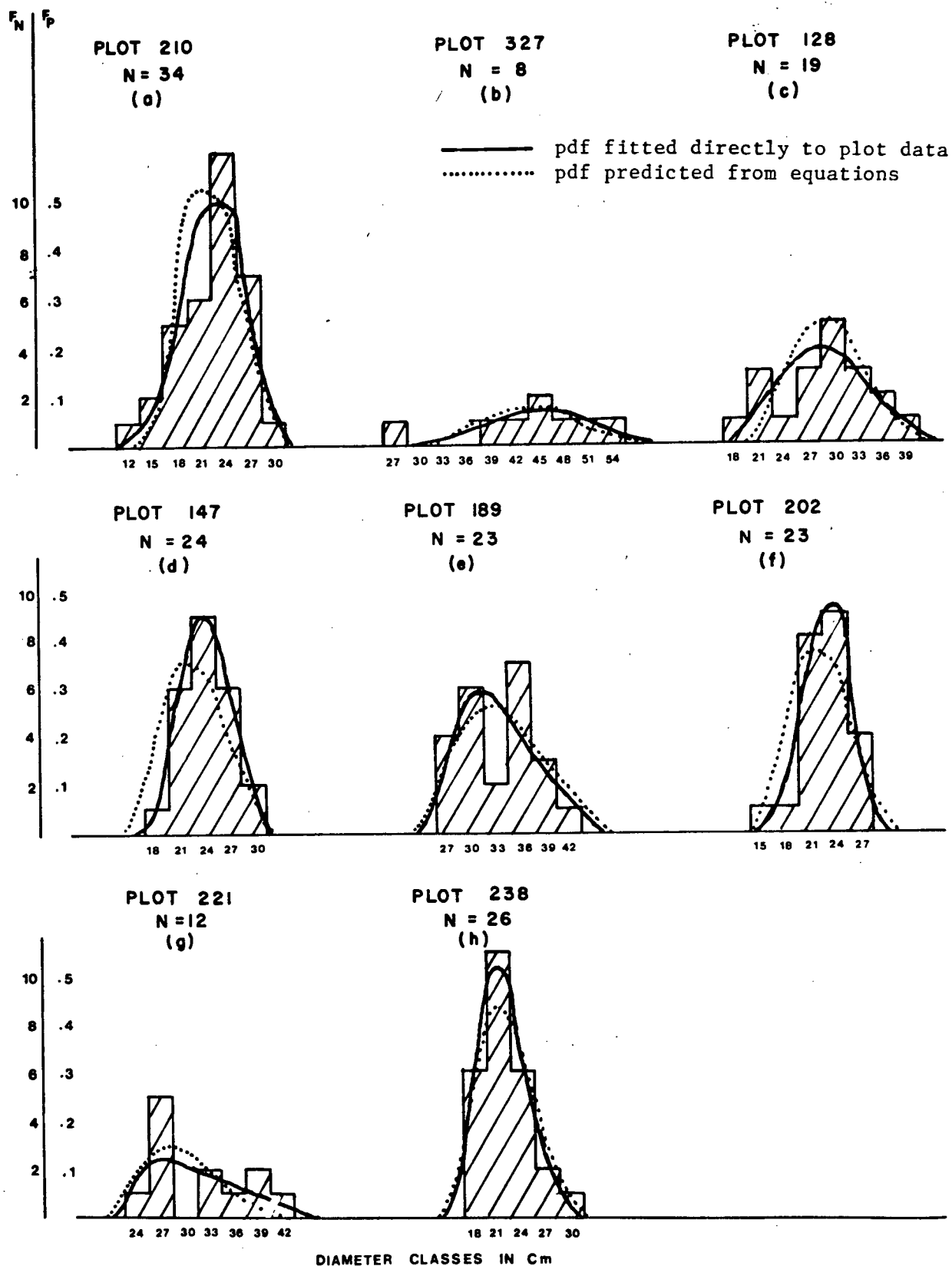
In general, the histograms indicate the range of diameter frequency distributions that can be expected in plantations where thinning is a standard practice. Thus, plot 327 represents an extreme case tending towards a uniform distribution while most of the other plots with multimodal distributions can be expected as depicted by plots 327, 128, 189 and 221. All these cases underline the problem associated with the use of any one probability distribution function to characterize all these shapes.

Assuming the unimodal shape and form to be the predominant characteristic, the fitted Weibull function (solid curve) appears to characterize this distribution quite satisfactorily. Similarly, the curves from the predicted parameters (dotted) follow similar shape and form to that fitted from the data, with no indication of bias or inconsistency. Thus, the Weibull parameter prediction equations were accepted for the diameter frequency distribution modeling in this study.

6.0 Volume Determination

Tree volume equations for $\underline{C}$. $\underline{lusitanica}$, $\underline{P}$. $\underline{patula}$ and $\underline{P}$. $\underline{radiata}$ in Kenya were developed by Wright in 1969 (Wright 1977). Since then, these volume equations have been very widely used in management practices and form the basis for the tree volume tables for these species (Wright 1974) and the yield tables (Wanene and Wachiuri 1975, Wanene 1975, 1976). They can therefore be said to have passed the field tests. These equations were used to determine the stand volumes in this study.

The tree volume equations provide for the determination of tree volume from the tree DBH and either the individual tree height or the tree dominant height, obtained from determining the dominant height of the stand. Only equations based on tree dominant height are of interest in this study since individual tree heights are not available. Table 34 gives the equations and the respective coefficients for each of the species. These equations give total overbark volume.

For all species, the conversion of the total volume to merchantable volume is achieved through multiplication by a factor R which is dependent on the tree DBH:

$$R = b_0 + b_1 \, e^{b_2 D} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad 2.44$$

Table 35 gives the relevant coefficients for each of the species for the merchantable standards in Kenya: 15 cm and 20 cm top diameter limits for P. patula and P. radiata, 15 cm only for C. lusitanica.

TABLE 34.   Equations and coefficients for the tree volume equations for
_C_. _lusitanica_, _P_. _patula_ and _P_. _radiata_ in Kenya

1. $\quad V = b_0 + b_1 D^2 + b_2 DH + b_3 D^2 H$	....	2.42
2. $\log_{10} V = b_0 + b_1 \log_{10} D + b_2 \log H$	....	2.43

	_C_. _lusitanica_	_P_. _patula_	_P_. _radiata_
b_0	−0.01733	−0.0072	−4.2643
b_1	0.0001937	0.00002887	2.0598
b_2	0.00005069	0.00002077	0.7875
b_3	0.00002296	0.00003276	

Equation 2.47 is for _C_. _lusitanica_ and _P_. _patula_

Equation 2.48 is for _P_. _radiata_

$\quad\quad\quad\quad$ V =   Tree volume in cu.meters
$\quad\quad\quad\quad$ D =   Tree DBH in cm
$\quad\quad\quad\quad$ H =   Stand dominant height in meters.

TABLE 35. Coefficients for R-factor equation (2.44) for the merchantable limits for the respective species

	15 cm			20 cm		
	b_0	b_1	b_2	b_0	b_1	b_2
C. lusitanica	0.9870	-11.1577	-0.1742	-	-	-
P. patula	0.98471	-8.6658	-0.16135	0.97352	-21.9737	-0.15407
P. radiata	0.98348	-14.7231	-0.17505	0.97622	-18.7751	-0.13971

CHAPTER   3

YIELD MODEL CONSTRUCTION AND VALIDATION

1.0 General Principle

The general principle on which growth and yield models are based
can be derived directly from the definition of these two terms. For
example in the simple case of an even-aged stand with a standing volume,
V, growth rate may be expressed as a function of age, A, in terms of
differential notation:

$$\frac{dV}{dA} = f(A) \quad \dotsb \quad 3.1$$

where $\frac{dV}{dA}$ =   rate of change of stand volume with respect to
stand age.

$f(A)$ =   a function of stand age.

When the age is expressed in years, the rate of change as given in
equation 3.1 is referred to as annual growth or annual increment in
volume. From this, volume yield from an initial age A_0 to a future
age A_{0+t} can be obtained as the summation of the growth rates within
this time period. Analytically, yield is obtained by integrating the
age function within the limits A_0 to A_{0+t}:-

$$Y = \int_{A_0}^{A_{0+t}} f(A)dA = F(A) \quad \dotsb \quad 3.2$$

where Y = Stand yield or the summation of the annual growth

increments between the initial stand age A_0, and a

future stand age, A_{0+t}.

F(A) = Yield function obtained by mathematically integrating

the growth-rate equation, f(A).

The essence of this principle helps put the whole concept of growth and yield into its historical perspective. Thus, the earlier yield models represented by normal yield tables and later by the variable density yield tables presented stand yield (derived using graphical and later by regression techniques) as a function of stand characteristics as discrete variables. Forest literature has numerous examples of this class of models: Plonski (1956), Barnes (1962), etc. This category of models is described as Static models in growth and yield literature. As a result of recent advances in computational techniques and computer technology, recent yield models presents stand yield derived from stand parameters which are rates of change (growth rates). This category of models is termed Dynamic where one (or more) of the independent variable is an integral of the dependent variable. The earliest example of a dynamic model appears to be the growth and yield model for ponderosa pine stands by Lemmon and Schumacher (1963) which estimated tree growth as a function of diameter growth after thinning.

The transition between the static models and dynamic models presented problems to the mensurationists, since most models tended to treat growth and yield as essentially independent phenomena. The result was that yield derived from conventional (static) models differed from

yield derived from dynamic models. This contradicted the basic principle of growth and yield which required that total growth (yield) be synonymous with the summation of continuous growth increments. This problem of incompatibility between the two categories of models was recognised by Clutter (1963) when he developed compatible growth and yield models for Loblolly pine. This he did by differentiating already accepted yield models (with respect to age) to produce cubic-foot and basal area growth functions. He defined as compatible those yield models whose algebraic form can be derived by mathematical integration of their growth model.

2. Simulation Application to Growth and Yield Models

By far, the most widely used method for growth and yield modeling is simulation technique (Lee 1967). Basically, the term refers to any model that exhibits a behaviour similar to the real system. Because of the complex nature of a forest stand and the need for a flexible and comprehensive technique to handle all the component interactions with as few restrictive assumptions as possible, simulation has become almost the standard tool. Its application has been stimulated by the advances in programming languages and access to high speed computers. Its role in simulating stand growth and the biological and economic assumptions underlying its application were discussed by Smith (1966), while Gould and O'regan (1965) discussed its role to better forest planning. Among its main advantages are the time compression effects whereby the technique accomplishes in seconds what might otherwise take several years of

actual experimentation and the facility to experiment with the simulated system rather than the actual system. It should however be stated here that simulation is not a perfect tool as it only provides estimates of the model state resulting from predetermined decision variables. Thus, according to Hillier and Lieberman (1980), it only compares alternatives rather than generating the optimal one. Besides this, one pays for the comprehensiveness and flexibility of simulation in terms of analytic intractibility.

The general approach to forest stand simulation involves the development of the individual growth relationships and functions to describe the individual interactions. These form the elements (blocks) of the system. These are then put together in a systematic and logical sequence (as a computer programme) to form the mathematical simulator of the forest stand system. This is the general approach adopted to this study.

2.1   Forest Stand Simulation Models

Computer based forest stand simulation models first appeared in the early 1960's, heralded by the pioneering work of Newnham (1964). Since then, their development has been very rapid so that as of 1980, Smith and Williams (1980) counted not less than 26 published models. Most of this development has been mainly in response to forest management needs for planning tools, academic endeavours to broaden the knowledge of forest stand modeling, or both. The level of detail obtainable from

each model depends on the type of model and the simulation approach, which itself is largely governed by the available data within the prevailing financial and technical constraints. Although several researchers have attempted to classify stand simulation models: Mitchell (1980), Smith and Williams (1980), Munro (1974): the terminology by Munro (1974) will be adopted here firstly because it is comprehensive and because it encompasses the philosophy on which these models are based. Munro's classification recognises three categories of models, based on inter-tree dependence status and primary unit parameter requirements:

1. Single tree - distance dependent forest stand models:

Newnham's (1964) yield model for Douglas-fir was not only the first computer based yield model but also introduced a new generation of forest stand models based on the individual tree in the stand as the basic unit, and characterized by the requirement that individual tree position in the stand be known. These models grow the physical attributes of the individual tree by first obtaining the potential growth for a free growing tree and then reducing this by a factor dependent on the degree of competition to which the tree is subjected. This procedure popularized the concept of a competition index which can be defined as a relative measure of the degree of competition. Different stand attributes have been used as competition indices including mean distance of subject tree to a predetermined number of competing neighbours (Adlard 1974), angle count density (Lowe 1971), crown overlap (Newnham 1964, Lee 1967) size-distance of competing neighbours relative to subject tree, etc. For further discussion on competition indices, the reader is

referred to Adlard (1974), Newnham and Mucha (1971), Gerrard (1968) and Opie (1968).

Since Newnham's (1964) model, several models based on similar concept but differing in complexity and level of attribute detail have been developed. Examples of some of those with unique features follow:

Arney's (1972) Douglas-fir model improved on Newnham's model by simulating the tree diameter growth at each whorl up the tree so that tree form was a reflection of differential growth rates at different sections up the tree. This feature was particularly significant in permiting modeling tree responses to such silvicultural treatments as pruning, thinning and fertilization. Hegyi's (1974) BUSH model for jack pine (Pinus banksiana Lamb.) used Arney's approach.

Mitchell's (1969, 1975) TASS I (white spruce, Douglas-fir and hemlock) and TASS II (Douglas-fir) models respectively represent the highest development in the single-tree distance dependent models based on the level of detail of stand attributes modeled. The unique feature of these models is that the crown of the simulated tree is modelled explicitly with the growth of individual branches responding to such factors as competition from other branches either of the same subject tree or from adjacent trees. After calculating individual branch size and foliar volume, the net production of photosynthates is then predicted and proportionately distributed to the stem bole which increases in diameter accordingly. Thus, these models come closest to modeling the whole tree biomass based on the photosynthetic activity of the foliage. They are therefore theoretically capable of modelling tree responses to cultural treatments (pruning, thinning and fertilizers)

and to insects and diseases which affect the quantity and quality of tree foliage.

Ek and Monserud's (1974) FOREST model is also a single-tree distance dependent model but is unique in that while most of the other models in this category are for even-aged stands of a single species, FOREST simulates growth and reproduction of even- or uneven-aged mixed species forest stands. This is accomplished through modeling the reproduction (regeneration) and understory development explicitly, with the spatial pattern of the new stems determined by the prior stand conditions.

As indicated by the few examples quoted above, this category of models is capable of providing very detailed information on individual tree growth in response to silvicultural treatments and insect and disease attacks, depending on the level of complexity. They are also capable of simulating the development of heterogenous stands (in terms of age, species and spatial distribution). However, their use is limited by their complexity and the requirement that the coordinates of each individual tree in the stand be known. This, according to Munro (1974) makes them very expensive in terms of time required to develop them and the excessive computer time required to execute the extra space for storage of tree position records. As an example of how expensive these models can be, Mitchell (1980) stated that TASS system had taken 17 years for development and testing at a cost of about $1,000,000 Canadian. Nonetheless, their potential value as a research tool in forest silviculture and economics of single forest stands may more than justify the commitment in time and funds. For this study, however, tree

position data were not available and so this category of models was not applicable.

2.   Single tree - distance independent stand models:

Conceptually, this term refers to the class of stand simulation models which recognise the individual tree in the stand as the basic production unit but do not require that the individual tree positions be provided. In application however, it is not clear what constitutes a single tree - distance independent model. For example, according to Munro (1974), it includes models where trees are grown in dimensions individually or in groupings of similar diameters. If this definition is accepted, then according to Moser (1980), most of the models in this category could be considered as similar to the traditional stand table projection approach presented in most mensuration texts. However, it should be noted that the concept of the single tree as the basic production unit is contradicted when growth is applied to a group of trees of similar diameters.

A common feature of all single tree - distance independent stand models is that the initial model state consists of a list of tree diameters or tree diameter classes. This list can be specified either from inventory data or from diameter probability density functions. Beyond this stage however, two general strategies for modeling stand growth appear:

1.   For some models, the potential growth is computed for the aggregate stand, and then allocated among the trees in the DBH list. Stand level competitive stress is thus incorporated in

the growth equation. Growth is then allocated among the individual trees or diameter classes according to their position in the ordered diameter list. Examples of this type of model are STANDSIM (Opie 1970), Clutter and Allisons (1974) model for P. radiata in New Zealand, FORSIM (Gibson et al., 1969, 1970), etc.

2. Other models predict the diameter increment of each tree or each diameter class explicitly as a function of other state variables, including at least one that is tree diameter (or class diameter) dependent to give differential growth rates between the classes. Examples of these are TOPSY (Goulding 1973), Prognosis (Stage 1973), PYMOD (Alder 1977), etc.

In general, these models do have appeal to forest managers mainly because they are computationally efficient and use conventional inventory data as input. In addition the tree diameter list is an invaluable feature, especially in evaluating the returns from management decisions in terms of product size and diameter distribution. This is especially important for planning purposes.

A serious shortcoming of single tree - distance independent models is that they cannot predict the growth of a specific single tree with any reliability. Thus, according to Munro (1974), they cannot be used to examine individual trees for crown shape and growth, bole shape changes or defoliation. Nonetheless, models with capability to respond to thinning, spacing and in some cases fertilization interventions have been developed. These models are of interest in this study and so a discussion of some of them is germane.

STANDSIM (Opie 1970) is a single tree - distance independent model developed to simulate preferred silvicultural treatments for Australian Mountain Ash (Eucalyptus regnans F. Muell). The model is considered as a silvicultural rather than a planning model in that it simulates the growth of a single stand only (Alder 1977). However, it has been incorporated into a planning and management system MARSH, for prediction of growth under alternative silvicultural schedules (Weir 1972). Model state consists of a list of individual tree diameters, while growth is accomplished by calculating the gross basal area increment per unit area. Thus competition is implicitly included. Individual tree growth is effected by distributing the gross basal area increment proportionately according to the individual tree size.

Clutter and Allison (1974) developed a single tree - distance independent model for P. radiata in New Zealand. Unlike STANDISM, the initial stand state consisted of a fixed number of diameter classes of equal probability instead of the single tree diameter list. Tree diameter distribution from which the diameter classes are derived is obtained from a Weibull probability density function. Annual growth is accomplished by predicting gross annual basal area increment and then distributing this to the diameter class medians as a function of stand age, current median diameter, current and projected basal area, and current and projected number of trees per acre. Similarly, gross mortality is predicted and distributed among the diameter class medians as a function of class basal area relative to stand basal area. This model is designed for single species even-age stands.

PROGNOSIS model for stand development (Stage 1973) represents a
very high level of development in this class of models in that it can
simulate growth of mixed stands in terms of species, age classes and
size classes. The high level of resolution in the model is accomplished
by recording not only the DBH list but also tree height and crown
dimensions. The key growth component is annual basal area increment
computed from DBH, site, habitat type, crown ratio, relative stand
density, and the percentile of the tree in the basal area distribution.
In addition, the basal area growth function incorporates a stochastic
element although the total growth process remains essentially deter-
ministic. Individual trees are incremented in DBH (as a function of
position of the particular tree in the basal area distribution), height
(as a function of DBH growth, habitat type, DBH and height) and crown
length or clear bole length (as a function of relative stand density,
basal area percentile and DBH). Thus, the model has a variety of tree
characteristics which allow simulation of a wide range of silvicultural
prescriptions. Stage (1973) has demonstrated use of this model to
prognose lodgepole pine stand development in the presence of an infesta-
tion of mountain pine beetle (Dendroctonus ponderosae Hopkins). VYTL-2
used as a subroutine in PYMOD forest planning programme (Alder 1977)
(discussed in the Introduction) falls in this class.

3. Whole stand - distance independent models:

This category of models is based on the same philosophy as the
conventional yield tables, normal or variable density, in that the basic
unit of production is the whole stand. However, conventional yield

tables differ from computer-based simulation models in that the later are dynamic while the former are static.

From a philosophical point of view, this class of models cannot be justified as the concept of the whole stand as the basic production unit contradicts the bionomic (ecological) theory of individualistic systems (such as the individual tree in the stand) as stated by Boyce (1978):

> "Each living organism and its environment forms an individualistic system with negative feedback loops guiding behaviour in accordance with the goal of survival. Behaviour is directed by decision mechanisms. These mechanisms are genetically and environmentally determined and are physiological, anatomical and morphological structure of the individual-istic system. Each individualistic system senses and reacts to its own state. Past actions influence future actions to achieve the goal of survival."

The single tree approach to growth and yield is consistent with this theory. On the other hand, the whole stand concept is consistent with the management objective of ordering the individualistic systems that make up the forest into a forest community with the suitable structure to achieve specific goals and objectives. Models based on this concept therefore have received attention since they are usually computationally less expensive and efficient as computation of individual tree information is eliminated.

As with single tree - distance independent models, whole stand - distance independent models take conventional inventory data as input. The major difference between the two classes therefore appears to be in the output information since the latter does not provide individual tree information. It should however be pointed out that whole stand

simulation models can recapture some of the individual tree information by incorporating diameter distribution models. This will provide frequency distribution of the trees by diameter classes into which growth or yield can be distributed whenever this information is required. This approach is more economical from the programming and computational point of view and therefore has been adopted for this study. An example of the models in this class is the Douglas-fir managed yield simulator (DFIT) of Bruce, De Mars and Reukema (1977). Stand state is represented as the number of trees per acre, stand basal area and the mean stand DBH. Height growth is obtained from a site index equation while stand volume growth (a function of state variables) is modified by a density dependent factor, the ratio of average stand basal area to the maximum limiting basal area of the stand.

3. Yield Model Construction

3.1 Essential Features for the Envisaged Growth and Yield Model

The overriding objective of this study is to extend the understanding of the theoretical and practical aspects of growth and yield of the three respective species under the climatic, edaphic and silvicultural conditions obtaining in Kenya. Consequently, the three major questions that the envisioned model must answer are:

1. What is the expected yield under present silvicultural practices?

2. What is the impact of the present silvicultural practices on stand development?

3. What is the impact of adopting alternative silvicultural
   practices on the future development of the stand?

Answers to these questions will depend on the quantitative informa-
tion provided by the growth and yield model. To do this effectively,
the model must contain the following essential features:

1. The model should permit specifications of the management
   practices (decision variables) as input.

2. The model output should provide not only total volume but also
   volume to different merchantable limits and by size classes.

3. The model should be able to evaluate different levels of stand
   management.

4. The final model should be integratable into the overall forest
   planning system.

Within the data and resource limitations, it was felt that all the
above features could be built into an interactive stand level simulation
model with sufficient detail for management, planning and silvicultural
research purposes. Figure 19 shows the position of the envisaged model
in the overall planning system and also serves to show the sequence of
the present research project (solid lines).

3.2 Growth and Yield Model Synthesis

The growth and yield functions developed in Chapter 2 form the
building blocks of the yield model EXOTICS; an acronym for Exotic
Species. These functions were coded as FORTRAN subroutines and then
organized into a logical sequence (programme) capable of simulating the

Figure 19[1]: Overall forest planning system showing the integration of the yield model.
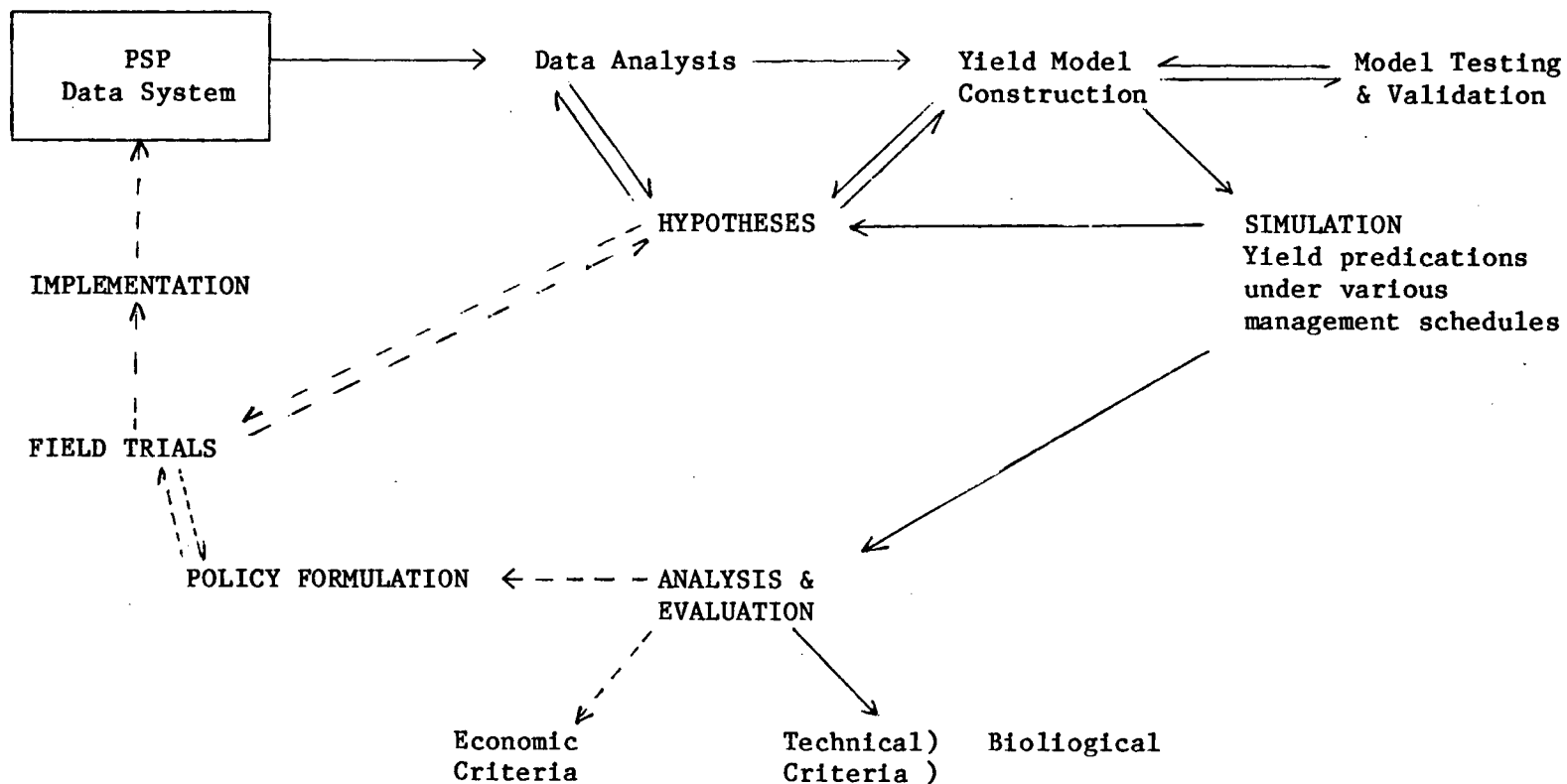
[1]Design model adopted from Munro (1974).

Broken lines indicate the stages of the overall sequence not covered in this study.

growth and yield of a single, even-aged monospecific stand. Figure 20 shows the flow chart of the final program configuration. Documentation and variable description for the main and auxiliary subroutines is given at the beginning of each subroutine on the program listing available from the author on request. The following is a detailed description of the main functional subprogrammes:

MAIN: This programme initializes and defines variables which are specific to it or are common or shared with other subprogramme. It is also responsible for control of the sequence in which various subprogrammes are called and basically directs the whole programme including initialization, input and output.

HDSTDC: Calculates stand dominant height as a function of stand age and site index using equation 2.21 for C. lusitanica and P. radiata and equation 2.22 for P. patula. Correction for establishment site is accomplished by deducting 2 meters and (0.156 x Age) meters from dominant height for P. radiata and P. patula respectively.

BACALC: Calculates the stand basal area before first thinning using equation 2.29 for all three species. This subroutine is only called if initial stand basal area is not provided (indicated by entering a negative value of basal area when using the model) and stand initialization age is 5 years.

FIGURE 20

FLOWCHART OF THE YIELD MODEL EXOTICS

INPUT VARIABLES
1.SPECIES
  1=C. LUSITANICA
  2=P. RADIATA
  3-8=P. PATULA

2.ESTABLISHMENT
  1=SHAMBA
  2=GRASSLAND

3.AGE=5-40 YEARS

4.SITE INDEX=10-35

5.STOCKING=100-1600 IF AGE>5 YEARS
  OR =1000-1600 IF AGE=5 YEARS

6.BASAL AREA
  -VE IF BA. IS UNKNOWN
  +VE IF BA. IS GIVEN
  (AGE MUST BE 5 YEARS IF BA. UNKNOWN)

7.THINNING SPECIFICATIONS (OPTIONS)
  0=NO THINNING
  1=BY NO. OF STEMS TO BE REMOVED
  2=BY BASAL AREA TO BE REMOVED

8.CLEARFELLING OPTIONS
  1=IF DBH>SPECIFIED VALUE
  2=IF AGE>SPECIFIED VALUE

GENERATE INITIAL STAND STATE
1.DOMINANT HEIGHT=F(A,SI,ESTAB.)
2.BA/HA.=F(A,H,N)
3.MEAN STAND DBH=F(BA.,N)
4.STAND DENSITY INDEX=F(H,N)
5.STAND VOLUME/HA=F(DBH,H,N)
  (TOTAL AND MERCHANTABLE)

SIMULATE THINNING BY SPECIFYING:-
1.THINNING OPTION
2.NO.STEMS TO BE LEFT
  OR
  %BA.TO BE REMOVED
3.THINNING CRITERIA (WHEN THE SPECIFIED AGE,DOMINANT HEIGHT OR BASAL AREA IS REACHED OR EXCEEDED)

CALCULATE THINNING OUTPUT
1.NO.STEMS REMOVED
2.BA. REMOVED
3.VOLUME REMOVED
  TOTAL AND MERCHANTABLE

STORE THINNING OUTPUT

CALCULATE RESIDUAL STAND STATE
1.NO.STEMS/HA
2.BA/HA

UPDATE STAND STATE
1.STAND DOMINANT HEIGHT
2.STAND DENSITY INDEX
3.STAND BA. VIA BASAL AREA INCREMENT EQUATION:
  BAI=F(A,BA.) FOR P.RADIATA
  BAI=F(A,BA,S%) FOR C.LUSITANICA
    AND P.PATULA
4.STAND DBH
5.STAND VOLUME

UPDATE STAND STATE
ONLY IF INITIAL BA.=-VE

IS CLEARFELLING DUE?
CHECK IF CRITICAL AGE OR DBH IS EQUALED OR EXCEEDED

IS THINNING DUE?
CHECK IF THE SPECIFIED AGE OR HEIGHT OR BASAL AREA IS.EQUALED OR EXCEEDED

ONLY IF INITIAL BA.=+VE

IS CLEARFELLING DUE?
CHECK IF CRITICAL AGE OR DBH IS EQUALED OR EXCEEDED

IS THINNING DUE?
CHECK IF THE SPECIFIED AGE OR HEIGHT OR BASAL AREA IS EQUALED OR EXCEEDED

CALCULATE
1.WEIBULL PARAMETERS
  1.X FROM DBH AND STOCKING
  2.b FROM DBH AND X
  3.c FROM DBH AND X
2.NO.STEMS BY DBH CLASSES USING WEIBULL DISTRIBUTION FUNCTION
3.TOTAL AND MERCHANTABLE VOLUME BY DBH CLASSES

OUTPUT RESULTS
1.YIELD TABLE (INCLUDING THINNINGS)
2.STAND TABLE

BABAI: This subroutine updates the stand basal area in thinned stands using basal area at the beginning of the growth period and age at the end of the growth period (equation 2.30 for P. radiata) and S% (equation 2.31 for C. lusitanica and P. patula) to calculate the basal area increment. This is then added to the basal area at beginning of growth period to give basal area at end of the growth period. This subroutine is called if initial stand basal area is known, for example from inventory data. Initializing stand simulation at an age >5 years automatically calls this routine and so initial stand basal area must be given. It allows for stand simulation from any given age, an important feature when validating the model using field data (cf. p.s.p.s').

VOLCAL: Calculates total overbark stand volume using tree volume equations 2.42 and 2.43 and the number of stems per hectare for the respective species. It also calculates the merchantable volume by first calculating the relevant R-factor for the respective species and merchantable limit (equation 2.44).

THIN: Controls thinning operations of which there are three options:

0 = No thinning

1 = Thinning based on number of stems to be left when a predetermined age interval or stand dominant height is equalled or exeeded.

2 = Thinning based on proportion of basal area to be removed when a critical predetermined basal area is equalled or exceeded.

This subroutine allows for the use of any one option or a combination of two or all three options in one simulation run, thus allowing for a change of management decision (with regard to thinning criteria) at any age within the life of the plantation.

THNCAL: This subroutine calculates thinning variables:

$$DBH(T) = f[DBH(BT), N(T), N(BT)] \qquad \text{equation 2.27}$$
if thinning option = 1

$$\text{or } DBH(T) = f[DBH(BT), BA(T), BA(BT)] \qquad \text{equation 2.28}$$
if thinning option = 2

$$N(T) = f[N(BT), N(AT)] \quad \text{if thinning option = 1}$$

$$\text{or } N(T) = f[BA(T), DBH(T)] \quad \text{if thinning option = 2}$$

$$BA(T) = f[DBH(T), N(T)] \quad \text{if thinning option = 1}$$

$$\text{or } BA(T) = \text{a specified proportion of } BA(BT)$$
if thinning option = 2

$$V(T) = f[DBH(T), H, N(T)]$$

Where   N(T)   = No. stems removed in a thinning/ha

N(BT) = No. stems before thinning/ha

N(AT) = No. stems after thinning/ha

DBH(T) = Mean DBH of thinnings in cm

DBH(BT) = Mean DBH of stand before thinning in cm

BA(T) = Basal area of thinnings in m^2/ha

BA(BT) = Basal area of stand before thinning in m^2/ha

V(T)   = Volume of thinnings in m^3.

CHKCLF: Checks if stand is due for clearfelling by checking if the predetermined clearfell age or DBH is equalled or exceeded. Clearfelling has priority over thinning operation (cf. Figure 20).

CLRFEL: Calculates total yield at clearfell by diameter classes:

1. Calculates Weibull parameters

$$X_0 = f(DBH, N)$$ equation 2.39

$$b = f(DBH, D_L)$$ equation 2.40

$$c = f(DBH, D_L)$$ equation 2.41

2. Calculates number of trees per diameter class from total number of trees/ha and the cumulative distribution function (equation 2.42) using the Weibull parameters calculated above.

3. Calculates volume yield by diameter classes:

$$V_i = f(D_i, H, N_i)$$

V_i refer to volume corresponding to diameter class (at breast height) D_i, H is stand dominant height at clearfell and N_i is number of stems/ha at clearfell in diameter class D_i.

Input variables for EXOTICS

At the beginning of each simulation run, the programme calls for several input variables:

State variables: Species, establishment site, age, site index, stocking and basal area.

Decision variables: Thinning option and control inputs (when to thin

and how much to remove) and clearfelling criteria.

These variables are given on Figure 20, while Table 36 gives their domain or the range within which their values should be. In establishing the variable domain, the main guiding factor was the range of the data used in developing the various growth and yield functions. It should be noted that the thinning variables entered at the beginning of the simulation run apply to first thinning only. The programme calls for further thinning structions at the end of each thinning.

Output from EXOTICS

In conformity with the basal area increment equation whose increment period is one year, the simulation cycle for EXOTICS is one year. At each cycle, several main stand state parameters are calculated, namely age, No. stems, dominant height, mean stand DBH, basal area, volume and the stand density index, S%. At each thinning, the parameters No. stems, DBH, basal area and volume of thinnings are calculated. Both main stand yield and yield of thinning are combined to give total stand production: basal area, volume, current annual increment (CAI) and mean annual increment (MAI). All these variables are stored in an array for output at the end of the simulation run. Table 37 (output as Table 1 in the programme) is an example using C. lusitanica sawtimber regime for site index 20.

In addition to Table 1, two other tables are output: Table 2 which gives the merchantable volume to the respective merchantable limits and Table 3 which gives the main stand final volume (total and merchantable)

TABLE 36. Domain of the yield model EXOTICS with respect to input variables

Species code	1	2	3	4	5	6	7	8
Establishment code	1 only	1 or 2	1 or 2	1 or 2	1 or 2	1 or 2	1 or 2	1 or 2
Age in year	5-40	5-35	5-20	5-20	5-20	5-20	5-20	5-12
Site index	12-24	21-33	15-27	15-27	15-27	15-27	15-27	21-30
Initial stocking	1000-1600	1000-1600	1000-1600	1000-1600	1000-1600	1000-1600	1000-1600	1000-1600
Basal area m^2	10-60	10-60	10-60	10-60	10-60	10-60	10-60	10-60
No. stems to remove	10-50%	10-50%	10-50%	10-50%	10-50%	10-50%	10-50%	10-50%
Basal area to remove	10-50%	10-50%	10-60%	10-50%	10-50%	10-50%	10-50%	10-50%

Species code:

1 = C. lusitanica
2 = P. radiata
3 = P. patula Nabkoi
4 = P. patula Nanyuki
5 = P. patula Elburgon
6 = P. patula Kiandongoro
7 = P. patula Kinale
8 = P. patula Turbo

Establishment code:

1 = Shamba
2 = Grassland

No. stems and basal area to remove are given as percent of values before thinning.

Table 37 EXAMPLE OF OUTPUT FROM EXOTICS

TABLE 1
TOTAL VOLUME YIELD TABLE

SPECIES: CUPRESSUS LUSITANICA
INITIAL SITE INDEX: 20.0
ESTABLISHMENT: SHAMBA

	STANDING CROP						THINNING				TOTAL PRODUCTION			
AGE	NO. OF STEMS	HDOM	DBH(1)	BA(1)	V(1)	S%	NO. OF STEMS	DBH(2)	BA(2)	V(2)	BA(3)	V(3)	CAI	MAI
YEARS		M	CM	SQ.M	CU.M			CM	SQ.M	CU.M	SQ.M	CU.M	CU.M	CU.M
5.0	1200.0	7.8	10.4	10.3	32.9	37.1					10.3	32.9	0.0	6.6
6.0	1200.0	9.2	12.5	14.6	61.6	31.3					14.6	61.6	28.7	10.3
7.0	1200.0	10.6	14.2	19.1	94.7	27.2					19.1	94.7	33.1	13.5
8.0	1200.0	12.0	15.8	23.4	130.1	24.2					23.4	130.1	35.4	16.3
							312.0	13.0	4.1	21.5				
9.0	888.0	13.2	18.1	22.9	140.6	25.3					27.0	162.1	32.0	18.0
10.0	888.0	14.5	19.4	26.3	173.3	23.2					30.4	194.8	32.7	19.5
11.0	888.0	15.7	20.5	29.4	206.3	21.4					33.5	227.9	33.1	20.7
12.0	888.0	16.8	21.5	32.3	239.6	20.0					36.4	261.1	33.2	21.8
13.0	888.0	17.9	22.4	35.1	272.9	18.7					39.2	294.5	33.3	22.7
							355.0	20.0	11.2	86.4				
14.0	533.0	19.0	25.0	26.2	213.7	22.8					41.5	321.7	27.2	23.0
15.0	533.0	20.0	26.1	28.4	241.2	21.7					43.7	349.2	27.5	23.3
16.0	533.0	21.0	27.0	30.6	268.9	20.6					45.9	376.9	27.7	23.6
17.0	533.0	21.9	27.9	32.6	296.7	19.8					47.9	404.6	27.8	23.8
18.0	533.0	22.8	28.7	34.6	324.4	19.0					49.9	432.4	27.8	24.0
							178.0	25.7	9.2	86.5				
19.0	355.0	23.7	31.2	27.1	261.6	22.4					51.6	456.1	23.7	24.0
20.0	355.0	24.5	32.1	28.8	285.4	21.7					53.3	479.9	23.8	24.0
21.0	355.0	25.3	33.1	30.5	309.3	21.0					55.0	503.8	23.9	24.0
22.0	355.0	26.1	33.9	32.1	333.3	20.4					56.6	527.7	23.9	24.0
23.0	355.0	26.8	34.7	33.6	357.3	19.8					58.2	551.7	24.0	24.0
							89.0	31.0	6.7	71.2				
24.0	266.0	27.5	36.9	28.4	307.5	22.3					59.6	573.1	21.4	23.9
25.0	266.0	28.2	37.8	29.8	329.0	21.8					61.0	594.7	21.5	23.8
26.0	266.0	28.8	38.7	31.2	350.6	21.3					62.4	616.3	21.6	23.7
27.0	266.0	29.5	39.5	32.6	372.2	20.8					63.8	637.8	21.6	23.6
28.0	266.0	30.0	40.3	34.0	393.8	20.4					65.2	659.4	21.6	23.6
29.0	266.0	30.6	41.1	35.3	415.3	20.0					66.5	681.0	21.5	23.5
30.0	266.0	31.2	41.9	36.6	436.8	19.7					67.8	702.5	21.5	23.4
31.0	266.0	31.7	42.6	37.9	458.3	19.3					69.1	723.9	21.4	23.4
32.0	266.0	32.2	43.3	39.2	479.7	19.0					70.4	745.3	21.4	23.3
33.0	266.0	32.7	44.0	40.4	501.0	18.8					71.7	766.6	21.3	23.2
34.0	266.0	33.1	44.7	41.7	522.2	18.5					72.9	787.8	21.2	23.2
35.0	266.0	33.6	45.3	42.9	543.3	18.3					74.1	808.9	21.1	23.1

Table 38 EXAMPLE OF OUTPUT FROM EXOTICS

TABLE 2
MERCHANTABLE VOLUME YIELD TABLE

SPECIES: CUPRESSUS LUSITANICA
INITIAL SITE INDEX: 20.0
ESTABLISHMENT: SHAMBA

AGE	V(15) CU.M			V(20) CU.M		
YEARS	MAIN	THINNING	TOTAL	MAIN	THINNING	TOTAL
5.0	0.0		0.0			
6.0	0.0		0.0			
7.0	4.91		4.91			
8.0	35.10		35.10			
		0.0				
9.0	72.03		72.03			
10.0	105.29		105.29			
11.0	139.28		139.28			
12.0	173.63		173.63			
13.0	208.11		208.11			
		55.82				
14.0	180.44		236.27			
15.0	209.37		265.20			
16.0	238.31		294.13			
17.0	267.20		323.02			
18.0	295.99		351.82			
		74.35				
19.0	245.44		375.61			
20.0	269.94		400.11			
21.0	294.42		424.59			
22.0	318.85		449.03			
23.0	343.22		473.39			
		66.65				
24.0	297.93		494.76			
25.0	319.68		516.51			
26.0	341.41		538.23			
27.0	363.10		559.93			
28.0	384.74		581.57			
29.0	406.33		603.15			
30.0	427.83		624.66			
31.0	449.26		646.09			
32.0	470.59		667.42			
33.0	491.83		688.66			
34.0	512.95		709.78			
35.0	533.97		730.80			

Table 39 EXAMPLE OF OUTPUT FROM EXOTICS

TABLE 3
STAND TABLE AT CLEARFELL

SPECIES: CUPRESSUS LUSITANICA
INITIAL SITE INDEX: 20.0
ESTABLISHMENT: SHAMBA

DIAMETER CLASS CM	NO. OF TREES	V(1) CU.M	V(15) CU.M	V(20) CU.M
33.0	9.00	9.81	9.33	
36.0	26.00	33.66	32.51	
39.0	39.00	59.15	57.64	
42.0	45.00	79.03	77.42	
45.0	43.00	86.57	85.06	
48.0	36.00	82.35	81.06	
51.0	27.00	69.64	68.62	
54.0	18.00	51.99	51.26	
57.0	11.00	35.36	34.88	
60.0	6.00	21.35	21.07	
63.0	3.00	11.76	11.60	
66.0	1.00	4.30	4.24	
TOTALS	264.00	544.95	534.71	

FINAL AGE AT CLEARFELL=   35.0 YEARS.

distributed by diameter classes. Table 38 and Table 39 are examples from the same simulation run as for Table 37. After these outputs, the programme returns to the beginning for further instruction: to stop or to begin another simulation.

As expected, the final number of stems in Table 37 is the same as those on Table 39, except for a rounding-off error of ± 2 stems. Similarly, we would expect that the final main stand volume on Table 37 should be the same as total volume (V(1)) in Table 39. Also the final volume V(15) and V(20) of Table 38 should be the same as V(15) and V(20) respectively of Table 39. However, as Tables 37 and 39 show, this may not always be the case. The main cause of the discrepancy is that the volume as calculated in Table 37 is based on the DBH of tree of mean basal area and stand dominant height and thus assumes a normal distribution of the trees by basal area. However, the volume as calculated for Table 39 will depend very much on the distribution of the trees by diameter classes. Thus, distributions skewed to the left will result in lower total volume and those skewed to the right will result in higher total volume in Table 39 compared to the final main stand volume (V(1)) of Table 37. One possible solution to this problem would be to calculate volumes at each cycle as the sum of the volumes calculated through the diameter distribution function. However, it was felt that for this study, the diameter distribution data did not cover the young stand ages adequately, especially before first thinning and so the diameter distribution function would not be valid in unthinned stands. At the moment, the discrepancy appears to be of the order of not more than $\pm 5\%$ and so can be considered insignificant for practical purposes.

4.0 Model Validation

4.1 Introduction

Model validation is the process of building an acceptable level of confidence that an inference about a simulated process is a correct or valid inference about a simulated process (Van Horn 1968). It is an essential accompaniment for any simulation model as a test that both the component parts of the model and the performance of the model as a whole are in agreement with the behaviour of the real system. If the model fails to pass this test, then changes must be made in either the variables, parameters estimates, or the structure of the model. This process serves two purposes:

1. It builds confidence of prospective model users in the model.

2. It helps delineate the limits to model validity.

The knowledge of the limits to model validity, especially with respect to accuracy and precision is very important to the user when choosing between alternative models.

The problems and procedures for model validation have been discussed by several researchers including Naylor and Finger (1967) and Van Horn (1968) with a detailed summary by Goulding (1972). Naylor and Finger (1967) suggested a three stage approach:

1. Construct a set of hypotheses and postulates for the process using all available information: observations, general knowledge, relevant theory, and intuition.

2. Attempt to verify the assumptions of the model by subjecting them to empirical testing.

3. Compare the input/output transformations generated by the model to those generated by the real system.

Steps one and two of this approach entail detailed testing of individual model components and the underlying assumptions while the third step validates the performance of the whole model. The order of testing was justified on the grounds that testing of assumptions and components (before synthesis of the model) is cheaper than testing the predictions.

Van Horn (1968) summed up the problems of validating simulations as similar to the standard problems of empirical research:

1. Small samples due to high cost of data.

2. Too aggregate data.

3. Data whose own validity is questionable.

He suggested the following possible validation actions – in rough order of decreasing value-cost ratio:

1. Find models with high face validity.

2. Make use of existing research, experience, observations and any other available knowledge to supplement models.

3. Conduct simple empirical tests of means, variances, and distributions using available data.

4. Run "Turing" type tests.

5. Apply complex statistical tests on available data e.g. spectral analysis, Theil's inequality coefficient (Naylor and Finger (1967)).

6. Engage in special data collection.

7. Run prototype and field tests.

8. Implement the results with little or no validation.

The appropriate validation action will depend on several factors
including availability of data (including available time and funds) and
the type of model. For example, complex statistical tests may be
appropriate for stochastic models but not for deterministic models. It
should be noted here that all the statistical tests in the validation
process constitute null hypotheses. Acceptance of the null hypothesis
will not be a "proof" that the model is correct but simply indicates
acceptance of the model as an acceptable approximation of the simulated
system at the required level of detail.

Validation of Forest Growth and Yield Models

The validation of most growth and yield models in forestry appears
to follow closely the approach proposed by Naylor and Finger (1967).
However, level of model accuracy and precision has in general received
little attention in spite of concern raised by some researchers
including Munro (1974), Row and Norcross (1978) and Smith and Williams
(1980). This may be attributed to among others:

1. For management and planning purposes (the object of most growth
    and yield models), the required level of accuracy is often not
    very high so that modellers have tended to downplay the process
    of model validation.

2. Most growth and yield models are deterministic so that

    validation has been restricted to simple tests of comparison of

    outputs from the model with the real system.

3. Field tests, which should be essential for any given model, are

    usually very expensive and time consuming and so are often not

    conducted.

With respect to the third problem, the general trend has been to
use long-term study samples or permanent sample plots data not used in
the construction of the model to test how well the model performs. This
approach was advocated by Munro (1974a) and has been effectively
employed by Ek and Mouserud (1979), Moser et al. (1979) and Alder
(1977). Ek and Mouserud (1979) used remeasured plot data to compare
the performance of two models, FOREST and SHAFT (both calibrated for
northern hardwood stands in Wisconsin) with respect to accuracy and
precision. They found the former to be more accurate. Moser et al.
(1979) used long-term study (cutting cycle) data to validate a simula-
tion model of uneven-aged northern hardwoods forest. They observed that
basal area and volume were more accurately predicted than number of
stems although the accuracy of the latter was acceptable for management
and planning purposes. Alder (1977) used psp data to validate PYMOD
although it was not clear whether the data had been used in the con-
struction of the model.

A more pressing concern in growth and yield model validation is the
length of period over which the test plots are remeasured. Most simula-
tion models are designed to "grow" the stand for the whole rotation.

Unfortunately, any one test plot usually covers only a fraction of the rotation period. It is therefore obvious that tests of accuracy and precision based on data from these short period test plots cannot be a true reflection of the model accuracy. Put in other words, the length of the simulation run governs the precision of estimates obtained by simulation just as sample size determines the precision of real-life experiment. This problem is demonstrated on Figure 21 from Alder (1977), which shows two simulations of thinning experiment 345 in Tanzania (P. patula) from different starting conditions. The figure indicates that in general, the total volume simulated from the actual diameter distribution at age 8 years is closer to the actual measured volume than the total volume simulated from age zero. Thus, validation of the model using the experimental plots between ages 8 to 15 does not tell the true picture of model validity between ages 0 to 15. This figure illustrates in general the problem of validating the growth and yield model using permanent sample plot data or other data whose remeasurement period covers only a fraction of the rotation period over which the model will be used. Any quoted measures of accuracy or precision will appear much better than they actually are when the model is used for long-term predictions. This problem will be partly resolved when permanent sample plots covering the whole rotation become available.

4.2 Validating EXOTICS Using Independent Permanent Sample Plot Data

The data available for model validation in this study consisted of 20 permanent sample plots for each species (see Chapter 1 Section 6) and

Figure 21 : Two Simulations of Thinning Experiment 345 in Tanzania (P.patula) from different starting conditions.

(from Alder 1977)

Total Volume (m³/ha)

●——● Actual measurements

·—·—· Simulated from age 0

———— Simulated from actual diameter distribution at age 8

Treatments

A	1390	stems/ha.
B	987	"
C	694	"
D	347	"
E	120	"

Age from Planting (years)
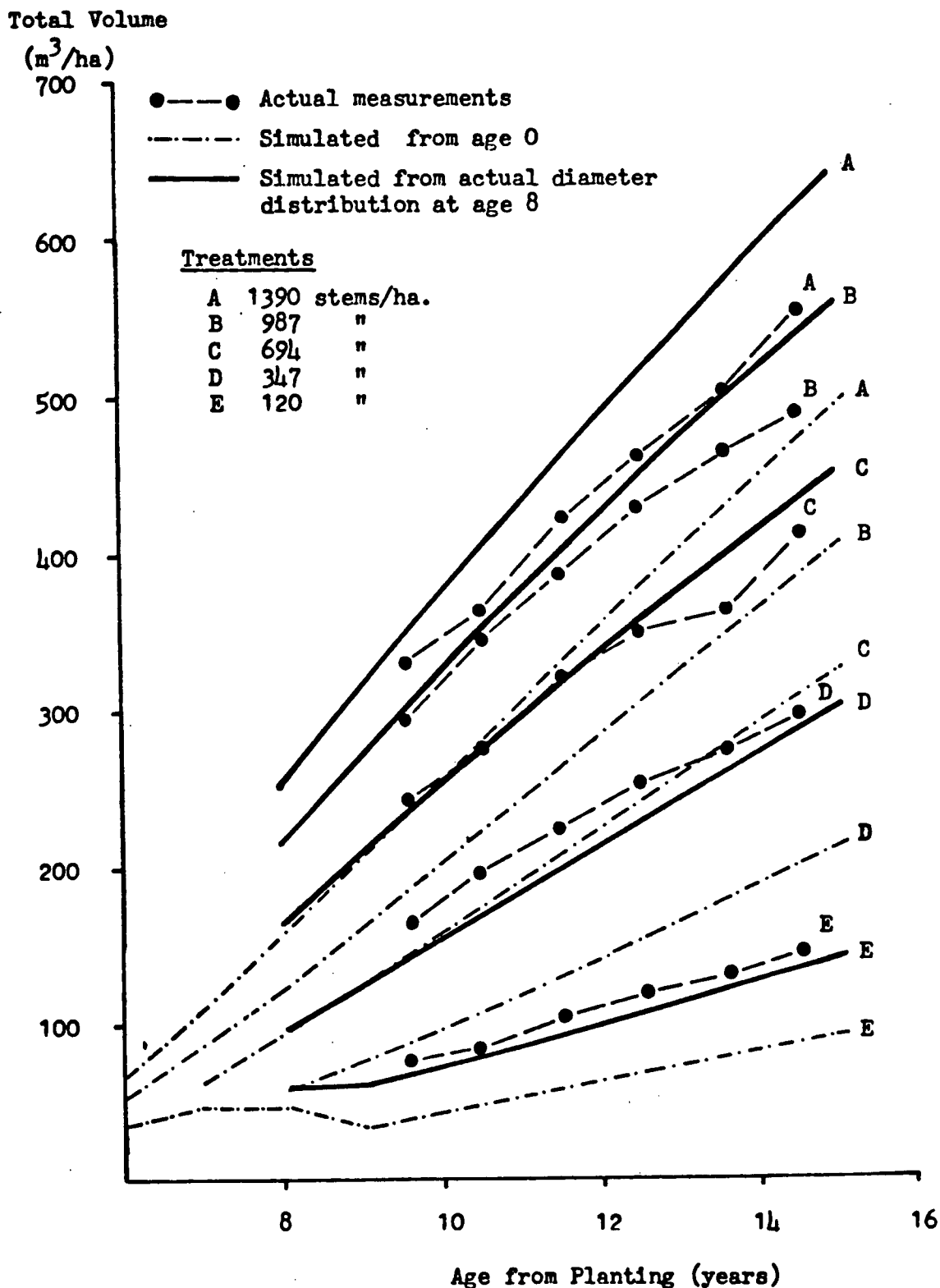
therefore constituted an independent set of data coming from the same population as those used to construct the model. The data consisted of the basic variables: age, dominant height, basal area and total over-bark volume, with some plots having received one or more thinnings during their remeasurement period.

The initial remeasurement age for most test plots was different from 5 years, the initialization age for the model. This presented problems when simulating basal area since prior stand state was not known. For these plots, the initial observed basal area was assumed to be the same as the predicted basal area and the simulation started on the second year of measurement. Where plot stocking was less than 1000 stems per hectare at age 5 years, thinning was assumed to have already been carried out and simulation done as for plots initialized at ages other than 5 years. For each plot, the stand dominant height, basal area, and the basal area removed in thinning (if any), all corresponding to the observed measurements were simulated and from these, the corresponding stand total volume overbark was calculated. Figure 22 shows the results of this procedure for two C. lusitanica plots, one initiated at age 5.5 years, the other at age 21.5 years.

Of the many output variables from the simulation model, total volume overbark was selected as the principle variable to be validated since it is the primary interest in forest management. Several statistics were computed for comparing the observed and simulated volume and are presented on Tables 40, 41 and 42 for C. lusitanica, P. patula and P. radiata respectively. These statistics were computed as follows:

FIGURE 22

COMPARISON OF SIMULATED AND OBSERVED TOTAL VOLUME (OVERBARK) FOR TWO
C. LUSITANICA TEST PLOTS

TABLE 40: Beta weights, mean bias, standard deviation and the 95% confidence limits of percentage differences between observed and simulated total volume overbark, and the Chi-square values for three hypothesized levels of accuracy.

C. lusitanica

Plot No.	N	Beta-weight %	Mean bias %	Standard deviation %	95% confidence limits	X^2 value		
						15	20	25
4	10	-0.84*	-0.40	4.42	3.16	3.41	1.92	1.23
37	12	0.64*	-6.42	5.03	3.20	17.09	9.61	6.15
54	12	0.27	-1.25	2.25	1.43	1.33	0.75	0.48
116	5	0.89*	-0.28	4.16	5.17	1.27	0.72	0.46
117	11	0.95*	-5.30	9.12	3.85	27.65*	15.55	9.95
121	11	-0.88*	-7.65	8.10	5.37	30.86*	17.36	11.11
181	11	-9.60*	1.32	4.83	3.24	4.20	2.36	1.51
190	11	0.55	4.92	5.44	3.66	8.10	4.56	2.92
202	12	-0.94*	-18.18	9.95	6.32	164.24*	92.38*	59.12*
233	13	-0.77*	-9.39	8.57	5.18	56.53	31.80*	20.35
246	10	-0.85*	-7.76	3.51	2.51	15.11	8.50	5.44
261	10	0.50	8.57	5.08	3.63	13.56	7.63	4.88
279	11	0.42	17.83	8.40	5.64	47.86	26.92*	17.23
288	11	0.95*	-1.39	4.34	2.92	3.86	2.17	1.39
295	10	-0.36	3.03	8.05	5.76	7.87	4.43	2.84
331	9	-0.88*	-4.65	5.31	4.08	8.83	4.97	3.18
336	9	-0.95*	-4.21	2.40	1.85	3.97	2.23	1.43
348	10	0.88*	2.32	13.93	9.97	33.73*	18.97*	12.14
379	9	0.60	0.36	3.98	3.06	2.09	1.18	0.75
388	7	-0.68	-14.63	12.11	11.20	66.02*	37.14*	23.77*
		$\bar{B}$ = -2.21	S.D.= 7.93	6.36			291.1*	186.335

Chi-square value at the .05 probability level of 204 degrees of freedom = 238.04.

TABLE 41: Beta weights, mean bias, standard deviation and the 95% confidence limits of percentage
differences between observed and simulated total volume overbark, and the Chi-square values
for three hypothesized levels of accuracy.

P. patula

Plot No.	N	Beta-weight %	Mean bias %	Standard deviation %	95% confidence limits	x^2 value		
						15	20	25
2	9	0.91*	2.46	19.83	15.24	101.65	57.18*	36.60*
12	11	-0.02	-1.21	3.39	2.28	2.32	1.30	0.83
34	12	-0.72*	5.37	14.20	9.02	26.20*	14.74	9.43
59	11	0.77*	22.68	13.47	9.05	74.44*	41.87*	26.80*
123	10	-0.92*	-15.42	14.87	10.63	106.95*	60.16*	38.50*
126	10	-0.02	-1.01	4.19	3.03	3.24	1.82	1.16
144	8	-0.45	0.54	6.86	5.74	5.13	2.89	1.85
147	12	-0.90*	-5.40	15.22	9.67	58.93	33.15	21.22*
154	11	-0.18	-8.10	4.71	3.16	20.71	11.65	7.46
167	12	-0.86*	-22.82	8.40	5.33	232.31*	130.67*	83.63*
203	12	-0.68*	0.04	11.84	7.52	25.30*	14.23	9.11
209	13	-0.86*	-9.51	11.99	7.24	69.24	38.95*	24.93*
252	11	-0.82*	12.84	10.61	7.13	33.91*	19.08*	12.21
270	11	0.64	3.88	2.56	1.72	3.55	2.00	1.28
276	11	-0.25	3.31	6.53	4.39	7.87	4.42	2.83
312	10	-0.71*	-8.53	4.25	3.04	19.63*	11.04	7.06
315	10	0.24	-0.88	4.46	3.19	3.39	1.91	1.22
324	9	-0.89*	-13.20	3.96	3.05	40.00*	22.52*	14.41
342	10	-0.84*	4.68	3.97	2.84	4.20	2.36	1.51
391	8	-0.81*	-0.28	11.43	9.56	15.05	8.46	5.41
			$\bar{B} = -1.53$	S.D.= 10.02	10.10			307.33*

Chi-square value at the .05 probability level of 207 degrees of freedom = 241.28.
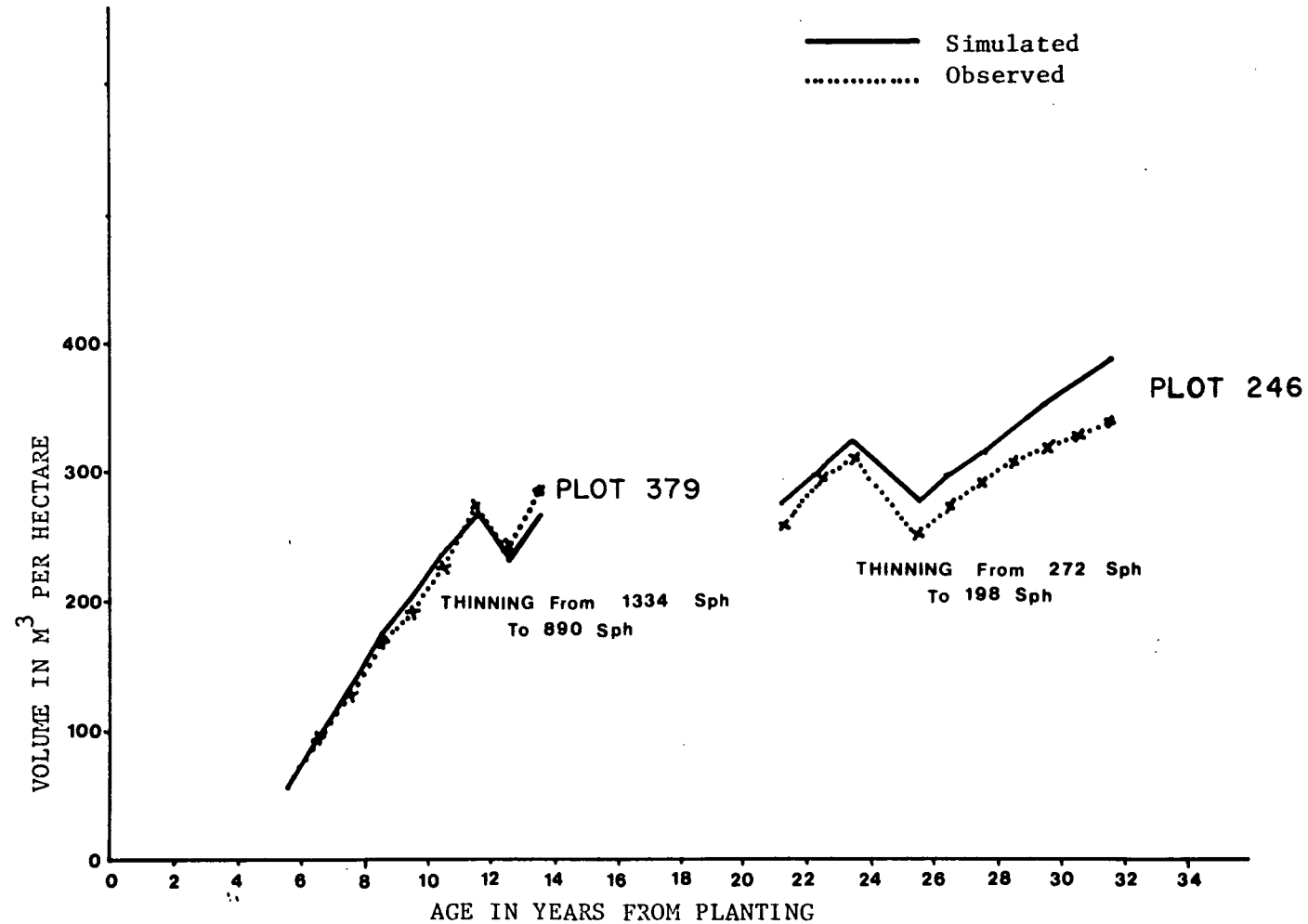
TABLE 42: Beta weights, mean bias, standard deviation and the 95% confidence limits of percentage differences between observed and simulated total volume overbark, and the Chi-square values for three hypothesized levels of accuracy.

P. radiata

Plot No.	N	Beta-weight %	Mean bias %	Standard deviation %	95% confidence limits	X^2 value		
						15	20	25
6	14	0.48	-7.17	11.24	6.49	57.91*	32.57*	20.84
18	11	0.44	2.58	3.55	2.38	3.07	1.73	1.11
31	11	0.63*	11.92	12.00	8.06	33.08*	18.61	11.91
91	6	-0.88*	-7.67	5.62	5.89	11.13	6.26	4.01
96	13	-0.84*	14.29	18.50	11.18	61.36*	34.51*	22.09
99	13	-0.93*	6.88	20.16	12.18	64.69*	36.39*	23.29*
103	9	0.34	6.52	3.62	2.78	7.06	3.97	2.54
112	9	0.44	-0.10	2.22	1.71	0.70	0.40	0.26
134	8	0.72*	-2.71	5.22	4.37	5.00	2.81	1.80
138	12	-0.48	20.22	6.45	4.10	60.29*	33.91*	21.70*
164	11	0.59	3.69	10.21	6.86	16.52	9.29	5.94
177	10	0.25	-8.19	3.10	2.22	16.06	9.03	5.78
238	13	-0.46	-8.43	10.56	6.38	53.75*	30.23*	19.35
256	10	-0.94*	-1.31	5.39	3.85	5.30	2.98	1.91
289	8	0.36	-2.13	3.73	3.12	2.54	1.43	0.92
340	8	-0.62	-2.00	3.69	3.08	2.42	1.36	0.87
373	9	0.19	-1.22	3.40	2.62	1.99	1.12	0.72
383	9	0.44	16.07	8.19	6.30	34.50*	19.41*	12.42
400	7	0.77*	8.86	6.42	5.94	10.49	5.90	3.78
402	8	-0.68	-3.32	3.84	3.21	3.77	2.12	1.36
		$\bar{B}$ = 2.34	S.D. = 8.50	10.14			254.02*	162.58

Chi-square value at the .05 probability level of 199 degrees of freedom = 232.64.

Beta-weight %: were obtained from the standardized regression of the residuals (express as percent of simulated value):

$$E = \frac{V_0 - V_s}{V_s} \cdot 100 \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots \quad 3.3$$

Where   E = Residual corresponding to each remeasurement

V_0 = Observed volume

V_s = Simulated volume

on remeasurement age. The positive values indicate positive correlation of residuals with respect to age and vice versa for negative values, while the magnitude of the beta weight indicate the degree of correlation. Ideally, the correlation should be zero. Significant correlations at the .05 probability level are shown in asterisks on Tables 40, 41 and 42.

Mean bias %: this was calculated as the mean residual for each plot:

$$B = \sum_{i=1}^{n} E_i/n \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad 3.4$$

Where   E = As in 3.3 above

n = Total number of remeasurements per plot.

Standard deviation %: computed as the standard deviation of the residuals in percent:

$$\text{s.d.} = \sum_{i=1}^{n} (E_i - B)^2 / n - 1 \quad \dots\dots\dots\dots\dots\dots\dots \quad 3.5$$

Where   E = As in 3.3

         B = As in 3.4

     s.d. = Standard deviation.

95% confidence limits: computed as:

$$\text{C.L.} = t_{(.05, \, n-1)} \cdot S_{\bar{d}} \quad \dots\dots\dots\dots\dots\dots \quad 3.6$$

Where   C.L. = Confidence limits

      $S_{\bar{d}}$ = Standard error of the residuals in percent for

              each plot.

Chi-square values: corresponding to three hypothesized levels of accuracy: 15, 20 and 25%. These were computed using Freese's 1960 test of accuracy:

$$X^2_{(n,p)} = \sum_{i=1}^{n} \frac{(V_s - V_0)^2}{\sigma^2} \quad \dots\dots\dots\dots\dots\dots \quad 3.7$$

Where $\sigma^2 = \dfrac{E_i^2}{1.96^2} = \dfrac{P^2 \, V_0^2}{196^2}$

      P = Hypothesized percent of the true value unless a 1-in-20

           chance has occurred

      E_1 = Specified allowable error as percent of the true

           (observed) value

     V_0, and V_s are as above.

The calculated Chi-square value for each plot was compared with the critical Chi-square value for .05 probability level and n-degrees of freedom. If the calculated Chi-square value exceeded the critical value, then the simulated volume did not meet our accuracy requirement and the null hypothesis of a common distribution of the observed and simulated volumes rejected. These are shown in asterisks on Tables 40, 41 and 42.

Results and Discussion

1. Beta-weight test:

The expected correlation between the residuals and age is zero. However, due to both random and systematic errors, both positive and negative correlations are expected. The true value of this test therefore is to detect systematic trends in the model by revealing if there is a preponderance of either positive or negative signs and if these are significant at the .05 probability level.

Table 40 for C. lusitanica shows that there were 10 positive and 10 negative beta-weights, an indication of lack of bias. Of the 13 plots whose beta-weights were significant, 5 were positive and 8 negative, which would indicate a slight tendency to overestimate.

Table 41 for P. patula indicate that 16 plots had negative correlations and only 4 were positive indicating overestimation by the model. Of the 13 plots with significant correlations, only 2 were positive, again pointing to overestimation.

Table 42 for P. radiata indicates 8 negative and 12 positive beta-
weights, a slight underestimate. Of the 7 plots with significant
correlations, 3 were positive and 4 negative, indicating lack of bias in
the model.

From this test, the models for C. lusitanica and P. radiata indi-
cate no apparent systematic trends while that for P. patula point to a
possible tendence for the residuals to increase with age.

2. Mean bias test:

The mean bias measured as percent of the predicted value is ideally
expected to be zero. For reasons mentioned above, however, this situation
cannot be realized and the best one can hope for is that over a large
number of simulations, the overall mean bias will be zero or close to
zero.

Table 40 for C. lusitanica indicates plot mean bias ranging from
±0.3% to ±18% with a mean of -2.21%. Table 41 for P. patula shows
a range of ±0.5 to ±23% with a mean of -1.53% while Table 42 for
P. radiata shows a range of ±0.1% to ±20% with a mean of 2.34%. For
all three species, the mean bias can be considered as negligible. It is
worth noting that in spite of the higher variability in the mean bias
for P. patula (measured by the range), it has a slightly lower mean bias
than the other two species. It is also worth noting that plot No. 59
and 167 (P. patula) represents outliers. However, the two compensate
each other so that their effect on the mean bias is almost nil.

3. Standard deviation and standard error of the residuals as percentage of simulated volume:

The standard deviation for the C. lusitanica plots is fairly homogeneous, ranging between 2 to 14% with a standard error of 7.93%. The variability for P. patula and P. radiata is higher, ranging between 1 to 20% with a standard error of 10% and 8.50% respectively. Thus, the true difference between the observed and simulated volume will in general lie within ±16% for C. lusitanica, ±20% for P. patula and ±17% for P. radiata unless 1-in-20 chance occurs. This is an improvement on VYTL2 whose 95% confidence limits ranged between 40% underestimation and 20% overestimation (Alder 1978).

4. The individual plot 95% confidence limits:

These indicate the range within which the true difference between the observed and simulated volume would be expected to be unless a 1-in-20 chance occurred-just as the standard error in 3 above. Thus, if the results of 3 above are correct, no more than one plot would be expected to have a 95% confidence limit greater than twice the standard error calculated in 3. As it turned out none of the three species had any plot with 95% confidence limits greater than twice the standard error, which could be considered very satisfactory result considering only twenty sample plots were available.

5. Chi-square test of accuracy:

Freese (1960) discussed the use of both the t-test and the Chi-square test for tests of accuracy. In regard to the t-test he concluded that it is not suitable as it uses one form of accuracy (precision) to

test for the other form (freedom from bias), frequently with anomalous results. He therefore recommended use of Chi-square test as it will reject inaccurate results, regardless of the source of inaccuracy.

To use the test as proposed by Freese (1960), three statements are required:

1. Statement of accuracy required

2. A measure of accuracy attained

3. An objective method of deciding whether the accuracy attained is equal to the accuracy required.

For this study, the statement of the required accuracy consisted of three hypothesized levels of accuracy: 15, 20 and 25% of the observed values, while the observed accuracy consisted of the calculated Chi-square values by equation 3.7. These are shown in the respective table for each species. The asterisks indicate plots where the simulated volume did not meet the required level of accuracy. This conclusion was reached by comparing the calculated Chi-square value with the critical Chi-square value for n-degrees of freedom at .05 probability level. For the overall model, all the measurements for each species were considered together and the overall Chi-square value calculated. This was compared with the critical Chi-square value approximated by:

$$X^2_{(V)df} = 0.853 + V + 1.645 \sqrt{2V - 1} \quad \ldots\ldots\ldots\ldots \quad 3.8$$

(From Freese (1969))

Where V = Degrees of freedom.

Table 40 for C. lusitanica indicates that at a 15% level of accuracy, the model gave 7 unacceptable results out of 20. This is unacceptable at .05 probability level. Similarly, a 20% level of accuracy gave 5 out of 20 unacceptable results, which again is unacceptable. However, at 25% level of accuracy only two plots were unacceptable and the overall model is accepted as meeting the stated level of accuracy. Thus, the true level of accuracy for the C. lusitanica model lies somewhere between 20 and 25%. These results apply also to the P. radiata model as shown on Table 42. It can therefore be stated that barring a 1-in-20 chance, the models for these two species are accurate if the required level of accuracy is 20% or less.

The model for P. patula (Table 41) on the other hand had a slightly lower level of accuracy compared to the other two species. At 15% level of accuracy, 11 plots out of 20 were unacceptable, 8 were unacceptable at 20% and 6 were unacceptable at 25%. The overall model was unacceptable at the required accuracy level of 25% but was acceptable at 30% (X^2 = 213.42 compared to critical X^2 = 241.28). Thus, the true accuracy level for this species at .05 probability level lies somewhere between 25 and 30%. This lower level of accuracy is seen from the table to be associated with the larger biases and/or standard deviations.

The above levels of accuracy are comparable with the accuracy of two models already in operation - FOREST and SHAFT (Ek and Monserud 1979). For example both models were found to predict basal area with approximately a 1-in-20 chance of a 20% or greater error. Number of stems for trees with DBH $\geq$ 12.7 cm were predicted with 22 and 39% or

greater error by FOREST AND SHAFT respectively. It should be noted here that FOREST is a single-tree, distance dependent model while SHAFT is a whole stand, diameter distribution model. EXOTICS is a whole stand diameter free model although diameter distribution is available in the final output. It is therefore of interest to note how different types of models can have claim to the same level of accuracy.

For purposes of application it should be noted that the levels of accuracy calculated above for EXOTICS are based on a .05 probability level. If a user is prepared to tolerate lower levels, the models appear acceptable down to 15% acceptable error for C. lusitanica and P. radiata and 20% for P. patula. Indeed Ek and Monserud (1979) considered FOREST suitable for development of management guides and analysis of silvicultural alternatives in detail at these levels of accuracy. It is therefore conceivable that EXOTICS will be a very useful tool for that purpose, in addition to yield predictions for management and planning purposes.

6. Sources of Errors:

The large bias and standard deviation exhibited by some of the plots on Tables 40, 41 and 42 could have arisen from three possible sources:

1. From model components.

2. Bias from age class or site index distribution.

3. Errors from exogenous factors.

In EXOTICS, two major components could give rise to errors: dominant height and basal area functions. The biases for

dominant height and basal area (as percent of predicted values) for all

three species are shown on Table 43. In general, the overall mean bias

for both dominant height and basal area was almost negligible for all

species, except the mean bias for P. radiata basal area with an under-

estimate of 2.74%. This may be the cause of the volume underestimate of

2.34% on Table 42. It should be noted here that the mean bias from

volume in this case is lower than mean bias from basal area because the

mean bias from dominant height is negative. In general the error in

volume is approximately the sum of the component errors.

For all species, the plots height biases are very low, ranging from

almost zero to 5%. This is confirmed by the low standard error of

estimate: 1.38, 3.07 and 1.04 for C. lusitanica, P. patula and

P. radiata respectively. Plot No. 324 for P. patula appears to be an

outlier with a -10.45% bias. This was because the plot age extended to

28 years which is beyond the range covered by the height over age data

for P. patula. Excluding this plot gave a standard error of 2.12%,

which is still higher than that for the other two species.

The plot basal area biases on the other hand are very variable as

indicated by the standard error of estimate: 7.94, 6.66 and 8.52 for

C. lusitanica, P. patula and P. radiata respectively. It therefore

appears that nearly all of the variability in the C. lusitanica and

P. radiata models is a result of this component while variability in the

P. patula model can be apportioned to both dominant height and basal

area functions in the ratio of 1:2. In addition to the sources of

variability in basal area estimate discussed in Chapter 2, it should be

noted that in the simulation model, errors could arise from three

TABLE 43: Bias percentage for dominant height and basal area for test permanent sample plots by species.

| ------ C. lusitanica ------ | | | ------- P. patula ------- | | | ------- P. radiata ----- | | |
Plot No.	Height	Basal area	Plot No.	Height	Basal area	Plot No.	Height	Basal area
4	-0.08	-0.30	2	-1.87	5.23	6	-0.49	-6.52
37	-1.12	-5.04	12	0.30	-1.49	18	0.10	2.41
54	-1.91	0.26	34	-.190	6.71	31	-0.73	12.27
116	-4.04	3.03	59	-1.04	23.78	91	-2.55	-5.65
117	-1.06	-4.09	123	1.40	-16.96	96	-1.55	15.08
121	-1.36	-6.61	126	-0.53	-0.45	99	-1.75	7.67
181	-1.81	2.85	144	-0.42	0.87	103	-0.33	6.68
190	-2.14	6.54	157	-0.05	-6.14	112	-0.84	0.56
202	-0.29	-17.36	154	-0.90	-7.01	134	0.12	-2.72
233	-1.20	-8.38	167	-0.74	-21.92	138	-1.83	21.29
246	-3.41	-5.25	203	0.55	-0.69	164	-0.98	4.41
261	-2.98	11.48	209	-0.42	-9.60	177	-1.66	-6.59
279	-0.93	17.21	252	2.55	9.60	238	2.33	-9.62
288	-0.64	-0.83	270	2.77	1.16	256	-0.14	-1.15
295	-0.34	3.19	276	2.59	0.69	289	-0.45	-1.76
331	-2.02	-3.21	312	-5.81	-2.59	340	0.40	-2.18
336	-1.79	-2.83	315	-3.14	2.25	373	-0.10	-1.11
348	0.79	1.47	324	-10.45	-3.35	383	-0.55	16.02
379	-0.61	1.04	342	-3.58	8.17	400	-0.10	8.69
388	1.82	-14.72	391	0.57	-1.34	402	-0.35	-2.93
Means	-1.26	-1.08		-1.01	-0.65		-0.57	2.74
S.D.	1.38	7.94		3.07	6.66		1.04	8.52

Excluding plot 348 for P. patula: Mean) -0.48
                                     S.D.)   2.12

sub-components: basal area function before first thinning, basal area increment equation and the thinning function. In general however, the variability appears to be of a random nature except for the tendency for the P. radiata model to slightly underestimate the basal area component. This may require further refinement in future work.

Figures 23, 24 and 25 show the distribution of the test plots by age and plot mean bias % for C. lusitanica, P. patula and P. radiata respectively. In all cases, there is no evidence of bias in the distribution of the bias with respect to age. Similarly, Figures 26, 27 and 28 show the distribution of the test plots by site index and plot mean bias and again there is no evidence of bias with respect to site index. Plot No. 238 for P. radiata appears to be an outlier. It is worth noting the range of the site indices within which the test plots belonged: 17 to 23, 18 to 28 and 24 to 31 for C. lusitanica, P. patula and P. radiata respectively. Similarly, the age range for test plots was 5 to 43, 5 to 20 and 5 to 30 for C. lusitanica, P. patula and P. radiata respectively.

Finally but not least, there are several exogenous factors that may introduce error in the model. These include:

1. Measurement errors.

2. Biotic factors: including game damage, insect and disease, etc.

3. Climatic and edaphic factors some of which may not have been covered in the study. These include annual weather fluctuations and cumulative drought effects, soil factors, etc.

FIGURE 23

DISTRIBUTION OF C. LUSITANICA TEST PLOTS BY AGE AND VOLUME BIAS %

FIGURE 24

DISTRIBUTION OF P. PATULA TEST PLOTS BY AGE AND VOLUME BIAS %

FIGURE 25

DISTRIBUTION OF P. RADIATA TEST PLOTS BY AGE AND VOLUME BIAS %

FIGURE 26

DISTRIBUTION OF C. LUSITANICA TEST PLOTS BY SITE INDEX AND VOLUME BIAS %

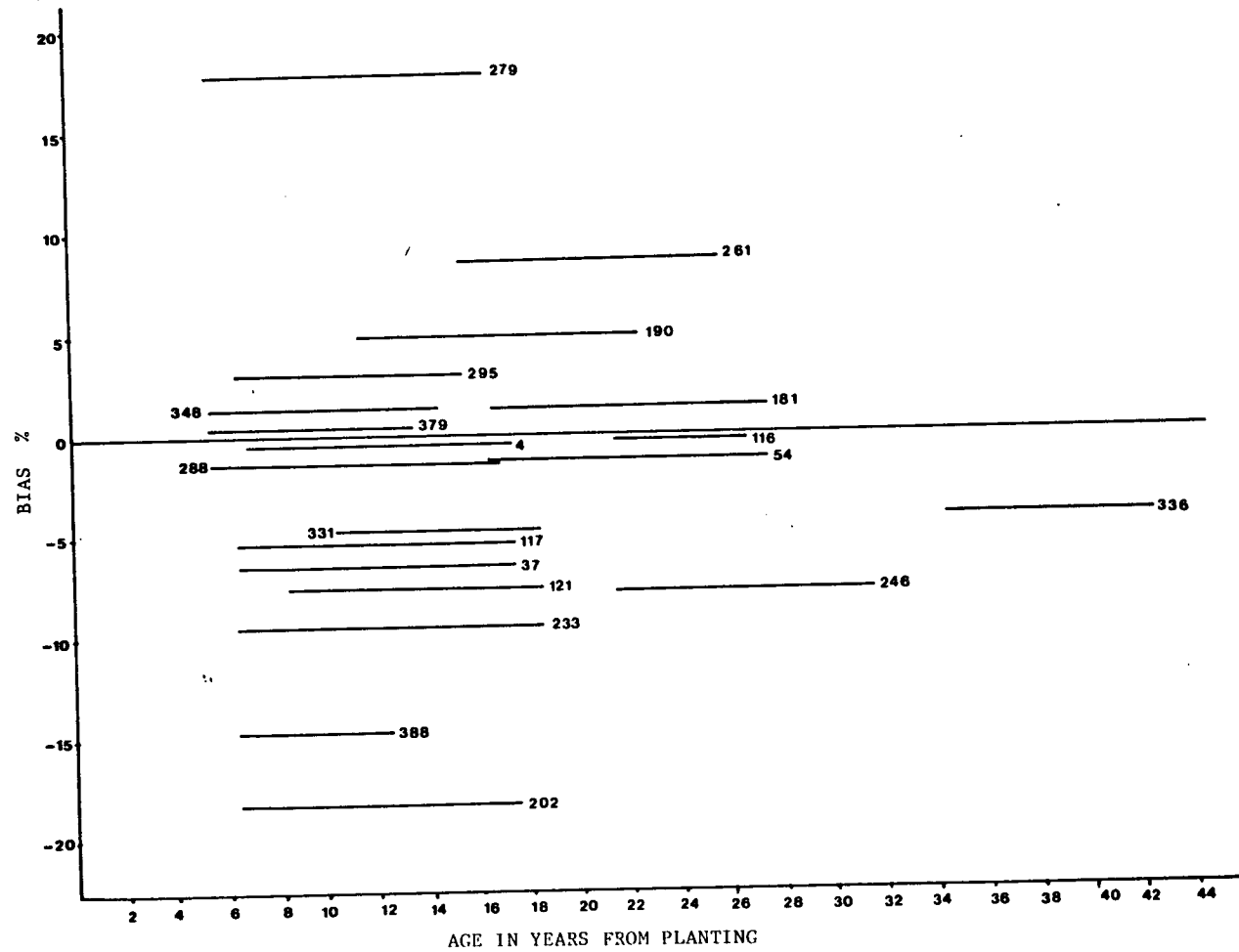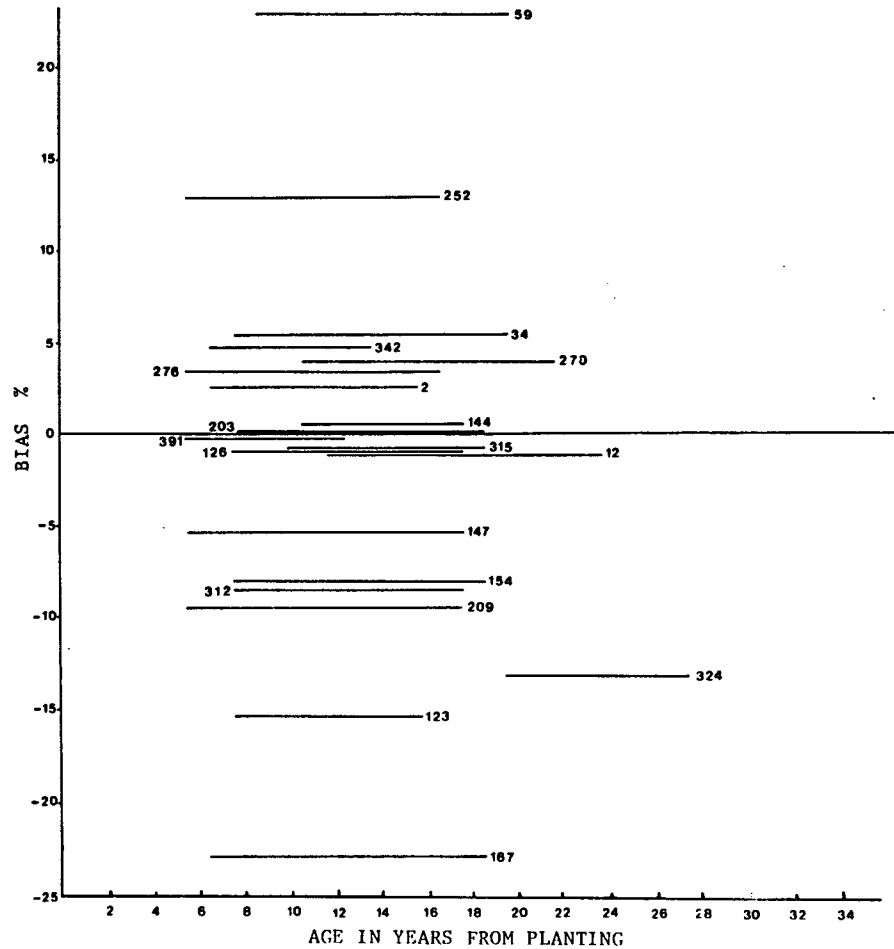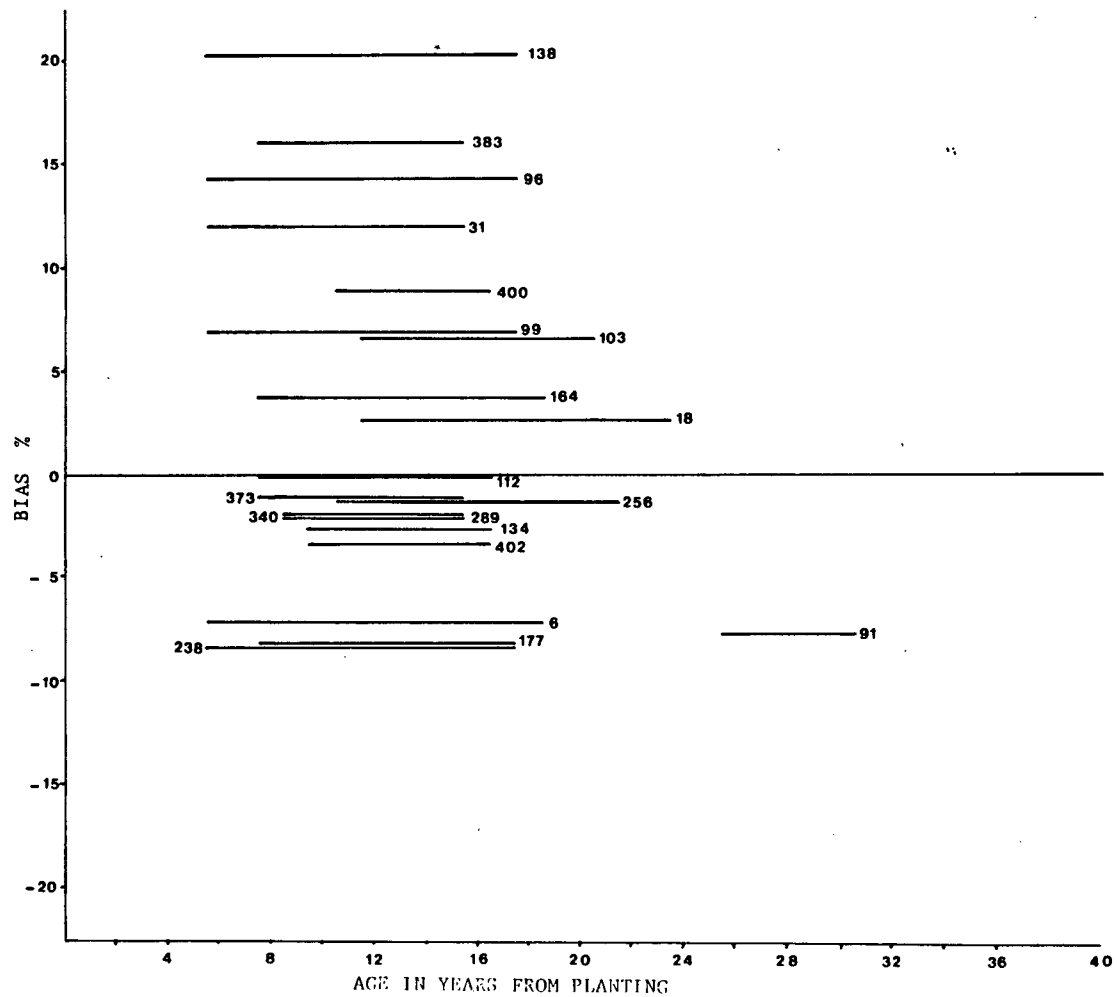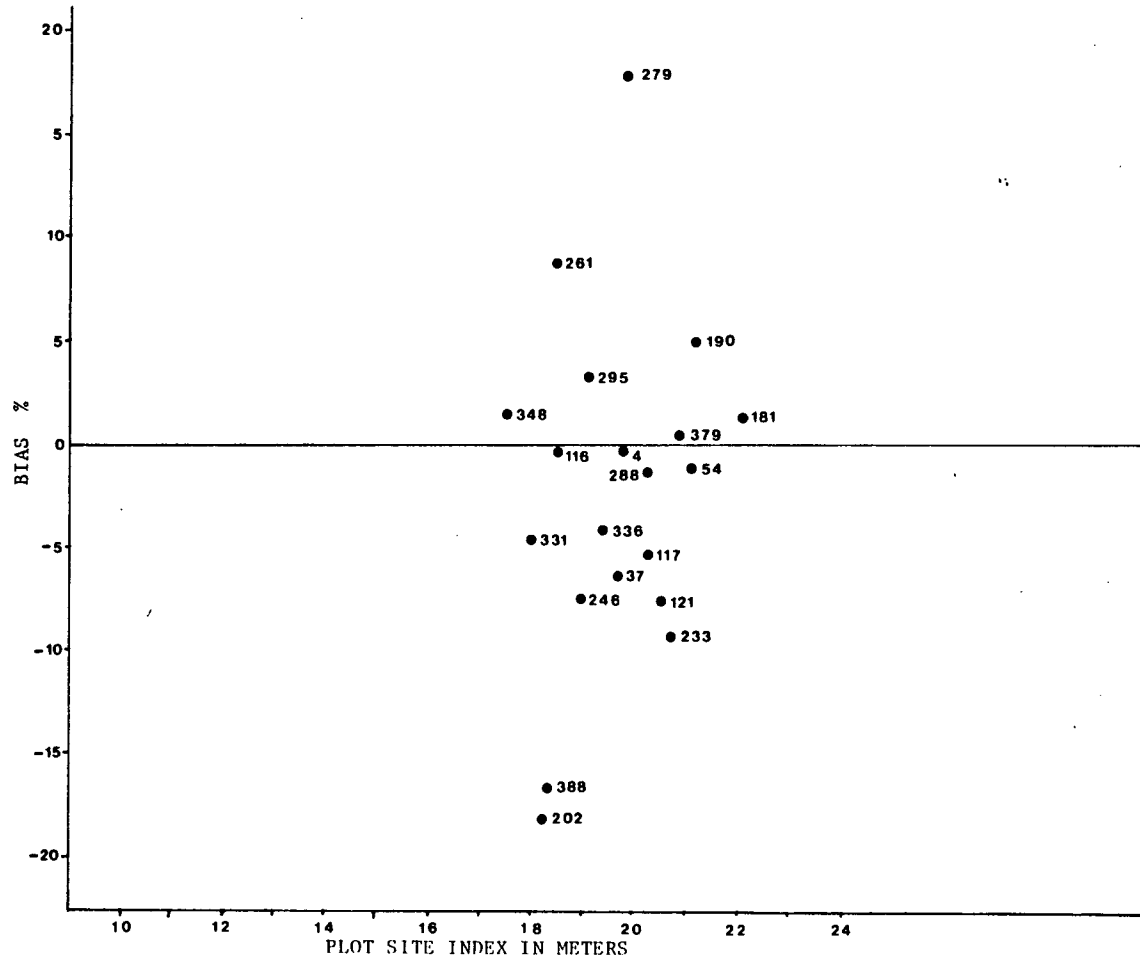FIGURE 27

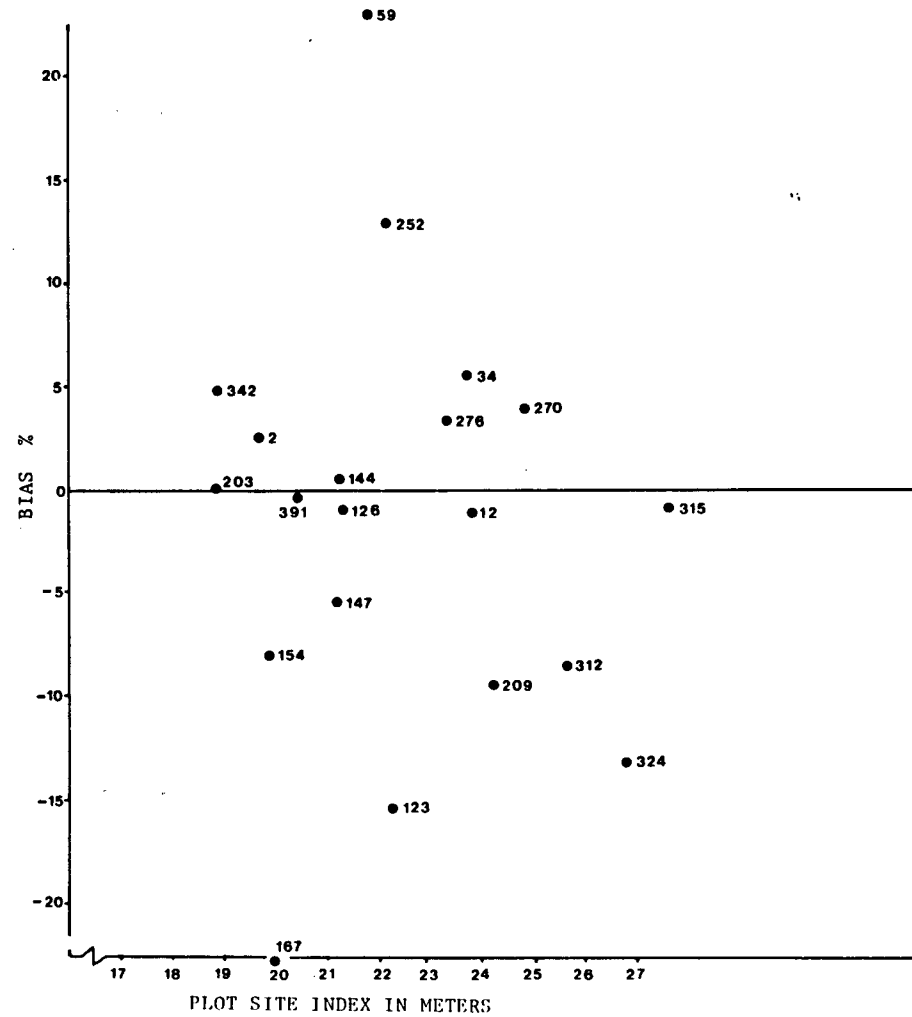DISTRIBUTION OF P. PATULA TEST PLOTS BY SITE INDEX AND VOLUME BIAS %

FIGURE 28

DISTRIBUTION OF P. RADIATA TEST PLOTS BY SITE INDEX AND VOLUME BIAS %

PLOT SITE INDEX IN METERS
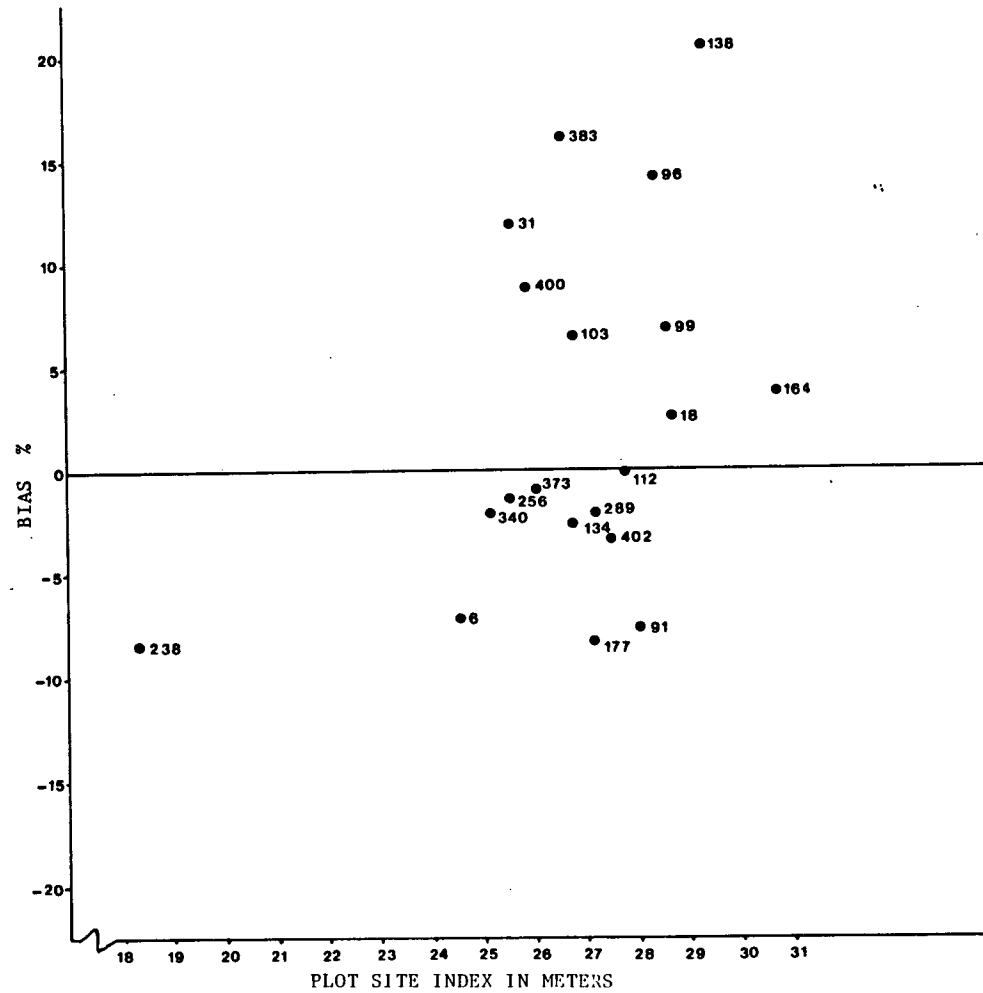
The effects of these factors is to introduce erratic behaviour in some plots so that their observed values will differ markedly from the simulated values. The question of how to deal with these factors is more philosophical than practical since these problems are for the most part there to stay. Thus, in my view, plots showing erratic behaviour (outliers) call for special attention to determine the cause but should not be eliminated unless there is clear evidence that they are from outside the population of interest.

4.3 Conclusion

The overall conclusion from the validation process is that the model is unbiased for all species except for a slight tendency to under-estimation for P. radiata. The 95% confidence limits for the difference between simulated and observed volume was ±16% for C. lusitanica ±20% for P. patula and ±17% for P. radiata. The model is acceptable at an error specification between 20 and 25% (C. lusitanica and P. radiata) and 25 to 30% for P. patula, unless a 1-in-20 chance has occurred. However, the model is fairly accurate for error specification up to 15% for C. lusitanica and P. radiata and up to 20% for P. patula if the lower probability level is acceptable. Basal area was identified as the main source of error for C. lusitanica and P. radiata models. Both dominant height and basal area contributed to the error for P. patula model in the ratio of 1:2. Thus future refinement to the model should be directed at basal area components for all species. Dominant height function for P. patula may also need further refinement.

The test plots covered site index ranges of 17 to 23, 18 to 28 and 24 to 31 for C. lusitanica, P. patula and P. radiata and age ranges of 5 to 43, 5 to 20 and 5 to 30 years for the same species respectively. The accuracy levels mentioned above apply to these ranges. It should also be noted that individual plot runs were limited to an average of 10 years. It is likely that longer simulations will not result in the same level of accuracy.

From the above discussion, it is clear that EXOTICS is capable of accurately simulating stand growth for the three species within the limitations stated above. Its utility for predicting stand yield and as a management guide in analyzing different silvicultural alternatives is the subject of the next chapter. This will serve as the sensitivity test with respect to input variables.

CHAPTER 4

SILVICULTURAL MANAGEMENT MODELS FOR KENYA

1. Introduction

As mentioned in the introduction (Chapter 1) a thorough knowledge of the growth and yield of the forest resources under different physical and biological conditions is basic to formulation of sound forest management plans, including silvicultural management schedules. Forest inventory systems, of which the permanent sample plot programme for Kenya forms a part, are the main source of this information, while growth and yield models are invaluable tools for planning and experimentation with alternative schedules. This chapter is devoted to the study of the growth and yield of the three species under the present management schedules and the formulation of alternative schedules using the yield model EXOTICS developed in the previous chapter. In this regard, thinning is singled out as the principal silvicultural means for stand manipulation towards the desired goals and objectives.

Fundamentally, thinning involves the periodic removal of some of the trees, with the main objective being to provide the remaining trees with adequate growing conditions. In principle, therefore, the whole process amounts to stand density control to achieve the desired objectives. The main concern to foresters has been to decide what measures of stand density to employ and the level of stand density control to apply.

Since thinning consists of removal of some of the trees in the stand, it seems obvious that stem count should be the logical means of

density control. However, as the number of trees diminishes over the rotation, the size of the individual trees increases. Thus, according to Wilson (1979), stem count must be qualified by some measure of tree size if it is to have meaning. Wilson proposed the use of spacing as a function of stand dominant height, the concept of which has already been discussed under the section on stand density.

Wilson's (1946) proposal has been applied in thinning research in several other countries as Hart's density index. In addition to its disadvantage already discussed, it is demonstrated later in this section that for some species, stands of the same stand density index will have different basal areas per hectare for different site index classes. For these species this index is inadequate as a measure of the degree to which a given species is utilizing the site.

A more recent approach to stand density control has been proposed by Drew and Flewelling (1977, 1979). Basically the approach employs the concept of maximum size-density as a general principle of plant population biology: In pure stands, the maximum mean tree size attainable for any density can be determined by a relationship known as the -3/2 power law:

$$v = a\rho^{-3/2} \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad 4.1$$

where v = mean tree volume

a = a constant

ρ = stand density expressed as number of trees.

The above law can be rewritten as:

$$\ln v = a' - \frac{3}{2} \ln \rho \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad 4.2$$

So that -3/2 represents the slope of the maximum size-density relationship as shown on Figure 29 for coastal Douglas-fir from Washington and Oregon (adopted from Drew and Flewelling 1979). The empirical determination of this law and its theoretical derivation were developed by Yoda et al.(1963) while its application to forestry has been demonstrated by Yoda et al. (1963) and Drew and Flewelling (1977, 1979). According to Harper (1977), there is evidence that this -3/2 power law holds true for forest trees as well as for annual plants.

The practical implication of this law is that a stand of a given initial density (in terms of number of trees per unit area) will maintain volume growth until the mean tree volume (or size) reaches the maximum size for that density given by equation 4.1. This indicates the size-density at which self-thinning (competition induced) mortality sets in and indicates the point at which the stand is due for thinning. The problem for the forest manager then is to determine that this law applies to the species he is dealing with and the relationship (equation 4.1) which will depend on the species and site factors. The applicability of this relationship is best determined from controlled experiments, especially the constant stocking trials.

The approach of Reukema and Bruce (1977) utilizes a similar principle to that of Drew and Flewelling (1977, 1979) except that they used maximum stocking level (basal area) per unit area as a guide to when a stand is due for thinning. Besides providing the forest manager
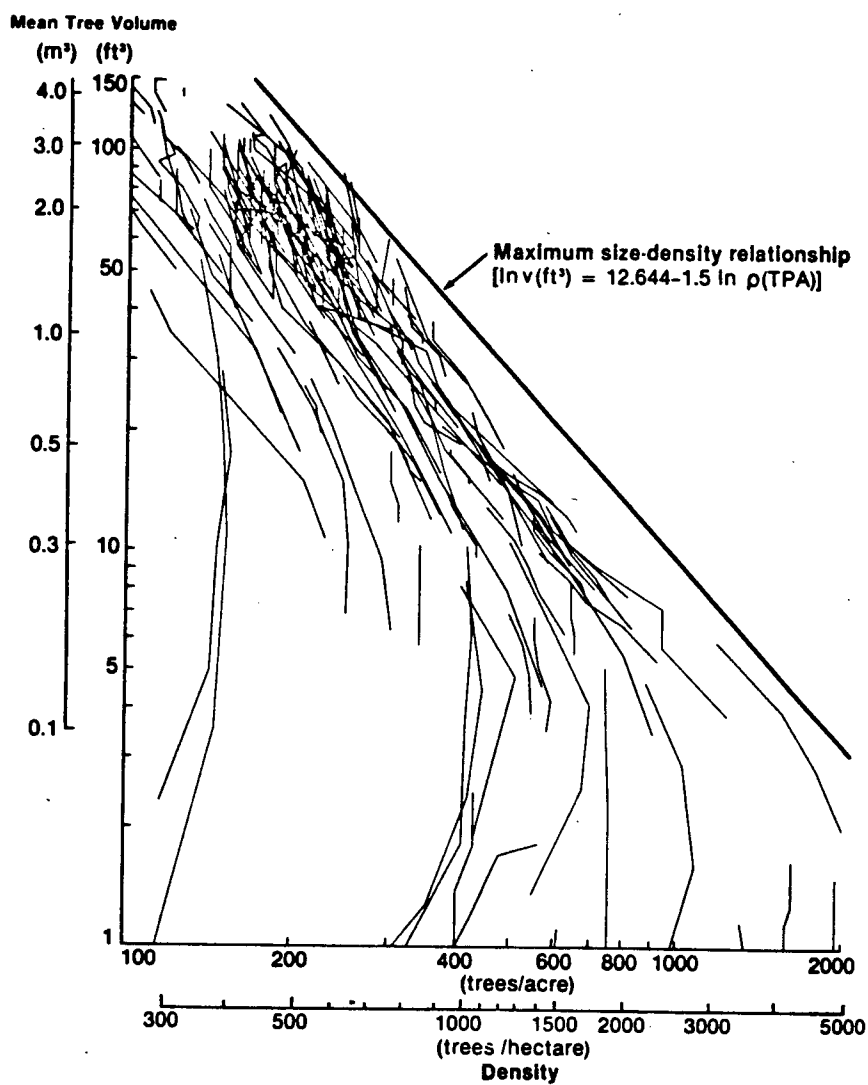
Figure 29 The maximum size-density relationship and the natural stand data used in positioning this relationship.

(from Drew and Flewelling 1979)

with an objective guide (maximum basal area) to thinning, this approach has the advantage of ensuring efficient utilization of site by a species. In addition, it provides a continuous mechanism for tree dimension control since mean stand DBH can be derived from the basal area at any time. Its main drawback rests in defining quantitatively the maximum stocking level.

In addition to deciding when a stand is due for a thinning, two other variables enter a thinning model: the intensity of thinning and the length of time between thinnings. As mentioned earlier in Chapter 2, these two are interrelated, since the higher the intensity, the longer the thinning interval and vice versa. Thus, if the basal area after thinning and basal area growth rate are known, then the time it takes before the stand is due for the next thinning is known. Both these variables are functions of the economics of thinning and the biological factors, as mentioned elsewhere. In this study, the economics of thinning is not considered and therefore only biological factors will be discussed. The problem reduces to one of determining the quantity of the stand to be removed at each thinning. In this respect, the current thinning intensity used in Kenya was used as a guide.

2. Current Thinning Models for Sawtimber Regimes in Kenya

Figure 30a,b, and c, illustrate the current basal area thinning model for C. lusitanica, P. patula and P. radiata respectively while Figure 31a,b, and c, illustrate the MAI and CAI (smoothed) curves for the respective species under the current sawtimber thinning regimes.

FIGURE 30

MAIN STAND BASAL AREA/AGE RELATIONSHIP UNDER THE CURRENT SAWTIMBER
THINNING REGIMES BY SPECIES AND S.I. CLASSES
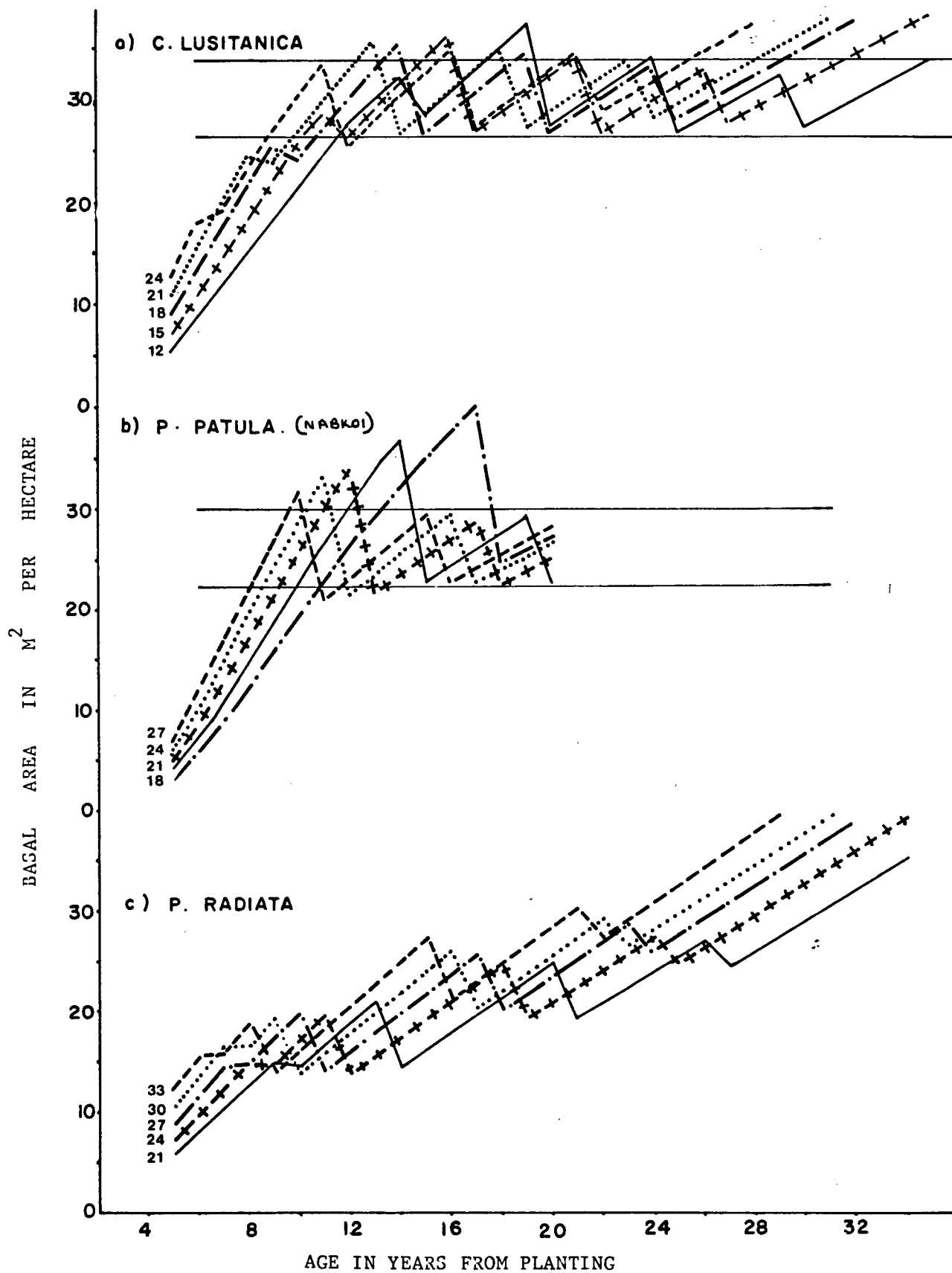
FIGURE 31

MEAN AND CURRENT ANNUAL VOLUME INCREMENT RELATIONSHIP WITH AGE FOR THE
CURRENT SAWTIMBER THINNING REGIME BY SPECIES AND S.I. CLASSES

M.A.I. and C.A.I. m^3 (smoothed out)   C.A.I. m^3 (unsmoothed)

a) C. LUSITANICA.

b) P. PATULA (NABKOI)

c) P. RADIATA.

AGE IN YEARS FROM PLANTING
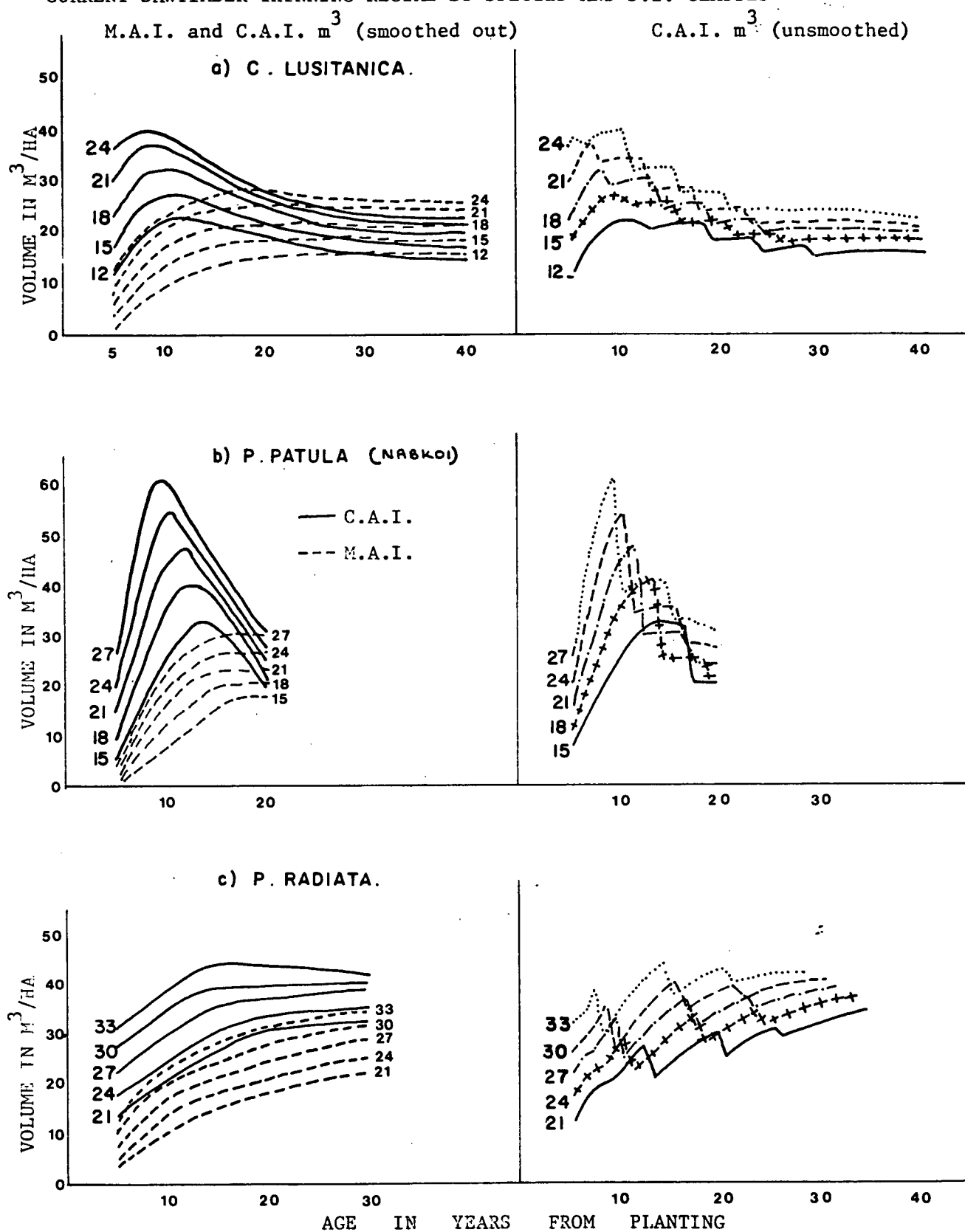
Unsmoothed CAI curves are also shown on Figure 31 for each species to illustrate the effects of thinning on the current annual volume increment development. Tables 44, 45 and 46 give the volume yield and other stand characteristics for C. lusitanica, P. patula and P. radiata respectively. The following features characteristic of the present sawtimber thinning model are worth noting:

(a) For C. lusitanica thinning model

    1. At first thinning, carried out when stands on all site classes have the same stand density index of 25%, stand basal areas are 32.2, 28.5, 25.3, 24.3 and 17.7 m^2 per hectare for site index classes 12, 15, 18, 21 and 24 respectivley (see Table 44). For this species therefore, thinning to a common stand density index results in different levels of site utilization, with the poor sites carrying a much heavier basal area than the good sites. This is the opposite to what the situation should be and demonstrates the weakness, already mentioned, inherent in using Hart's stand density index as a guide to thinning for this species.

    2. Except for first thinning, the average maximum basal area before thinning is 33 m^2 per hectare, and the average basal area after thinning is 26 m^2 per hectare. Thus, there is an implied maximum basal area which, judging from the basal area curve trends, appear to be well below the maximum consistent with maximum basal area yield, especially for site classes ≥ 18.

TABLE 44. Volume yield and other relevant stand parameters under the current sawtimber thinning regime for C. lusitanica to a rotation age of 40 years: Technical Order No. 42 of March 1969.

Site Index	12	15	18	21	24
H_{dom} at 1st thinning	11.25	11.25	11.25	11.25	11.25
Age at 1st thinning	14	11	9	8	6
BA (m^2) before 1st thinning	32.2	28.5	25.3	24.3	17.7
Culmination age (approx.)	30	26	24	21	19
MAI max (m^3)	16.0	19.0	22.0	25.2	28.1
CAI max (m^3)	23(12)	27(11)	32(10)	37(9)	40(7)
DBH at age 40 years	43.7	46.1	47.6	48.3	50.1
Total V(1) m^3 at age 40 years	637.5	749.3	849.7	943.0	1037.7
Thinning volume as %	37.3	33.0	30.3	29.7	28.1
Total V(15) m^3 at age 40 years	567.3	674.2	771.4	860.6	961.8
Thinning V(15) m^3 as %	30.8	26.7	24.4	24.2	21.6

No. in bracket indicate age of max. CAI.

TABLE 45. Volume yield and other relevant stand parameters under the current sawtimber thinning regime for P. patula (Nabkoi) to a rotation of 20 years: Technical Order No. 53 of May 1981

P. patula (Nabkoi) Shamba					
Site Index	15	18	21	24	27
H_{dom} at 1st thinning	16.9	16.8	16.8	17.5	17.7
Age at 1st thinning	17	14	12	11	10
BA (m^2) before 1st thinning	40.1	36.6	33.7	33.0	31.5
MAI max (m^3) at age 20 year	18	21	24	27	30
CAI max (m^3)	33(14)	40(13)	48(12)	55(11)	61(10)
Total V(1) m^3 at age 20 year	358.9	416.2	472.0	542.6	642.0
Thinning volume as %	35	45	39	35	32
Total V(15) m^3 at age 20 year	261.0	312.8	364.3	428.8	520.7
Thinning V(15) m^3 as %	28	37	29	26	22
Total V(20) m^3 at age 20 year	101.9	160.5	218.0	277.0	374.3
Thinning volume as %	0	12.0	8.0	8.0	7.0

No. in bracket indicate age of max. CAI.

TABLE 46. Volume yield and other relevant stand parameters under the
current sawtimber thinning regime for P. radiata to a rotation
age of 30 years: Technical Order No. 44 of March 1969.

	P. radiata Shamba				
Site Index	21	24	27	30	33
H_{dom} at 1st thinning	12.2	12.5	12.4	14.1	13.5
Age at 1st thinning	9	8	7	7	6
BA m^2 at 1st thinning	14.9	14.9	14.5	16.3	15.4
BA m^2 at 2nd thinning	21.0	19.5	19.8	19.1	18.9
MAI max m^3 up to age 35	22	25	28	31	34
CAI max m^3	32(35)	35(35)	38(35)	40(17)	44(16)
DBH to age 30 years	41.6	44.3	46.2	47.7	49.5
Total V(1) m^3 at age 30 years	655.8	751.8	855.8	946.9	1052.8
Thinning volume as %	33.1	28.7	27.2	25.8	24.2
Total V(15) m^3 at age 30 years	542.8	642.6	743.4	831.0	939.1
Thinning V(15) as %	21.4	18.5	18.0	17.1	16.7
Total V(20) m^3 at age 30 years	471.3	573.6	713.4	760.9	869.5
Thinning volume as %	14.4	12.4	11.9	12.0	12.0

No. in bracket indicate age of max. CAI.

3. The CAI curves (unsmoothed) indicate that except for first thinning, all other thinnings have a marked effect on the current annual volume increment, indicated by the drop in CAI after thinning. This inevitably has an effect on total volume yield which indicates that for this species, Moller's theory that thinning has no effect on total volume yield does not hold under the present thinning regime in Kenya.

4. Important figures to note in Table 44 are the volume of thinning (total and merchantable) as a percentage of the volume yield (total and merchantable) which on the average works out to 30% and 24% respectively. These percentages, along with the DBH at age 40 years are important in comparing outputs from alternative schedules.

(b) For P. patula thinning model

1. At first thinning which is carried out at the common stand density index of 17%, stand basal areas are 40.1, 36.6, 33.7, 33.0 and 31.5 m^2 per hectare for site index classes 15, 18, 21, 24 and 27 respectively. Thus, as for C. lusitanica, Hart's density index is inappropriate as a measure of site occupancy.

2. The first thinning appears very severe, removing an average of 42% of the basal area before thinning. This is confirmed by Figure 31b which shows a very drastic drop in current annual increment after this thinning for all site classes. Subsequent thinnings also appear to have an effect on CAI. It is evident

therefore that for this species, Moller's theory does not hold at the present level of thinning intensity.

3. Except for the first thinning, subsequent thinnings appear limited to an average maximum basal area before thinning of 30 m^2 per hectare and an average minimum basal area after thinning of 22.5 m^2 per hectare. The maximum appears well short of the maximum consistent with maximum basal area yield for all site classes.

4. Table 45 shows that thinning volume constitutes a very high percentage of the total volume yield up to age 20 years, a result of the heavy thinnings for this species.

5. At the present level of thinning intensity, culmination of growth does not occur before age 20 years on any site class. From the smoothed CAI and MAI curves (Figure 31b) it would appear from extrapolation that culmination would occur at the same age on all site classes: between age 20 and 21 years. However it should be noted that this may be due to the heavy thinnings affecting the stand development or to the smoothing out of curves using subjective judgement.

(c) For P. radiata thinning model

1. For this species, basal area at first and second thinning are an average 15.2 and 19.7 m^2 per hectare respectively on all site classes (see Table 46). These thinnings are carried out at a common stand density index of 23% and 18% respectively on

all site classes. It therefore appears that for this species, Hart's stand density index is a good approximation of the degree to which the species is utilizing the site. It would be an appropriate basis for timing when a stand is due for a thinning for this particular species.

2. In general the thinning model indicates that the level of basal area before thinning increases with age (Figure 30c). Figure 31c for CAI (unsmoothed) shows that the first thinning on all site index classes has no marked effect on current annual volume increment. However, subsequent thinnings do have an appreciable effect as indicated by the drop in CAI after each thinning.

3. From extrapolation, it would appear that culmination age for P. radiata would occur well beyond the range covered by the data in this study (see Figure 31c). Indeed the CAI appears to be still accelerating up to age 35 years for site index classes 21, 24 and 27. This suggests that this species has higher yield potential and that the rotation (up to age 35 years) does not exploit this potential fully.

4. At age 30 years, thinning volume on the average constitutes 27.2%, 18.0% and 11.9% of total volume yield, merchantable volume to 15 cm top DBH and merchantable volume to 20 cm top DBH respectively (Table 46). Thus, the thinnings are considerably lighter than those for P. patula and C. lusitanica.

2.1 Summary on the Current Thinning Model for Kenya

1.   Hart's stand density index is inadequate as a guide to thinning for
     C. lusitanica and P. patula as it results in higher site occupancy
     on poor sites than on good sites, based on basal area. For
     P. radiata the index appears quite satisfactory as a measure of the
     degree of site utilization by the species.

2.   For C. lusitanica and P. radiata, first thinning appears to have no
     marked effect on CAI. However, subsequent thinnings do appear to
     have an appreciable effect, resulting in lowering of the current
     annual volume increment. For P. patula, both first and subsequent
     thinnings do have a drastic effect on CAI.

3.   As a follow-up to the observations on 2 above, it is inferred that
     under the current sawtimber thinning regimes, Moller's theory that
     thinning has no appreciable effect on total volume production does
     not hold for the three species in Kenya.

3.   Alternative thinning model for sawtimber crop in Kenya

3.1 Thinning Policy Considerations

     As mentioned in Chapter 1 Section 3, the thinning policy for Kenya
aims at production of large-sized material in as short a rotation as
possible at the expense of some loss in total yield. At the time this
policy was adopted in the fifties and early sixties and documented in
the relevant Technical Orders in 1969, the predominant purpose of
plantation management was production of sawlogs as quickly as possible

as the shortage of sawtimber from indigenous forests was already being felt. At that time, there were no other major wood-using industries, neither was the pressure on the limited forest resource acute as the population was still very low with low per capita consumption of wood. Since then, several developments have occurred:

1. The population has increased from an estimated 6 million in 1950 to 8 million in 1960 and to 15 million in 1980, with a population growth rate of 4%, estimated to be the highest in the world (according to Kenya Bureau of Statistics 1982). This has put a lot of pressure on the forests for the supply of sawtimber, firewood, general purpose wood, pulp and paper products, etc.

2. There has been a very rapid increase in forest industries, ranging from modern sawmills, particle board manufacturing industries, plywood industries and a modern pulpmill, which came into production in 1972. The implication of this development is that while a few plantations may still be managed exclusively for supply of only one end product, the majority of plantations will be managed for supply of multiple end products. Thus even in a predominantly sawtimber management zone, there will be a component for pulpwood, particle board and plywood.

3. There has been a rapid increase in standard of living, resulting in an increase in consumption of wood and wood products. For example, the per capital roundwood consumption

for Kenya in 1950 was 0.1 m^3. This had risen to 1.8 m^3 by
1979 (F.A.O. Yearbook of forest products statistics 1947-1951,
F.A.O. Yearbook of forest products 1979). Most of this
increase has been a result of increased literacy level, result-
ing in higher consumption of pulp and paper products, and the
change to modern styles of building which require more timber.

All these factors point to a need for a change in thinning policy
in favour of the objective of maximum volume production. The develop-
ment of integrated forest industries which can utilize both small size
logs from thinnings and large size logs from final fellings favour this
policy. It should also be noted that forests in Kenya constitute only
3% of the land area and therefore the mounting population and demand for
wood products can only favour the adoption of maximum volume yield on
any available forest land.

The need for changing the thinning policy to accommodate the
changes in the forestry industrial sector appear already to have been
appreciated by the Kenya Forestry Department. This is evidenced by the
1981 revision of the management schedule for P. patula (Technical Order
No. 53 of May 1981). The most significant changes in this Technical
Order are in regard to the delay and heaviness of the first thinning.
These changes appear to have been instituted to provide a higher volume
of larger-sized thinnings to go to the pulpmill. Unfortunately, as has
already been demonstrated in the previous section, this thinning
schedule is not consistent with the concept of maximum volume yield over
the whole rotation.

3.2 Thinning Experiment for C. lusitanica

In order to investigate the possibility of alternative thinning regimes for the exotic timber species in Kenya, a thinning experiment was designed with the following objectives:

1. To investigate the effects of different thinning levels and thinning intensities on growth and yield on different site index classes.

2. Based on results from (1) above, to identify the appropriate thinning regime based on the criteria of highest merchantable yield.

In order to draw reasonable bounds to the study, only one species, C. lusitanica was considered. This species was singled out on two counts; (1) it is the preferred species for sawtimber, and (2) its model domain covered the whole range of its rotation under the current management schedules.

Experimental design: Five thinning levels A, B, C, D and E were arbitrarily selected in order of increasing basal area before thinning. These levels are given on Table 47. Within each thinning level, four thinning intensities were selected based on the proportion of basal area to be removed as a percentage of basal area before thinning. These were 10, 20, 30 and 40%. These treatments were repeated over the five site index classes for C. lusitanica i.e. 12, 15, 18, 21 and 24 for a total of 100 treatment combinations. All the experiments were conducted using the yield model EXOTICS to simulate results. Figure 32 shows how these thinning regimes translates in terms of basal area before and after

TABLE 47.   Basal area before thinning (M^2/ha) for the alternative
            thinning regimes

Thinning level	1st thinning	2nd thinning	3rd thinning	4th thinning
A	25	35	35	35
B	25	35	40	40
C	25	35	45	45
D	25	40	45	45
E	25	40	50	50

thinning and number of stems (initial stocking of 1200 s.p.h. assumed)

at different ages for site index class 18.

A major concern in selecting the thinning levels was whether these

exceeded the maximum basal area potential for each site quality class.

A preliminary attempt to find these maxima using the -3/2 power law

(Drew and Flewelling 1977, 1979) failed, suggesting that the plantations

from which the data was drawn were managed below the maximum site

potential. Faced with the problem of defining the maximum basal area

for these stands, Alder (1977) had fitted hand-drawn curves over the

maximum basal area observed on the p.s.p.s. and then quantified these

curves using a nonlinear equation:

$$G_{max} = b_0 (1 - e^{(-b_1 H)})^{b_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 4.3$$

where G_{max} = Maximum basal area in m^2/ha.

   H   = Stand dominant height (represents effects of age and site).

FIGURE 32
NUMBER OF STEMS AND BASAL AREA AT DIFFERENT AGES FOR DIFFERENT THINNING LEVELS AND THINNING INTENSITIES FOR C. LUSITANICA S.I. CLASS 18
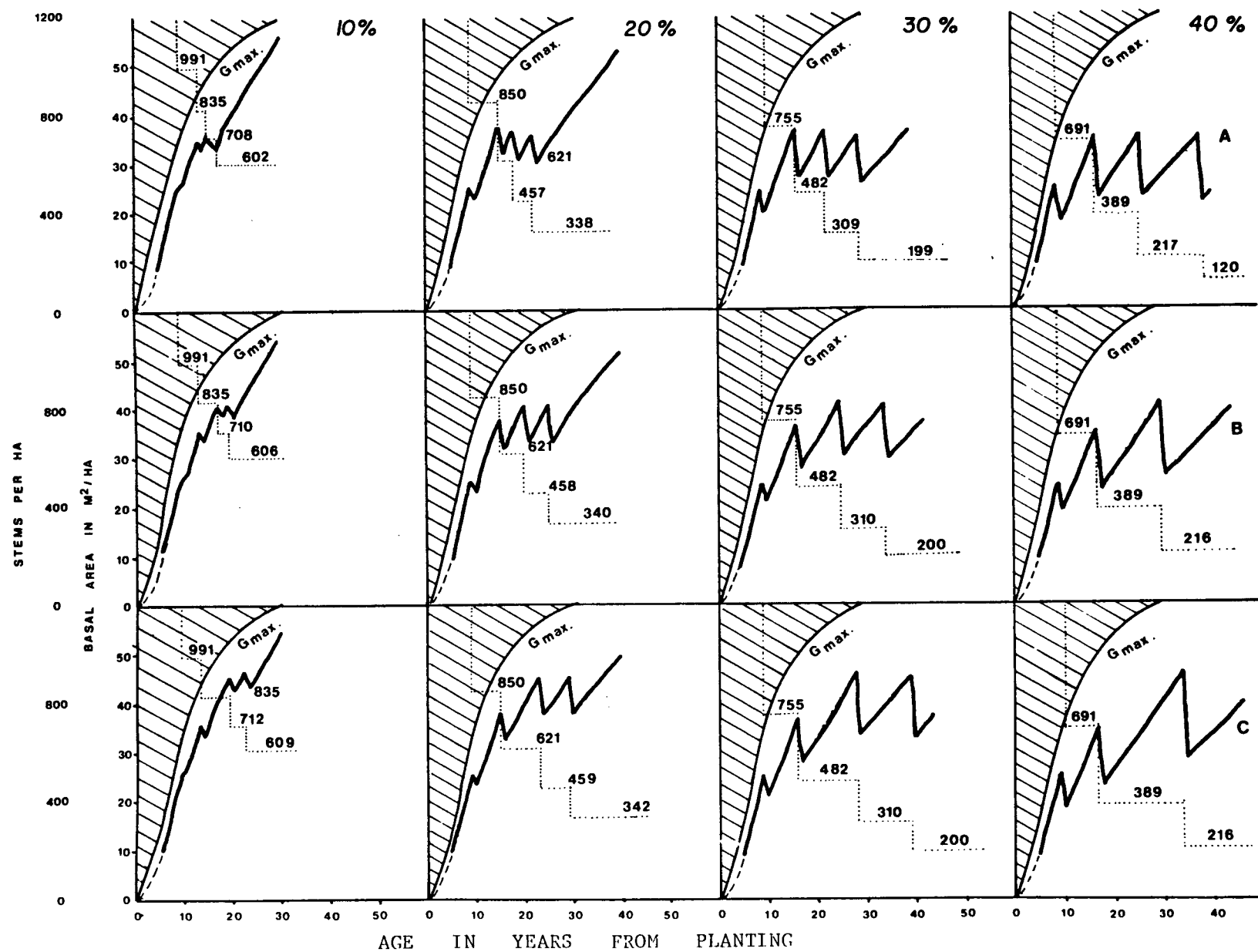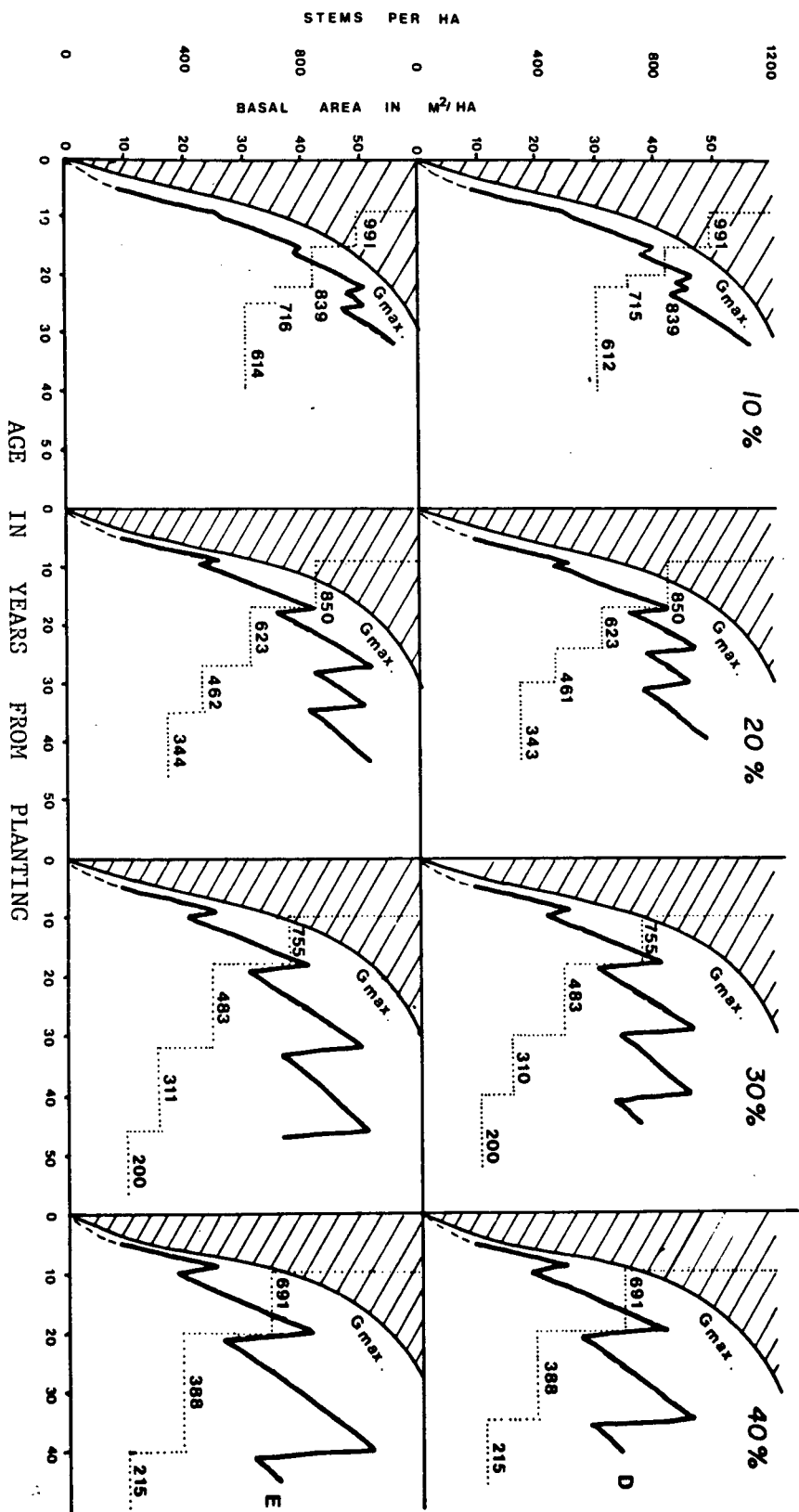
FIGURE 32 con't

b_0, b_1 and b_2 are the regression coefficients. For $\underline{C}$.

$\underline{lusitanica}$ in Kenya, he obtained the values: b_0 = 63.9, b_1 = 0.1219 and

b_2 = 2.551. No criteria for goodness of fit was given for this

equation as it was based upon a hand-drawn curve and hence such criteria

would be meaningless. For lack of better means of guidance in this

study, this equation was used to determine the G_{max} curves shown on

Figure 32.

3.3 Results from the Simulated Thinning Experiment

(a) Effects of alternative thinning regimes on MAI and biological
     rotation age:

Figure 33 gives the MAI and CAI curves for the different thinning

levels and thinning intensities for $\underline{C}$. $\underline{lusitanica}$ site index 18 while

Table 48 gives a summary of the maximum MAI and the age at which this

maximum is obtained (culmination age) for each thinning level and

thinning intensity for the same site index class. The maximum MAI and

the culmination age for the current thinning regime and some site index

class are also shown on Table 48 as control. Several observations can

be noted from both Figure 33 and Table 48.

1. For all thinning levels, MAI decreases with increasing severity

   of thinning. For example under 10% thinning intensity, the

   effects of thinning are minimal so that growth can almost be

   considered as for unthinned stands. MAI can therefore be

   expected to be at maximum and to decrease with increasing

   severity of thinning so that it is minimum at 40% intensity.

FIGURE 33

M.A.I. AND C.A.I. OVER AGE CURVES FOR DIFFERENT THINNING LEVELS AND THINNING INTENSITIES FOR C. LUSITANICA S.I. 18

AGE   IN   YEARS   FROM   PLANTING

FIGURE 33 con't

VOLUME IN M³ PER HECTARE

AGE IN YEARS FROM PLANTING

TABLE 48. Maximum MAI (m^3/ha) and biological rotation age (culmination age) for different thinning regimes for C. lusitanica S.I. 18

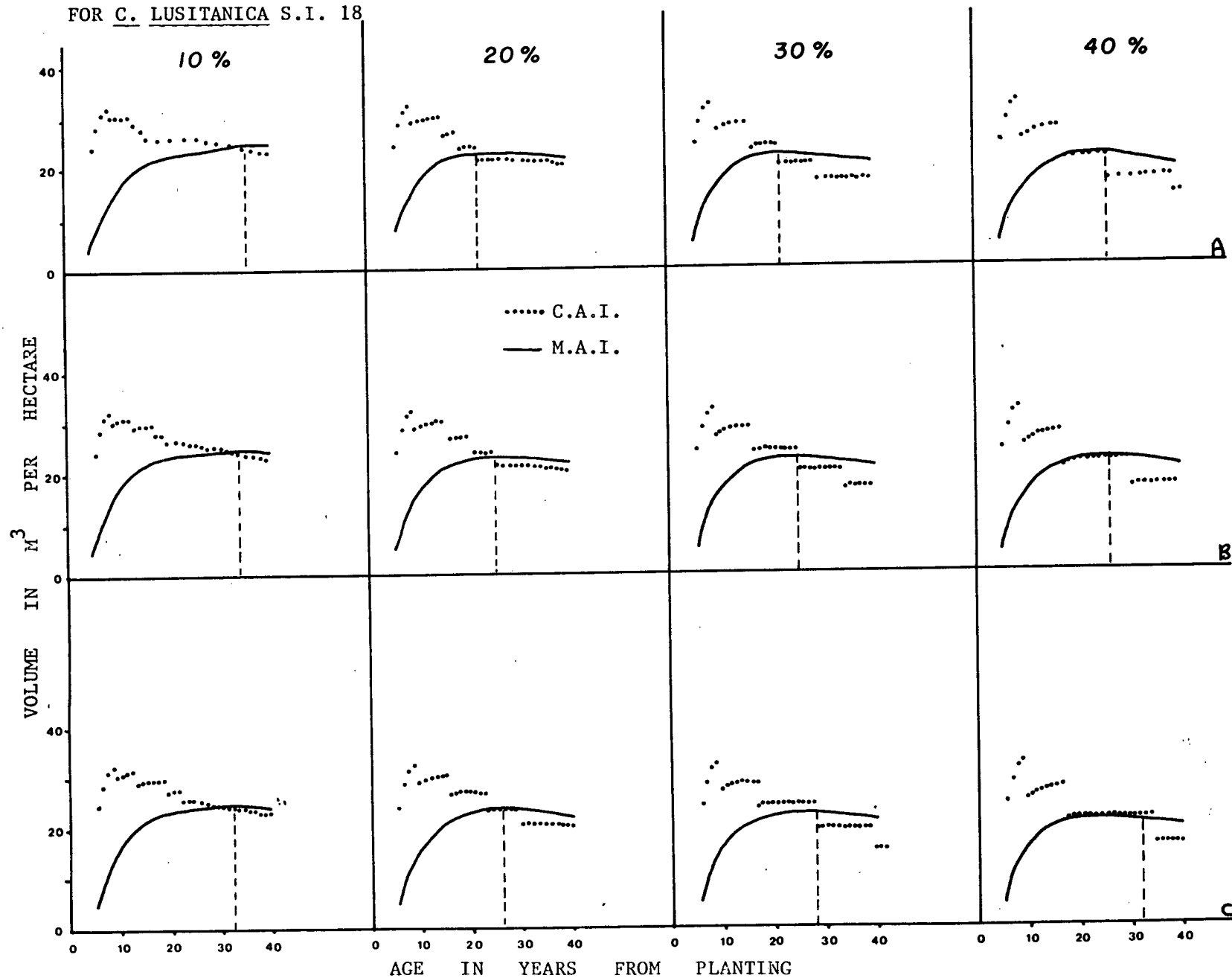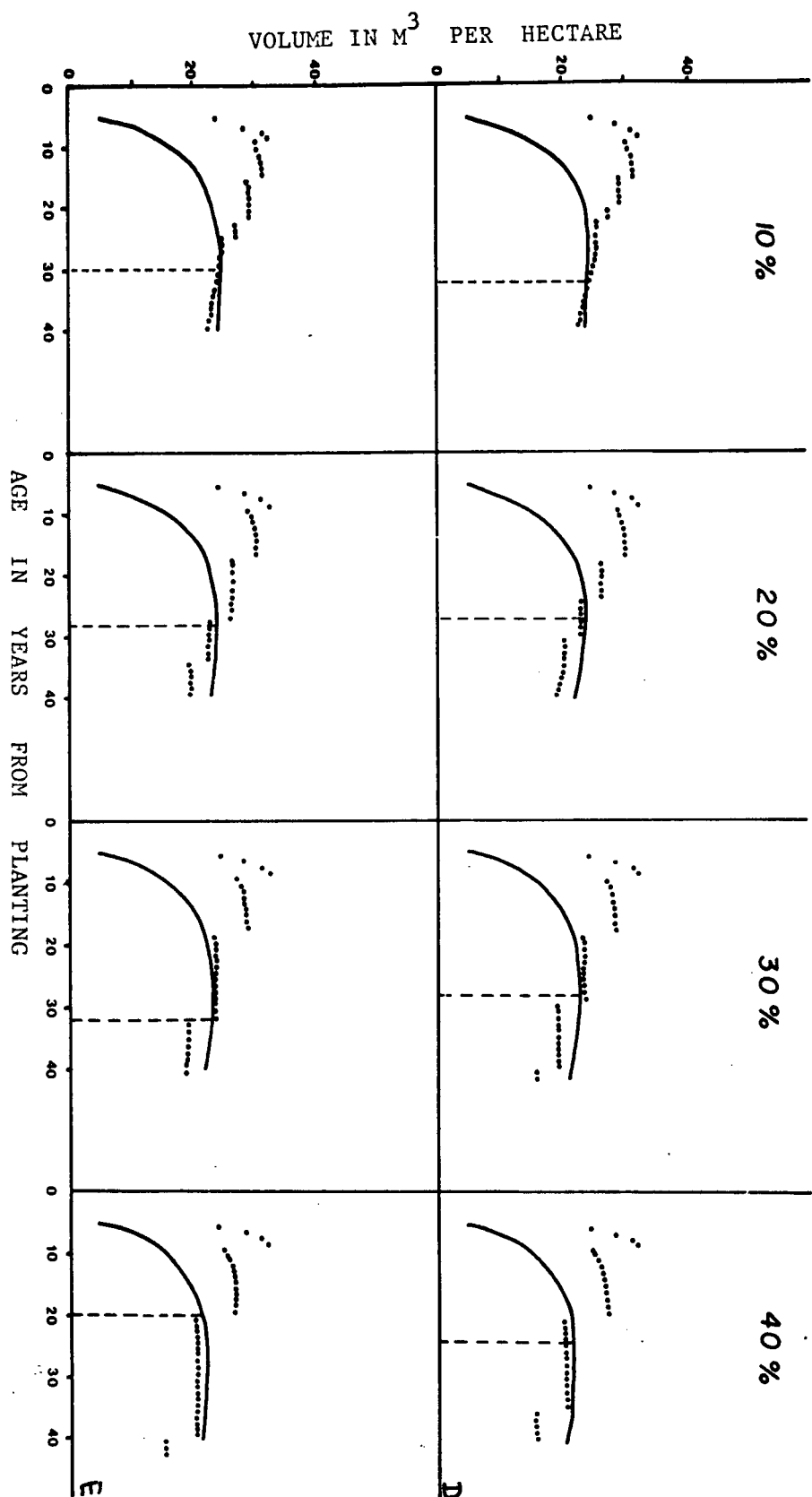| Intensity	10		20		30		40		Control	
Level	MAI	Age	MAI	Age	MAI	Age	MAI	Age	MAI	Age
A	24.2	36	22.6	22	22.0	22	21.0	26		
B	24.2	34	22.9	25	22.2	25	21.0	26		
C	24.3	32	23.3	26	22.4	28	21.1	32		
D	24.4	32	23.5	27	22.6	28	21.7	24		
E	24.6	30	23.8	28	22.7	32	21.7	20		
Control									22.0	24

This confirms the earlier observation (Chapter 4 Section 2) that Moller's theory with respect to effects of thinning on volume yield does not hold for C. lusitanica within the thinning intensities considered in this study.

2. Within a given thinning intensity, MAI increases with increasing level of thinning i.e. increases from thinning level A to E. This is as expected since MAI is a function of basal area increment which in turn is a function of basal area before thinning. This increase however is very small compared to the increase resulting from changes in thinning intensity and may be considered unimportant for practical purposes.

3. From the above observations, it is concluded that for C. lusitanica, thinning intensity rather than thinning level (measured by basal area before thinning) is the more critical consideration with regard to MAI.

4. For 10% thinning intensity, the culmination age decreases with increasing level of basal area before thinning. This indicates that this thinning intensity is so light that stand development is as for unthinned stand. Increasing basal area before thinning therefore has same effect as improving site quality.

    For 20 and 30% thinning intensities, culmination age increases with increasing basal area before thinning i.e. from thinning levels A to E. This is mainly a result of the CAI curves being shifted further to the right as the basal area

before thinning is raised (resulting in delay in thinnings) while the MAI curves are little affected (see Figure 33). Thus raising level of basal area before thinning when thinning intensities are heavy has the same effects as decreasing site quality. This effect is also apparent for 40% thinning intensity but is reversed for thinning levels D and E as the effects of the third thinning on MAI and CAI curves diminishes.

5. Within a given thinning level, the culmination age is expected to increase with increasing thinning intensity. This is manifest in thinning levels C, D and E for thinning intensities 20, 30 and 40% (levels A, B and C only).

Based on MAI and culmination age, the most promising thinning regimes are those with 20 and 30% thinning intensity. The 10% thinning intensity gives high culmination age inspite of the higher MAI. Besides this, the light thinnings are accompanied by short thinning cycles and therefore are unattractive economically. The 40% thinning intensity results in low MAI compared to the current thinning schedule, suggesting that it is probably too severe.

Between the 20 and 30% thinning intensities, the former has an edge in both MAI and culmination age. Thinning regime A:20 appears to be the best with a higher MAI and lower culmination age than the current thinning regime. This however does not mean that this is the optimum regime. All the other thinning regimes under 20% thinning intensity have higher MAI but longer rotation age than the current thinning regime. It is therefore not possible to determine the best regime without an economic analysis.

The biological rotation of a plantation (as discussed above) provides the rotation of highest total volume yield. For sawtimber production however, the main interest is the total merchantable volume production for a given end product. As a result, biological rotation is hardly ever used in sawtimber production regimes. As mentioned earlier, the current rotation for sawtimber plantations in Kenya is the age at which a DBH of 48 cm is attained. This however is a gpoor criteria for a rotation since the 48 cm DBH can be attained in a plantation at different ages depending on the initial stocking and thinning intensities. It therefore does not relate to volume yield. A commonly used method in forestry is to calculate the economic rotation, defined either as the rotation of the highest economic land value or of the highest rate of return (Crowe 1967, Grut 1970, and others). This would require such information as the economics of plantation establishment, log class assortments and a clear definition of product mix, all of which were not available to this study. For purposes of yield analysis under different thinning regimes, a common rotation age of 40 years was adopted, mainly because it is the average age at which sawtimber crop attains 48 cm DBH under the current thinning regime in Kenya.

(b) Effects of alternative thinning regimes on productivity

Table 49 shows various measures of productivity up to age 40 years for C. lusitanica site index 18 for the various thinning regimes, including the current thinning regime as control. The table also gives the increase in yield of the alternative thinning regimes (expressed as percentage) relative to the yield under the current thinning regime.

TABLE 49. Volume yield (m³/ha), increase % (relative to current thinning regime) and other stand parameters at 40 year rotation age for different thinning regimes for C. lusitanica S.I. 18

Stand parameter		V(1) total m³	Increase %	V(15) total m³	Increase %	V(15) Thinning m³	Increase %	V(15) main m³	Increase %	DBH(40) cm
Thinning regime control		849.7		771.4		188.5		582.9		47.6
A	10	966.1	13.7	894.1	15.9	45.9	-75.6	848.2	45.5	38.3
	20	883.0	3.9	806.1	4.5	152.1	-19.3	654.0	12.2	44.7
	30	821.5	-3.3	744.1	-3.5	282.9	50.1	461.2	-20.9	48.9
	40	784.9	-7.6	709.2	-8.1	309.6	64.2	399.6	-31.4	49.1
B	10	966.8	13.8	895.0	16.0	67.0	-64.4	834.0	43.1	37.9
	20	888.2	4.5	812.3	5.3	177.3	-5.9	635.0	8.9	44.0
	30	839.6	-1.2	763.2	-1.1	332.4	76.3	430.8	-26.1	47.2
	*40	801.0	-5.7	726.1	-5.9	289.8	53.7	436.3	-25.2	45.7
C	10	969.7	14.1	898.2	16.4	75.9	-59.7	822.3	41.1	37.5
	20	899.1	5.8	824.3	6.8	211.9	12.4	612.4	5.1	43.1
	30	861.3	1.4	785.7	1.8	380.7	102.0	405.0	-30.5	45.8
	*40	816.4	-3.9	741.9	-3.8	324.5	72.1	417.4	-28.4	44.7
D	10	969.9	14.1	897.2	16.3	83.4	-55.8	813.8	39.6	37.2
	20	903.9	6.4	829.3	7.5	230.7	22.4	598.6	2.7	42.5
	*30	869.3	2.3	794.5	3.0	236.3	25.4	558.2	-4.2	43.1
	*40	836.8	-2.7	753.3	-2.3	356.9	89.3	396.4	-32.0	43.6
E	10	974.4	14.7	902.7	17.0	98.7	-47.6	804.0	37.9	37.0
	20	917.7	8.0	844.0	9.4	263.8	39.9	580.2	-0.5	41.8
	*30	878.5	3.4	804.1	4.2	257.7	36.7	546.4	-6.3	42.7
	**40	847.9	-0.2	774.9	0.4	147.9	-21.5	627.0	7.6	40.9

* Received only three thinnings.
**Received only two thinnings.

Figure 34 shows the distribution of the merchantable volume for the same
thinning regimes between thinnings and final crop. The following
observations may be noted:

1. The difference in yield between the different thinning intensi-
   ties is considerably greater than the difference between the
   different thinning levels within a given thinning intensity.
   This confirms the earlier observation that thinning intensity
   is a more critical consideration in choosing a thinning regime.
   It also confirms the observation that within the range of
   thinning intensities considered in this study, Mollers theory
   that thinning has little effect on volume yield does not hold
   for C. lusitanica in Kenya.

2. The 10% thinning intensity has the highest total and merchant-
   able volume yield up to age 40 years. Most of this yield comes
   at final harvest, with only about 5-10% (depending on thinning
   level) recovered as thinning volume. Besides the shortcomings
   already mentioned regarding this regime, it should also be
   noted on Table 49 that it also results in the lowest stand DBH,
   a result of the large number of stems at rotation age (see
   Figure 32).

3. Of the rest of the thinning intensities, 20% resulted in the
   highest percent increase in both total volume and total
   merchantable volume. The total merchantable volume increase
   ranged from 4.5% for thinning regime A:20 to 9.4% for thinning
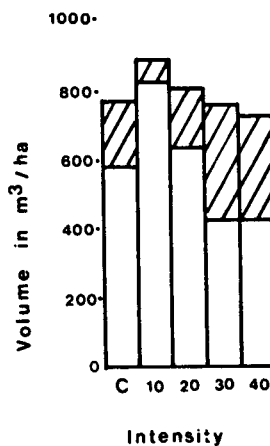   regime E:20.

FIGURE 34

DISTRIBUTION OF MERCHANTABLE VOLUME (M^3/HA) FOR DIFFERENT THINNING REGIMES FOR C. LUSITANICA S.I. 18

Thinning Volume
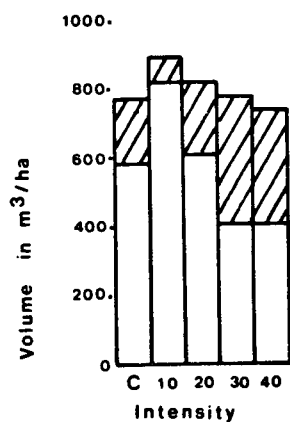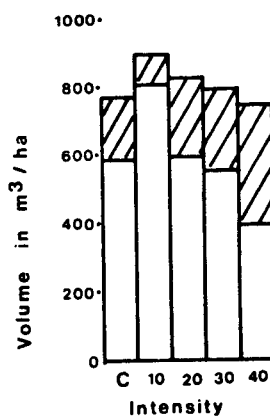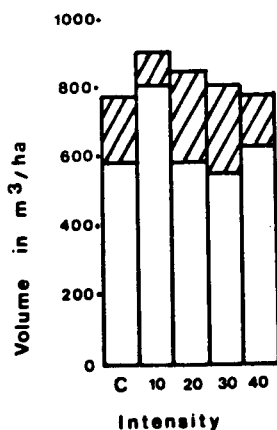Final Stand Merchantable Volume to 15 cm top dbh
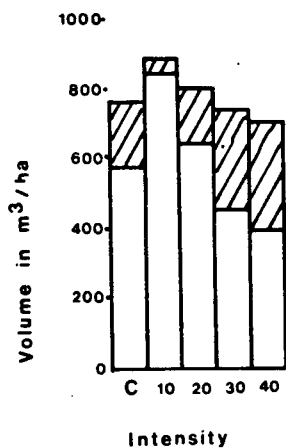
4. Within a given thinning intensity, mean stand DBH decreases
with increasing level of basal area before thinning i.e.
decreases from thinning level A to E. This is as expected
since raising the basal area level has the effect of increasing
the length of the thinning cycle and so the stand is at a
higher stocking level.

All the thinning regimes under the 20% thinning intensity could be
considered for adoption depending on the production priority. For
example if the final crop is the priority, thinning regime A:20 with
highest final crop merchantable volume increase f 12.2% and highest DBH
(among those considered) would be preferred. If on the other hand the
distribution of yield over the rotation is a priority, thinning regime
E:20 with merchantable volume of thinning increase of 39.9% would be
preferred. The optimum regime however cannot be identified without
economic inputs, as already mentioned elsewhere.

It should be noted here that the above observations apply only to
productivity on site index 18. Possibility therefore existed that the
effects of these alternative regimes on productivity may be different on
different site quality classes. This possibility is explored in the
following section, using thinning regimes under the 20% thinning
intensity only.

(c) Effects of the new thinning regimes on productivity on different
site quality classes

Table 50 gives the productivity and stand mean DBH up to age 40
years for the various site index classes for C. lusitanica under the

TABLE 50. Volume productivity (m³/ha) and stand mean DBH (cm) up to age 40 years for various thinning levels at 20% thinning intensity for various site index classes for C. lusitanica relative to the current thinning regime

Thinning regime	Site index	V(1) total m³	Increase %	V(15) total m³	Increase %	V(15) thinning m³	Increase %	V(15) main m³	Increase %	DBH(40) cm
Current regime	12	637.5		567.3		175.0		392.3		43.7
	15	749.3		674.2		180.2		494.0		46.1
	18	849.7		771.4		188.5		582.9		47.6
	21	943.0		860.6		208.1		652.5		48.3
	24	1037.7		961.8		207.3		754.5		50.1
A:20	12	671.0	5.2	604.3	6.5	122.7	-29.9	481.6	22.8	42.9
	15	781.2	4.2	710.3	5.4	134.1	-25.6	576.2	16.6	44.1
	18	883.0	3.9	806.1	4.5	152.1	-19.3	654.0	12.2	44.7
	21	977.9	3.7	891.1	3.5	166.5	-20.0	724.6	11.0	45.1
	24	1075.6	3.6	983.8	2.3	178.9	-13.7	804.9	6.7	45.9
B:20	12	675.6	6.0	610.0	7.5	150.1	-14.2	459.9	17.2	41.3
	15	787.1	5.0	717.4	6.4	165.6	-8.1	551.8	11.7	43.1
	18	888.2	4.5	812.3	5.3	177.3	-5.9	635.0	8.9	44.0
	21	984.3	4.4	898.6	4.4	194.3	-6.6	704.3	7.9	44.3
	24	1083.1	4.4	992.6	3.2	209.7	1.2	782.9	3.8	45.1

Table 50 (cont'd)

Thinning regime	Site index	V(1) total m^3	Increase %	V(15) total m^3	Increase %	V(15) thinning m^3	Increase %	V(15) main m^3	Increase %	DBH(40) cm
	12	684.0	7.3	619.2	9.1	177.3	1.3	441.9	12.6	40.9
	15	797.1	6.4	728.3	8.0	196.6	9.1	531.7	7.6	42.2
C:20	18	899.1	5.8	824.3	6.8	211.9	12.4	612.4	5.1	43.1
	21	966.7	5.7	912.3	6.0	232.1	11.5	680.2	4.2	43.5
	24	1097.1	5.7	1008.0	4.8	251.2	21.2	756.8	0.3	44.3
	12	685.7	7.6	621.0	9.5	187.7	7.2	433.3	10.4	40.5
	15	797.4	6.4	728.7	8.1	204.4	13.4	524.3	6.1	41.9
D:20	18	903.9	6.4	829.3	7.1	230.7	22.4	598.6	2.7	42.5
	21	1002.4	6.3	918.2	6.7	253.0	21.6	665.2	1.9	42.9
	24	1099.2	5.9	1010.1	5.0	263.1	26.9	747.0	-1.0	43.9
	12	698.4	9.6	634.3	11.8	218.1	24.6	416.2	6.1	39.6
	15	811.6	8.3	743.7	10.3	238.8	32.5	504.9	2.2	41.0
E:20	18	917.7	8.0	844.0	9.4	263.8	39.9	580.2	-0.5	41.8
	21	1017.5	7.9	934.3	8.6	288.7	38.7	645.6	-1.1	42.2
	24	1115.2	7.5	1027.2	6.8	302.2	45.8	725.0	-3.9	43.2

current and alternative thinning regimes at 20% thinning intensity.

Figure 35a,b and c shows the percent increase in productivity (v(1),
V(15) main stand and V(15) thinning respectively) relative to the
current thinning regime on the different site index classes for the same
thinning regimes. The following observations may be noted:

1. Figure 35a shows that all the thinning regimes resulted in an
   increase in the total merchantable volume, with highest increase
   on regime E:20. The increase decreased with increasing site
   index class ranging between 11.8% for site index class 12 to
   6.8% for site index class 24. This suggests the highest
   response to the new thinning regimes is on the poor sites,
   which confirms the suspicion expressed in Chapter 2 Section 2.3
   that the full site capacity on poor sites may not be getting
   fully utilized under the current thinning regimes in Kenya.

2. Figure 35b shows the increase in final crop merchantable volume
   decreasing with increasing site index class. This is a result
   of the greater difference in DBH between the current and
   alternative thinning regime as site index class increases (see
   Table 50). The response in this case is highest on thinning
   regime A:20 and lowest on E:20. This is as expected since, as
   pointed above, the highest basal area levels imply delaying
   thinnings and consequently lower final crop mean DBH to produce
   lower final crop merchantable volume. This effect is reversed
   for the merchantable volume of thinnings (Figure 34c) which
   shows thinning regime E:20 with highest response because of the

FIGURE 35

MERCHANTABLE VOLUME INCREASE (%) FOR DIFFERENT THINNING REGIMES (RELATIVE TO CURRENT THINNING REGIME) ON DIFFERENT SITE INDEX CLASSES
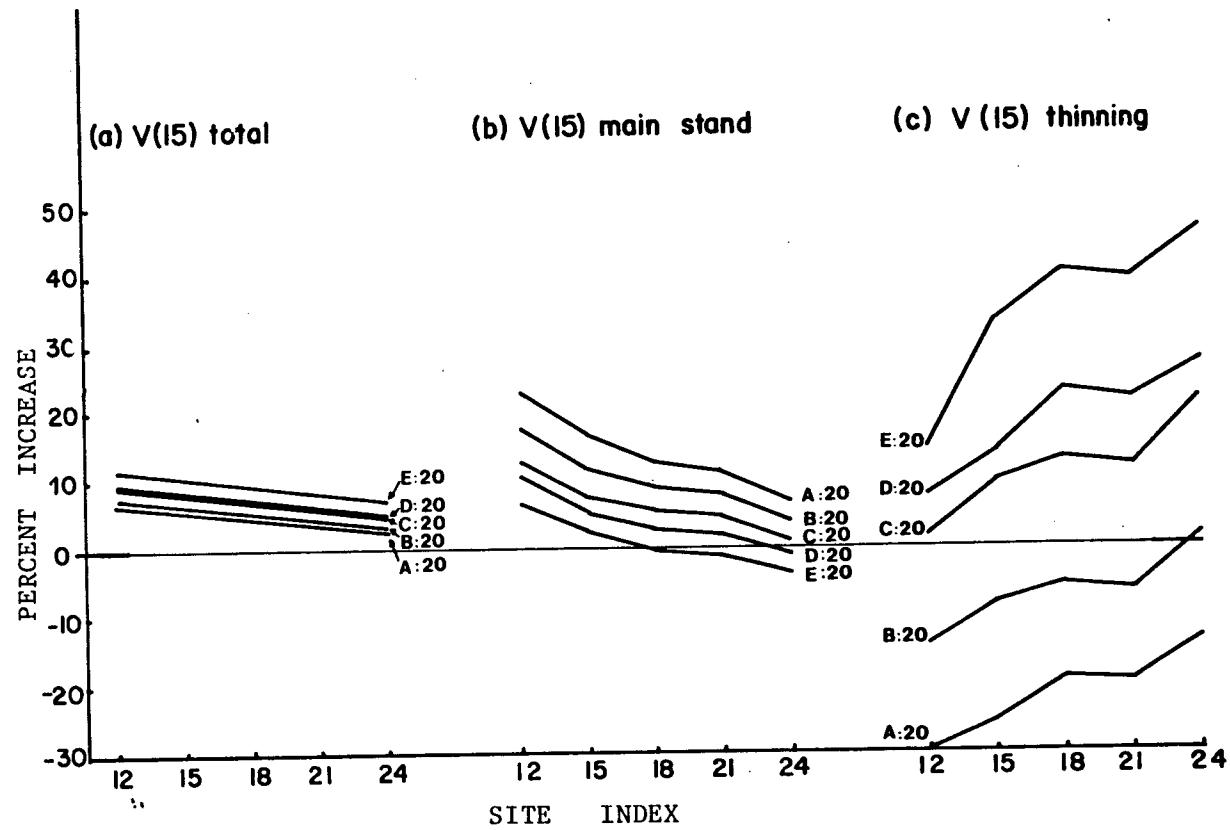
larger-sized thinnings resulting from the delay. Figure 35c also shows the response increasing with increasing site index class within each thinning regime. Thus the highest response with respect to thinning volume occurs on the best sites.

The results from this section complement the observations of the previous section that thinning model A:20 would be preferable if the final crop is the priority, while E:20 would be preferred if distribution of yield over the whole rotation is a major concern. On the average, thinning model C:20 would be a good compromise as it results in positive increase of both merchantable final crop volume and volume of thinnings (see Figure 35b and c). The response is dependent on the site quality class, the poorest sites responding best to the final crop merchantable volume (12.6% on S.I. 12 compared to almost zero on S.I. 24) while the best sites responds best to the merchantable volume of thinning (21.2% on S.I. 24 compared to 1.3% on S.I. 12).

(d) Effects of initial stocking on yield under a specific thinning regime

Under the current thinning model for C. lusitanica (and for P. patula and P. radiata as well), the emphasis is on the number of stems to be left after thinning. Increasing the initial number of stems say from 1200 to 1600 stems per hectare (sph) will have very little effect on the yield of the stand with respect to volume production. However, a slight decrease in DBH may result. For example for site index 18 under the current thinning regime, C. lusitanica DBH (to 40 years) decreased from 47.6 cm to 46.6 cm when initial number of stems were increased from

1200 to 1600 sph. This decrease is a result of the individual stems having a lower DBH at time of first thinning, an effect that is carried forward to age 40 years.

Under the new thinning model proposed for C. lusitanica in this study, the number of stems to be removed at each thinning is a function of the basal area removed in the thinning and the mean DBH of thinnings (see equation 2.28). Increasing the initial stocking, while holding both the basal area before thinning and the proportion of basal area to be removed constant results in an increase in the level of stocking to be maintained after each thinning. This inevitably results in a fixed amount of basal area being allocated among the higher number of stems and therefore a lower mean stand DBH. The net result is a decrease in DBH to age 40 years since the stand will be at a higher stocking level. This effect is demonstrated on Table 51, which shows the number of stems and basal area before and after each thinning, DBH and merchantable volume (to 15 cm top diameter) at age 40 years for C. lusitanica site index 18 under the thinning regime C:20 at the two stockings of 1200 and 1600 sph. The difference in merchantable volume to age 40 years does not appear much different under the two stockings, mainly because the decrease of 4.7 cm in DBH under the 1600 sph stocking is almost made up for by the larger number of stems removed in thinnings. However, this decrease in DBH is quite appreciable. Thus, in using this thinning model, this effect must be taken into consideration. It should be noted that this effect can be minimized by adjusting the proportion of basal area to be removed at first thinning so as to leave a reasonably lower

TABLE 51. Effect of initial stocking on yield under thinning regime
C:20 for C. lusitanica i.e. thinning based on proportion
of basal area to remove when a critical stand basal area
is equalled or exceeded.

Stocking	----- 1200 -----		----- 1600 -----	
	Before	After	Before	After
1st thinning	1200 (25.0)	850 (20.0)	1600 (25.0)	1124 (20.0)
2nd thinning	850 (35.0)	621 (28.0)	1124 (35.0)	813 (28.0)
3rd thinning	621 (45.0)	459 (36.0)	813 (45.0)	597 (36.0)
4th thinning	459 (45.0)	342 (36.0)	597 (45.0)	442 (36.0)
DBH (40*) cm	43.1		38.4	
V(15) (40*) m^3	824.3		812.6	

SI = 18.

No. in brackets are basal area in m^2.

40* = age 40 years.

number of stems. Lowering the initial number of stems would result in higher final crop DBH.

3.4 Summary on the Simulated Thinning Experiment

The preceding analysis of the productivity under the different thinning regimes served to demonstrate the ability of the yield model EXOTICS as a versatile tool for stand manipulation to study stand development under various silvicultural schedules. Thinning intensity was identified as the most critical consideration when formulating a thinning policy, with level of stocking before thinning having very little effect on total and merchantable volume yield for C. lusitanica up to age 40 years.

From a practical perspective, the analysis demonstrated that by adopting thinning regime C:20 for C. lusitanica, total merchantable thinning volume could be increased by between 1 to 21% for site index classes 12 to 24 respectively while at the same time increasing the final crop merchantable volume by between zero and 12.6% for site index classes 24 to 12 respectively. This thinning schedule is not necessarily optimal and is but one of several alternatives that can be formulated for various silvicultural and economic constraints, including product mix, minimum DBH at clearfell age and the availability of facilities to utilize thinning volume.

4. Pulpwood Production Regime for Kenya

For primary pulpwood production plantations, the basic management policy is not to thin but to manipulate the initial stand density

to maximize total volume production. P. patula is the favoured species for pulpwood plantations and so it is not surprising that for this species, data for unthinned stands covered up to age 16.5 years (see Table 25 - P. patula, rest of the country which includes Nabkoi, the zone for pulpwood production). P. patula (Nabkoi) was therefore used to study volume yield for pulpwood production under various stocking levels and establishment sites at a 15 year rotation age.

Table 52 gives the total yield at age 15 years for the various stocking levels, site index classes and establishment sites. The percentage decreases in volume under grassland establishment sites are also given. Figure 36a and b shows the CAI and MAI curves for the various stocking levels at the two establishment sites for site index class 21 while Figure 37 shows the DBH development under shamba establishment site for site index 21 (average site index class for P. patula).

As expected, Table 52 shows that volume yield increases as site index class increases and with increase in number of stems for both Shamba sites and grassland sites, with the yield of the latter establishment site being lower than the former for a given site index class. The percentage decrease on grasslands also decreases with increasing site index class and increasing stocking. This is an effect of the constant reduction in height being expressed as a percentage of an increasing height as site index class increases or as basal area increases (as a result of increase in number of stems). The important point to note however is that yield under grassland establishment sites is on the average about 16% lower than on shamba establishment sites for

TABLE 52. Total volume yield V(1) for P. patula (Nabkoi) by site index classes for various stocking levels and establishment sites up to age 15 years.

S.I.	15		18		21		24		27	
s.p.h.	S	G	S	G	S	G	S	G	S	G
1000	201.8	150.6 (25.4)	272.8	217.0 (20.4)	347.8	289.0 (16.9)	425.4	364.7 (14.3)	504.5	442.7 (12.2)
1200	233.0	176.3 (24.3)	309.5	249.5 (19.4)	388.5	326.8 (15.9)	468.6	406.1 (13.3)	548.6	486.2 (11.4)
1400	258.7	198.5 (23.3)	338.3	276.0 (18.4)	418.7	355.9 (15.0)	498.8	436.4 (12.5)	577.9	516.3 (10.6)
1600	279.4	217.1 (22.3)	360.1	297.1 (17.5)	440.4	377.9 (14.2)	519.3	457.8 (11.8)	596.6	536.4 (10.0)

No. in bracket indicate % decrease in yield under grassland relative to Shamba yield.

S = Shamba sites.

G = Grassland sites.

FIGURE 36

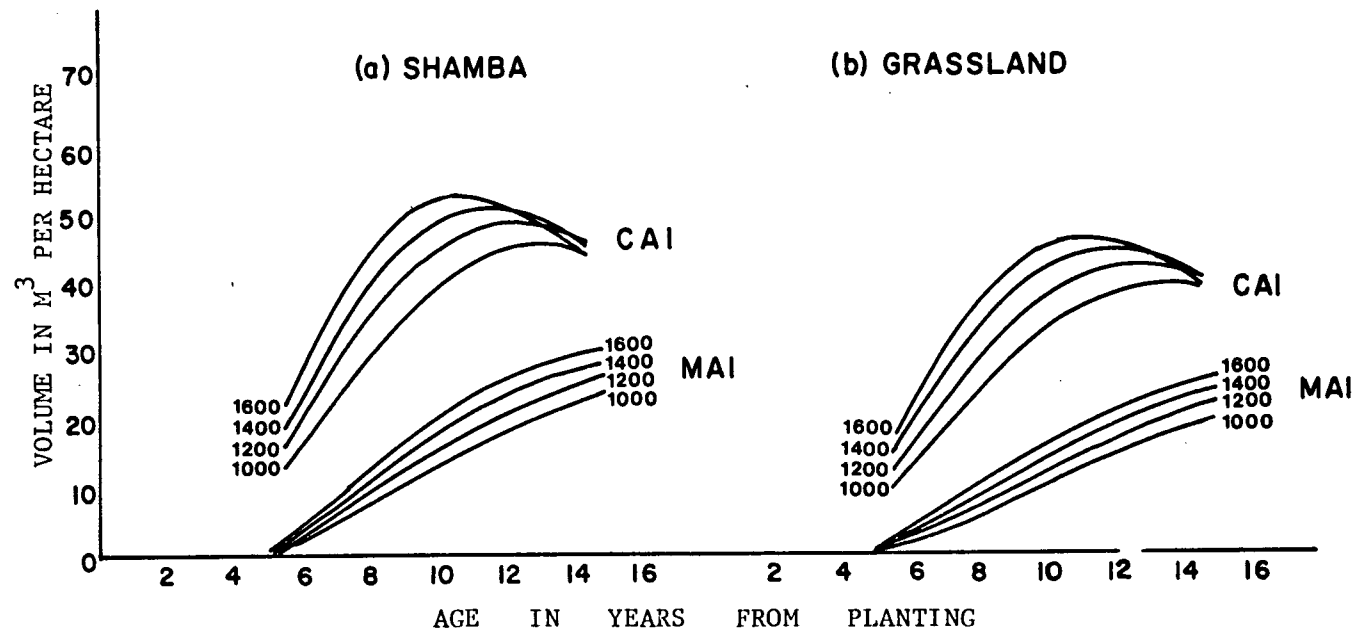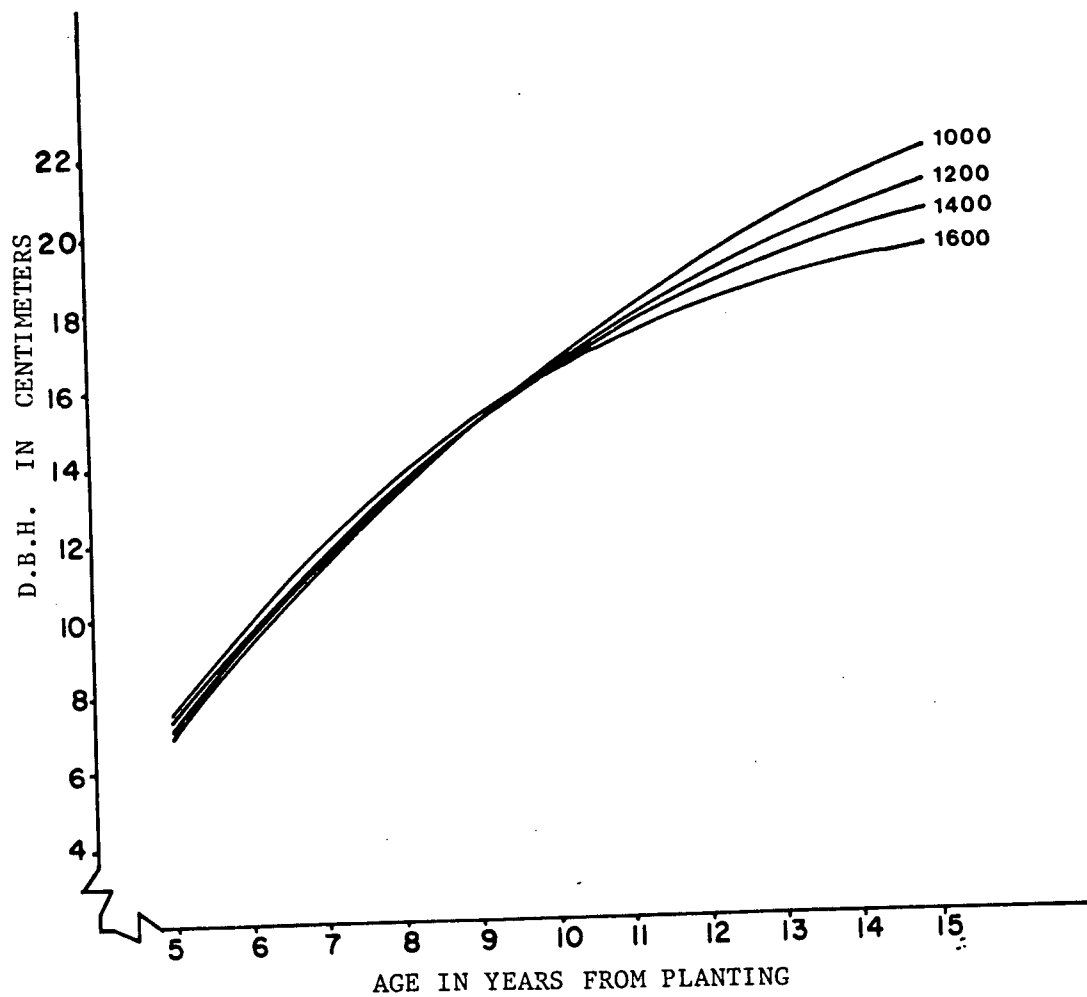C.A.I. AND M.A.I. CURVES FOR VARIOUS STOCKING LEVELS FOR <u>P. PATULA</u>
SITE INDEX 21

FIGURE 37

DIAMETER/AGE RELATIONSHIP AT VARIOUS STOCKING LEVELS FOR SITE
INDEX 21 FOR P. PATULA (NABKOI)

a stocking of 1200 sph. This is an important finding hitherto not

recognized by the forest managers in Kenya.

Figure 36a and b shows the CAI and MAI curves for higher stocking

levels being higher than for the lower levels, with those for grassland

sites being lower than for Shamba sites, again as expected. However, at

some points in time, the CAI curves for higher stocking levels are seen

to fall below those of lower curves. This indicates the effects of

competition. This is confirmed on Figure 37 which shows the DBH

development on all stocking levels being almost the same at the lower

ages (in absence of competition) but with the curves for the higher

stocking levels falling below those of lower stocking levels much

earlier: 9, 10 and 11 years for stockings 1600, 1400 and 1200 respec-

tively. This is as expected since competition is expected to set in

earlier on stands with higher stocking. It should however be noted that

the age at which CAI curves of a given stocking level falls below that

of the next lower stocking level is later than the age at which that

stockings DBH curve falls below the general growth trend curve. This is

because the CAI is not only a frunction of DBH but also of the number of

stems. Thus when DBH development starts slowing down due to competi-

tion, the CAI is maintained above that of the next lower stocking level

due to the higher number of stems until a critical DBH is reached below

which the higher number of stems do not compensate the CAI sufficiently.

The true onset of competition therefore is marked not by the age at

which CAI starts falling below that of the lower stocking level but by

the age at which DBH development starts slowing down due to competition.

The conceptual basis for the use of DBH development as a criteria for stand density control is similar to that of the maximum size-density proposed by Drew and Flewelling (1977, 1979). It therefore relies on constant stocking experiments to provide the critical size-density values at which stands should be thinned. As has just been demonstrated, EXOTICS provides a useful tool for conducting constant stocking experiments, provided data from unthinned stands is available, both for calibrating the model and for validation. As it is, the model is valid for constant stocking experiments for up to 10 years (for C. lusitanica and P. radiata) and 15 years (for P. patula) and for stocking between 1000 to 1600 sph for all species.

CHAPTER 5

SUMMARY: THEORETICAL AND PRACTICAL ASPECTS OF THIS STUDY,

SUGGESTED FUTURE DEVELOPMENTS AND APPLICATION

As stated in the introductory chapter, the main objective of this study was to advance our knowledge of the growth and yield of the three species: C. lusitanica, P. patula and P. radiata under the prevailing climatic, edaphic and silvicultural regimes in Kenya. This objective was pursued in three phases:

1. A study of the growth and yield relationship and derivation of the appropriate growth functions.

2. Construction of a growth and yield model as a means of predicting growth and yield under various physical, biological and management constraints.

3. An anlysis of the growth and yield of these species under the present and alternative silvicultural management regimes.

This chapter summarizes the accomplishments of the study, its theoretical and practical implications and suggests areas for future development and application. The summary is presented by phases as they occur in the study.

1. Growth and Yield Relationships

Different aspects of stand development were studied and relevant growth functions derived as follows:

(a) <u>Dominant height development</u>:

Stand dominant height (defined as the mean height of the 100 largest diameter tres per hectare) was studied as a function of age from planting and site index (defined as dominant height of the stand at age 15 years). Two nonlinear functions, the Chapman-Richards (equation 2.5) and the modified Weibull function (equation 2.6) were considered and the former found to be more appropriate, based on the asymptotic standard deviation. The final equation was of the form:

$$H_{dom} = b_0(1 - e^{-b_1 ASI})^{b_2}$$

where A = Age of stand from planting

SI = Site index

H_{dom} = Stand dominant height in meters

b_0, b_1 and b_2 are regression constants.

On validation, this function was accepted for <u>C. lusitanica</u> and <u>P. radiata</u>. For <u>P. patula</u>, height development was found to differ from one region to another, suggesting that height development was polymorphic. Covariance analysis for the development curves for each region indicated that for at least some of the regions, the growth curves were significantly different at the .05 significance level. This phenomenon was suspected to be due to edaphic differences in the different regions but more research is required in this regard. Data for this species was stratified by geographical regions and a linear quadratic model (equation 2.17) fitted:

$$H_{dom} = b_0 + b_1SI + b_2A + b_3A^2 + b_4ASI + b_5A^2SI$$

where variable names are as above.

The finding that height development for P. patula is poly-morphic is unique to this study. All previous studies on this species have used one set of site index curves for the whole country. The practical implication of this finding is that planta-tions may be of the same site index class at a given point in time but that the development curves may be different. Hence the need for different site index curves for different geographical regions.

For both P. patula and P. radiata, two types of establishment sites are used - Shamba and grassland. Dominant height under each type of establishment was studied, again using covariance analysis. The conclusion was that up to age 20 years, height development under grassland was significantly (at .05 level) lower than under Shamba. This finding, which hitherto had not been recognised, has two important practical significance:

(1) Where the forest manager has a choice, Shamba planting is to be preferred.

(2) Any growth and yield model for the two pine species should have establishment site as one of the input variables.

(b) Mortality, stand density development and thinning practices in Kenya:

Due to the intensive nature of stand management, including thinning, mortality was not considered in this study. Stand density

development and thinning practices were intensively studied and the
following important findings noted:

(1) Under the present silvicultural prescriptions, the stand

   density index (S%) varies between 18-30% for C. lusitanica and

   15-25% for P. patula and P. radiata.

(2) Stand density index varies for different site classes for all

   species, with wide spacing developing on poor sites and over-

   crowding on good sites.

The second observation was suspected to have an influence on
productivity. This possibility was explored further in Chapter 4.

Thinning types for Kenya, based on the classification of Eide

and Langsaeter (Braathe 1957) (based on $\frac{DBH(T)}{DBH(BT)}$ ratio) was found to

be 0.80 for P. radiata (no definite low or crown thinning), 0.85

and 0.88 for C. lusitanica and P. patula respectively, which

borders on the lower side of crown thinning.

DBH of thinning was expressed as a function of DBH before

thinning and intensity of thinning, measured as a ratio either of

the number of stems thinned over number of stems before thinning or

as basal area thinned over basal area before thinning. These

functions were necessary for the simulation of thinnings in the

latter part of the study.

(c) <u>Basal area development before first thinning:</u>

Basal area before thinning was described as a function of stand age, stand dominant height (which includes effects of site quality) and number of stems using nonlinear equation 2.29 as follows:

$$BA = b_0 \left(1 - e^{-b_1 A^{b_2} H^{b_3} N^{b_4}} \right)$$

where BA = Basal area in m^2/ha

   A = Age in years from planting

   H = Stand dominant height in meters

   N = No. stems/ha.

An unexpected finding from this study was that basal area development for <u>P. patula</u> from Kinale region differed from that for the rest of the country, a phenomenon that could not be explained from any of the biological or climatic factors available to this study. More investigation will be required to determine the under-lying factor or factors:

(d) <u>Basal area development in thinned stands:</u>

Basal area increment rather than basal area per se was studied in thinned stands as it is relatively independent of the effects of thinning. Nonlinear equation 2.31 which is an extension and more generalized form of the basal area increment equation for <u>P. radiata</u> for New Zealand (Clutter and Allison 1974) was used in this study:

$$BAI = e^{\left(b_1 A^{-b_2} - b_3 BA^{-b_4} + b_5 S \right)}$$

where A = Age in years at the end of growth period

BA = Stand basal area at beginning of growth period in m^2

per ha

S = Stand density index, calculated as:

$$S = \frac{a}{H_{dom}} \times 100$$

where $a = \sqrt{\frac{10,000}{N}}$

N = No. stems per hectare

For P. radiata, the term S% was found non-significant at .05 level. This term was also not included in the New Zealand equation which suggests that its effects on basal area increment may be species specific.

(e) Diameter distribution:

The Weibull probability density function was selected to model diameter distribution for several reasons:

(1) It is simple and mathematically handy.

(2) Its ability to assume a variety of curve shapes.

(3) On fitting this model to 58 diameter distribution histograms, only four plots (with a multimodal histogram) were rejected as not having a Weibull distribution, based on a goodness of fit test.

The cumulative form of this distribution (equation 2.35) was fitted to the data:

$$F(x) = 1 - e^{-\left(\frac{x - x_0}{b}\right)^c}$$

for $x > x_0$

$$0 \leq F(x) \leq 1$$

where x = observed diameter class

x_0 = minimum observed diameter

b and c are the Weibull constants.

The estimated parameters for each plot were then correlated with stand parameters. Final equations for the prediction of these parameters were:

$$\hat{x}_0 = b_0 + b_1 \bar{x} + b_2 \frac{1}{N}$$

$$\hat{b} = b_0 + b_1(\bar{x} - x_0) + b_2 \frac{x_0}{\bar{x}}$$

$$\hat{c} = b_0 + b_1 \frac{x_0}{\bar{x}} + b_2 \bar{x}$$

where $\bar{x}$ = Mean stand DBH in cm.

x_0 = Mininum stand DBH in cm.

b and c are predicted Weibull parameters.

(f) Stand volume calculations:

Tree volume equations for the three species discussed in this study have been in existence in Kenya since 1969. These have been the basis for the volume tables and the yield tables and so were deemed to have passed the test of time in the field. Therefore they were used in this study to derive stand volume.

In the study of the dominant height development, the procedure adopted implicitly implied that the site index curves for the three species were anamorphic. Therefore the validation procedure amounted to a test of the null hypothesis that dominant height development is anamorphic. This hypothesis was rejected for P. patula only.

Another important theoretical consideration in this study related to basal area development in thinned stands. A generally accepted supposition in forestry literature is that basal area increment is not affected by changes in stand density over a wide range of densities, a theory that has come to be known as Moller's theory (Baskerville 1965). This theory is consistent with intuition since a decrease in number of stems on a unit area basis is compensated for by an increase in diameter growth of the remaining trees and thus increment in basal area should vary very little. In this study however, basal area increment was found to be a function of the basal of the stand at the beginning of the growth period for all three species. Inasmuch as basal area is a measure of stand density, it was concluded that for these species and at the present level of stand densities, Moller's theory does not hold.

2. Construction of the Growth and Yield Model

A growth and yield model EXOTICS was constructed with the main objective being to provide a planning and silvicultural management tool that would allow manipulation of a single stand to meet forest management objectives. Written in FORTRAN IV G level which is compatible with IBM System/360 and System/370, EXOTICS is an interactive whole-stand/distance independent model designed to handle a single even-aged

monospecific stand at a time. The model also provides diameter distribution by 3 cm diameter classes which allows output of the final main stand yield by size classes. The following features make this model unique in the Kenya scene:

1. Refinement of the site index curves through inclusion of establishment site as an input variable, and the polymorphic growth pattern for P. patula. These are new findings from this study.

2. The model allows for three thinning options, all of which can be addressed in the same simulation run:

    0 = No thinning.

    1 = Thinning based on number of stems to leave after thinning when a predetermined age or stand dominant height is equalled or exceeded.

    2 = Thinning based on a proportion of basal area to remove when a predetermined basal area is equalled or exceeded.

    This feature allows for flexibility in thinning decision and for use of different options at different stages of stand development.

3. The interactive aspect of the model makes it a very handy tool for silvicultural research.

On validation, EXOTICS was found to be acceptable within the following limitations:

1. The model was found to have no apparent bias for all three species.

2. 95% confidence limits for the difference between observed and simulated volumes were

   C. lusitanica : ± 16%

   P. patula : ± 20%

   P. radiata : ± 17%

   This was a lot of improvement on VYTL-2 which had an average 95% confidence limits of ±30% (Alder 1977).

3. The model was found acceptable for error specification of between 20-25% (C. lusitanica and P. radiata) and 25-30% for P. patula unless a 1-in-20 chance has occurred. This compared well with the accuracy of some models already in operation: FOREST and SHAFT (Ek and Monserud 1979).

4. Nearly all variability for C. lusitanica and P. radiata was from the basal area component. Thus, for these two species, future refinement of the model should be directed to this component. For P. patula, total variability in the predicted volume was contributed to by dominant height and basal area components in the ratios of 1:2. For this species future refinement should be addressed to both components.

As noted earlier in the study, the validation process constituted a test of the null hypothesis that the model is an acceptable approximation of the real system. In this case the null hypothesis was accepted within the above stated limitations.

3. Silvicultural Management Models for Kenya

The current thinning policy for Kenya aimed at production of large-
sized sawlog crop in as short a rotation as possible at the expense of
some loss in total yield was discussed and found to have been overtaken
by events. A new thinning policy based on the concept of maximum volume
production was proposed as more appropriate in the presence of limited
forest land, increasing demand for wood products and increased integra-
tion of the forestry industrial sector.

Using the yield model EXOTICS, growth and yield under the current
thinning prescriptions was studied and the following main observations
noted:

1. Hart's stand density index was found to be inadequate as a
   guide to when a stand is due for thinning for C. lusitanica and
   P. patula as this led to development of different levels of
   site occupancy (with respect to basal area) on different site
   quality classes. However this index was found to be appro-
   priate for P. radiata.

2. For C. lusitanica and P. radiata, first thinning was found to
   have no apparent effect on volume CAI. Subsequent thinnings
   were found to have marked effects on CAI. For P. patula, all
   thinning had marked effects on volume CAI.

3. Consequent to 2 above, it was concluded that Moller's theory
   (Moller 1947) that thinning has no appreciable effects on total
   volume yield does not hold for these species at the present
   level of silvicultural management.

Using C. lusitanica, a thinning experiment was designed to investigate the effects of alternative thinning regimes on growth and yield. Five thinning levels (based on basal area levels before thinning) were arbitrarily selected for study. Within each level, four thinning intensities: 10, 20, 30 and 40% of the stand basal area to be removed were investigated over the range of site index classes for C. lusitanica. Several important findings were observed:

1. Within the range of thinning levels and thinning intensities considered, thinning intensity is the most important consideration with respect to volume yield. Thinning level has very little effect on both the MAI and the total yield of merchantable volume up to age 40 year.

2. The thinning intensity of 20% was the most appropriate, based on biological rotation age. Without economic data however, it was not possible to identify the optimum thinning level under this thinning intensity. Biological rotation age ranged between 22 to 28 years for site index class 18 depending on thinning level, shortest rotation associated with the lower levels of basal area before thinning.

3. By adopting thinning model C:20, it was possible to increase the total merchantable yield for C. lusitanica (up to age 40 years) by between 5 to 10% depending on the site quality class. The poorest site quality class (12) responded best to final crop merchantable volume (12.6% increase compared to 0.3% for

S.I. 24) while the best site quality class (24) responded best to merchantable volume of thinning (21.2% compared to 1.3% for S.I. 12). This model was not necessarily the optimum but one of the possible alternatives depending on both the economic and biological constraints that may be imposed.

4. Using the thinning model C:20, it was observed that increasing the initial stocking resulted in lowering the final stand DBH but had very little effect on total merchantable volume up to age 40 years.

Using P. patula (Nabkoi), yield for pulpwood production regimes under different stand densities was studied under the two establishment sites. Yield under grassland sites was found to be between 10-25% lower than that on shamba sites depending on site index class and the stocking. High stocking and better site qualities were associated with lower percentage decrease. Effects of competition on DBH and CAI development were also studied using simulated results from these pulpwood regimes.

Besides indicating possible alternative management strategies for increasing yield, results from this phase of the study served to demonstrate the use of EXOTICS as a silvicultural research tool with the silvicultural models as the framework within which the yield model must operate. The model appears to provide both realistic and reliable results with respect to stand development, thus providing the framework on which economic analysis can be based.

4. <u>Future Research and Development Arising from this Study</u>

One of the characteristics of most research undertakings is that they tend to unearth areas that require further research and/or refinement. Since most research is proscribed within specified time, financial or other limitations, it is not always possible to address these areas in the particular study. The following areas were identified or are anticipated for improvement on the present study:

1. More data are required on the mature phase of plantation development for all species and, in particular, those for <u>P. patula</u> are urgently required. Immediately, these data could be obtained from temporary sample plots but in the long run, permanent sample plot data will be more appropriate. This information is necessary to provide a basis for estimation of the asymptotes in the site index curve and basal area development functions.

2. Constant stocking experiments are required covering a wide range of densities and replicated over a wide range of site qualities. This will provide a basis for the study of effects of density and site quality on basal area development, maximum basal area and maximum size-density concept: all of which are necessary for stand density control.

3. More detailed studies on factors affecting basal area development are needed. In particular, climatic factors and effects of thinning need to be investigated for possible inclusion in the basal area increment function.

4. Refinement of the diameter distribution model through inclusion of data covering the early phase of plantation development. An alternative to the procedure used in this study may also include modeling basal area frequency by diameter classes rather than stem frequency. This requires detailed study of basal area development over the whole rotation.

5. Inclusion of an economic analysis model to provide economic analysis of any chosen silvicultural treatment. In this connection, optimization techniques such as network analysis or critical pathway analysis should be investigated to allow for optimization of silvicultural treatments for given economic and biological constraints. This requires more involved research and therefore may not be immediately tenable.

6. Future studies should be addressed to the effects of subsequent rotations on stand growth and yield.

5. Application of the Results

The results from this study will be immediately applicable in three main areas:

1. Production of up-to-date yield tables for any specified silvicultural treatment, site index and establishment site: These tables are required by the Kenya Forest Department for day-to-day planning and management purposes.

2. For research in formulation of alternative silvicultural treatments. The role of the yield model EXOTICS will be to provide quantitative information on stand response to various treatments. This application will be useful to the Forest Research Section of the Kenya Forest Department, the Kenya Agricultural Research Institute and the staff at the Forest Department of the University of Nairobi.

3. For teaching purposes at the University of Nairobi Forestry Department: The results from this study and the author's experience on growth and yield will be transferred to the University of Nairobi to the benefit of the students and other interested parties. For the first time, reliable information on stand development for the three species will be available as a basis for teaching and further research in the field of growth and yield. In addition, EXOTICS could form a basis for student's experiments, particularly in silviculture and mensuration experiments.

6. Conclusion

A growth and yield study on C. lusitanica, P. patula and P. radiata under the prevailing climatic, edaphic and silvicultural management regimes in Kenya has been presented. This study represents a significant extension of our knowledge of the development of these species, especially with respect to yield under different site qualities and silvicultural regimes, including establishment site.

A growth and yield model EXOTICS was developed as a planning and silvicultural research tool. This model represents an improvement on an earlier model VYTL-2, both in terms of precision and in flexibility in handling thinning decision models. It is therefore hoped that this model will be an invaluable aid to forest management (producing yield tables), silvicultural research (in formulating and monitoring stand response to various treatments) and as a teaching aid.

The present thinning policy is discussed and found to be inconsistent with the current conditions in the country. A new policy based on the concept of maximum volume production on available forest land is proposed. Alternative management schedules are proposed which demonstrate the possibility of increasing merchantable volume yield over the whole rotation.

Finally, areas for further research and development are discussed. It is anticipated that the present study will have a significant impact on the management of the three species.

BIBLIOGRAPHY

Adlard, P.G. 1974. Development of an empirical competition model for
    individual trees within a stand. In Fries (1974) pp. 22-37.

Alder, D. 1977. A growth and management model for coniferous
    plantations in East Africa. Oxford University. Ph.D. thesis.
    Unpublished. pp. 97.

Arney, J.D. 1972. Computer simulation of Douglas-fir tree and stand
    growth. Oregon State University, Corvallis, Oregon. Ph.D. thesis.
    pp. 69.

Bailey, R.L. and T.R. Dell. 1973. Quantifying diameter distributions
    with the Weibull function. Forest Science 19(2):97-104.

Barnes, G.H. 1962. Yield of even-aged stands of Western hemlock. USDA
    Technical Bulletin 1273. pp. 52.

Baskerville, G.L. 1965. Dry-matter production in immature balsam fir
    stands. Forest Science Monograph No. 9. pp. 42.

Beck, D.E. 1971. Polymorphic site index curves for white pine in the
    Southern Appalachians. USDA Forest Service Research Paper SE-80.
    pp. 8.

Beck, D.E. and K.B. Trousdell. 1973. Site index: Accuracy and
    Prediction. USDA Forest Service Research Paper SE-108. pp. 7.

Beekhuis, J. 1966. Prediction of yield and increment in Pinus radiata
    stands in New Zealand. Forest Research Institute, New Zealand
    Forest Service, Technical Paper No. 49. pp. 41.

Boyce, S.G. 1978. Multiple benefits from forests: a solution to a
    most puzzling problem. In Fries, Burkhart and Max (eds.), "Growth
    Models for Long Term Forecasting of Timber Yields". Virginia
    Polytechnic, Institute, and State University. Publication
    FWS-1-78:40-52. Proceedings of a meeting: pp. 40-52.

Braathe, P. 1952. Planteavstandens virkning pa bestandsutvikling og
    masseproduksjon i granskog. Summary: The effect of different
    spacing upon stand development and yield in Forests of Norway
    spruce. Medd. f. Det norske Skogforsoksvesen, XI:429-469.

Braathe, P. 1957. Thinning in even-aged stands. Faculty of Forestry,
    University of New Brunswick, Fredericton, Canada. pp. 92.

Brickell, J.E. 1968. A method for constructing site index curves from
    measurements of tree age and height - its application to inland
    Douglas-fir. USDA Forest Service Research Paper INT-47. pp. 23.

Bruce, D., D.J. DeMars and D.L. Reukema. 1977. Douglas-fir managed yield simulator-DFIT users guide. USDA Forest Service General Technical Report PNP-57. pp. 26.

Buckman, R.E. 1962. Growth and yield of red pine in Minnesota. U.S. Department of Agriculture Bulletin 1272. pp. 50.

Carmean, W.H. 1956. Suggested modifications of the standard Douglas-fir site curves for certain soils in southwestern Washington. Forest Science 2:242-250.

Chinh, L. 1980. Equality of slope test. Univ. of B.C. Computing Center SLTEST manual. pp. 10.

Chisman, H.H. and F.X. Schumacher. 1940. On the tree area ratio and certain of its applications. Journal of Forestry 38:311-317.

Clutter, J.L. 1963. Compatible growth and yield models for loblolly pine. Forest Science 9:354-371.

Clutter, J.L. and B.J. Allison. 1974. A growth and yield model for Pinus radiata in New Zealand. In Fries 1974:136-149.

Clutter, J.L. and F.A. Bennett. 1965. Diameter distribution in old-field slash pine plantations. Georgia Forest Research Council Report 13. pp. 9.

Craib, I.J. 1939. Thinning, pruning and management studies on the main exotic conifers grown in South Africa. Sci. Bull. No. 196. Dept. of Agriculture and Forestry. Government Printer, Pretoria. pp. 28.

Craib, I.J. 1947. The silviculture of exotic conifers in South Africa. British Empire Forestry Conference. Government Printer, Pretoria. pp. 35.

Cromer, D.A.N. and C.K. Pawsey. 1957. Initial spacing and growth of Pinus radiata. Forestry and Timber Bureau Australian Bulletin 36. pp. 41.

Crowe, D.N. 1967. Growth, yield and economics of Pinus patula in the Natal Midlands. Anale Universiteit Van Stellenbosch. D. Sc. Thesis. pp. 152.

Curtis, R.O. 1964. A stem analysis approach to site index curves. Forest Science 10:241-256.

Curtis, R.O. 1967. A method of estimation of gross yield of Douglas-fir. Forest Science monograph. pp. 13.

Curtis, R.O. 1970. Stand density measures: an interpretation. Forest Science 16(4):402-414.

Curtis, R.O., D.J. DeMars and F.R. Herman. 1974. Which dependent variable in site index, height-age regression? Forest Science 20(1):74-87.

De Villiers, P.C., E.K. Marsh, A.E. Sonntag, and J.H. Van Wyk. 1961. The silviculture and management of exotic conifer plantations in South Africa. Forestry in South Africa 1:13-29.

Drew, T.J. and J.W. Flewelling. 1977. Some recent Japanese theories of yield-density relationships and their application to Monterey pine plantations. Forest Science 23(4):517-534.

Drew, T.J. and J.W. Flewelling. 1979. Stand density management: an alternative approach and its application to Douglas-fir plantations. Forest Science 25(3):518-532.

Durbin, J. and G.S. Watson. 1950. Testing for serial correlation in least-squares regression. Biometrica 37:409-428.

Dyson, W.G. 1968. Studies on the identity and hybridization of Cupressus lusitanica species grown for timber in Kenya. University of East Africa. Ph.D. Thesis. Unpublished. pp. 250.

East African Meteorological Department. 1973. Summary of rainfall in Kenya. Republic of Kenya, Meteorological Department, Nairobi. pp. 40.

East African Meteorological Department. 1975. Climatological statistics for East Africa Part-1, Kenya. E.A. Meteorological Department, Nairobi. pp. 92.

Ek, A.R. and R.A. Monserud. 1974. FOREST: A computer model for simulating the growth and reproduction of mixed species forest stands. University of Wisconsin. College of Agricultural and Life Sciences. Research Report R2635. pp. 85.

Ek, A. and R.A. Monserud. 1979. Performance and comparison of stand growth models based on individual tree and diameter class growth. Canadian Journal of Forest Research 9:231-244.

Evans, J. 1975. Two rotations of Pinus patula in the Usutu Forests, Swaziland. Commonwealth Forestry Review 54-56:69-81.

F.A.O. 1947-1951. Yearbook of Forest Products Statistics. F.A.O., Rome.

F.A.O. 1974. Tree planting practices in African Savannas. Food and Agriculture Organization of the United Nations, Rome. Forestry Development Paper No. 19. pp. 185.

F.A.O. 1979. Yearbook of Forest Products. F.A.O., Rome.

Fenton, R.T. 1972. New approach in softwood silviculture. New Zealand Forest Service. Reprint No. 631. pp. 9.

Forde, B.B. 1966. Pinus radiata in California. New Zealand Journal of Forestry 2(1):20-42.

Freese, F. 1960. Testing accuracy. Forest Science 6:139-145.

Gaussen, H. 1954. Theories et classification des climats et microclimats. Proceedings of the eighth International Botanical Congress, Paris. pp. 125-130.

Gerrard, D.J. 1968. Competition quotient: an index of the competitive stress affecting individual forest trees. Ph.D. Thesis. Michigan State University.

Gibson, B.F., R.G. Orr and D.W.M. Paine. 1969. Improved forest management through operations research. Australian Forestry 33:111-118.

Gibson, B.F., R.G. Orr and D.W.M. Paine. 1970. FORSIM: a computer programme for planning management of even-aged forests. Forest Commission, Victoria, Australia. pp. 62.

Gilead, M. and N. Roseman. 1958. Climatological observational requirements in Arid Zones. In "Climatology. Reviews of Research". Paris. UNESCO. pp. 181-188.

Gould, E.M. and W.G. O'Regan. 1965. Simulation, a step toward better forest planning. Harvard Forest Papers No. 13. pp. 86.

Goulding, C.J. 1973. Simulation techniques for a stochastic model of the growth of Douglas-fir. Ph.D. Thesis, University of British Columbia, Vancouver, B.C. Unpublished. pp. 234.

Griffith, A.L. and P. Howland. 1961. Preliminary yield tables for the cypresses of the Cupressus lusitanica group. E.A.A.F.R.O. Forestry Technical Note No. 11. pp. 16.

Grut, M. 1970. Pinus radiata, growth and economics. A.A. Balkema, Cape Town. pp. 234.

Hamilton, D.A. 1980. Modelling mortality: a component of growth and yield modelling. In Brown and Clark (eds.), "Forecasting Forest Stand Dynamics". Lakehead University. pp. 82-99. Proceedings of a Workshop.

Hamilton, G.J. and J.M. Christie. 1971. Forest management tables (metric). Forestry Commission Booklet No. 34. Her Majesty's Stationery Office. pp. 201.

Harper, J.L. 1977. Population Biology of Plants. Academic Press, London, New York. San Francisco. pp. 892.

Hart, H.M.F. 1928. Stamtal en dunning. Medd. v.h. Proefstation voor het boschwezen, 21. pp. 219.

Hawley, R.C. and D.M. Smith. 1954. The practices of silviculture. John Wiley & Sons Inc., New York. pp. 525.

Hegyi, F. 1974. A simulation model for managing jack pine stands. In Fries, 1974:74-87.

Hegyi, F., J. Jelinek, and D.B. Carpenter. 1979. Site index equations and curves for the major tree species in British Columbia. Province of British Columbia, Ministry of Forests Paper. pp. 32.

Hiley, W.E. 1959. Conifers: South African Methods of Cultivation. Faber and Faber, London. pp. 123.

Hillier, F.S. and G.J. Lieberman. 1980. Introduction to operations research. Holden-Day, Inc., San Francisco. pp. 829.

Hummel, F.C. 1947. The Bowmont Norway Spruce Sample Plots (1930-45). Forestry 21:30-42.

Hummel, F.C. 1953. The definition of thinning treatments. Proceedings of the 2nd Congress of I.U.F.R.O., Rome.

Hummel, F.C. and J. Christie. 1953. Revised yield tables for conifers in Great Britain. Forest Record No. 24. pp. 23.

Husch, B., C.I. Miller and T.W. Beers. 1972. Forest Mensuration. 2nd Edition. Ronald Press Company, New York. pp. 410.

Hyink, D.M. 1980. Diameter distribution approaches to growth and yield modeling. In Brown and Clark (eds.), Proceedings of the Workshop. "Forecasting Forest Stand Dynamics". Lakehead University. pp. 138-160.

Ilvessalo, Y. 1927. Methods for preparing yield tables. Silva Fennica 5:1-30.

Johnston, D.R. 1962. Growing conifers in South Africa. Empire Forestry Review 41(1):37-43. pp. 437.

Johnston, J. 1960. Econometric Methods. 2nd Edition. McGraw-Hill Book Company, New York.

Keeve, A. 1965. Some evidence of loss of productivity with successive rotations of Pinus radiata in the South-East of South Australia. Australian Forestry 30:51-63.

Kenya Bureau of Statistics. 1982. Personal communication.

Kenya Forest Department. 1969. Treatment of Cypress plantations. Technical Order No. 42. pp. 13.

Kenya Forest Department. 1969. Treatment of Pinus radiata plantations. Technical Order No. 44. pp. 12.

Kenya Forest Department. 1981. Treatment of Pinus patula plantations. Technical Order No. 53. pp. 13.

Kenya Forest Department. 1981. Personal communication.

King, J.E. 1966. Site index curves for Douglas-fir in the Pacific Northwest. Weyerhaeuser Forest Paper No. 8. pp. 49.

Kozak, A. 1970. A simple method to test parallelism and coincidence for curvilinear, multiple linear and multiple curvilinear regressions. Paper to 3rd Conference – Advisory Group of Forest Statisticians, Section 25, IUFRO, France. pp. 18.

Kuusela, K. 1968. Growing stock management in Central Europe and in British Forestry Institutum Forestalis Fenniae Communicationes 66(2): pp. 31.

Lee, J.Y. 1967. Stand models for lodgepole pine and limits to their application. Ph.D. Thesis. University of British Columbia, Faculty of Forestry, Vancouver, B.C. pp. 320.

Lee, J.Y. 1974. Mortality of lodgepole pine in modelling. In Fries (1974):240-252.

Lemmon, P.E. and F.X. Schumacher. 1963. Theoretical growth and yield of hypothetical ponderosa pine under different thinning regimes. Forest Science 9(1):33-43.

Lenhart, J.D. and J.L. Clutter. 1971. Cubic foot yield tables for old-field loblolly pine plantations in the Georgia Piedmont. Georgia Forest Research Council Report 22(3). pp. 13.

Lewis, N.B. 1964. Observations on thinning and pruning in South Africa. Commonwealth Forestry Review 43(2):116-133.

Lowe, R.G. 1971. Some effects of stand density on the growth of individual trees of several plantation species in Nigeria. Ph.D. Thesis. University of Ibadan.

Marsh, E.K. 1957. Some preliminary results from O'Connors correlated curve trend (CCT) experiments on thinning and their practical significance. Commonwealth Forestry Conference, Australia and New Zealand. Government Printer, Pretoria. pp. 21.

Marshall, H.G.W. and D.L. Foot. 1969. Growth and silviculture of Pinus patula in Malawi. The Government Printers, Zomba, Malawi.

Mathu, W.J.K. 1977. Cuypressus lusitanica growth and yield studies in Kenya. M.Sc. Thesis. University of Dar-es-Salaam. Unpublished. pp. 115.

McArdle, R.E., W.H. Meyer and D. Bruce. 1961. The yield of Douglas-fir in the Pacific Northwest. USDA Technical Bulletin 201 (revised). pp. 74.

McGee, C.E. and L. Della-Bianca. 1967. Diameter distributions in natural yellow-poplar stands. USDA Forest Service Research Paper SE-25. pp. 7.

Meyer, H.A. 1940. A mathematical expression for height curves. Journal of Forestry 38:415-420.

Meyer, W.H. 1930. Diameter distribution series in even-aged forest stands. Yale University School of Forestry Bulletin 28. pp. 105.

Mirov, N.T. 1967. The genus Pinus. The Ronald Press Co., N.Y. pp. 602.

Mitchell, K.J. 1969. Dynamics and simulated yield of Douglas-fir. Forest Science monograph 17. pp. 39.

Mitchell, K.J. 1969a. Simulation of the growth of even-aged stands of white spruce. Yale University School of Forestry Bulletin 75. pp. 48.

Mitchell, K.J. 1980. Distance dependent individual tree stand models: concepts and applications. pp. 100-137. In Brown and Clarke (eds.), Proceedings of a Workshop. "Forecasting Forest Stand Dynamics". Lakehead University.

Moller, C.M. 1947. The effects of thinning, age, and site on foliage, increment and loss of dry matter. Journal of Forestry 45:393-404.

Moser, J.W. 1980. Historical chapters in the development of modern forest growth and yield theory. pp. 42-61. In Brown and Clarke (eds.), Proceedings of the Workshop Forecasting. "Forest Stand Dynamics". Lakehead University.

Moser, J.W., C.H. Tubbs and R.D. Jacobs. 1979. Evaluation of a growth projection system for unevenaged northern hardwoods. Journal of Forestry 77(7):421-423.

Munro, D.D. 1974. Forest growth models - a prognosis. In Fries (1974) pp. 7-21.

Munro, D.D.   1974a.   A four volume report on managed stand yield tables based on revisions to Gouldings program.   University of British Columbia, Faculty of Forestry.   Report to Productivity Committee, BCFS.

Naylor, T.H. and J.M. Finger.   1967.   Verification of computer simulation models.   Management Science 14(2):92-101.

Nelson, T.C.   1964.   Diameter distribution and growth of loblolly pine. Forest Science 10:105-115.

Newnham, R.M.   1964.   The development of a stand model for Douglas-fir. Ph.D. Thesis.   University of British Columbia, Vancouver, B.C. pp. 201.

Newnham, R.M. and H. Mucha.   1971.   A test of the effectiveness of different competition indices in predicting diameter growth in a young red pine stand.   FM1.   Ottawa, Ontario.   Internal report FMR-20 C.F.S.

Opie, J.E.   1968.   predictability of individual tree growth using various definitions of competing basal area.   Forest Science 14(3):314-323.

Opie, J.E.   1970.   STANDSIM: a general model for simulating the growth of even-aged stands.   Paper to 3rd Conference - Advisory Group of Forest Statisticians, Section 25, IUFRO, France.

Osborne, J.G. and F.X. Schumacher.   1935.   The construction of normal-yield and stand tables for even-aged timber stands.   Journal of Agricultural Research 51:547-564.

Paterson, D.N.   1967.   Volume and yield from East African softwood crops in highland sites, and a fresh approach to East African silviculture.   E.A.A.F.R.O. Forestry Technical Note No. 19.   pp. 25.

Penman, H.L.   1948.   Natural evaporation from open water, bare soil and grass.   In Proceedings of The Royal Society, Series A, 193:120-145.

Pienaar, L.V. and K.J. Turnbull.   1973.   The Chapman-Richard's generalization of Von Bertalanffy's growth model for basal area growth and yield in even-aged stands.   Forest Science 19:2-22.

Plonski, W.L.   1956.   Normal yield tables for black spruce, jack pine, aspen, white birch, tolerant hardwoods, white pine and red pine for Ontario.   Silviculture Service Bulletin No. 2.   pp. 39.

Powers, R.F.   1972.   Estimating site index of ponderosa pine in Northern California: standard curves, soil series, stem analysis.   USDA Forest Service Research Note PSW-265.   pp. 7.

Pudden, H.H.C. 1957. Exotic Forest Trees in the Kenya Highlands. Government Printers, Nairobi. pp. 34.

Rawat, A.S. and F. Franz. 1974. Detailed non-linear asymptotic regression studies on trees and stand growth with particular reference to forest yield research in Bavaria (Federal Republic of Germany) and India. In Fries (1974) pp. 180-221.

Reineke, L.H. 1933. Perfecting a stand-density index for even-aged forests. Journal of Agricultural Research 46:627-638.

Reukema, D.L. and D. Bruce. 1977. Effects of thinning on yield of Douglas-fir: concepts and some estimates obtained by simulation. USDA Forest Service General Technical Report PNW-58. pp. 36.

Richards, F.J. 1959. A flexible growth function for empirical use. Journal of Experimental Botany 10(29):290-300.

Row, C. and E. Norcross. 1978. Grouping forest growth simulation procedures into a general user-oriented system. In Fries, Burkhart and Max (eds.), "Growth models for long-term forecasting of timber yield." Virginia Polytechnic, Institute and State University. Publication FWS-1-17: 179-192. Proceedings of a meeting.

Rustagi, K.P. 1978. Predicting stand structure in even-aged stands. In Fries, Burkhart and Max (eds.), "Growth models for long-term forecasting of timber yield". Virginia Polytechnic, Institute, and State University. Publication FWS-1-78:193-208. Proceedings of a meeting.

Schreuder, H.T. and W.T. Swank. 1974. Coniferous stands characterized with the Weibull distribution. Canadian Journal of Froest Research 4:518-523.

Schumacher, F.X. 1939. A new growth curve and its application to timber-yield studies. Forestry 37:819-820.

Schumacher, F.X. and T.S. Coile. 1960. Growth and yield of natural stands of the southern pines. T.S. Coil Inc., Durham, N.C.

Scott, C.W. 1960. Pinus radiata. FAO Forestry and Forest Product Studies No. 14, FAO, Rome. pp. 328.

Seegrist, D.W. and L.A. Stanford. 1978. Statistical analysis of linear growth and yield models with correlated observations from permanent plots measured at fixed intervals. In Fries, Burkhart and Max (eds.), "Growth models for long term forecasting of timber yields", Virginia Polytechnic, Institute, and State University. Publication FWS-1-78:209-223. Proceedings of a meeting.

Smith, D.M. 1962. The practices of silviculture. 7th edition. John Wiley & Sons, N.Y. pp. 578.

Smith, J.H.G. 1966. Simulating stand growth can improve decision making. University of British Columbia, Faculty of Forestry Paper. pp. 9.

Smith, J.H.G. and D.H. Williams. 1980. A proposal to develop a comprehensive forest biomass growth model. University of British Columbia, Faculty of Forestry. Final Report to the Canadian Forest Service. pp. 47.

Spurr, S.H. 1952. Forest Inventory. Ronald Press Company, New York. pp. 476.

Spurr, S.H. 1955. Soils in relation to site-index curves. Society of American Foresters Proceedings, October 1955. pp. 80-85.

Stage, A.R. 1963. A mathematical approach to polymorphic site index curves for Grand Fir. Forest Science 9:167-180.

Stage, A.R. 1973. Prognosis model for stand development. USDA Forest Service Research Paper INT-137. pp. 32.

Sullivan, A.D. and J.L. Clutter. 1972. A simultaneous growth and yield model for Loblolly pine. Forest Science 18:76-86.

Swindel, B.F. 1968. On the estimation of forest growth parameters in a linear model with correlated errors. Ph.D. Thesis. North Carolina State University. University Microfilms.

Thornthwaite, C.W. 1948. An approach toward a rational classification of climate. Geographical Review, 38(1):55-94.

Trorey, L.G. 1932. A mathematical expression for the construction of diameter height curves based on site. Forestry Chronical 18:3-14.

Trousdell, K.B., D.E. Beck and F.T. Lloyd. 1974. Site index for Loblolly pine in the Atlantic Coastal Plain of the Carolinas and Virginia. U.S.D.A. Forest Service Research Paper SE-115. pp. 11.

U.C.L.A. California. 1981. BMDP Statistical software. pp. 725.

Van Horn, R. 1968. Validation. pp. 232-251. In T.H. Naylor (ed.), The Design of Computer Simulation Experiments, Durham, N.C. Duke University Press.

Vuokila, Y. 1965. Functions for variable density yield tables of pine based on temporary sample plots. Institutum Forestalis Fenniae Communicationes 60(2): pp. 86.

Wanene, A.G. 1975. A provisional yield table for Pinus patula grown in Kenya. Forest Department Technical Note No. 143. pp. 25.

Wanene, A.G. 1976. Variable density yield tables for Pinus radiata grown in Kenya. Forest Department Technical Note No. 145. pp. 34.

Wanene, A.G. and P. Wachiori. 1975. Variable density yield tables for the cypresses of the Cupressus lusitanica group in Kenya. Kenya Forest Department Technical Note No. 144. pp. 35.

Weibull, W. 1939. A statistical theory of the strength of material. Ing. Vestesk Akad Handl. pp. 17.

Weibull, W. 1951. A statistical distribution function of wide applicability. Journal of Applied Mechanics 18:293-296.

Weir, I.C.A. 1972. Planning of wood production using systems analysis. Appita 26(2):107-112.

Wilson, F.G. 1946. Numerical expression of stocking in terms of height. Journal of Forestry 44:756-761.

Wilson, F.G. 1979. Thinning as an orderly discipline. Journal of Forestry. August 1979:483-486.

Wimbush, S.H. 1945. The management of Cypress plantations in Kenya. Government Printers, Nairobi. pp. 31.

Wright, H.L. 1974. Introductory notes to Kenya volume tables. Unpublished.

Wright, H.L. 1977. Personal communication on tree volume equations.

Yang, R.C., A. Kozak and J.H.G. Smith. 1978. The potential of Weibull-type functions as flexible growth curves. Canadian Journal of Forest Research 8:424-431.

Yoda, K., T. Kira, H. Ogawa and K. Hozumi. 1963. Intraspecific competition among higher plants. XI. Self thinning in over-crowded pure stands under cultivated and natural conditions. Journal of Biology, Osaka City University, 14:107-129.