

GROWTH AND YIELD STUDIES OF PINUS PATULA AT MOUNT MERU
PLANTATIONS

By

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ABSTRACT

The main objective of the study was to produce a precise method for estimating growth and yield for *Pinus patula* at Mount Meru plantations. Using data from 75 temporary sample plots (with size varying from 0.04 to 0.71 ha) distributed over the whole plantation, different functions necessary for the building-up of the model were developed.

Statistical packages (QUATRO and EXCEL) were used to fit equations for site index curves, single tree volume, height /diameter, taper, Weibul diameter distribution, diameter increment, stand basal area, stand volume and mortality. These submodels were integrated into computer model in BASIC language capable of estimating yields at a particular age under different stocking levels and thinning regimes.

The stand inputs necessary to run the program are present and projection age, number of stems per ha, stand mean and standard deviation of dbh, dominant height, site, basal area per hectare and minimum top diameter.

The model gives out yearly figures per ha for number of stems, total and merchantable volume, total basal area, mean dbh, mean height, mean tree volume and thinning products. The cumulative volumes, basal areas and their increments are also produced.

Based on cumulative volume production, mean tree size, the mean annual volume increment and the current problem of funds for thinning operations, the no thinning option with a wider spacing of 3.0 x 3.0 m was recommended instead of the current option with three thinnings and an initial spacing of 2.5 x 2.5 m. Yield table printouts were produced based on this option and over all site classes found at Meru plantations. A stand volume table was also constructed for quick stand volume estimation.

DECLARATION

I, Tharcisse TWAGIRAYEZU, do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is a result of my own original work and it has never been submitted for a degree award in my other University.

Signature:



Date:

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To my beloved daughter, Mary-Gertrude.

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CHAPTER ONE

1. INTRODUCTION

Tanzania forest plantations cover 98000 ha with *Pinus patula* as a major species (Chamshama and Malimbwi, 1996). These fast growing exotic species were introduced in 1950's to supplement wood deficits (home consumption and exports) from natural forest resources which are important also for biodiversity conservation and water catchment.

The deficit in wood production from natural forests is attributed to the generally slow growth of local species and high population growth in rural areas which results in increasing pressure on forest ecosystems (deforestation in favour of agriculture).

The exotic species plantations constitute an important source of raw material for different wood-based industries in the country.

However a continuous supply of raw material from these plantations must be ensured by a proper and efficient

management. This requires a reliable growth and yield model capable of incorporating different tree sizes required by forest industries. A growth and yield model provides a robust tool for forest manager to plan and manage commercial timber. Some models have been constructed for few of these plantations (Adegbehin and Philip, 1979; Malimbwi, 1984 & 1987; Isango, 1994).

The main objective of this study is to develop a growth and yield model for *Pinus patula* at Meru plantations.

The specific objectives were as follows:

- a) to construct a variable density stand growth model (with diameter distribution) which under different stocking levels and thinning regimes, can predict total and merchantable volumes, basal area/ha and stems/ha at any given age after initial establishment over a wide range of site qualities;
- b) to develop a more efficient volume estimation system capable of estimating volume for different utilization classes;

- c) to implement (a) and (b) in a computer language (BASIC) which can be used by MERU plantations management.

The choice of variable density model was based on its flexibility by accommodating different density stands (compared to normal and empirical stand models), its easiness to construct/apply and efficient computation of product assortments.

CHAPTER TWO

2. LITERATURE REVIEW

This chapter reviews the available literature on growth models, thinning, density, mortality, site indices, diameter distribution, diameter increment and compatible taper/volume estimation system since these are the major components in growth and yield modelling.

2.1 Growth and yield models

Vanclay (1983) defines stand growth as an increase in volume per ha of a stand over a given time period. For individual tree, growth is a change of its parameters (dbh, height, volume) with time. Yield on the other hand, refers to the total volume production (standing volume + thinnings) at the end of a given period of time. A growth model is defined as a system of equations, tables or graphs used to predict growth and yield of a forest under a wider range of conditions.

Depending on its intended use and the structure of forest, growth models may range from simple statistical stand models to those of physiological process within a single tree or gap models developed by ecologists to explore ecological mechanisms and patterns of structure and functional dynamics within natural forest ecosystems (Adlard, 1995).

Taken in the context of a forest crop itself rather than the whole ecosystem, growth and yield information will help the manager to maximize or economically optimize timber production and build hypothesis for optimizing silvicultural manipulations of a forest stands (Alder 1980; Liu and Ashton, 1995; Mohren and Burkhart, 1994).

Adlard (1995) further mentions that yield models are needed for the extent of intensively managed plantations of improved genotypes grown on short rotations to ensure their sustainability and acceptability by the society.

2.1.1 Classification of growth and yield models

There is extensive nomenclature in modelling but classification by Munro (1974) and Philip (1983) are mostly used by forest growth modellers.

2.1.1.1 Munro's classification

Munro (1974) classifies forest models into two major categories: individual tree and stand models. Individual tree models simulate each individual tree as a unique entity to establish growth and mortality. Stand growth is obtained from the sum of representative individuals (Huston, 1992). They are further subdivided into distance-dependent and distance-independent models depending on the tree inter-distance parameters or competition indices. The tree distance-dependent models need information about the distance among individuals trees and location of each tree in the construction.

The basic assumption is that competition among individuals is determined by factors such inter-tree distance and size as measured by dbh. The competition indices are used as a

predictor variable in the construction of the models. They have an advantage of producing detailed information about the structure of the stand and possibilities to assess different silvicultural treatments.

The disadvantage of this type of tree model is that a significant amount of effort and expenses are required to obtain spatially referenced stand data (Wimberly and Bare, 1996). Furthermore, the construction of the model consumes large amount of computing resources in term of time and data storage space without necessarily assuring the precision of estimates.

Garcia (1994) suggests that this kind of model be used in more complex situations like uneven-aged stands of (and) mixed species, planting in rows or other patterns in agroforestry. He recommends the use of stand models in the homogenous even-aged pure stands.

Example of tree distance-dependent models are those by Burkhart et al (1984), Olga and Burhart (1992) and Wimberly and Bare (1996).

On the other hand, the tree distance-independent models utilize non spatial competition indices based on the size distribution of trees within a given area. The advantage of this model is that they do not need information about the distance among individual trees and the location of each tree in the construction although the basic simulation unit remains the individual tree.

They provide also good information about thinning and spacing. The disadvantage lies in their inability to predict reliably the single tree information for such variables as crown and bole shape or growth. These kind of models have been constructed by William (1990) and August and Burhart (1992).

The second category is stand models. The approach in stand modelling is that the primary unit is the stand. They are constructed on stand information basis and predict growth through general stand parameters such as basal area and volume per hectare. Information about individual trees is not necessary in stand models. Stand models include

functions estimating stand growth and are easier to construct and apply than single tree models.

2.1.1.2 Classification by Philip (1983)

The difference between classification by Munro and that by Philip is that the latter considers also modelling complex uneven-aged stands with many species of different ages, sizes and regeneration. Philip's classification subdivides stand models into constant stocking and variable density yield tables. Empirical yield table, not mentioned by Philip (1983), is considered by Husch *et al* (1982) as type of stand model.

In the construction of a constant yield table, the density variable is held constant by attempting to select sample plots of the same density. The density required has been called full or normal stocking describing a stand that completely occupies a given site and makes full use of its potentialities. The disadvantage of a constant yield table lies in the subjective nature of choosing the so-called fully stocked sample plots. Example of such models is that

by Klitgaard and Mikkelsen (1976). The empirical yield table is similar to normal yield table but the construction is based on sample plots of average rather than full stocking. The judgement necessary for selecting fully stocked stand is eliminated hence simplifying the collection of field data.

With variable density yield table, stand density is incorporated as an independent variable. The model has an advantage of not requiring samples to be fully or averagely stocked. It is more efficient than the other stand models since samples plots of any density can be used. Examples of this model are those constructed by Malimbwi (1984, 1987) and Isango (1994).

2.1.1.3 Other Classifications

Besides Munro's and Philip's classifications, other terminologies associated with modelling are currently used by some researchers. These terms include static, dynamic, deterministic, stochastic, compatible and process models.

A static model predicts stand or tree volume at a stated time (or age) and infers growth by subtracting the previous from the current standing volume. Example of this model was constructed by Adegbehin and Philip (1979). A dynamic model predicts volume increment directly and deduces cumulative volumes by summing growth.

A deterministic model predicts expected values under given set of conditions. They assume conditions of certainty such that for a particular input there is an uniquely determined outcome. A stochastic model incorporates uncertainty in the outcome by generating random variable from prescribed probability function, and adjusts the prediction by including the effect of this stochastic element.

For instance, a very sophisticated growth model might incorporate a variable representing the occurrence of abnormally dry periods. Then the prediction of growth and survival would be adjusted by using value for the degree of drought in a particular period drawn from the probability distribution.

A compatible growth and yield model has the properties of both dynamic and static models. Similar results are obtained by using either form of model.

Process models are based on processes that determine growth, thus provide a basis for predicting future growth under changed conditions in the ecosystem. This model is very costly and complex and remains in the domain of forest scientist rather than being used by forests managers.

2.2 Thinning

Thinning is defined as a felling done in a stand at any time between establishment and the initiation of a regeneration, cutting or clearfelling in which trees removed are of the same species as trees favoured (Evans, 1982). Thinnings are characterized by the number of stems and basal area removed per hectare or by thinning ratio (Alder, 1980).

They constitute the most silvicultural operations in the life of a stand. Through them the forester can control

density, spacing, potential volume losses due to mortality and distribution of volume by vigour. Reliable estimates of stand growth and yield are needed to determine the optimal thinning regime (Knoebel *et al*, 1986). The effects of thinning and spacing on stand parameters are similar but for thinning, they depend on its intensity. The dominant height is less affected by thinning compared to stand mean height (Alder, 1980). In spacing study with *P. patula*, Malimbwi *et al* (1992) found that:

- a) the stand mean height growth increased significantly with spacing;
- b) spacing had effect on basal area per hectare;
- c) greater volume production was associated with closer spacing;
- d) there was taper tendency with increasing spacing.

Evans (1982) states that within the limits of stand closure and maximum density, diameter growth increases with increasing growing space. With increasing thinning intensity, there is an increasing shift of the dimensions

and volumes from small and medium diameter classes to higher diameter classes.

2.3 Density

According to Avery and Burkhart (1983), stand density is a quantitative measure of a stand describing the degree of stems crowding within the stocked stand. It may be expressed by basal area per hectare, number of trees per hectare or stand density index (Husch et al, 1982).

Stand density can be controlled by choosing an initial planting stock and by thinning operation. Since density is related to thinning, its effects on other stand parameters are similar to those of thinning or spacing treatments. It is responsible of the incidence of competition-induced mortality within the stand.

2.4 Mortality

Mortality in a stand is defined as the number of trees dying periodically from natural causes such as old age,

competition, insects and diseases (Husch et al, 1982). Mortality may be neglected in intensively managed stands (Alder, 1980).

However in a forest stand, there is always a reduction of stocking over time which must be taken into account in growth modelling.

Mortality results from suppression or competition for limited source of light, water and nutrients. Irregular mortality occurs because of density independent forces including insects and pathogens attack and catastrophic factors such as wind storms, floods and fires.

Many methods have been developed to model regular (or natural) mortality while irregular mortality is usually treated as stochastic because it is very variable and difficult to predict (Liu and Ashton, 1995).

Projecting stand survival through rotation is important for estimating future yield, updating inventories and evaluating stand dynamics based on trees or stand characteristics. Most of survival models have been

developed for unthinned stand conditions where intra-specific competition is on-going. This emphasis may have happened because reliable data are abundant for these types of stands and because the dynamics of stand survival for unthinned conditions are better understood (Amateis *et al*, 1997).

Liu and Ashton (1995) pointed out that modelling mortality has greater sampling error since mortality probability over similar time period for a given tree is usually low and the number of dead trees in a forest is often relatively small.

Thinning has a direct effect on stand survival for it alters the amount and distribution of growing stock. It changes the overall vigour of the stand by removing smaller, slower growing trees (if it is from below) and provides additional room for the residual stand.

In modelling survival, Malimbwi (1987) found that the future trees number tended to decrease with spacing in an exponential decay relationship.

Amateis *et al* (1997) developed a survival model in young loblolly pine plantations: $\ln N_2 = \ln N_1 + b [A_2^{b_2} - A_1^{b_1}]$

where: N_1 and N_2 are the number of stems per hectare at age A_1 and A_2 ,
 A_1 and A_2 are stand ages at time 1 and 2,
 b_1 and b_2 are parameters to be estimated

Gadow (1983) predicted future number of stems using an exponential function:

$$N_a = N_o (\exp b_o A)$$

where: N_a = number of stems at age A ,
 N_o = number of stems at planting,
 b_o = regression constant

Although easy to model, stand mortality equations are limited by the information available on individual trees and size distribution of dying trees and can be developed using temporary sample plots data.

2.5 Site indices

According to Husch *et al* (1982), site quality for forest production can be evaluated in two general ways:

- a) by the measurement of one or more of the individual site factors that are considered closely associated with tree growth. This approach evaluates site quality in terms of the environmental causal factors themselves;
- b) by the measurement of some characteristics of trees or lesser vegetation (e.g. indicators) that are considered sensitive to site quality. The approach assesses site quality from the effects of the environment on the vegetation.

Site quality has traditionally been evaluated quantitatively by site index as a measure of the productivity potential of the stand.

Goelz and Burk (1996) consider site index as an intrinsic property of the site and that the observed height at base age is an estimate of the true site index. The site index is used as an explanatory variable in developing equations for yield prediction in forest growth modelling and is measured by average height reached by dominant and codominant trees at reference age.

A more meaningful site index requires that the degree of dominant trees remains constant over time (Magnussen and Penner, 1996). Significant variation in the degree of dominance may bring inconsistencies in the use of site index curves.

The dominant height is used as a measure of site index for it is relatively unaffected by thinning or density variations compared to stand mean height generally sensible to age, fertility and density (Alder, 1980). Dominant height (also known as top height) is defined as the mean height of 100 tallest trees per hectare.

2.5.1 Site index curves

The construction of height/age curves corresponding to different site classes constitutes the first step in the construction of a growth and yield model. Krumland and Wensel (1977) mention three uses of site index curves:

- (a) They are used to estimate site indices which in turn are used as an explanatory variable to predicts yield and growth of stand components other than height;
- (b) They are used to estimate site index to access the prediction equations developed in (a) above in application to specific stands;
- (c) They are used directly to estimate height growth of stand component for which the curve are based.

The determination of site index of any stand requires the estimation of its age and dominant height and location of

these coordinates in the site index curves. The site index is then read from the closest site index curve. The construction of site index curves requires data from permanent sample plots, stem analysis or temporary plots. Whichever source of data, the plots must be distributed throughout the forest to cover all sites and age variations.

Some foresters consider permanent sample plots as a main source of data for the construction of growth and yield model and hence the site index curves. Height/age curves also can be developed from stem analysis data for they provide a continuous record of tree height growth (Wang and Payandesh, 1993).

Stem analysis can be used for site index curves construction in the absence of permanent sample plots if the species exhibits distinct annual growth rings but where both data exist, they can be combined for more precision (Kolh *et al*, 1995).

This would especially eliminate the possibility of dominant height underestimation for younger trees by sites curves from stem analysis (Goelz and Burk, 1996) although most height - age curves are not useful for very young stands (Garcia, 1994).

Although stem analysis method assumes the maintenance of the degree of dominance by dominant trees in a stand, it has the advantage of being cheaper and shorter time consuming compared to the permanent sample plots. Many researchers raise the problems associated with upkeep, control and regular measurements of permanent sample plots (Malimbwi, 1987 ; Vanclay et al, 1995). Discipline and seriousness are required in data collection for the reliability of measurements.

According to Devan and Burkhart (1982), the desirable attributes for a site index model are as follows:

- a) it must be age-invariant (estimation and application of the model not affected by the base age used) and should show a maximum increment point (asymptote);

- b) the upper asymptote should be a function of site index with trees on better sites reaching a higher height than those on poorer sites (lower asymptote);

- c) the model must agree to have height zero at zero age and height equals site index at reference age.

2.5.2 Methods of fitting site index curves

The site index curves may be constructed by graphical or statistical (regression) methods.

2.5.2.1 Graphical methods

The graphical methods are subdivided into strip and harmonized methods. In the strip method the height/age data are plotted and two limiting curves are drawn on the lower and upper borders of the data. The space between the two limiting curves is then subdivided into strips of equal heights intercepts at each age starting from the reference

age. The main objection to this method is that the shape of the middle curves are determined by the two extreme boundaries; the best and the poorest curves, which in most cases are represented by only few data points.

In the harmonized curve method a guiding curve is drawn by hand through the approximate central trend of the height/age data to represent the average site curve. A convenient set of intervals is determined at the reference age and other curves are fitted on either side of the guiding curve by determining their positions at other ages by proportions.

This method has an advantage over strip one in that the shape of the other curves follows that of the average curve where in most cases the majority of data points lie (Malimbwi, 1987). The simplicity of graphical method is evident but presents major disadvantages of subjectivity, inability to analyze large amount data and lack of statistical validity (Alder, 1980).

2.5.2.2 Mathematical methods

Alder (1980) gives three ways of fitting site index curves by regression analysis:

- (a) proportional curves method;
- (b) minimum - maximum method;
- (c) Multiple regression technique.

In proportional method an average height/age curve is fitted by either the non linear form of the equation or its linear form in the logarithm transformation. Using the following equation of Schumacher, the application of the method can be demonstrated such that:

$$H_d = S \exp (b/A^k) \dots\dots\dots 2.5.2.2.1$$

where: H_d = dominant height in m,

S = site index in m,

b and k = constants

The equation is then transformed as follows:

$$\ln(H_d) = \ln(S) + b/A^k \dots\dots\dots 2.5.2.2.2$$

From the mean curve, other curves are constructed by

varying the value of site index S . According to Alder (1980), the value of k lies between 0.2 and 2 (assumed to be 1 for most species).

In the minimum - maximum method, the data are divided into three sets representing the mean minimum and maximum values of site potential. Then three separate regression equations are fitted using the equations. Finally the three equations are harmonized to give one single equation from which site index curves can be generated as in the proportional curve method. The harmonization technique is rather complex and may render the method unattractive. Multiple regressions involve the use of more than one predictor variable in the equation and are of two types: the constrained and the unconstrained form. The constrained form is conditioned so that the dominant height equals site index at the reference age:

$$Hd - S = b_1(A - A_r) + b_2(A - A_r)^2 \dots\dots\dots 2.5.2.2.3$$

where Hd = dominant height,

A = age corresponding to Hd ,

A_r = reference age

S = Site index

The unconstrained form does not necessarily require that Hd equals S at reference age:

$$Hd = b_0 + b_1A + b_2S + b_3AS + b_4A^2 \dots\dots\dots 2.5.2.2.4$$

The functions are only constrained after fitting. The technique of multiple regression has the advantage of freedom in the choice of models.

They have however an inconvenience of the necessity of and the false hypothesis that the predictor variable site index is a prior known with high precision (Alder, 1980). This reduces the precision of dominant height estimation.

2.6 Diameter distribution

Prediction of stand diameters distribution is important for forest managers. Stand diameter distribution models can be used to forecast the range of products expected from a stand. Tree size, particularly diameter, is often important in considering the end use of the products of trees. The knowledge of diameter distribution can help the manager to plan harvesting of resources efficiently.

Several functions used to model diameter distribution include the Log-normal, Gama, Beta, Normal and the Weibul probability density. The Weibul probability density function was found flexible, simple and associated with satisfactory results especially in young unthinned stands (Krumland and Wensel, 1979; Krug et al, 1984; Rennolls et al, 1985). In other distribution models such as Beta or Gama, the evaluation of probability function is more difficult and the parameters do not lend themselves to easy interpretation.

Rennolls et al (1985) mention that old unthinned stands tend to show a diameter distribution which is approximately normal and that the Weibul probability density would be less appropriate for a stand having received different thinning types.

2.6.1 The Weibul distribution function

According to Bailey and Dell (1973), the 2-parameters Weibul probability density function has the following form:

$$f(x) = (c/b) (x/b)^{c-1} \exp(-x/b)^c \dots\dots\dots 2.6.1.1$$

where: $f(x)$ = frequency of diameter x per ha,
 b and c = scale and shape parameters
 respectively.

The function is usually used in its integrated (cumulative) form giving the proportion of trees having dbh less than the stated one:

$$F(x) = 1 - \exp(-x/b)^c \dots\dots\dots 2.6.1.2$$

(Bailey and Dell, 1973).

The estimated number of trees with diameter less than x is obtained by multiplying $F(x)$ by the number of stems per hectare.

The use of Weibul probability function requires a set of plots data, estimation of the Weibul parameters for each plot and the fit of regression between estimated parameters and easily measured stand variables (Bailey, 1980; Mathu, 1983; Krumland and Wensel, 1979).

2.6.2 The Weibul parameters and predictor variables

Different methods exist for estimating the Weibul parameters so that the resulting distribution fits a given set of data.

Since the Weibul function is a non-linear equation, there is no means of deriving a unique estimate of the parameters and the least squares solution is obtained by iteration. Because of the flexibility of the Weibul function the choice of starting values is important in achieving meaningful results.

Among the method of estimating the Weibul parameters the maximum likelihood was found best with good statistical properties but requiring extensive iteration (Bailey and Dell, 1973).

Berger and Lawrence (1974); Krug et al (1984) estimated the initial values of the Weibul parameters using linear least squares by transforming the cumulative function:

$$\ln \ln(1/1-F) = c \ln x - c \ln b \dots \dots \dots 2.6.2.1$$

Where: F, c, b and x are as defined in section 2.6.1

The linealization procedure produced very satisfactory initial estimates of scale (b) and shape (c) parameters.

In order to use the Weibul model for the determination of diameter distribution, it is necessary to express the parameters in terms of easily measured variables in the stand. In the development of diameter distribution in unthinned stand of *Pinus radiata*, Gadow (1983) used the stem number, mean Dbh, smallest recorded diameter in the plot and standard error of mean dbh as four criteria required to calculate the Weibul parameters. Mathu (1983) used mean diameter, number of stems and minimum diameter as predictors of the parameters for conifers in Kenya.

De Castro (1985) found that both scale and shape parameters were highly correlated with mean dbh. Malimbwi (1987) found that parameter b was highly correlated with mean dbh while parameter c was correlated with the term b/sd (sd being the standard deviation of dbh in a plot).

2.7 Diameter increment

Diameter constitutes the most important tree parameter. In a stand individual tree volume and basal area increment are reduced due to competition for moisture, light and nutrients. The effect of this competition is more reflected on diameter growth because of its sensitivity to density. Diameter increment is assessed by periodic or annual radial growth by increment borer or ring width measurement on the cross section at breast height. Radial growth measurements are fundamental component of forest growth assessment and the development of silviculture guidance (Little *et al*, 1995).

According to Szeicz and Glem (1994) radial growth in any given year integrates the effects of both climate and growth over the preceding several years and is further modified by environmental factors, disturbance and site factors. He further states that radial growth response of a tree to climate varies significantly with age due to difference in genotype between the cohorts of each age class, stand dynamics and physiological changes within a

tree. Diameter growth is important in tree and stand modelling and cannot be studied outside the framework of forest growth models.

In fact the classification of forest growth models (e.g. single tree and stand models) refers to the various philosophies assumed to influence diameter growth. Single tree distance-independent models use size (diameters) and other local stand characteristics such as density, site and age. Huang and Stephen (1995) developed an age-independent diameter increment model for white spruce by incorporating tree (dbh, height) and stand (relative competitiveness, species composition, site productivity and growth interval length) variables.

Malimbwi (1987) found that the logarithm of diameter increment was best correlated with age, plot basal area, dominant height and the product of dominant height and relative basal area.

Diameter increment can be based on diameter classes where each class is incremented independently. Such models are

called diameter models. They are essentially single tree models dealing with the increment of individual group of trees of the same diameter class.

2.8 Compatible taper/volume estimation system

Accurate estimation of timber volume is the most important information required by the manager.

2.8.1 Tree volume equation

Total tree volumes are generally estimated by volume equations or tables using dbh, total tree height and a form factor incorporated because of tree taper. If needed, merchantable volume may be estimated using stem profile or taper equations (Rustagi and Loveless, 1991).

Philip (1983) gives different forms of volume equations and details for their construction. The inability of standard volume tables/equations to quantify all possible products from a stem (sawlogs, pulpwood) has increased interest to develop suitable taper tables/equations (Cao et al, 1980).

2.8.2 Taper functions

Stem taper can be defined as the rate of narrowing in diameter in relation to increase in tree height for a given tree shape (Muhairwe et al , 1994).

Understanding the variation in stem form and taper is important since trees with the same dbh and total height can have different forms and tapers hence different volumes (Muhairwe, 1994). Taper functions can be constructed using measurement of diameters taken at successive points along the stem. Figueiredo et al (1996) suggest that 10 well-distributed points along the stem are necessary to obtain a reliable taper function. If a taper line is rotated along the height axis a three dimensional solid of the stem appears. According to Philip (1983), the solid is called "solid of revolution".

The volume of the solid of revolution is obtained by summing up the volume of thin slices of known cross sectorial areas and lengths along the entire stems height. This is mathematically done by integrating the diameter "d"

with respect to "h" in the taper equation. The resulting volume equation allows the determination of volume to any part of the tree.

2.8.3 Compatible taper/volume estimation system

A taper/volume estimation system is obtained when a tree volume equation is used together with a taper equation. This means that the tree volume obtained from the integration of taper equation must be the same as the volume obtained from a normal tree volume equation for all trees of the same dbh and height. Furthermore the compatibility is obtained when the coefficients of derived volume or taper equation can be written in terms of initial taper equation or volume equation respectively.

According to Munro and Demaeschalk (1974), there are two types of compatible taper/volume estimation systems: Volume based and taper based systems. In volume based system, a tree volume equation is used to develop a taper equation.

e.g. $\text{Log}V = a + b \log D + c \log H$ 2.8.3.1

is converted into logarithmic taper equation:

$$d = b_0 + b_1 \log D + b_2 \log L + b_3 \log H \dots \dots \dots 2.8.3.2$$

where: V = total tree volume in m³,

D = Diameter at breast height in cm,

H = Total tree height in m,

d = diameter at any given length L in
meters from the tip

This type of estimation system was used by Malimbwi (1987).

In a taper-based system, a tree taper equation is constructed from independent data and then integrated to produce a tree volume equation. An example of this estimation system is by Isango (1994).

Demaeschalk and Kozak (1977) suggested that the taper-based system would be better than volume-based one provided the taper function describes precisely the stem profile. Yamatoto (1994) notes that the reliability of either estimation system depends on the precision of initial (or basic) equation and the selection of sample trees.

CHAPTER THREE

3 BACKGROUND INFORMATION OF STUDY AREA

3.1 Description of study area

(a) Location

The Meru plantations lie along middle and lower slopes of Mount Meru (Arusha Region, northern part of Tanzania). They cover 5660 ha of *Pinus patula*, *Cuppressus lusitanica* and other species representing respectively 32.5%, 55.2% and 12.3%. The plantations are managed by SUATF (SUA Training Forest) office and Mount Meru forest project.

(b) Topography

The plantations run from 1500-2500 m and the slopes range from moderate to steep exceeding 20%. They are often intersected by numerous perennial and periodic streams flowing down the mountain.

(c) Geology and Soils

The rocks are volcanic, varying from coarse vehicular grey lavas to fine grained basalts. They are overlain by drop soils originating from volcanic ash. In some exposures along the streams lines, coarser deposits with graded layers can be seen.

The soils are generally deep, black or dark brown, freely -drained silts which become "greasy" during the rain reasons, they erode easily and have very low bearing strength and provide poor traction.

During the dry season the surface layer becomes extremely powdery and dusty especially when loosened by feet, hooves or wheels. Soil fertility is very high and the sites have high values for permanent crops but soils are highly erodible when disturbed.

(d) Climate

The climate is very seasonal with a marked and consistent five months dry season from June to October followed by short and long rains. The short rains season occurs between November and December while long rains start with March and end by June. The annual rainfall averages 750 mm per year but a high figure records up to 1200 mm per year. The temperature ranges between 15°C and 28°C.

3.2. Silviculture of *Pinus patula*

(a) Nursery

SUA Training Forest and Meru Forest Project have each a central nursery with annual production capacity of 60000 and 600000 seedlings respectively. The species currently raised is *P. patula*. The production of Cypress seedlings has been stopped because of the attack by *Cnara cupressi*. It takes 8 to 10 months to raise *Pinus patula* seedlings to the required height (30 to 40 cm). Sowing seed in nursery beds is done in December/January for plantations in

November and July/August for planting in April. The soil mixture used is as follows :

- top forest soil : 5 parts
- pine litter : 2 parts
- cow manure : 2 parts
- NPK :0.025 parts

(b) Planting

Planting is done during the rainy seasons at spacing 2.5 by 2.5 m giving 1600 initial stems per ha. Survival in field is usually more than 80% if tending is done and grazing controlled. Beating up is done when survival is less than 80%.

(C) Weeding

Weeding is done by taungya farmers when tending their agricultural crops. The system continues till the canopy closure (usually 2 to 4 years after planting) rendering it impossible further growth of agricultural crops.

(d) Pruning

The first pruning is done by taungya farmers usually before the prescribed age in an attempt to extend the taungya system. The second pruning (quality pruning) is done by paid labourers. The third pruning is prescribed but currently not executed.

Table 1: Pruning schedule for *P. patula* at Mount MERU

Age (yrs)	Hd (m)	No. of stems/ha	Height (m)
4	6	all	2
7	12	1000	5
10	15	1000	8

Source: SUA (1991)

(e) Thinning

Thinning is done by paid labourers. Three thinnings are carried out. The aim is to reduce the number of stems per ha by 30% each thinning. The first thinning is mechanical where every fourth row is removed. The mechanical thinning facilitates accessibility to the compartments by skidding equipment. The second and third thinning are done according to Queensland selection method. This method is not currently applied and remains in the scope of prescription only.

Table 2: Thinning schedule for *Pinus patula* at MERU

Type of thinning	Age(years)	Left stems/ha
First thinning	10	1000-1100
Second thinning	14	600-700
Third thinning	18	400-500

Source: SUA (1991)

CHAPTER FOUR

4. METHODOLOGY DATA COLLECTION

4.1 Methodology

A stratification by age-classes followed by systematic design within compartments were used. These were adopted to cover all age-classes present in the plantation. The systematic sampling was used to facilitate the location of the plots on the map and in field. The section 4.2 gives details of data collected for different equations necessary for the construction of the model.

The choice of sample equations to test in data analysis were based on their performance in earlier researches. Statistical packages were used for regression analysis and the selection of the best equations was based on criteria such higher R^2 , unbiased pattern residuals, low standard error of estimates and residuals sum of squares.

4.2 Data collection

Data were collected from 75 circular plots located in both thinned and unthinned compartments on different sites.

In some plots, the taunya system used in planting and weeding operations significantly reduced initial stocking (1600 stems/ha). The plot size varied then from 0.040 up to 0.071 ha with a target to get at least 15 trees per plot.

The distribution of plots within age-classes was as follows:

Age-classes	number of plots
6-10	24
11-15	15
16-20	18
21-25	18
TOTAL	75

4.2.1. Data for current plot basal area and volume/ha

In each of the 75 plots, all trees were measured for dbh and bark thickness. A total of 70 trees including some site index trees were felled and sectioned for establishing volume table and height/dbh relationship.

The distribution of volume table data trees into 10 dbh classes present in the forest is as follows:

No	dbh classes	No of trees
1	13-16	7
2	16-19	11
3	19-22	12
4	22-25	10
5	25-28	7
6	28-31	7
7	31-34	4
8	34-37	8
9	37-40	2
10	40-43	2
TOTAL	-	70

4.2.2 Data for diameter distribution and mortality equations

Dbh measurements and survival counts were made in 15 unthinned plots of 10 years. They were rectangular in shape and had each 200 trees. For mortality equation, survival counts were made in unthinned plots after bringing to 200 the number of trees per plot (dead ones included).

4.2.3 Data for site index curves construction

The initial plan was to fell 4 trees for site index curves in 0.04 ha-circular plot beyond the reference age (15 years). With the problem of hung-ups and breakdown of some site trees especially in unthinned plots, only 53 site trees managed to fall properly and were crosscut at 4 meters interval and 2 meters near the tip.

The annual rings at the top of each section were counted and recorded. The felled trees were also measured for five years radial growth at 1.3 m.

Because of the problem of hung-ups and breakdown of some site trees, it became necessary to measure first their heights with a hypsometer to make sure that at least data for dominant heights are available. In the plots younger than the reference age, the dominant trees were not felled but rather measured standing for subsequent site determination of the plot.

4.2.4 Data for taper equation

Data for taper equation were collected on the same trees used for volume equation construction. Diameter measurements were taken at 8 to 10 height points regularly distributed along the stem. The range of dbh covered is then the same as volume table equation.

4.2.5. Data for radial growth and diameter increment equation and secondary data

Bark thickness and 5 years dbh radial growth measurements were made on felled trees in each plot.

Information about study area, map, compartments (area,

age,treatments) and silviculture of *Pinus patula* were collected from management offices of SUATF and Meru Project. Data about thinning intensity were not available and actual thinning fraction was obtained through stump diameters measurement in field.

CHAPTER FIVE

5. DATA ANALYSIS AND RESULTS

5.1. Site index curves

The stem analysis data were used for fitting height/age relationship. The compilation of annual rings counts and sections lengths to get height/age pairs followed steps as shown in ad-hoc form in Appendix 1. A total of 373 pairs of dominant height/age were used to fit a dominant height/age equation. Based on their performance in earlier works (Farr, 1981; Alder, 1984), the following mathematical models were tested for the selection of the average site index curve equation:

$$(i) \quad Hd = \exp(b_0 + b_1(A^{-1}) + b_2(A^{-2}) + b_3(A^{-3}) + b_4(A^{-4})) \dots 5.1.1$$

(Farr, 1981)

$$(ii) \quad Hd = b_0(1 - \exp(b_1 A))^{b_2} \dots 5.1.2$$

(Chapman-Richards)

$$(iii) \quad Hd = b_0 \exp(b_1/A^k) \dots 5.1.3$$

(Alder, 1984)

Where: Hd=dominant height in m,

A=Age in years,

b_i =regression coefficients

The resulting regression equations are presented in the following table.

Table 3: Site index curves equations

No	Equation	R2	SEE	RSS
5.1.4	$Hd = \exp(3.61 - 6.28(A_{.1}) - 4.89(A^{-2})$ $(1.06) \quad (5.83)$ $+ 30.15(A^{-3}) - 20.67(A^{-4})$ $(11.17) \quad (6.36)$	0.93	1.18	1340
5.1.5	$Hd = 25.617(1 - \exp(-0.15A))^{1.378}$ (0.03)	0.88	1.24	150
5.1.6	$Hd = 1016.9 \exp(-6.187/A^{0.18})$	0.88	1.22	1703

Based on R^2 , residuals sum of squares and better superimposing with raw data, equation 5.1.5 was found more

favourable. Looking at properties of a good site index curve as mentioned in section 2.5.1, equations 5.1.4 and 5.1.6 had not height zero at age zero and tended to overestimate heights at younger ages. Equation 5.1.5 did not have these problems and it was therefore selected for the rest of study.

The equations for site index curves were derived using proportional curves method (see section 2.5.1) and conditioning equation 5.1.5 so that dominant height equals site index at reference age. The equations for pertinent site index S (18, 21, 24, 27) were obtained as follows:

$$\ln H_d = 0.1534785 + \ln S + 1.3780 \ln(1 - \exp(-0.15A)) \dots 5.1.7$$

Figure 1 shows the site curves generated from equation 5.1.5 and 5.1.7. It can be seen that they fit well into the raw data. Figure 2 shows the final set of site index curves for *P. patula* at Mount Meru plantations.

The curves are numbered 18-27 m indicating the dominant height at reference age of 15 years.

The roman numbering gives a good reference of the position of the curves and simplifies references made to sites not exactly equal to those shown in the figure 1. Thus starting from the best to the poorest the curves have the following classes:

<u>Site class</u>	<u>Site index range</u>
I	=>25.5
II	22.5-25.49
III	19.5-22.49
IV	<19.5

Hdom (m)

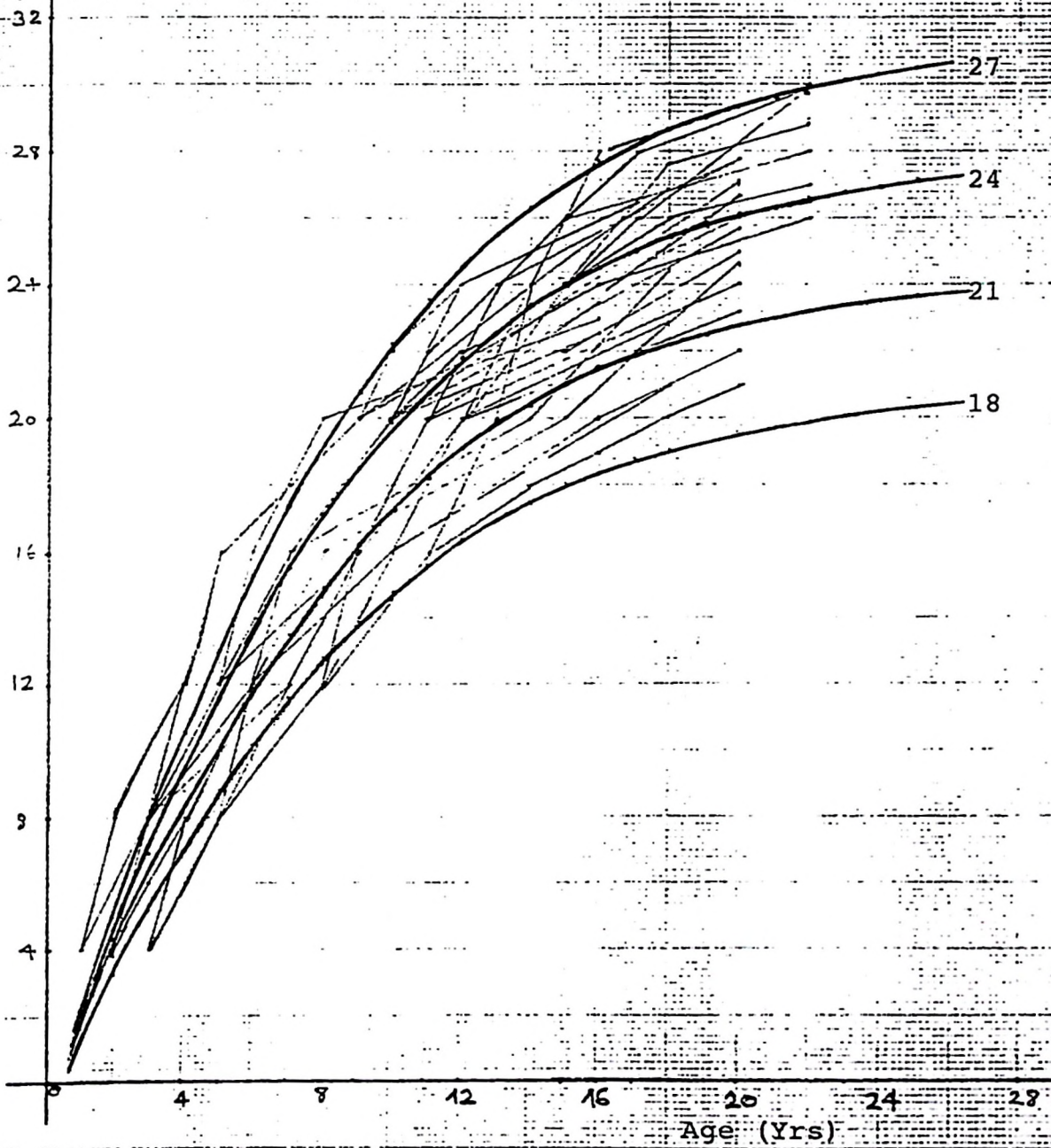


Figure 1: Site index curves with raw data

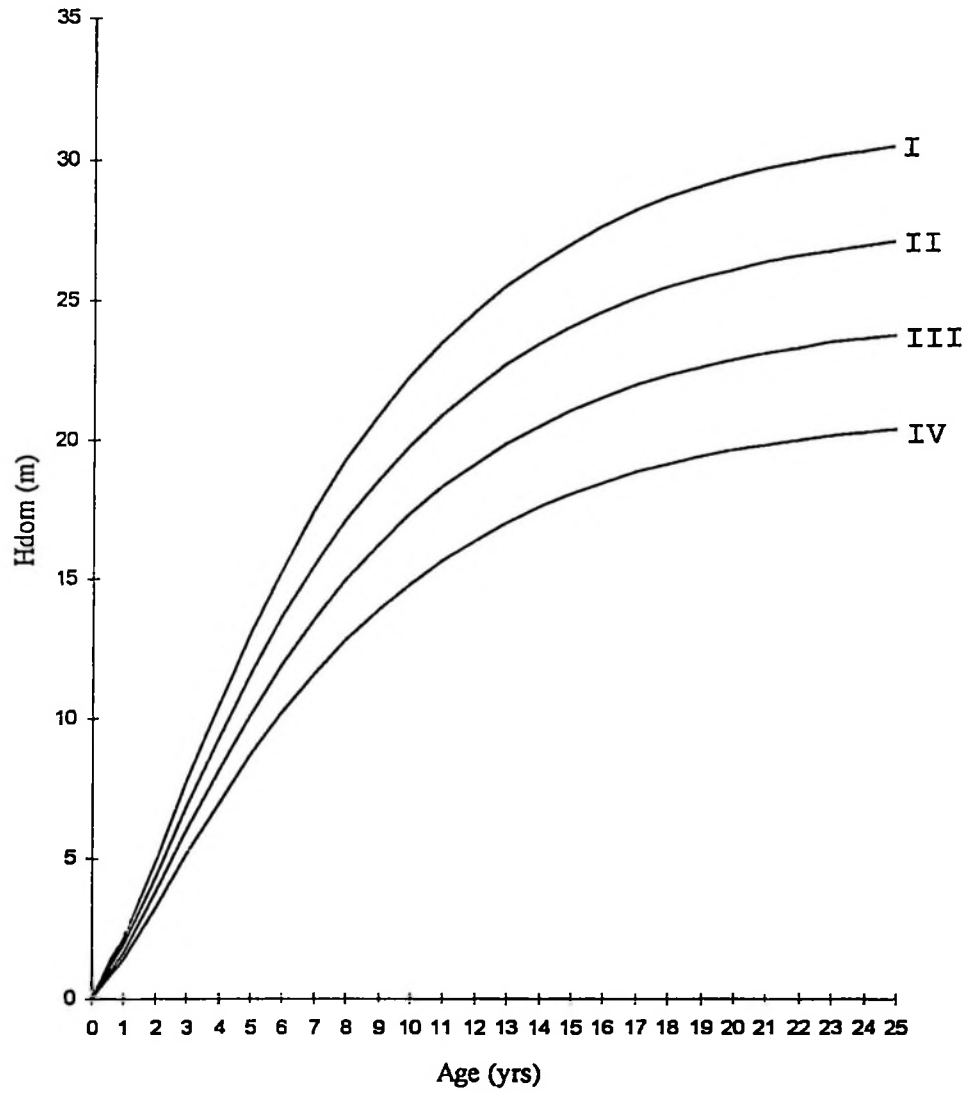


Figure 2. Site index curves for *P. patula* at Meru plantations

5.2 Construction of tree volume equation

A set of 50 trees including the site trees were used to fit volume equation. The individual tree sections volumes were calculated using Huber's formula and were summed up to give total tree volume. The following single tree volume models were fitted (Philip, 1983):

- (i) $\ln V = b_0 + b_1 \ln D + b_2 \ln H$5.2.1
- (ii) $V = b_0 + b_1 D^2 H$5.2.2
- (iii) $V = b_0 D^{2.1}$5.2.3

Where: V =Volume of a tree in m^3 ,

D =Diameter at breast height in cm,

H =Total tree height in m,

b_i = Regression coefficients

The results are shown in the following table:

Table 4: Tree volume equations

No	Equation	R ²	SEE
5.2.1	$\ln V = -10.5369 + 1.9049 \ln D + 1.2125 \ln H$ (0.0547) (0.1018)	0.99	1.0834*
5.2.2	$V = 0.014587 + 3.66E-05 D^2 H$ (7.86E-07)	0.98	0.0608
5.2.3	$\ln V = -8.32500 + 2.3782 \ln D$ (0.07465)	0.95	1.1723*

* the figures are real numbers of SEE to enable comparison with the SEE of the non logarithmic equation.

All the three equations tended to have higher coefficients of determination. The validation of the equations was done using 20 independent trees data set aside for that purpose. Appendix 2 shows the plot of measured against estimated trees volumes. The first two models show no obvious bias.

In addition to having no bias with higher R², model 5.2.2 was selected for its smaller standard error of estimate. It was adopted to calculate the volumes of individual trees and later of the plots.

5.3. Height/diameter equation

The heights of trees measured for dbh only had to be estimated in order to calculate individual trees and later plots volumes. Data for fitting height/diameter equation came from trees felled for volume table (dbh & height) and stand variables(age, Hd and number of stems per ha). A set of four models were tested for selecting an equation capable of better estimating tree height:

(i) $\log H = b_0 + b_1(A^{-1}) + b_2 \log Hd + b_3 \log N + b_4(AD)^{-1} + b_5(D^{-1}) \dots 5.3.1$

(Malimbwi, 1987)

(ii) $H = b_0 + b_1A + b_2D + b_3Hd \dots 5.3.2$

(Isango, 1994)

(iii) $\log H = b_0 + b_1(D^{-1}) + b_2(A^{-1}) + b_3(AD)^{-1} \dots 5.3.3$

(Malimbwi, 1987)

(iv) $H = b_0 + b_1D + b_3D^2 \dots 5.3.4$

(Alder, 1980)

Where: H and D are as defined in section 5.2,

Hd = plot dominant height in m,

A = plot age in years,

N = plot number of stems per ha,

b_i = regression coefficients

The resulting regression equations are presented in the following table.

Table 5: Height/ diameter equations

No	Equation	R ²	SEE
5.3.5	$\log H = 0.57 + 0.81(A^{-1}) + 0.57 \log Hd - 0.02 \log N$ $-46.12(AD)^{-1} + 2.03(D^{-1})$	0.75	1.09
	(1.31) (0.19) (0.04) (32.37) (2.73)		
5.3.6	$H = 1.553 + 1.148A + 1.116D + 0.668Hd$	0.76	1.74
	(0.10) (0.04) (0.16)		
5.3.7	$\log H = 1.41 + 2.26(D^{-1}) + 0.10(A^{-1}) - 54.96(AD)^{-1}$	0.72	1.09
5.3.8	$H = 7.36 + 0.80D - 0.08D^2$	0.64	2.10
	(0.20) (0.004)		

Equations 5.3.5 and 5.3.6 showed better fit on the basis of R^2 . The plot of residuals distribution showed however they were over estimating heights for smaller diameter trees. Equation 5.3.7 did not show such behaviour and was then selected for tree height estimation.

5.4. Taper-based volume estimation system

In this study a taper-based estimation system was constructed by first fitting a taper equation from which a tree volume equation was derived.

Hence an effort was made to develop an unbiased taper function. The system uses dbh, total height, minimum top diameter and its corresponding height from the ground as inputs to predict total or merchantable volume. The volume of wood between two stated diameters along the stem can also be given by the system.

5.4.1 Construction of a taper equation

The data for fitting a taper equation were collected on the same 50 trees as tree volume equation and a total of 515

observations were used to fit the equation. Based on their performance in earlier researches (Demaeschalk, 1972: Munro, 1974), the following two models were tested:

$$(i) \quad d = b_0 + b_1 \log D + b_2 \log h + b_3 H \dots \dots \dots 5.4.1$$

(Demaeschalk, 1972)

$$(ii) \quad (d/D)^2 = b_2 (h/H)^2 + b_1 (h/H) + b_0 \dots \dots \dots 5.4.2$$

(Munro, 1974)

Where: d = diameter at height h from the ground in m

D = diameter at breast height (dbh) in cm,

H = total tree height in m,

h = height from the ground up to diameter d in m,

b_i = regression coefficients

The resulting equations were as follows:

$$(i) \quad d = -45.813 + 34.955 \log D - 17.225 \log h + 21.861 \log H$$

(2.3979) (0.5514) (4.8104)

$R^2 = 0.73$, $SEE = 4.9775 \dots \dots \dots 5.4.3$

$$(ii) \quad (d/D)^2 = 0.047655 (h/H)^2 - 1.1198 (h/H) + 1.036751 \dots 5.4.4$$

(0.0365) (0.0374)

$R^2 = 0.96$ $SEE = 0.0675$

Equation 5.4.4 was selected based on its higher R^2 and smaller SEE and its integrated tree volume equation was validated using data from 20 independently selected trees.

5.4.2 Derivation of a taper-based tree volume equation

According to Philip (1983), the taper equation 5.4.2 can be integrated as follows:

$$\begin{aligned} V &= \pi/4 \int (d/D)^2 d(h/H) \\ &= \pi/4 \int (b_2 (h/H)^2 + b_1 (h/H) + b_0) d(h/H) \\ &= \pi/4 [b_2/3 (h/H)^3 + b_1/2 (h/H)^2 + b_0 (h/H)] D^2 h, \text{ m}^3 \dots 5.4.5 \end{aligned}$$

The term h/H varies between 0 ($h=0$) and 1 ($h=H$) and h , H & D are expressed in meters. Substituting the values of b_2 , b_1 and b_0 from the equation 5.4.4, the resulting tree equation becomes:

$$V = 0.7854 [0.01588 (h/H)^3 - 0.5599 (h/H)^2 + 1.036751 (h/H)] D^2 h \dots 5.4.6$$

The set of 20 independently selected trees data were used to validate this equation for prediction of total or merchantable volume up to 15 cm top diameter. As can be seen on Appendix 3, the plot of measured against predicted volumes shows no trend of bias. This equation was then adopted for this study.

5.4.3 Taper-based volume estimation system

Given a total tree height (H), dbh(D) and a specified top diameter (d) along the tree, the height (h) from the ground up to d can be calculated using equation 5.4.4 such that:

$$h = [-b_1H - ((b_1H)^2 - 4b_2H^2(b_0 - d^2D^{-2}))^{0.5}] / 2b_2 \dots \dots \dots 5.4.7$$

The merchantable volume up to d can then be calculated by putting this value into equation 5.4.6. The total tree volume is obtained by letting h=H and the waste by the difference between total and merchantable (pulp or sawlog) volume.

5.5 Diameter distribution

Data for fitting the cumulative probability density function of the two parameters Weibul diameter distribution were collected from 15 unthinned 200-trees plots. The survival ranged from 181 to 195. The cumulative Weibul probability density has the following form:

$$F(x_i) = \exp[-(x/b)^c] \dots \dots \dots 5.5.1$$

$$x > 0, b > 0, c > 0$$

Where: $F(x_i)$ = proportion of trees with dbh less than
diameter x_i ,

b , c = scale and shape parameters respectively

Trees in each plot were grouped into 10 diameter classes identified by their mid-diameters. The mid-diameters or class marks are just the sum of the upper and the lower limits divided by two.

The class width was the difference between the maximum and the minimum recorded dbh (in the concerned plot) divided by 10. The observed cumulative frequency (no) were obtained by compilation of data from field.

For a given plot and diameter class i the observed cumulative proportion of trees with dbh less than mid-class x_i was calculated as follows:

$$F(x_i) = \text{no}/N \dots \dots \dots 5.5.2$$

Where: $F(x_i)$ = observed cumulative proportion of trees
with dbh less than x_i

x_i = class mid-diameter in cm,

no=observed number of trees with dbh less
than x_i ,

N= number of stems for the concerned plot

5.5.1 Fitting cumulative function to each plot

Using values of $F(x_i)$ from equation 5.5.2 the Weibul cumulative density function (cdf) was fitted to each plot data for estimating the parameters b and c . The function was linearized by taking successive logarithm (Berger and Lawrence, 1974) as follows:

$$\text{given } F=1-\exp(-x/b)^c$$

$$\ln(1-F) = -(x/b)^c$$

$$\ln(1/1-F) = (x/b)^c$$

$$\ln \ln(1/1-F) = c \ln x - c \ln b \dots \dots \dots 5.5.1.1$$

Equation 5.5.1.1 is a linear equation with a constant $-c \ln b$ and a regression coefficient c. If $a=c \ln b$ then $\ln b=a/c$ hence $b=\exp(a/c)$. According to Rennols et al (1985), the value of c can be used to determine the skewness of the distribution as follows:

If $1 < c < 3.6$ then distribution right-skewed,

If $c > 3.6$ then distribution left-skewed,

If $c = 3.6$ then distribution normal

The different values of parameters b and c for each plot are shown in Table 6.

The calculated values for parameter c showed left-skewed distribution for all plots.

Table 6 :Weibul / other plots parameters

Pno	Dmin	Dmax	Dmean	Spp	b	c	sd
1	10.0	25.0	16.84	183	17.2148	5.7420	3.395
2	7.5	24.0	15.28	181	15.5165	5.0671	3.611
3	10.0	25.0	17.25	187	17.7165	6.0963	3.538
4	11.5	25.0	17.75	187	18.1200	6.9343	3.299
5	11.0	25.0	17.49	193	17.9847	6.0665	3.589
6	11.0	25.0	17.47	194	17.9678	6.0556	3.513
7	9.0	24.0	15.56	184	16.3000	6.5224	3.014
8	8.0	22.5	15.01	195	15.4268	6.2253	3.178
9	9.0	24.0	14.91	190	15.5435	5.5136	2.978
10	9.5	21.0	14.65	192	14.9142	6.6261	2.763
11	8.0	21.5	15.00	186	15.1503	6.0770	3.115
12	7.0	22.5	15.30	191	15.3398	5.4331	3.461
13	10.0	22.0	15.68	182	16.0612	6.9009	2.642
14	10.5	24.0	15.75	191	16.4155	5.9799	3.153
15	10.5	23.0	16.70	190	16.9268	6.5095	3.219

Pno = plot number, Dmin = minimum plot dbh, Dmean
= mean dbh

Dmax = maximum plot dbh, Sd= standard deviation of
dbh in plot

Spp= number of stems per plot

5.5.2 Test of goodness of fit of Weibul cdf

The values of b and c for each plot were substituted into equation 5.5.1 to calculate the expected cumulative probabilities. For a given diameter class and plot, the expected cumulative frequency (ne) in trees number was obtained by multiplying the corresponding cumulative probability with the number of stems in the plot.

The calculated χ^2 was given by the following relationship:

$$\chi^2 = \text{sum}[(\text{no}-\text{ne})^2/\text{ne}]$$

Where: χ^2 = calculated value of χ^2 for the plot

no= observed number of trees with dbh

less than the mid-diameter of class i,

ne=expected number of trees with dbh less

than the mid-diameter of class i,

sum= summation for all diameter classes for

the plot

The calculated χ^2 was then compared with the tabulated one with seven degrees of freedom at 5% level of probability. For a given plot a good fit was showed by the calculated χ^2 being less than the tabulated one. As seen in Table 6, only two plots rejected the hypothesis of goodness of fit.

Then in general the Weibul cumulative probability function describes well the diameter distribution of *Pinus patula* at Mount Meru.

Table 7: Goodness of fit of Weibul cdf to plots

plot no	calculated χ^2	tabulated χ^2	fit
1	1.878	14.067	good
2	4.163	14.067	good
3	5.579	14.067	good
4	7.418	14.067	good
5	4.083	14.067	good
6	2.883	14.067	good
7	20.380	14.067	--
8	8.482	14.067	good
9	6.176	14.067	good
10	10.776	14.067	good
11	5.919	14.067	good
12	5.861	14.067	good
13	2.644	14.067	good
14	20.956	14.067	--
15	8.249	14.067	good

5.5.3 The Weibul parameter estimators

To enable the use of Weibul function in the determination of diameter distribution in different stands, it is necessary to define the Weibul parameters in terms of easily measured stand parameters. The following equations were tried to find the correlation between stand and Weibul parameters:

$$(i) b = b_0 + b_1 D \dots \dots \dots 5.5.2.1$$

(Malimbwi, 1987)

$$(ii) b = b_0 + b_1 (D - d_0) \dots \dots \dots 5.5.2.2$$

(De Castro, 1985)

$$(iii) c = c_0 + c_1 (b/sd) \dots \dots \dots 5.5.2.3$$

(Malimbwi, 1987)

$$(iv) c = c_0 + c_1 (D^{0.5}) + c_2 (D) \dots \dots \dots 5.5.2.4$$

(De Castro, 1985)

Where: D=plot mean dbh, d_0 =minimum plot
recorded dbh,

sd= standard deviation of dbh,

b , c =scale and shape parameters,

b_i and c_i are regression coefficients

The resulting regression equations are presented in the following table.

Table 8: Weibul parameter estimators equations

No	Equation	R ²	SEE
5.5.2.5	$b = 1.030D - 0.085$ (0.049)	0.97	0.20
5.5.2.6	$b = 16.939 - 0.076(D - do)$ (0.361)	0.30	1.18
5.5.2.7	$c = 0.851 + 1.030(b/sd)$ (0.191)	0.70	0.31
5.5.2.8	$c = 113.663 - 54.420(D^{0.5}) + 6.876(D)$ (102.321) (12.712)	0.10	0.55

The results showed that the scale parameter b is more correlated to the mean dbh than D-do. On the other hand the shape parameter c is better predicted by the term b/sd than

the mean dbh and its square root. Therefore, at Mount Meru plantations, the diameter distribution in *Pinus patula* stands is well estimated by the stand mean diameter and the standard deviation of dbh. Equation 5.5.1 uses values of b and c from equations 5.5.2.5 and 5.5.2.7 in estimating cumulative frequencies and mid-diameters of diameter classes.

5.6. Diameter increment equation

Diameter increment equation was fitted using data from measurement of five-years dbh radial growth. The diameter at the beginning of the period was calculated using the following equation:

$$D_1 = D_2(1-2R/(D_2-2B)) \dots\dots\dots 5.6.1$$

Where: D_1 & D_2 are respectively dbh at the beginning and the end of the growth period in cm,

R = radial growth in cm,

B = bark thickness in cm

The annual diameter increment is the difference between D_2 and D_1 divided by the growth period:

$$\text{inc D} = (D_2 - D_1) / (A_2 - A_1) \dots\dots\dots 5.6.2$$

Where inc D is annual diameter increment in cm/year.
The two following equations was tried to fit diameter increment equation :

$$(i) \ln (\text{incD}) = \ln b_0 + b_1 (D^{-1}) \dots\dots\dots 5.6.3$$

(Husch, 1982)

$$(ii) \ln (\text{incD}) = b_0 + b_1 A + b_2 B + b_3 \text{HR} \dots\dots\dots 5.6.4$$

(Malimbwi, 1987)

Where: incD=annual diameter increment in cm/yr,

B=plot basal area in m^2/ha ,

A=plot age in years,

HR= $Hd \cdot dbh / \text{Max plot dbh}$

b_i =regression coefficients

The resulting equations were as follows:

$$(i) \ln (\text{incD}) = 0.3713 - 12.3177 (D^{-1}) \dots\dots\dots 5.6.5$$

(4.2370)

$R^2 = 0.14$, SEE=0.2629

$$(ii) \ln(\text{incD}) = 0.8441 - 2.6E-05A - 0.0277B + 0.00126HR \dots 5.6.6$$

$$(0.0104) \quad (0.0034) \quad (0.0069)$$

$$R^2 = 0.64, \quad \text{SEE} = 0.1733$$

It appeared that the annual diameter increment was better predicted by the variables age, basal area and the term HR than the dbh alone. Hence equation 5.6.6 was selected for use in this study.

5.7. Stand basal area equation

The basal area per ha for each plot was obtained by dividing the sum of individual trees basal areas by the plot size. The following equations were tested to relate the basal area per ha with some of other stand parameters (Isango, 1994):

$$(i) \ln Ba = b_0 + b_1 Hd + b_2 N \dots 5.7.1$$

$$(ii) Ba = b_0 + b_1 Hd + b_2 N \dots 5.7.2$$

$$(iii) \ln Ba = b_0 + b_1 \ln Hd + b_2 \ln A \dots 5.7.3$$

Where: Ba = stand basal area per ha in m²/ha,

Hd = dominant height in m,

N=number of stems per ha,

A=stand age in years,

b_i =regression coefficients

The resulting equations are presented in the following table.

Table 9: Stand basal area equations

No	Equation	R ²	SEE
5.7.4	$\ln Ba = 1.007 + 0.069Hd + 0.0012N$ (0.004) (0.0001)	0.84	1.24
5.7.5	$Ba = -20.687 + 1.577Hd + 0.025N$ (0.104) (0.003)	0.82	5.43
5.7.6	$\ln Ba = 0.192 + 1.558 \ln Hd - 0.571 \ln A$ (0.104) (0.196)	0.69	1.36

The selection of equation 5.7.4 was based on its higher R², lower SEE and lack of bias in residuals distribution (see Appendix 4).

5.8. Stand volume equation

The heights and volumes of individual trees in a plot were obtained by using height equation (5.3.7) and then tree volume equation (5.2.2). The plot volume per ha was obtained by dividing the sum of trees volumes by plot size. The following models were tried in order to determine relationship between stand volume per ha with some of other stand parameters:

$$(i) \ln V = b_0 + b_1 \ln Ba + b_2 A^{-1} + b_3 \ln Hd \dots \dots \dots 5.8.1$$

(Isango, 1994)

$$(ii) \log V = b_0 + b_1 \log Ba + b_2 \log Hd \dots \dots \dots 5.8.2$$

(Wensel and Krumland, 1983)

$$(iii) \log V = b_0 + b_1 \log A + b_2 \log N + b_3 \log Hd \dots \dots \dots 5.8.3$$

(Isango, 1994)

Where: A = stand age in years,

V = stand volume per ha in m³/ha,

N = number of stems per ha,

Ba = stand basal area per ha ,

Hd = stand dominant height in m ,

b_i = regression coefficients

The results of regression analysis are presented in the following table.

Table 10: Stand volume equations

No	Equation	R ²	SEE
5.8.4	$\ln V = 2.209 + 2.990 \ln B - 3.445 A^{-1} + 0.143 \ln Hd$ (0.064) (1.705) (0.148)	0.96	0.14
5.8.5	$\log V = 0.595 + 0.937 \log Ba + 0.401 \log Hd$ (0.060) (0.078)	0.96	0.06
5.8.6	$\log V = -0.689 + 0.285 \log A + 0.730 \log N$ $+ 1.353 \log Hd$ (0.172) (0.975) (0.162)	0.88	0.10

Equation 5.8.5 was selected based on its higher R², lower standard error of estimate and unbiased pattern of residuals. (see Appendix 5). The equation was used to construct a stand volume table for quick stand volume estimation (see Appendix 7).

5.9. Survival equation

The following equations were tried to get a better equation capable of predicting the number of trees surviving at a given age in a given stand:

$$(i) \ln N = b_1 + b_2 A \dots \dots \dots 5.9.1$$

(Isango, 1994)

$$(ii) \ln N = \ln b_0 + (b_1 E + b_2 H_d) \dots \dots \dots 5.9.2$$

(Malimbwi, 1987)

Where: N = number of trees surviving at age A ,

E = current spacing (= $\sqrt{10000/\text{stems per ha}}$),

A and H_d are as defined earlier,

b_i = regression coefficients

The resulting equations were as follows:

$$(i) \ln N = 6.5901 + 0.0173A \dots \dots \dots 5.9.3$$

(0.01012) $R^2 = 0.10$, $SEE = 0.1510$

$$(ii) \ln N = 8.3428 + (0.0115H_d - 0.4863E) \dots \dots \dots 5.9.4$$

(0.0028) (0.05203) $R^2 = 0.80$

$SEE = 0.074$

The equation 5.9.3 gave very poor fit meaning that the variable age alone does not predict well the future number of trees. However, the dominant height and the current spacing predict better the future number of trees at time defined by dominant height H_d . Hence equation 5.9.4 was selected and transformed into its original form for use in this study.

5.10.Thinnings

Information about thinning removals was not available at Meru plantations management office. An attempt was made therefore to estimate thinning fraction by counting and measuring diameters of stumps in different thinned plots. The percentage of trees thinned was found to be about 32.7%. The prescribed thinning removal percentages for softwood plantations in Tanzania are 21% for first and 33.3% for second and third thinning (Malimbwi, 1987).

The estimated figure (32.7%) is not significantly different from the ones prescribed for second and third thinning. It is however higher than the prescribed one for the first

thinning. According to the management office (Personal communication, 1997), this may be explained by the combination of the first and the second thinning since stands were overdue for the first thinning.

Using data of stumps and breast height diameters of felled trees for volume table, the stump diameter/dbh relationship was established as follows:

$$(i) \text{ dbh} = -3.9288 + 0.9465(\text{stump dia}) \dots\dots\dots 5.10.1$$

$$(0.0395) \quad R^2 = 0.92, \quad \text{SEE} = 2.1390$$

Equation 5.10.1 was then used to calculate the dbh of thinned trees, their basal areas and hence volumes.

5.10.1 Systematic thinning

Since the model is a stand model with diameter distribution, for each diameter class i , the number of trees removed in mechanical thinning was calculated as follows:

$$(ii) N_i = (Sph * FR1) / 10 \dots \dots \dots 5.10.2$$

Where : Sph =stems per ha,

N_i =number of stems thinned in
diameter class i ,

FR1=thinning fraction in decimal number

The mean diameter of thinned trees being the same as the mid -class diameter (d_i), the basal area removed in that particular class is simply given by the following equation:

$$(iii) Ba_i = 0.00007854 * (N_i * d_i^2) \dots \dots \dots 5.10.3$$

The summation for all 10 diameter classes from equations 5.10.2 and 5.9.3 gives respectively number of trees and basal area removal per ha. The total volume follows the same procedure but uses the height equation to determine height for (d_i) before calculating volume.

5.10.2 Selective thinning from below

While the number of trees thinned mechanically is the same for all diameter classes, in selective thinning this number

varies from class to class. Since it is from below, we thin the weak, dying and malformed trees out to leave space for better trees. Therefore, the number of trees thinned tend to decrease with increasing tree size. In modelling, the prediction of the number of thinned trees in each diameter class was based on the simulation technique by Alder (1977).

Malimbwi (1987) used this method and gives good details of it. It is based on a power function of percentiles of the cumulative diameter distribution before thinning and uses thinning intensity:

$$Pa_i = P_i^{1/L} \dots \dots \dots 5.10.2.1$$

Where: Pa_i =cumulative probability for trees left after thinning (up to diameter class i),
 P_i = the before thinning cumulative probability up to diameter class i ,
 L = total proportion of trees left (=1-proportion of thinned trees)

Alder's technique allows computation of new diameter vectors (d_j) given the before thinning diameter classes and their mid-points (d_i) and the percentage of trees left (L) as follows:

$$d_j = d_i + d \dots \dots \dots 5.10.2.2$$

With $d = (d_{i+1} - d_i) (P_i - Pa_i) / (Pa_{i+1} - Pa_i)$ and d_i , P_i and Pa_i are as defined above.

New diameter classes frequencies (na) are computed based on the after thinning cumulative probabilities Pa as follows:

$$na_j = Na (Pa_j - Pa_{j-1}) \dots \dots \dots 5.10.2.3$$

Where na_j = frequency for diameter class with an after mid-point d_j .

$$Na = \text{stocking after thinning} (=L \cdot Nb)$$

The difference between the before thinning and the after thinning frequencies gives the number of trees thinned in the corresponding diameter class.

CHAPTER SIX

6. CONSTRUCTION OF THE YIELD MODEL

A growth and yield model was constructed by integrating into BASIC language different equations developed in section 5.1. Those equations were:

- (i) Site index curves equation
- (ii) Height/diameter equation
- (iii) Taper-based tree volume equation
- (iv) Diameter distribution
- (v) Diameter increment
- (vi) Stand basal area equation
- (vii) Survival equation

Thinnings were integrated in modelling using methods described under section 5.10. The program produced is made of main part and different subroutines responsible for specific tasks. Some subroutines call for others in performing their functions.

6.1. Main part of the Model

The main part of the program gives access to subroutines ,calculates initial basal area (if zero) and diameter distribution. It also gives options to immediately clearfell or to grow the stand and whether the crop is to be thinned or not. The output is yield predictions as shown in Appendix 6 and 8 for all site classes. The input to the main part are compartment number (CPT), present age (AGE), projection age (PA), present number of stems per ha (SPH), mean dbh (Dmean), standard deviation of dbh (SD), present basal area per ha (BA), dominant height (Hd), site index (SITE) and minimum top diameter (MD) for merchantable volume.

6.2. Subroutines

6.2.1. Subroutine increment

This subroutine is responsible for incrementing the diameter classes using diameter increment equation, increasing age by 1 and hence recalculates dominant height

and basal area, calculating survival and volume (using subroutine volume).

6.2.2. Subroutine selective thinning

With the methods described under section 5.10 this subroutine calculates size and frequencies of thinned trees in each diameter class, volume removed (using subroutine thinvolume), new diameter classes and volume after thinning (using subroutine volume).

6.2.3. Subroutine mechanical thinning and thinning type selection

The subroutine mechanical thinning is another thinning type where all diameter classes have the same number of thinned trees (stocking times thinning fraction divided by 10). Subroutine thinning type selection gives choice between mechanical or selective thinning.

6.2.4. Subroutine volume and subroutine thinvolume

The subroutine volume uses the taper-based tree volume equation to calculate total and merchantable volume for each diameter class. The height for each class is obtained by using the height/diameter equation. The subroutine thinvolume is similar to that of volume. The difference is that this one calculates the thinning volume from 10 diameter classes produced by subroutine selective thinning.

6.2.5. Subroutine thinnage

This subroutine sets an array of the number of thinnings required and store age and intensity of each thinning.

6.2.6. Subroutine cumul and subroutine summary

The subroutine cumul keeps the cumulative values for basal area and volume by adding removals from thinnings. The subroutine summary gives summary of the yearly output by giving information on compartment number, site class, age, range of simulation, present stocking, thinning ages and intensities and products specification.

CHAPTER SEVEN

7. DISCUSSIONS AND CONCLUSIONS

The main result of this study is the construction of a variable density growth model which, under different stocking levels and thinning regimes, can predict merchantable and total volume at any age after initial establishment over a wide range of site qualities.

This was achieved by first fitting and testing regression equations for the different components of the model. The unbiased selected submodels were integrated into computer model using BASIC language to produce a program which can easily be used by the forest management. With the taper-based volume estimation system, the manager can predict different assortments (sawlogs or pulplogs) desired by customers.

With stand volume table at the Appendix 7, he can get quick estimation of stand volumes even after the projection age (24 yrs).

The model then gives, as an example, merchantable yields up to 15 cm top diameter and any other top diameter can be used as an input to the program. Inconsistencies may however be encountered especially by using hypothetical figures or data out of range used in developing the submodels of the program. For the original data, the ranges available for some stand variables used were as follows:

Stocking level: 650-1250 stems per ha

Mean dbh: 14.65-17.75 cm

Sd of dbh: 2.5-3.6 cm

Dominant height: 8.0-30.0 m

(v) Ages: 10-24 years

The variables mean dbh and Standard deviation of dbh are the ones obtained from fifteen 200-trees plots for the diameter distribution equation. As an example of yield printouts, with the current thinning regime and the no thinning option with initial spacing of 3.0 x 3.0 m, the model gives stand and trees parameters for sites classes I, II, III, and IV (see Appendices 6 & 8).

At the end of the projection age (24 yrs), stand cumulative total volume (CUVOL), maximum mean annual volume increment (MAIVOL) and standing mean tree volume (SMTV) for the four different site classes would be summarized in the following table.

Table 11: Cumulative volume (m³/ha), MAIVOL (m³/ha/yr), and SMTV (m³) for site classes I, II, III, & IV.

Site class	SI*	CUVOL	MAIVOL	SMTV
I	27.0	754.97	31.58	1.01
II	24.0	646.69	30.49	0.83
III	21.0	528.16	27.10	0.67
IV	18.0	418.46	22.29	0.55

* SI is site index and equals Hd (m) at 15 years.

As can be noticed from the table, stand and trees variables increase with increasing site quality.

7.1. Comparison of the different thinning regimes

Over the site class (II), four different thinning regimes were compared for optimum volume production with a reasonable size of the trees at the end of the simulation period. The thinning ages and removals percentages remain as prescribed for Meru plantations.

Table 12: Possible thinning regimes for Meru plantations

Regime	No.of thinnings	Age	Removals (%)
A	-	-	-
B	1	10	30
C	2	10,14	30,30
D	3	10,14,18	30,30,30

The results of cumulative volumes (CUVOL), maximum mean annual volume increment (MAIVOL) and standing mean tree volume (SMTV) at 24 years are shown in Table 13.

Table 13. Cumulative volume (m³/ha), mean tree volume (m³) and MAIVOL (m³/ha/yr)

Regime	CUVOL	SMTV	MAIVOL
A	839.93	0.64	35.04
B	703.53	0.70	30.90
C	625.19	0.73	30.26
D	646.69	0.83	30.49

With exception of thinning Regime D, the results show that at 24 years cumulative volume production and MAIVOL decrease with increasing thinning frequencies. It can also be seen that tree size, on the other hand increases with increasing thinning number. These observations about effects of thinning frequency on cumulative total volumes and trees size are in agreement with earlier findings (Malimbwi, 1987).

Compared to others, thinning Regime B is associated with reasonable cumulative volume production, tree size and maximum mean volume increment. With the problem of funds

for thinning operations, thinning Regime B would be more attractive sawnwood production. However, at the end of the projection age and over the same site quality (II), a no thinning option with a wider initial spacing of 3.0 x 3.0 m gives a higher cumulative total volume production (802 m³/ha), tree size (0.72 m) and MAIVOL (33.44 m³/ha/year) than thinning Regime B. As one would expect, this option gives lower cumulative volume and a higher tree size than the initial closer spacing of 2.5 x 2.5 m without thinning (Regime A, see table 8).

With this no thinning option, thinning costs are not incurred and especially in the case of Meru plantations, access pruning operations are done by taungya farmers hence reducing the overall pruning expenditures. The thinning costs and eventual lack of thinning products market make thinning Regime B less attractive than the no thinning option with a spacing of 3.0 x 3.0 m. For future plantations, this option is recommended as a management practice and Appendix 8 shows *Pinus patula* yield tables for five site classes found at Meru plantations.

7.2 Comparison with other studies

The cumulative volume from this study was compared to those of Isango (1994) and Malimbwi (1987) for unthinned stands with the same initial stocking (1600/ha), present age (5 years) and the projection age (24 years) over site quality II. The cumulative volume production from this study was 840.0 m³/ha while 814.0 and 748.0 m³/ha figures were obtained respectively by Malimbwi (1987) and Isango (1994). It is clear that the value from this study is higher than those of the two other studies.

Since the site indexing system is the same for all the three studies, the differences may be attributed to the effects of the different submodels used, mortality predictions and stand management assumptions for the simulation period. Comparison was also made with the results of Klitgaard and Mikkelsen (1976) for site index 24. The dominant height of 26 m (at base age of 20 years) was first converted to 24 m (at base age of 15 years) of this study. The same number of stems per ha and dominant height from Klitgaard and Mikkelsen were then used in the

model. At 24 years the cumulative total volume (598 m³/ha) was lower than that of the other study (632 m³/ha). The reasons advanced when comparing with the results of Malimbwi (1987) and Isango (1994) still hold.

7.3 Conclusions

In this study, different equations were developed, tested for unbiasedness and then integrated into computer to produce a program capable of estimating yields under different stocking levels and thinning regimes for *Pinus patula* at Meru plantations.

However, the program must be supplied with stand inputs (from forest inventory) as described in section 6.1 for its applicability. As said earlier, the use of data outside the limits of those used in developing the model components may produce biased figures due to overestimations or underestimations by either component. Furthermore, the use of the model must be within the limits of the simulation period (5 to 24 years). Stand volumes after the simulation age may be obtained using stand volume table at Appendix 7.

Thinning prescriptions are not followed at Meru plantations and important reason advanced is lack of funds. With sawnwood production and problem of funds, the management should use a rather wider spacing of 3.0 x 3.0 m without thinning and respect pruning schedules. Research is also needed to help determination of stocking levels in pulpwood stands.

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Appendix 1. Data form for stem analysis

Project..... Comp. No.....Plot No.....Plot age (yrs).....tree No.....

BT (cm)..... Dbh(cm).....total height (m).....radial growth.....(cm)

Section No.	Length of section (m)	Section top do (cm)	Number of annual rings at the top	height up to the top of section (m)	yrs of grow the section	years to attain height at the section top
1 (STUMP)						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						

Remarks

Appendix 2. Validation of volume equations.

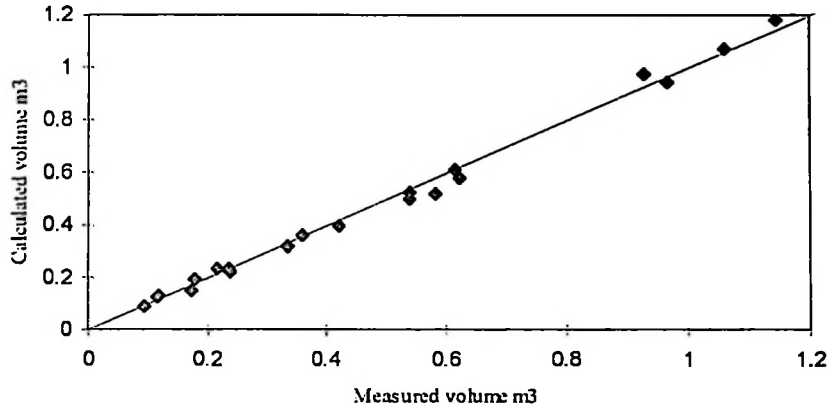


Figure 3. Validation of equation 5.2.1

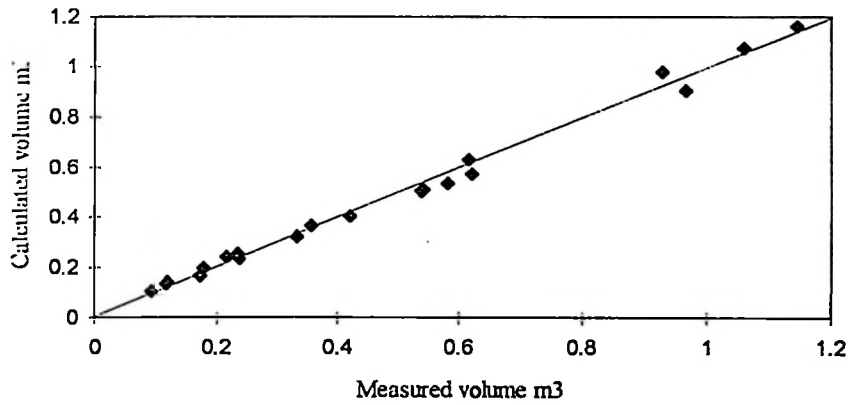


Figure 4. Validation of equation 5.2.2.

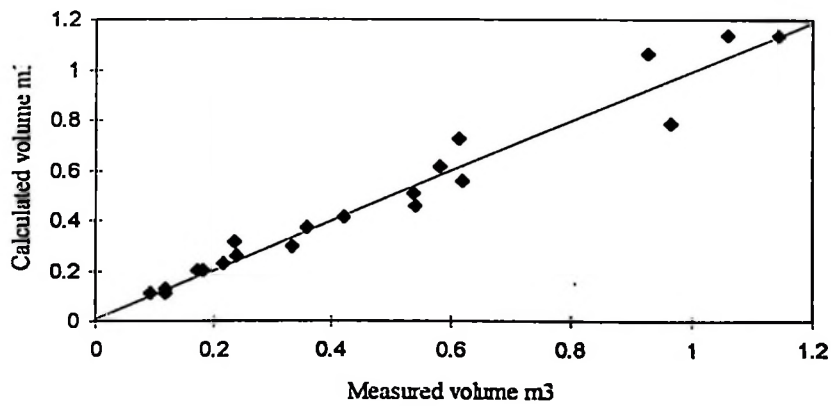


Figure 5. Validation of equation 5.2.3.

Appendix 3. Validation of the taper-based volume equation.

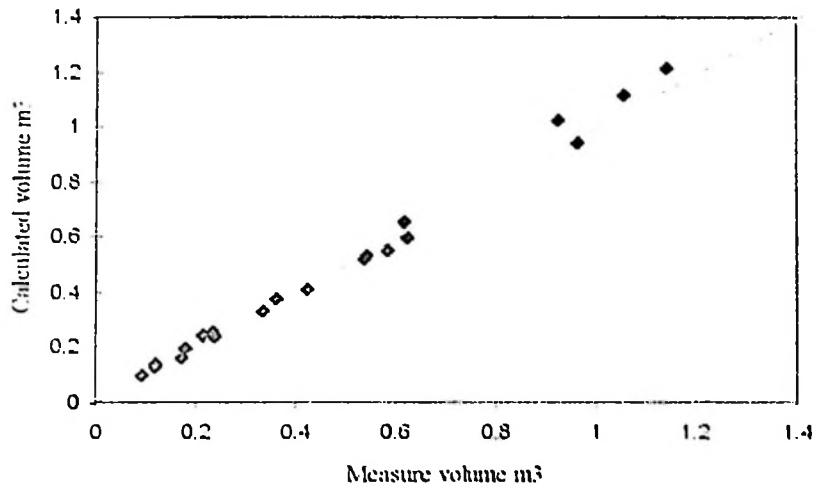


Figure 6. Validation for total tree volume

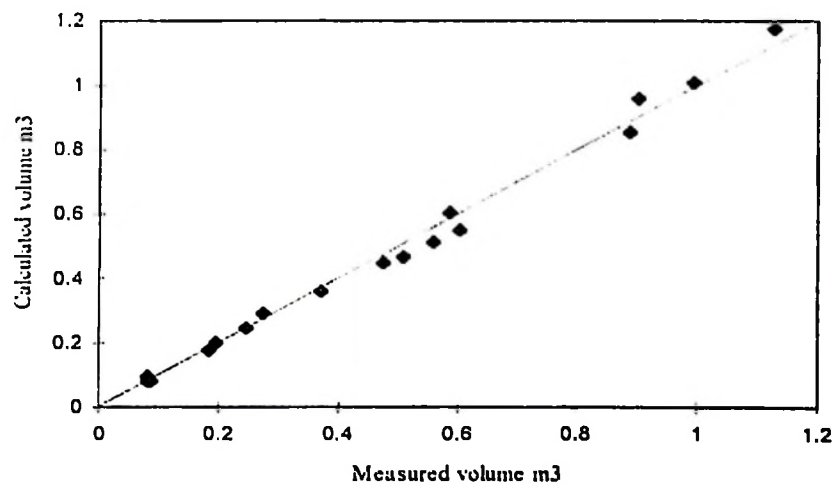


Figure 7. Validation for merchantable tree volume up to 15 cm top diameter.

Appendix 4. Residuals distribution for basal area equations.

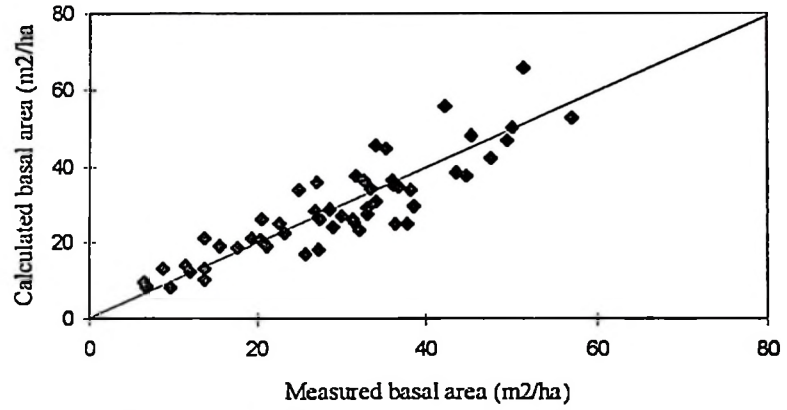


Figure 8. Residuals distribution for equation 5.7.3.

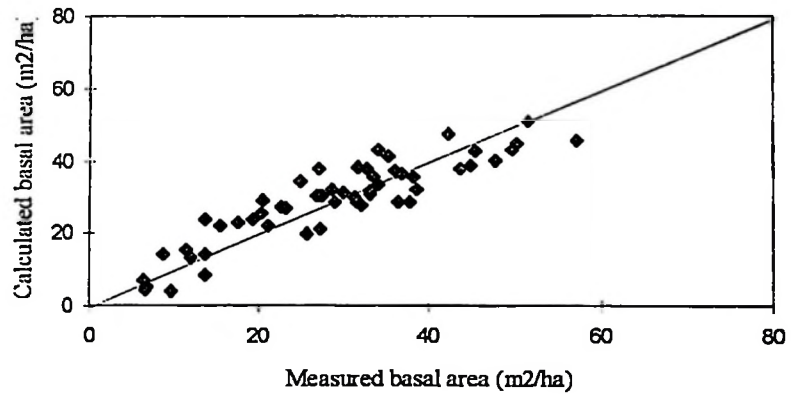


Figure 9. Residuals distribution for equation 5.7.4.

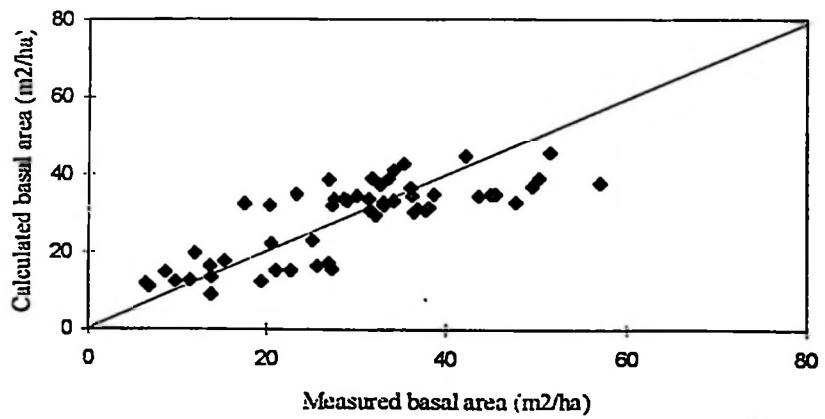


Figure 10. Residuals distribution for equation 5.7.5.

Appendix 5. Residuals distribution for stand volume equations.

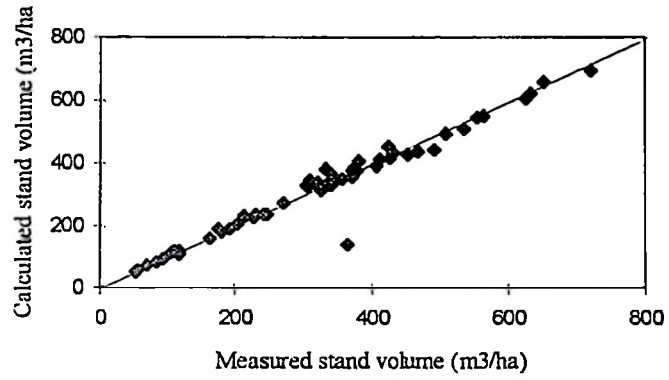


Figure 11. Residuals distribution for equation 5.8.4.

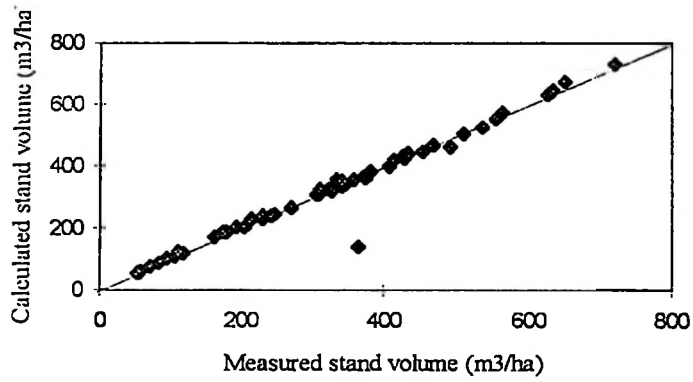


Figure 12. Residuals distribution for equation 5.8.5.

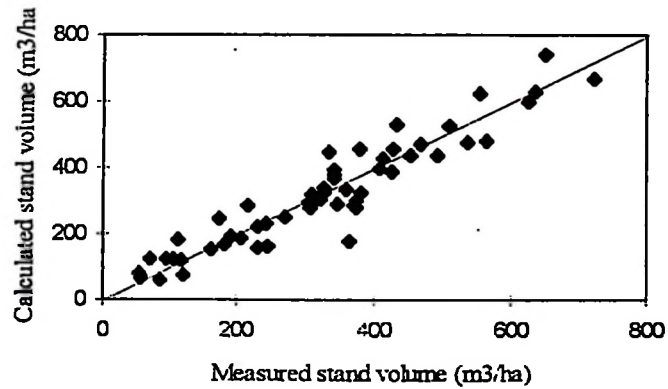


Figure 13. Residuals distribution for equation 5.8.6.

Appendix 6. PINUS PATULA YIELD TABLE FOR SITE CLASS I, II, III, IV

COMPARTMENT NO 2 ,SITE CLASS I (HDOM AT 15 YRS = 27 m)

SIMULATED FROM AGE 5 TO 24 YRS

STAND VARIABLES AT 5 YRS :

STOCKING= 1471 STEMS/HA (SPACING = 2.6 m)

DBH= 9 cm ,SD= 2.5 cm, BA= 11 sq.m/ha

THINNED 3 TIMES BY STEM NUMBER

AGE	REMOVAL %
10	30
14	30
18	30

MERCHANTABLE VOLUME SPECIFICATION

MINIMUM TOP DIAMETER = 15 cm

AGE	SPH	MEANDBH	MAIN CROP		VOL/TR	MERC.VOL	TOTBA
			MEANHT	TOT.VOL			
5.00	1471.00	8.49	2.50	13.65	0.01	0.00	8.77
6.00	1373.15	9.59	3.05	23.43	0.02	0.00	10.27
7.00	1348.67	11.36	3.45	61.75	0.05	0.00	14.03
8.00	1348.67	12.97	11.56	106.76	0.08	0.80	18.16
9.00	1348.67	14.40	14.16	158.79	0.12	5.39	22.32
10.00	1348.67	15.68	16.27	214.43	0.16	16.74	26.40
11.00	944.07	17.11	19.09	197.37	0.21	29.27	21.95
12.00	944.07	18.41	19.55	245.77	0.26	54.71	25.37
13.00	944.07	19.59	20.71	294.17	0.31	86.02	28.70
14.00	944.07	20.67	21.67	341.83	0.36	120.81	31.93
15.00	660.85	21.96	22.49	279.90	0.42	117.55	25.20
16.00	660.35	23.15	23.17	320.05	0.48	151.31	27.39
17.00	660.35	24.35	23.73	359.43	0.54	136.73	30.71
18.00	660.35	25.23	24.20	397.32	0.50	221.44	33.34
19.00	462.59	26.54	24.60	311.84	0.67	136.11	25.71
20.00	462.59	27.71	24.95	344.68	0.75	217.06	28.03
21.00	462.59	28.82	25.23	376.87	0.81	247.61	30.30
22.00	462.59	29.86	25.48	408.31	0.88	277.61	32.52
23.00	462.59	30.84	25.59	438.95	0.95	306.95	34.67
24.00	462.59	31.76	25.87	468.75	1.01	335.57	36.77

AGE	SPH	THINNING PRODUCTS		MERC.VOL	%
		TOT.VOL	VOL/TR		
10.00	404.60	64.33	0.16	5.02	7.81
14.00	283.22	102.55	0.36	36.24	35.34
18.00	198.25	119.35	0.50	66.43	55.66

AGE	CUVOL	CMVOL	CUMULATIVE CUBA	VOLUMES CAIVOL	CAIBA	MAIVOL	MAIBA
5.00	13.65	0.00	8.77	0.00	0.00	2.73	1.75
6.00	28.43	0.00	10.27	14.79	1.50	4.74	1.71
7.00	61.75	0.00	14.03	33.32	3.76	8.82	2.00
8.00	106.76	0.80	18.16	45.02	4.14	13.35	2.27
9.00	158.79	5.39	22.32	52.03	4.16	17.64	2.48
10.00	214.43	16.74	26.40	55.64	4.08	21.44	2.64
11.00	261.70	34.29	29.87	47.27	3.47	23.79	2.72
12.00	310.10	59.73	41.21	48.40	11.34	25.84	3.43
13.00	358.50	91.04	52.47	48.40	11.25	27.58	4.04
14.00	406.16	125.83	63.61	47.66	11.14	29.01	4.54
15.00	446.77	158.81	66.46	40.61	2.85	29.78	4.43
16.00	486.93	193.17	78.83	40.15	12.37	30.43	4.93
17.00	526.30	228.00	91.13	39.38	12.30	30.96	5.36
18.00	564.70	262.70	103.34	38.39	12.21	31.37	5.74
19.00	598.06	293.80	105.71	33.37	2.37	31.48	5.56
20.00	630.91	324.75	118.04	32.84	12.33	31.55	5.90
21.00	663.09	355.31	130.31	32.19	12.27	31.58	6.21
22.00	694.54	385.31	142.53	31.44	12.22	31.57	6.48
23.00	725.17	414.65	154.69	30.64	12.16	31.53	6.73
24.00	754.97	443.26	166.78	29.80	12.10	31.46	6.95

Appendix 6: (CONTINUED)

COMPARTMENT NO 2 ,SITE CLASS II (HDCM AT 15 YRS = 24 m)
 SIMULATED FROM AGE 5 TO 24 YRS
 STAND VARIABLES AT 5 YRS :
 STOCKING= 1471 STEMS/HA (SPACING = 2.6 m)
 DBH= 8.5 cm ,SD= 2.5 cm, BA= 10 sq.m/ha
 THINNED 3 TIMES BY STEM NUMBER

AGE	REMOVAL %
10	30
14	30
18	30

MERCHANTABLE VOLUME SPECIFICATION
 MINIMUM TOP DIAMETER = 15 cm

AGE	SPH	MEANDBH	MAIN CROP		VOL/TR	MERC. VOL	TOTBA
			MEANHT	TOT. VOL			
5.00	1471.00	8.00	2.27	10.91	0.01	0.00	7.81
6.00	1350.60	9.13	4.55	23.70	0.02	0.00	9.18
7.00	1308.14	10.95	8.11	53.66	0.04	0.00	12.67
8.00	1307.72	12.62	11.30	96.03	0.07	0.40	16.59
9.00	1307.72	14.11	13.98	146.04	0.11	3.73	20.78
10.00	1307.72	15.45	16.15	200.20	0.15	13.39	24.83
11.00	915.41	16.91	18.02	186.17	0.20	25.30	20.80
12.00	915.41	18.25	19.50	233.58	0.26	49.52	24.18
13.00	915.41	19.47	20.69	281.21	0.31	80.00	27.48
14.00	915.41	20.58	21.65	328.28	0.36	114.26	30.69
15.00	640.78	21.90	22.49	269.71	0.42	112.38	24.29
16.00	640.78	23.12	23.17	309.27	0.48	145.25	27.05
17.00	640.78	24.24	23.73	348.15	0.54	180.69	29.75
18.00	640.78	25.29	24.20	386.11	0.60	215.07	32.36
19.00	448.55	26.57	24.61	303.11	0.68	181.18	24.99
20.00	448.55	27.77	24.95	335.48	0.75	211.71	27.28
21.00	448.55	28.07	25.22	346.26	0.77	221.13	27.86
22.00	448.55	28.33	25.46	355.91	0.79	229.55	28.37
23.00	448.55	28.55	25.67	364.56	0.81	237.10	28.82
24.00	448.55	28.75	25.87	372.31	0.83	243.85	29.21

AGE	SPH	THINNING PRODUCTS		MERC. VOL	%
		TOT. VOL	VOL/TR		
10.00	392.32	60.06	0.15	4.02	6.69
14.00	274.62	98.48	0.36	34.28	34.81
18.00	192.24	115.83	0.60	64.52	55.70

AGE	CUVOL	CMVOL	CUMULATIVE VOLUMES		CAIBA	MAIVOL	MAIBA
			CUBA	CAIVOL			
5.00	10.91	0.00	7.81	0.00	0.00	2.18	1.56
6.00	23.70	0.00	9.18	12.79	1.37	3.95	1.53
7.00	53.66	0.00	12.67	29.96	3.48	7.67	1.81
8.00	96.03	0.40	16.69	42.37	4.02	12.00	2.09
9.00	146.04	3.73	20.78	50.01	4.09	16.23	2.31
10.00	200.20	13.39	24.83	54.17	4.05	20.02	2.48
11.00	246.23	29.32	28.25	46.02	3.41	22.38	2.57
12.00	293.64	53.53	39.07	47.42	10.83	24.47	3.26
13.00	341.27	84.02	49.83	47.63	10.75	26.25	3.83
14.00	388.34	118.27	60.48	47.06	10.66	27.74	4.32
15.00	428.25	150.67	63.30	39.92	2.81	28.55	4.22
16.00	467.82	184.55	75.26	39.56	11.97	29.24	4.70
17.00	506.69	218.98	87.16	38.88	11.90	29.81	5.13
18.00	544.66	253.36	98.98	37.97	11.82	30.26	5.50
19.00	577.49	283.99	101.32	32.83	2.33	30.39	5.33
20.00	609.85	314.52	113.32	32.37	12.00	30.49	5.67
21.00	620.64	323.95	123.61	10.79	10.29	29.55	5.89
22.00	630.28	332.37	133.83	9.64	10.22	28.65	6.08
23.00	638.93	339.91	143.98	8.65	10.15	27.78	6.26
24.00	646.69	346.66	154.08	7.76	10.10	26.95	6.42

Appendix 6. (CONTINUED)

COMPARTMENT NO 2 ,SITE CLASS III (HDOM AT 15 YRS = 21 m)
 SIMULATED FROM AGE 5 TO 24 YRS
 STAND VARIABLES AT 5 YRS :
 STOCKING= 1471 STEMS/HA (SPACING = 2.6 m)
 DBH= 8 cm ,SD= 2.5 cm, BA= 9 sq.m/ha
 THINNED 3 TIMES BY STEM NUMBER

AGE	REMOVAL %
10	30
14	30
18	30

MERCHANTABLE VOLUME SPECIFICATION
 MINIMUM TOP DIAMETER = 15 cm

AGE	SPH	MEANDBH	MAIN CROP		VOL/TR	MERC. VOL	TOTBA
			MEANHT	TOT. VOL			
5.00	1471.00	7.50	1.96	8.57	0.01	0.00	6.91
6.00	1328.11	8.56	4.25	19.34	0.01	0.00	8.13
7.00	1258.53	10.53	7.73	46.04	0.04	0.00	11.35
8.00	1252.62	12.25	11.02	84.63	0.07	0.12	15.07
9.00	1252.62	13.81	13.79	132.11	0.11	2.41	19.06
10.00	1252.62	15.20	16.03	184.34	0.15	10.26	23.04
11.00	876.83	16.72	17.94	173.44	0.20	21.45	19.46
12.00	876.83	18.10	19.45	219.53	0.25	44.29	22.78
13.00	876.83	19.37	20.66	266.08	0.30	73.82	26.04
14.00	876.83	20.52	21.64	312.28	0.36	107.44	29.21
15.00	613.78	21.87	22.48	257.56	0.42	106.87	23.21
16.00	613.78	22.17	23.05	271.74	0.44	116.23	23.83
17.00	613.78	22.54	23.56	286.19	0.47	127.63	24.52
18.00	613.78	22.87	24.01	299.96	0.49	138.15	25.33
19.00	429.65	24.33	24.48	242.07	0.56	126.16	20.06
20.00	429.65	25.12	24.84	261.79	0.61	144.04	21.38
21.00	429.65	25.36	25.14	269.77	0.63	150.58	21.77
22.00	429.65	25.56	25.40	276.94	0.64	156.46	22.12
23.00	429.65	25.74	25.64	283.39	0.66	161.75	22.43
24.00	429.65	25.90	25.96	289.18	0.67	166.48	22.69

AGE	SPH	THINNING PRODUCTS		MERC. VOL	%
		TOT. VOL	VOL/TR		
10.00	375.79	55.30	0.15	3.08	5.57
14.00	263.05	93.59	0.36	32.23	34.40
18.00	184.13	89.99	0.49	41.44	46.06

AGE	CUVOL	CMVOL	CUMULATIVE VOLUMES		CAIBA	MAIVOL	MAIBA
			CUBA	CAIVOL			
5.00	8.57	0.00	6.91	0.00	0.00	1.71	1.38
6.00	19.34	0.00	8.13	10.77	1.21	3.22	1.35
7.00	46.04	0.00	11.35	26.70	3.23	6.58	1.62
8.00	84.63	0.12	15.07	38.59	3.72	10.58	1.88
9.00	132.11	2.41	19.06	47.48	3.99	14.68	2.12
10.00	184.34	10.26	23.04	52.23	3.98	18.43	2.30
11.00	228.74	24.53	26.37	44.40	3.33	20.79	2.40
12.00	274.83	47.36	36.60	46.09	10.23	22.90	3.05
13.00	321.39	76.90	46.77	46.56	10.17	24.72	3.50
14.00	367.59	110.52	56.86	46.20	10.09	26.26	4.06
15.00	406.55	142.18	59.62	38.96	2.76	27.10	3.97
16.00	420.03	151.54	69.00	13.48	9.39	26.25	4.31
17.00	435.18	162.94	78.56	15.15	9.56	25.60	4.62
18.00	448.94	173.45	88.03	13.76	9.47	24.94	4.89
19.00	481.05	202.92	90.36	32.10	2.32	25.32	4.76
20.00	500.77	220.79	99.28	19.72	8.92	25.04	4.96
21.00	508.74	227.33	107.27	7.97	8.00	24.23	5.11
22.00	515.91	233.22	115.22	7.17	7.95	23.45	5.24
23.00	522.36	238.50	123.12	5.45	7.90	22.71	5.35
24.00	528.16	243.24	130.99	5.80	7.87	22.01	5.46

Appendix 6: (CONTINUED)

COMPARTMENT NO 2 ,SITE CLASS IV (HDOM AT 15 YRS = 18 m)
 SIMULATED FROM AGE 5 TO 24 YRS
 STAND VARIABLES AT 5 YRS :
 STOCKING= 1471 STEMS/HA (SPACING = 2.6 m)
 DBH= 7 cm ,SD= 2.5 cm, BA= 8 sq.m/ha
 THINNED 3 TIMES BY STEM NUMBER

AGE	REMOVAL %
10	30
14	30
18	30

MERCHANTABLE VOLUME SPECIFICATION
 MINIMUM TOP DIAMETER = 15 cm

AGE	SPH	MEANDBH	MAIN CROP				
			MEANHT	TOT.VOL	VOL/TR	MERC.VOL	TOTBA
5.00	1471.00	6.52	1.39	4.98	0.00	0.00	5.29
6.00	1306.30	8.14	3.80	15.46	0.01	0.00	7.10
7.00	1230.19	10.07	7.30	38.95	0.03	0.00	10.08
8.00	1199.50	11.85	10.69	73.83	0.06	0.00	13.51
9.00	1195.12	13.47	13.56	118.17	0.10	1.54	17.31
10.00	1195.12	14.93	15.88	168.18	0.14	7.85	21.20
11.00	836.58	16.49	17.85	160.30	0.19	17.94	18.07
12.00	836.58	17.93	19.40	204.88	0.24	39.11	21.32
13.00	836.58	18.42	20.41	226.91	0.27	49.46	22.47
14.00	836.58	18.83	21.28	246.64	0.29	59.50	23.46
15.00	585.61	20.33	22.23	209.97	0.36	59.54	19.13
16.00	585.61	20.14	22.77	210.72	0.36	67.11	18.75
17.00	585.61	20.43	23.32	221.91	0.38	74.22	19.29
18.00	585.61	20.69	23.81	232.06	0.40	80.83	19.76
19.00	409.93	22.31	24.35	192.99	0.47	83.57	16.08
20.00	409.93	22.76	24.73	203.98	0.50	92.66	16.73
21.00	409.93	22.95	25.05	209.91	0.51	97.04	17.00
22.00	409.93	23.11	25.35	215.24	0.53	100.99	17.23
23.00	409.93	23.25	25.51	220.06	0.54	104.55	17.43
24.00	409.93	23.37	25.86	224.39	0.55	107.75	17.61

AGE	SPH	THINNING PRODUCTS			
		TOT.VOL	VOL/TR	MERC.VOL	%
10.00	358.54	50.45	0.14	2.35	4.67
14.00	250.97	73.99	0.29	17.85	24.13
18.00	175.68	59.62	0.40	24.25	34.83

AGE	CUVOL	CMVOL	CUMULATIVE VOLUMES		CAIBA	MAIVOL	MAIBA
			CUBA	CAIVOL			
5.00	4.98	0.00	5.29	0.00	0.00	1.00	1.06
6.00	15.46	0.00	7.10	10.48	1.81	2.58	1.18
7.00	38.95	0.00	10.08	23.49	2.98	5.56	1.44
8.00	73.83	0.00	13.51	34.87	3.42	9.23	1.69
9.00	118.17	1.54	17.31	44.34	3.80	13.13	1.92
10.00	168.18	7.85	21.20	50.01	3.89	16.82	2.12
11.00	210.76	20.29	24.43	42.58	3.23	19.16	2.22
12.00	255.33	41.47	34.04	44.57	9.60	21.28	2.84
13.00	277.37	51.81	41.55	22.04	7.51	21.34	3.20
14.00	297.10	61.86	48.90	19.73	7.35	21.22	3.49
15.00	334.42	89.75	51.61	37.32	2.71	22.29	3.44
16.00	335.17	87.31	58.27	0.75	6.66	20.95	3.64
17.00	346.35	94.43	65.84	11.18	7.57	20.37	3.87
18.00	356.51	101.04	73.35	10.15	7.51	19.81	4.08
19.00	387.05	128.02	75.59	30.55	2.24	20.37	3.98
20.00	398.05	137.11	82.18	11.00	6.59	19.90	4.11
21.00	403.97	141.49	88.38	5.92	6.19	19.24	4.21
22.00	409.31	145.45	94.54	5.34	6.16	18.60	4.30
23.00	414.12	149.00	100.67	4.81	6.13	18.01	4.38
24.00	418.46	152.20	106.78	4.34	6.11	17.44	4.45

Appendix 7 (continued)

BA (m ²)	Hdom (m)							
	13	14	15	16	17	18	19	20
2	21.1	21.7	22.3	22.9	23.5	24.0	24.5	25.0
3	30.8	31.7	32.6	33.5	34.3	35.1	35.9	36.6
4	40.3	41.6	42.7	43.9	44.9	46.0	47.0	48.0
5	49.7	51.2	52.7	54.1	55.4	56.7	57.9	59.1
6	59.0	60.8	62.5	64.1	65.7	67.2	68.7	70.1
7	68.2	70.2	72.2	74.1	75.9	77.7	79.4	81.0
8	77.3	79.6	81.8	84.0	86.1	88.0	90.0	91.8
9	86.3	88.9	91.4	93.8	96.1	98.3	100.5	102.6
10	95.3	98.1	100.9	103.5	106.1	108.5	110.9	113.2
11	104.2	107.3	110.3	113.2	116.0	118.7	121.3	123.8
12	113.0	116.4	119.7	122.8	125.9	128.8	131.6	134.3
13	121.8	125.5	129.0	132.4	135.7	138.8	141.8	144.8
14	130.6	134.5	138.3	141.9	145.4	148.8	152.0	155.2
15	139.3	143.5	147.5	151.4	155.1	158.7	162.2	165.6
16	148.0	152.5	156.7	160.9	164.8	168.6	172.3	175.9
17	156.7	161.4	165.9	170.3	174.5	178.5	182.4	186.2
18	165.3	170.3	175.0	179.6	184.1	188.3	192.4	196.4
19	173.9	179.1	184.1	189.0	193.6	198.1	202.5	206.7
20	182.4	187.9	193.2	198.3	203.2	207.9	212.4	216.8
21	191.0	196.7	202.3	207.6	212.7	217.6	222.4	227.0
22	199.5	205.5	211.3	216.8	222.2	227.3	232.3	237.1
23	208.0	214.3	220.3	226.0	231.6	237.0	242.2	247.2
24	216.5	223.0	229.2	235.2	241.0	246.6	252.0	257.3
25	224.9	231.7	238.2	244.4	250.4	256.2	261.9	267.3
26	233.3	240.4	247.1	253.6	259.8	265.8	271.7	277.3
27	241.7	249.0	256.0	262.7	269.2	275.4	281.4	287.3
28	250.1	257.7	264.9	271.8	278.5	285.0	291.2	297.3
29	258.5	266.3	273.7	280.9	287.8	294.5	301.0	307.2
30	266.8	274.9	282.6	290.0	297.1	304.0	310.7	317.1
31	275.2	283.5	291.4	299.0	306.4	313.5	320.4	327.0
32	283.5	292.0	300.2	308.1	315.7	323.0	330.0	336.9
33	291.8	300.6	309.0	317.1	324.9	332.4	339.7	346.8
34	300.0	309.1	317.8	326.1	334.1	341.9	349.4	356.6
35	308.3	317.6	326.5	335.1	343.3	351.3	359.0	366.4
36	316.6	326.1	335.3	344.0	352.5	360.7	368.6	376.2
37	324.8	334.6	344.0	353.0	361.7	370.1	378.2	386.0
38	333.0	343.1	352.7	361.9	370.8	379.4	387.7	395.8
39	341.2	351.5	361.4	370.9	380.0	388.8	397.3	405.6
40	349.4	360.0	370.1	379.8	389.1	398.1	406.8	415.3
41	357.6	368.4	378.7	388.7	398.2	407.4	416.4	425.0
42	365.8	376.8	387.4	397.5	407.3	416.8	425.9	434.7
43	0.0	385.2	396.0	406.4	416.4	426.1	435.4	444.4
44	0.0	0.0	404.7	415.3	425.5	435.3	444.9	454.1

Appendix 7 (continued)

BA (m ²)	Hdom (m)							
	21	22	23	24	25	26	27	28
2	25.5	26.0	26.5	26.9	27.4	27.8	28.2	28.7
3	37.3	38.0	38.7	39.4	40.0	40.7	41.3	41.9
4	48.9	49.8	50.7	51.6	52.4	53.3	54.1	54.9
5	60.3	61.4	62.5	63.6	64.6	65.7	66.7	67.7
6	71.5	72.9	74.2	75.5	76.7	77.9	79.1	80.3
7	82.6	84.2	85.7	87.2	88.6	90.0	91.4	92.7
8	93.7	95.4	97.1	98.8	100.4	102.0	103.6	105.1
9	104.6	106.6	108.5	110.3	112.2	113.9	115.7	117.4
10	115.5	117.6	119.7	121.8	123.8	125.8	127.7	129.6
11	126.2	128.6	130.9	133.2	135.4	137.5	139.6	141.7
12	137.0	139.6	142.1	144.5	146.9	149.2	151.5	153.7
13	147.7	150.4	153.1	155.8	158.3	160.8	163.3	165.7
14	158.3	161.3	164.2	167.0	169.7	172.4	175.1	177.6
15	168.9	172.0	175.1	178.1	181.1	183.9	186.7	189.5
16	179.4	182.8	186.0	189.2	192.4	195.4	198.4	201.3
17	189.9	193.4	196.9	200.3	203.6	206.8	210.0	213.1
18	200.3	204.1	207.8	211.3	214.8	218.2	221.6	224.8
19	210.7	214.7	218.6	222.3	226.0	229.6	233.1	236.5
20	221.1	225.3	229.3	233.3	237.1	240.9	244.6	248.2
21	231.5	235.8	240.1	244.2	248.2	252.2	256.0	259.8
22	241.8	246.3	250.8	255.1	259.3	263.4	267.4	271.3
23	252.1	256.8	261.4	265.9	270.3	274.6	278.8	282.9
24	262.3	267.3	272.1	276.8	281.3	285.8	290.2	294.4
25	272.6	277.7	282.7	287.6	292.3	296.9	301.5	305.9
26	282.8	288.1	293.3	298.3	303.3	308.1	312.8	317.4
27	293.0	298.5	303.9	309.1	314.2	319.2	324.0	328.8
28	303.1	308.8	314.4	319.8	325.1	330.2	335.3	340.2
29	313.3	319.2	324.9	330.5	336.0	341.3	346.5	351.6
30	323.4	329.5	335.4	341.2	346.8	352.3	357.7	362.9
31	333.5	339.8	345.9	351.8	357.6	363.3	368.8	374.3
32	343.6	350.0	356.3	362.5	368.4	374.3	380.0	385.6
33	353.6	360.3	366.8	373.1	379.2	385.2	391.1	396.8
34	363.7	370.5	377.2	383.7	390.0	396.2	402.2	408.1
35	373.7	380.7	387.6	394.2	400.7	407.1	413.3	419.4
36	383.7	390.9	397.9	404.8	411.4	418.0	424.3	430.6
37	393.7	401.1	408.3	415.3	422.2	428.8	435.4	441.8
38	403.6	411.2	418.6	425.8	432.8	439.7	446.4	453.0
39	413.6	421.4	428.9	436.3	443.5	450.5	457.4	464.1
40	423.5	431.5	439.2	446.8	454.2	461.4	468.4	475.3
41	433.4	441.6	449.5	457.3	464.8	472.2	479.4	486.4
42	443.3	451.7	459.8	467.7	475.4	483.0	490.3	497.5
43	453.2	461.7	470.1	478.1	486.0	493.7	501.3	508.6
44	463.1	471.8	480.3	488.6	496.6	504.5	512.2	519.7

Appendix 7 (continued)

BA (m ²)	Hdom (m)							
	29	30	31	32	33	34	35	36
2	29.1	29.5	29.8	0.0	0.0	0.0	0.0	0.0
3	42.5	43.1	43.7	44.2	0.0	0.0	0.0	0.0
4	55.7	56.4	57.2	57.9	58.6	0.0	0.0	0.0
5	68.6	69.5	70.5	71.4	72.3	73.1	0.0	0.0
6	81.4	82.5	83.6	84.7	85.7	86.8	87.8	0.0
7	94.1	95.3	96.6	97.8	99.1	100.2	101.4	102.6
8	106.6	108.1	109.5	110.9	112.3	113.6	114.9	116.3
9	119.0	120.7	122.3	123.8	125.4	126.9	128.4	129.8
10	131.4	133.2	135.0	136.7	138.4	140.1	141.7	143.3
11	143.7	145.7	147.6	149.5	151.3	153.1	154.9	156.7
12	155.9	158.0	160.1	162.2	164.2	166.2	168.1	170.0
13	168.0	170.3	172.6	174.8	177.0	179.1	181.2	183.3
14	180.1	182.6	185.0	187.4	189.7	192.0	194.2	196.5
15	192.2	194.8	197.4	199.9	202.4	204.8	207.2	209.6
16	204.2	207.0	209.7	212.4	215.0	217.6	220.1	222.7
17	216.1	219.1	222.0	224.8	227.6	230.3	233.0	235.7
18	228.0	231.1	234.2	237.2	240.1	243.0	245.9	248.6
19	239.9	243.1	246.4	249.5	252.6	255.6	258.6	261.6
20	251.7	255.1	258.5	261.8	265.1	268.2	271.4	274.5
21	263.4	267.1	270.6	274.1	277.5	280.8	284.1	287.3
22	275.2	279.0	282.7	286.3	289.8	293.3	296.7	300.1
23	286.9	290.8	294.7	298.5	302.2	305.8	309.4	312.9
24	298.6	302.7	306.7	310.6	314.5	318.2	322.0	325.6
25	310.2	314.5	318.6	322.7	326.7	330.7	334.5	338.3
26	321.9	326.3	330.6	334.8	339.0	343.0	347.1	351.0
27	333.4	338.0	342.5	346.9	351.2	355.4	359.6	363.6
28	345.0	349.7	354.4	358.9	363.4	367.7	372.0	376.3
29	356.5	361.4	366.2	370.9	375.5	380.0	384.5	388.8
30	368.1	373.1	378.0	382.9	387.6	392.3	396.9	401.4
31	379.6	384.7	389.8	394.8	399.7	404.5	409.3	413.9
32	391.0	396.4	401.6	406.8	411.8	416.8	421.6	426.4
33	402.5	408.0	413.4	418.7	423.9	429.0	434.0	438.9
34	413.9	419.6	425.1	430.6	435.9	441.1	446.3	451.4
35	425.3	431.1	436.8	442.4	447.9	453.3	458.6	463.8
36	436.7	442.6	448.5	454.3	459.9	465.4	470.9	476.2
37	448.0	454.2	460.2	466.1	471.9	477.5	483.1	488.6
38	459.4	465.7	471.8	477.9	483.8	489.6	495.4	501.0
39	470.7	477.1	483.5	489.7	495.7	501.7	507.6	513.3
40	482.0	488.6	495.1	501.4	507.6	513.7	519.8	525.7
41	493.3	500.0	506.7	513.2	519.5	525.8	531.9	538.0
42	504.6	511.5	518.2	524.9	531.4	537.8	544.1	550.3
43	515.8	522.9	529.8	536.6	543.2	549.8	556.2	562.5
44	527.1	534.3	541.3	548.3	555.1	561.8	568.3	574.8

Appendix 7 (continued)

BA (m2)	Hdom (m)							
	37	38	39	40	41	42	43	44
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	117.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	131.3	132.7	0.0	0.0	0.0	0.0	0.0	0.0
10	144.9	146.4	148.0	0.0	0.0	0.0	0.0	0.0
11	158.4	160.1	161.8	163.5	0.0	0.0	0.0	0.0
12	171.9	173.7	175.6	177.4	179.1	0.0	0.0	0.0
13	185.3	187.3	189.2	191.2	193.1	194.9	0.0	0.0
14	198.6	200.8	202.9	204.9	207.0	209.0	211.0	0.0
15	211.9	214.2	216.4	218.6	220.8	222.9	225.1	227.1
16	225.1	227.5	229.9	232.3	234.6	236.8	239.1	241.3
17	238.3	240.8	243.4	245.8	248.3	250.7	253.1	255.4
18	251.4	254.1	256.8	259.4	262.0	264.5	267.0	269.5
19	264.5	267.3	270.1	272.9	275.6	278.2	280.9	283.5
20	277.5	280.5	283.4	286.3	289.1	292.0	294.7	297.5
21	290.5	293.6	296.7	299.7	302.7	305.6	308.5	311.4
22	303.4	306.7	309.9	313.1	316.2	319.2	322.3	325.3
23	316.3	319.7	323.1	326.4	329.6	332.8	336.0	339.1
24	329.2	332.8	336.2	339.7	343.0	346.4	349.7	352.9
25	342.1	345.7	349.4	352.9	356.4	359.9	363.3	366.7
26	354.9	358.7	362.4	366.1	369.8	373.4	376.9	380.4
27	367.7	371.6	375.5	379.3	383.1	386.8	390.5	394.1
28	380.4	384.5	388.5	392.5	396.4	400.2	404.0	407.8
29	393.1	397.4	401.5	405.6	409.6	413.6	417.5	421.4
30	405.8	410.2	414.5	418.7	422.9	427.0	431.0	435.0
31	418.5	423.0	427.4	431.8	436.1	440.3	444.5	448.6
32	431.1	435.8	440.3	444.8	449.3	453.6	457.9	462.2
33	443.8	448.5	453.2	457.8	462.4	466.9	471.3	475.7
34	456.4	461.3	466.1	470.8	475.5	480.1	484.7	489.2
35	468.9	474.0	478.9	483.8	488.6	493.4	498.0	502.7
36	481.5	486.7	491.7	496.8	501.7	506.6	511.4	516.1
37	494.0	499.3	504.5	509.7	514.8	519.8	524.7	529.5
38	506.5	512.0	517.3	522.6	527.8	532.9	538.0	542.9
39	519.0	524.6	530.1	535.5	540.8	546.1	551.2	556.3
40	531.5	537.2	542.8	548.3	553.8	559.2	564.5	569.7
41	543.9	549.8	555.5	561.2	566.8	572.3	577.7	583.0
42	556.3	562.3	568.2	574.0	579.7	585.3	590.9	596.4
43	568.7	574.9	580.9	586.8	592.6	598.4	604.1	609.7
44	581.1	587.4	593.5	599.6	605.6	611.4	617.2	622.9

Appendix 7 (continued)

BA (m2)	Hdom (m)							
	37	38	39	40	41	42	43	44
45	593.5	599.9	606.2	612.4	618.4	624.5	630.4	636.2
46	605.9	612.4	618.8	625.1	631.3	637.5	643.5	649.5
47	618.2	624.9	631.4	637.8	644.2	650.4	656.6	662.7
48	630.5	637.3	644.0	650.6	657.0	663.4	669.7	675.9
49	642.8	649.8	656.6	663.2	669.8	676.4	682.8	689.1
50	655.1	662.2	669.1	675.9	682.7	689.3	695.8	702.3
51	667.4	674.6	681.6	688.6	695.4	702.2	708.9	715.4
52	679.7	687.0	694.2	701.2	708.2	715.1	721.9	728.6
53	691.9	699.4	706.7	713.9	721.0	728.0	734.9	741.7
54	704.1	711.7	719.2	726.5	733.7	740.9	747.9	754.8
55	716.4	724.1	731.6	739.1	746.5	753.7	760.9	767.9
56	728.6	736.4	744.1	751.7	759.2	766.6	773.8	781.0
57	740.8	748.7	756.6	764.3	771.9	779.4	786.8	794.0
58	752.9	761.0	769.0	776.8	784.6	792.2	799.7	807.1
59	765.1	773.3	781.4	789.4	797.2	805.0	812.6	820.1
60	777.3	785.6	793.8	801.9	809.9	817.8	825.5	833.2
61	789.4	797.9	806.2	814.5	822.6	830.5	838.4	846.2
62	801.5	810.1	818.6	827.0	835.2	843.3	851.3	859.2
63	813.6	822.4	831.0	839.5	847.8	856.0	864.2	872.2
64	825.7	834.6	843.3	852.0	860.4	868.8	877.0	885.1
65	837.8	846.8	855.7	864.4	873.0	881.5	889.9	898.1
66	849.9	859.0	868.0	876.9	885.6	894.2	902.7	911.0
67	0.0	871.2	880.4	889.3	898.2	906.9	915.5	924.0
68	0.0	0.0	892.7	901.8	910.7	919.6	928.3	936.9
69	0.0	0.0	0.0	914.2	923.3	932.3	941.1	949.8
70	0.0	0.0	0.0	0.0	935.8	944.9	953.9	962.7

Appendix 8. PINUS PATULA YIELD TABLES AT MERU PLANTATIONS

COMPARTMENT NO 2 ,SITE CLASS I (HDOM AT 15 YRS = 27 m)
 SIMULATED FROM AGE 5 TO 24 YRS
 STAND VARIABLES AT 5 YRS :
 STOCKING= 1111 STEMS/HA (SPACING = 3.0 m)
 DBH= 9 cm ,SD= 2.5 cm, BA= 11 sq.m/ha
 UNTHINNED
 MERCHANTABLE VOLUME SPECIFICATION
 MINIMUM TOP DIAMETER = 15 cm

AGE	SPH	MEANDBH	MAIN CROP		VOL/TR	MERC.VOL	TOTBA
			MEANHT	TOT.VOL			
5.00	1111.00	8.49	2.60	10.31	0.01	0.00	6.62
6.00	1111.00	10.45	5.78	30.93	0.03	0.00	9.86
7.00	1111.00	12.25	9.17	63.85	0.06	0.24	13.42
8.00	1111.00	13.88	12.20	106.15	0.10	2.85	17.14
9.00	1111.00	15.35	14.71	154.38	0.14	11.12	20.91
10.00	1111.00	16.69	16.74	205.73	0.19	27.26	24.63
11.00	1111.00	17.89	18.38	258.20	0.23	51.06	28.25
12.00	1111.00	18.98	19.71	310.48	0.28	80.77	31.77
13.00	1111.00	19.97	20.80	361.72	0.33	114.61	35.13
14.00	1111.00	20.87	21.70	411.46	0.37	150.67	38.35
15.00	1111.00	21.70	22.45	459.41	0.41	187.67	41.43
16.00	1111.00	22.46	23.08	505.45	0.45	224.79	44.36
17.00	1111.00	23.16	23.62	549.56	0.49	261.49	47.15
18.00	1111.00	23.81	24.08	591.76	0.53	297.46	49.81
19.00	1111.00	24.41	24.49	632.12	0.57	332.51	52.35
20.00	1111.00	24.98	24.83	670.70	0.60	366.52	54.78
21.00	1111.00	25.50	25.14	707.61	0.64	399.44	57.10
22.00	1111.00	26.00	25.41	742.94	0.67	431.25	59.32
23.00	1111.00	26.46	25.65	776.77	0.70	461.96	61.45
24.00	1111.00	26.89	25.87	809.19	0.73	491.53	63.49

AGE	SPH	THINNING PRODUCTS		MERC.VOL	%
		TOT.VOL	VOL/TR		

AGE	CUMULATIVE VOLUMES						
	CUVOL	CMVOL	CUBA	CAIVOL	CAIBA	MAIVOL	MAIBA
5.00	10.31	0.00	6.62	0.00	0.00	2.06	1.32
6.00	30.93	0.00	9.86	20.62	3.24	5.15	1.64
7.00	63.85	0.24	13.42	32.93	3.56	9.12	1.92
8.00	106.15	2.85	17.14	42.30	3.72	13.27	2.14
9.00	154.38	11.12	20.91	48.23	3.76	17.15	2.32
10.00	205.73	27.26	24.63	51.35	3.72	20.57	2.46
11.00	258.20	51.06	28.26	52.47	3.63	23.47	2.57
12.00	310.48	80.77	31.77	52.27	3.51	25.87	2.65
13.00	361.72	114.61	35.13	51.25	3.37	27.82	2.70
14.00	411.46	150.67	38.35	49.73	3.22	29.39	2.74
15.00	459.41	187.67	41.43	47.95	3.07	30.63	2.76
16.00	505.45	224.79	44.36	46.05	2.93	31.59	2.77
17.00	549.56	261.49	47.15	44.11	2.79	32.33	2.77
18.00	591.76	297.46	49.81	42.20	2.66	32.88	2.77
19.00	632.12	332.51	52.35	40.35	2.54	33.27	2.76
20.00	670.70	366.52	54.78	38.59	2.43	33.54	2.74
21.00	707.61	399.44	57.10	36.91	2.32	33.70	2.72
22.00	742.94	431.25	59.32	35.32	2.22	33.77	2.70
23.00	776.77	461.98	61.45	33.83	2.13	33.77	2.67
24.00	809.19	491.63	63.49	32.43	2.04	33.72	2.65

Appendix 8: (CONTINUED)

COMPARTMENT NO 2 ,SITE CLASS II (HDOM AT 15 YRS = 24 m)
 SIMULATED FROM AGE 5 TO 24 YRS
 STAND VARIABLES AT 5 YRS :
 STOCKING= 1111 STEMS/HA (SPACING = 3.0 m)
 DBH= 8.5 cm ,SD= 2.5 cm, BA= 10 sq.m/ha
 UNTHINNED
 MERCHANTABLE VOLUME SPECIFICATION
 MINIMUM TOP DIAMETER = 15 cm

AGE	SPH	MEANDBH	MAIN CROP		VOL/TR	MERC.VOL	TOTBA
			MEANHT	TOT.VOL			
5.00	1111.00	8.00	2.27	8.24	0.01	0.00	5.90
6.00	1111.00	9.99	5.39	26.69	0.02	0.00	9.04
7.00	1111.00	11.83	8.83	57.61	0.05	0.06	12.53
8.00	1111.00	13.50	11.93	98.39	0.09	1.79	16.22
9.00	1111.00	15.01	14.51	145.61	0.13	8.41	19.97
10.00	1111.00	16.37	16.60	196.36	0.18	22.57	23.71
11.00	1111.00	17.60	18.28	248.53	0.22	44.75	27.36
12.00	1111.00	18.71	19.64	300.70	0.27	73.30	30.89
13.00	1111.00	19.73	20.74	351.99	0.32	106.42	34.28
14.00	1111.00	20.65	21.65	401.34	0.36	142.12	37.53
15.00	1111.00	21.49	22.42	449.96	0.41	178.97	40.63
16.00	1111.00	22.27	23.06	496.22	0.45	216.07	43.59
17.00	1111.00	22.98	23.60	540.55	0.49	252.85	46.41
18.00	1111.00	23.64	24.07	582.98	0.52	288.94	49.10
19.00	1111.00	24.25	24.48	623.56	0.56	324.14	51.66
20.00	1111.00	24.83	24.83	662.37	0.60	358.32	54.11
21.00	1111.00	25.36	25.14	699.49	0.63	391.42	56.45
22.00	1111.00	25.86	25.41	735.02	0.66	423.41	58.70
23.00	1111.00	26.33	25.65	769.05	0.69	454.31	60.84
24.00	1111.00	26.79	25.37	801.66	0.72	484.14	62.90

AGE	SPH	THINNING PRODUCTS		MERC.VOL	%
		TOT.VOL	VOL/TR		

AGE	CUVOL	CMVOL	CUMULATIVE VOLUMES		CAIBA	MAIVOL	MAIBA
			CUBA	CAIVOL			
5.00	8.24	0.00	5.90	0.00	0.00	1.65	1.18
6.00	26.69	0.00	9.04	18.46	3.13	4.45	1.51
7.00	57.61	0.06	12.53	30.92	3.49	8.23	1.79
8.00	98.39	1.79	16.22	40.78	3.69	12.30	2.03
9.00	145.61	8.41	19.97	47.22	3.76	16.18	2.22
10.00	196.36	22.57	23.71	50.75	3.73	19.64	2.37
11.00	248.53	44.75	27.36	52.17	3.65	22.59	2.49
12.00	300.70	73.30	30.89	52.17	3.53	25.06	2.57
13.00	351.99	106.42	34.28	51.28	3.39	27.08	2.64
14.00	401.84	142.12	37.53	49.85	3.25	28.70	2.68
15.00	449.96	179.97	40.63	48.13	3.10	30.00	2.71
16.00	496.22	216.07	43.59	46.25	2.96	31.01	2.72
17.00	540.55	252.85	46.41	44.33	2.82	31.80	2.73
18.00	582.98	288.94	49.10	42.43	2.69	32.39	2.73
19.00	623.56	324.14	51.66	40.58	2.57	32.82	2.72
20.00	662.37	358.32	54.11	38.81	2.45	33.12	2.71
21.00	699.49	391.42	56.45	37.12	2.34	33.31	2.69
22.00	735.02	423.41	58.70	35.53	2.24	33.41	2.67
23.00	769.05	454.31	60.84	34.03	2.15	33.44	2.65
24.00	801.66	484.14	62.90	32.62	2.06	33.40	2.62

Appendix 8: (CONTINUED)

COMPARTMENT NO 2 ,SITE CLASS III (HDOM AT 15 YRS = 21 m)
 SIMULATED FROM AGE 5 TO 24 YRS
 STAND VARIABLES AT 5 YRS :
 STOCKING= 1111 STEMS/HA (SPACING = 3.0 m)
 DBH= 8 cm ,SD= 2.5 cm, BA= 9 sq.m/ha
 UNTHINNED
 MERCHANTABLE VOLUME SPECIFICATION
 MINIMUM TOP DIAMETER = 15 cm

AGE	SPH	MEANDBH	MAIN CROP		VOL/TR	MERC.VOL	TOTBA
			MEANHT	TOT.VOL			
5.00	1111.00	7.50	1.96	6.47	0.01	0.00	5.22
6.00	1097.16	9.53	5.00	22.54	0.02	0.00	8.14
7.00	1097.16	11.41	8.49	51.13	0.05	0.00	11.53
8.00	1097.16	13.12	11.67	89.99	0.08	1.07	15.15
9.00	1097.16	14.63	14.32	135.79	0.12	5.16	18.87
10.00	1097.16	16.08	16.46	195.56	0.17	13.48	22.58
11.00	1097.16	17.34	18.18	237.08	0.22	33.93	26.23
12.00	1097.16	18.49	19.57	288.85	0.26	66.29	29.77
13.00	1097.16	19.53	20.70	339.90	0.31	98.67	33.18
14.00	1097.16	20.48	21.62	389.65	0.36	133.97	36.45
15.00	1097.16	21.34	22.40	437.76	0.40	170.65	39.57
16.00	1097.16	21.98	23.02	476.76	0.43	200.91	41.95
17.00	1097.16	22.35	23.54	503.48	0.46	220.84	43.35
18.00	1097.16	22.67	23.99	527.77	0.48	239.22	44.59
19.00	1097.16	22.96	24.39	549.76	0.50	256.04	45.70
20.00	1097.16	23.21	24.75	569.64	0.52	271.14	46.68
21.00	1097.16	23.43	25.07	587.56	0.54	285.20	47.55
22.00	1097.16	23.61	25.36	603.72	0.55	297.69	48.31
23.00	1097.16	23.78	25.62	618.26	0.56	308.93	48.97
24.00	1097.16	23.92	25.86	631.35	0.58	319.02	49.55

AGE	SPH	THINNING PRODUCTS		MERC.VOL	%
		TOT.VOL	VOL/TR		

AGE	CUVOL	CMVOL	CUMULATIVE VOLUMES				MAIBV
			CUBA	CAIVOL	CAIBA	MAIVOL	
5.00	6.47	0.00	5.22	0.00	0.00	1.29	1.04
6.00	22.54	0.00	8.14	16.07	2.92	3.76	1.36
7.00	51.13	0.00	11.53	28.59	3.39	7.30	1.65
8.00	89.99	1.07	15.15	38.86	3.62	11.25	1.89
9.00	135.79	6.16	18.87	45.80	3.72	15.09	2.10
10.00	185.56	18.48	22.58	49.76	3.72	18.56	2.26
11.00	237.08	38.93	26.23	51.52	3.65	21.55	2.38
12.00	288.85	66.29	29.77	51.77	3.54	24.07	2.48
13.00	339.90	98.67	33.18	51.06	3.41	26.15	2.55
14.00	389.65	133.97	36.45	49.75	3.27	27.83	2.60
15.00	437.76	170.65	39.57	48.10	3.12	29.18	2.64
16.00	476.76	200.91	41.95	39.00	2.38	29.80	2.62
17.00	503.48	220.84	43.35	26.72	1.40	29.62	2.55
18.00	527.77	239.22	44.59	24.28	1.25	29.32	2.48
19.00	549.76	256.04	45.70	22.00	1.11	28.93	2.41
20.00	569.64	271.34	46.68	19.87	0.98	28.48	2.33
21.00	587.56	285.20	47.55	17.93	0.86	27.98	2.26
22.00	603.72	297.69	48.31	16.15	0.75	27.44	2.20
23.00	618.26	308.93	48.97	14.54	0.66	26.88	2.13
24.00	631.35	319.02	49.55	13.09	0.58	26.31	2.06

Appendix 8: (CONTINUED)

COMPARTMENT NO 2 ,SITE CLASS IV (HDOM AT 15 YRS = 18 m)
 SIMULATED FROM AGE 5 TO 24 YRS
 STAND VARIABLES AT 5 YRS :
 STOCKING= 1111 STEMS/HA (SPACING = 3.0 m)
 DBH= 7 cm ,SD= 2.5 cm, BA= 8 sq.m/ha
 UNTHINNED
 MERCHANTABLE VOLUME SPECIFICATION
 MINIMUM TOP DIAMETER = 15 cm

AGE	SPH	MEANDBH	MAIN CROP		VOL/TR	MERC.VOL	TOTBA
			MEANHT	TOT.VOL			
5.00	1111.00	6.52	1.39	3.76	0.00	0.00	3.99
6.00	1079.14	8.62	4.21	15.72	0.01	0.00	6.57
7.00	1074.99	10.58	7.76	39.77	0.04	0.00	9.72
8.00	1074.99	12.37	11.10	74.87	0.07	0.26	13.20
9.00	1074.99	14.01	13.91	117.88	0.11	3.01	16.84
10.00	1074.99	15.49	16.17	165.74	0.15	11.72	20.53
11.00	1074.99	16.82	17.98	216.05	0.20	28.65	24.18
12.00	1074.99	18.03	19.43	267.13	0.25	53.42	27.74
13.00	1074.99	18.67	20.48	300.98	0.28	71.11	29.70
14.00	1074.99	19.08	21.33	326.95	0.30	84.91	31.00
15.00	1074.99	19.45	22.07	350.86	0.33	98.46	32.18
16.00	1074.99	19.78	22.71	372.74	0.35	111.45	33.25
17.00	1074.99	20.06	23.27	392.68	0.37	123.69	34.19
18.00	1074.99	20.31	23.77	410.80	0.38	135.09	35.04
19.00	1074.99	20.53	24.21	427.22	0.40	145.61	35.78
20.00	1074.99	20.73	24.61	442.07	0.41	155.23	36.44
21.00	1074.99	20.89	24.97	455.50	0.42	163.99	37.02
22.00	1074.99	21.04	25.29	467.62	0.44	171.92	37.52
23.00	1074.99	21.16	25.58	478.58	0.45	179.09	37.96
24.00	1074.99	21.27	25.85	488.48	0.45	185.54	38.35

AGE	SPH	THINNING PRODUCTS		MERC.VOL	%
		TOT.VOL	VOL/TR		

AGE	CUVOL	CMVOL	CUMULATIVE VOLUMES				
			CUBA	CAIVOL	CAIBA	MAIVOL	MAIBA
5.00	3.76	0.00	3.99	0.00	0.00	0.75	0.80
6.00	15.72	0.00	6.57	11.96	2.58	2.62	1.10
7.00	39.77	0.00	9.72	24.04	3.15	5.68	1.39
8.00	74.87	0.26	13.20	35.10	3.48	9.36	1.65
9.00	117.88	3.01	16.84	43.01	3.64	13.10	1.87
10.00	165.74	11.72	20.53	47.86	3.68	16.57	2.05
11.00	216.05	28.65	24.18	50.31	3.65	19.64	2.20
12.00	267.13	53.42	27.74	51.08	3.56	22.26	2.31
13.00	300.98	71.11	29.70	33.85	1.96	23.15	2.28
14.00	326.95	84.91	31.00	25.98	1.31	23.35	2.21
15.00	350.86	98.46	32.18	23.91	1.18	23.39	2.15
16.00	372.74	111.45	33.25	21.88	1.06	23.30	2.08
17.00	392.68	123.69	34.19	19.94	0.95	23.10	2.01
18.00	410.80	135.09	35.04	18.12	0.84	22.82	1.95
19.00	427.22	145.61	35.78	16.42	0.75	22.49	1.88
20.00	442.07	155.23	36.44	14.85	0.66	22.10	1.82
21.00	455.50	163.99	37.02	13.42	0.58	21.69	1.76
22.00	467.62	171.92	37.52	12.13	0.51	21.26	1.71
23.00	478.58	179.09	37.96	10.95	0.44	20.81	1.65
24.00	488.48	185.54	38.35	9.90	0.39	20.35	1.60