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INDIVIDUAL TREE VOLUME AND STAND YIELD PREDICTION FOR EUCALYPTS IN KENYA

by

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Abstract

Individual tree volume data obtained from 365 trees collected from five forest regions in Uasin Gishu district of Kenya were used to derive regression equations for estimating total and merchantable tree volume and in comparing the forest regions. The predictor variables were diameter at breast height outside bark and total tree height. The techniques used in comparing the various methods included regression analysis, analysis of variance and multiple comparison analysis.

The best equation for total tree volume was a nonlinear standard volume function, while merchantable volume was appropriately estimated by a ratio function. All the equations tested for the two estimations gave closely similar results within the range of the data. Forest region comparisons revealed some differences between one region and the others, but the real cause for this difference could not be evaluated with the data available in this study.

Yield estimation variables included number of trees, average top height, basal area and age of plantations. Equations based on age only gave poor estimation compared to equations derived from field measurements of both basal area and average top height in a nonlinear equation. The poor relation is probably due to the excessive variation in number of trees. However, equations based on age are cheaper to use since no field measurement is required.

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I. Introduction

A basic requirement for objective forest management and planning is the ability to assess the growing stock available at the present time and in the future. In Kenyan forest management practices, the basic unit for planning is the plantation, and consequently, an accurate estimate of stand volume within the plantation at various ages over the entire rotation is essential. Although recognized as a valuable resource, well adapted to intensive management, the yield of eucalypt plantations in Kenya is not adequately documented. This thesis reports on a study of the basic relationships necessary to estimate individual tree and stand volumes for Eucalyptus saligna/grandis in Uasin Gishu district in Kenya.

The two main exotic softwood species in Kenya, Cupressus lusitanica Miller and Pinus patula Schlecht and Cham., have had acceptable individual tree volume and stand yield functions for over ten years due to their importance as sawtimber species. There is an increasing need for volume and stand yield functions for other species due to fuelwood demand in the rural areas, where wood is the only source of energy. In the past, individual tree volume estimation has been based on scaling. Scaling is time consuming and expensive, and therefore, stand volume estimation is preferred as stipulated in the Kenya Forest department general order number 232. This study was undertaken to facilitate the application of this approach in eucalypt plantations.

While an individual tree volume function exists for eucalypts, its application in any particular area is unjustified for several reasons. The data that were used to derive the function were comprised of 553 sample trees collected over the whole country. As such, the number was too small to represent any particular area adequately. Secondly, the sample trees were older and consequently larger than trees currently being harvested from plantations. Experience elsewhere (Bredenkamp 1982), on the same species, has shown that aggregation of all tree-sizes in a single equation results in poor tree volume prediction. Thirdly, several eucalypt species, growing in different areas were included making the adequacy of volume prediction for any one species unknown. Finally, both seedling and coppice regenerated trees were used as sample trees, with no study carried out to determine if the aggregation of the two types of stems was acceptable.

The purpose of this study was to derive individual tree volume and stand yield functions for <u>Eucalyptus saligna/grandis</u> in order to overcome the problems discussed above. The data for the present study were collected in the pulpwood working circle (Uasin Gishu district) in the summers of 1985/86. Although this species is successfully grown in most parts of Kenya, this study area, consisting of five forest regions, was selected, since it is planned as the major concentration of eucalypt plantations comprising at least 25% of all plantations in the district.

Curve fitting procedures, both linear and nonlinear least squares, were used to evaluate the various relationships of interest. Based on felled tree data, local and standard volume functions were fitted and compared. Regional variation was evaluated using analysis of covariance, and merchantable volume relationships were evaluated using regression procedures. Additional data were collected to evaluate stand yield relations for plantations between ages 2 and 10 years.

The remaining chapters of the thesis present the results of the major components of the study. The second chapter describes the data used to derive the tree volume function, merchantable volume function and evaluation of the regional differences. The next three chapters deal with the total tree volume functions, merchantable volume functions and the regional differences respectively. The last chapter is devoted to an evaluation of stand yield functions.

II. Tree Volume Data

A. Site Description

The data for both individual tree volume and stand yield equations were collected in Uasin Gishu district in Kenya. The Uasin Gishu district is in the pulpwood working circle. The district lies between 0° 30' South and 1° 0' North latitude and 33° 30' and 35° 0' East longitude. It rises from 1200 to 2500 metres above sea level. The altitudes of the different forest regions are shown in table 1. The total forest land under forest department management is 61,150 hectares and is comprised of softwood and hardwood plantations and natural forests.

Although no detailed soil studies have been carried out in the district, Ochieng (1968) did a preliminary soil survey which showed that the whole district is situated on tertiary volcanic rocks. The brief soil descriptions of individual forest regions are included in table 1. Kapsaret and Turbo have slightly different soils from the other three forest regions, but the soils are similar and the whole region can be assumed to be of the same quality.

Gilead and Roseman (1958) suggested that the most important elements for plant growth are temperature and rainfall. The temperatures in the district are fairly constant by virtue of its location near the equator. The district experiences one long rainy season between March and September and one season with minimum rainfall between

Table 1: Distribution of Sample Trees in the Forest Regions.

Forest Region	Area (ha)	Altitude (m.a.s.l)	Rainfall (mm)	No. of trees	Age-Range (Years)	Soil Description
Kapsaret	1,420	1950	1100	56	4-8	Poorly drained soils with rounded iron concretions characterised by pockets of well drained friable clay. The subsoils are derived from volcanic and basement complex rocks.
Turbo	12,951	1850	1330	72	2-10	Poorly drained clay with grey mottled subsoils characterised by shallow soils that are poorly drained.
Sabor	11,734	2440	1260	68	2-8	Well drained humic friable clay with dark red subsoil derived from volcanic rocks.
Kaptagat	27,464	2440	1260	70	4-9	Imperfectly drained friable clay with red to dark brown subsoil with hard iron concretions which are massive at depth.
Pénon	4,109	2440	1260	99	3-8	Imperfectly drained loam with dark brown subsoil derived from tuff.

October and February (Mathu 1983). The average rainfall for each forest region in this study is shown in table 1.

In all forest regions except Turbo, stands were established on cleared natural forest sites which were initially put under agricultural use. Cultivation (taungya system) was allowed until canopy closure, usually at the third year after planting. The seedlings were planted 2.5 metres apart in rows spaced at 2.75 metre intervals. In Turbo, the fields, which were mostly grasslands, were ploughed prior to planting. The seedlings were weeded for the first two years to eliminate grass competition. The stands receive no further silvicultural tending during the entire rotation.

B. Collection of Tree Volume Data

In each forest region, approximately 10 trees were sampled from each age between 3 and 10 years. The sample trees had to be visually straight, with no multiple leaders and no signs of suppression. The age range and number of trees sampled from each forest are listed in table 1. In total, 365 trees were sampled covering the full range of diameters. Their distribution in height-diameter classes is shown in table 2. Overbark diameters for the sampled trees were measured with a diameter tape at stump height (15 cm), 1 metre and at breast height (1.3 m) from ground level before felling. The breast height point was marked on two opposite sides.

Table 2: Distribution of trees in Height-Diameter Classes.

	Height						
Dbh	10	15	20	25	30	35	Total
10	16	6	2	0	0	0	24
15	33	68	42	10	1	0	154
20	0	26	45	42	4	0	117
25	0	3	20	25	3	4	55
30	0	0	0	6	5	0	11
35	0	0	2	1	0	0	3
40	0	0	0	1	0	0	1
Total	49	103	111	85	13	4	365

The sample trees were felled, after taking the preceding measurements, and overbark diameters were taken at 2.0 metres and at one metre intervals above this point to the top of the tree. Overbark diameters were measured to the nearest 0.1 cm, up to a point where diameter was less than or equal to 5 cm. Where the mark fell on a knot, it was moved upwards to the nearest point free of the knot effect. The total tree height was measured to the nearest 0.05 metre from ground level. The sample trees had an average height of 19.08 metres and an average diameter at breast height of 18.45 cm.

C. Calculation of Individual Tree Volume

Total tree volume can be calculated using any of several formulas (Husch et al. 1982). However, Smalian's formula, though not the most accurate for long sections, is commonly used since the necessary measurements are easier to obtain. When Smalian's formula is used on a frustum other than that of a paraboloid or cone, it results in biased estimates (Husch et al. 1982, Philip 1983). Husch et al. (1982) cited a study which concluded that when log lengths are 4 feet (1.2 m) or less, Smalian's formula yields accurate estimates. Philip (1983) stated that errors due to application of this formula are proportional to the length of the log and the square of the difference between the diameters at the two ends. In other words, the longer the log and the greater the taper, the greater the error.

The eucalypts in this study have been described as 'shaft-like' (Penfold and Willis 1961), implying that they are not buttressed. Further the trees are young and have little taper. These factors together with short section lengths justify using Smalian's formula for all sections of the tree.

a) **Total tree volume**

Total tree volume is here defined as the volume overbark from the stump (15 cm) to the top of the tree. The volumes of the individual sections were computed using Smalian's formula and summed to obtain total tree volume.

b) **Merchantable Volume**

Merchantable tree volume was defined as the overbark volume from the stump height to a 5 cm top diameter. This volume was obtained by subtracting the unmerchantable portion of the stem from the total tree volume. As only a few trees had a 5.0 cm diameter on the last diameter measurement, linear extrapolation was used to determine the height to the 5.0 cm top diameter as illustrated in figure 1.

The data described above are used in the next three chapters to derive total tree volume functions, to evaluate merchantable volume estimation and to compare the forest regions from which the data were collected.

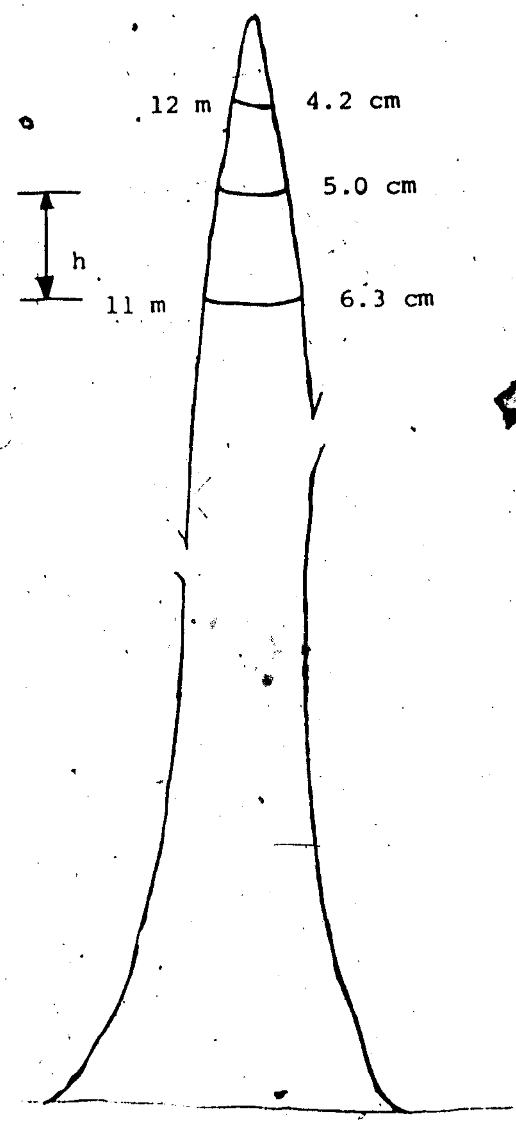


Figure 1: An illustration of determination of height to 5.0 cm top overbark diameter.

$$h = \frac{1.3}{2.1} \times 1 = 0.62$$

So height to 5.0 cm top diameter is 11.62 m.

III. Estimation of Total Tree Volume

A. Introduction

Individual tree and stand volume equations are essential quantitative tools in forest management (Aguirre-Bravo and Smith 1985). These equations are critical elements in inventory systems and growth and yield estimation procedures (Clutter et al. 1983).

Since it is not practical to carry out direct measurements of individual tree volumes in daily forest mensuration work, indirect methods of estimating volume are needed. Of the various methods available, the volume table method is perhaps the most important, both by reason of the length of time that volume tables have been used and their almost universal application (Spurr 1952). The objective of a single tree volume table is to predict accurately the total volume of a tree, without felling it, using measurements that can be obtained accurately, easily and cheaply (Philip 1983). Many independent variables have been incorporated into regression equations for predicting tree volume, although measurements of stem diameter and height tend to account for the greatest proportion of the variability in volume (Avery 1975).

Tree volume is usually considered to be a function of tree diameter at breast height (DBH), height (ht), and sometimes an expression of tree form (Avery 1975, Husch et al. 1982, Clutter et al. 1983). However, tree form is a difficult variable to describe and there is often a high degree of variability in form, both within and between species (Honer 1965, Avery 1975). Clutter et al. (1983) gave four reasons that make form undesirable in volume estimation equations. These are:

1. Measurement of upper stem diameter is time consuming, expensive and subject to large errors.
2. Variation in tree form has a much smaller impact on tree volume as compared to diameter and height.
3. With some species, form is relatively constant regardless of tree size.
4. In other species, form is often correlated with tree size, so that DBH and height variables often explain much of the variation caused by the form difference.

Generally, three types of volume functions have been used to predict individual tree volume. In simplified form, these are

- Volume = f(dbh)
- Volume = f(dbh, ht)
- Volume = f(dbh, ht, form).

The first type of relation is referred to as a local volume function and requires only DBH as the independent variable. The term local is used because the resulting functions are restricted to the locale for which the height-diameter relationship is relevant (Husch et al. 1982). The second relation, referred to as the standard volume function, has DBH and height as the independent variables (Avery 1975, Husch et al. 1982, Clutter et al. 1983). Standard volume functions, in one form or the other, are the most common and widely used type of volume functions. Finally, form class volume functions require three independent variables: DBH, height and form. These functions may be more accurate and applicable to larger areas than the other two (Behre 1927). However, owing to the limitations cited earlier, these tables are less common and are not given further consideration in this study.

To derive the most appropriate volume equation from the two types of volume functions for eucalypts, two comparisons were made:

Comparison 1: Compare the alternative equations among local and standard volume functions.

Comparison 2: Compare the Schumacher logarithmic form, equation (10 below), with the currently used model.

The first comparison was carried out to arrive at an appropriate equation for volume prediction for eucalypts in the study region, depending on the measurements available. For other eucalypt species, equations based on either DBH only or DBH and height and their interactions as independent variables have been used (Jacobs 1981). No comparison of alternative models have been reported previously for this species.

For *Eucalyptus saligna/grandis*, the logarithmic transformed equation (Schumacher and Hall 1933), has been fitted both in Kenya (Wanene 1986) and in South Africa (Schonau 1971, Bredenkamp 1982). In Bredenkamp's (1982) study, subdivision of the trees into various diameter classes was found to improve the accuracy of prediction. The trees were divided into below 20 cm, 20 to 40 cm, and above 40 cm diameter classes. Since the tree sizes in the study reported here ranged from 15 to 30 centimeters DBH, grouping them into one group was appropriate.

The second comparison tries to assess how reasonable it is to use the existing volume equation within present forest management practices. The planting of eucalypts in the study area is being intensified to cover at least 25% of all plantation areas. In development of the previous volume equation, out of 553 trees, only 32 were sampled from this region. Of these 32 trees, 24 were coppice. Further, the two plantations from which the 32 trees were sampled were 13 and 24 years old. The use of this equation in stands that are to be harvested by age 10 needs to be verified.

B. Methods

To assess the local and standard volume functions, 10 commonly applied equations were fitted on 315 trees to test the equations ~~for~~ suitability. The local volume functions tested were:

$Vol = b_0 + b_1 dbh^2$ ---------------------------------(1)

(Kopenzky-Gehrhardt cf. Higuchi and Ramm 1985).

$Vol = b_0 + b_1 dbh + b_2 dbh^2$ -------------------------(2)

(Cunia 1964).

$Log(vol) = b_0 + b_1 log(dbh)$ -------------------------(3)

(Bruce and Schumacher 1950).

where:

Vol = total tree volume (m^3)

dbh = diameter at breast height (cm)

log = logarithm to base 10 and

b's = regression coefficients.

The standard volume functions fitted, which were linear, linear transformed and nonlinear functions are listed below:

$Vol = b_0 + b_1 dbh^2 ht$ ---------------------------------(4)

(Combined variable, Spurr 1952)

$Log(vol) = b_0 + b_1 log(dbh^2 ht)$ ---------------------(5)

(Logarithmic combined variable, Spurr 1952)

$Vol = b_0 dbh^{b_1} ht^{b_2}$ --------------------------------(6)

(Schumacher and Hall 1933)

$Wtvol = b_0 dbh^{b_1} ht^{b_2}$ ---------------------------(7)

(Furnival 1961)

$Vol = b_0 dbh^2 ht$ ---(8)

(Constant form factor, Spurr 1952)

$Vol = b_0 (dbh^2 ht)^{b_1}$ ---------------------------------(9)

(Spurr 1952)

$Log(vol) = b_0 + b_1 log(dbh) + b_2 log(ht)$ -----------(10)

(Schumacher and Hall 1933)

where:

Wtvol = volume divided by (diameter squared times height)

ht = total height (m)

Equation (7) is equivalent to (6) weighted by diameter squared multiplied by height and equation (2) is a quadratic expression (Cunia 1964). Equations (3), (5) and (10) are logarithmic transformations, initially developed so a linear regression procedure could be used (Spurr 1952). Equation (4) uses diameter squared times height as the independent variable and is similar to equation (8) except that the latter is forced through the origin. Equations (6), (7) and (9) are nonlinear but have equations (10) and (5) as their linear form excluding equation (7). The currently used equation is similar to equation (10), but its coefficients were obtained using data with the drawbacks mentioned earlier.

According to (Philip 1983), before models can be included for further analysis, they must comply with the basic conditions:

- the variance ratio (F) must be significant at
- the chosen level of probability,
- a plot of residual must exhibit,

  a. no bias;

  b. constant variance.

Linear equations were fitted to the data using the Minitab statistical package (Ryan et al. 1976), and the nonlinear equations using the BMDP package (Dixon 1979).

Honer (1965) used two factors for evaluating volume functions. These were simplicity and accuracy. He defined simplicity as: the relationship between dependent and independent variables should be linear and the assumptions concerning homogeneity of variance should be satisfied.

Accuracy was defined as predicted volume errors being consistent and relatively independent of tree size. With the use of the computer, the requirement of linearity is not a necessity. Grey (1983) indicates that the main aim of model building is to achieve (i) a high coefficient of determination, (ii) a low standard error of estimate, and (iii) to match predicted to measured values as closely as possible with the smallest number of easily measured, readily comphrensible, independent variables. The statistics necessary to evaluate the functions should therefore be the sum of squared residuals and their distribution with respect to predicted values, and the performance of the equations when applied to independent data.

To carry out the first comparison, the coefficient of determination (R^2), the plot of residuals and the standard errors of equations with the same form of dependent variables were compared (Burley et al. 1972, Johnstone 1976). For equations with transformed dependent variables, values of R^2 and standard errors could not be compared with those of untransformed functions. The standard errors of the logarithmic and weighted equations were therefore calculated directly from observed and predicted values of the dependent variable as shown below:

$$Se = SQRT\left(\frac{SUM((Y - Y')^2)}{n - m}\right)$$

where:

Se = standard error

SQRT = square root

Y and Y' = observed and predicted values of dependent variable

n = number of observations

m = number of regression coefficients in the model.

Similarily, an estimated coefficient of determination (R^2) was obtained directly from

$$R^2 = \left(\frac{SST - SSR'}{SST}\right) \times 100$$

where:

SST = sum of squares of untransformed Y

$SSR' = SUM(Y - Y')^2$ (Johnstone 1976).

To assess the second comparison, a subsample of 50 trees was selected randomly from the original 365 trees sampled. Using coefficients of equation (10) and those of the currently used function, two sets of volume estimates for the 50 trees were obtained and compared using a paired t-test (Freese 1967). The test was performed between the estimated volumes and the actual volumes and between the two estimated volumes.

C. Results and Discussion

Local Volume Functions

The regression results for the three equations (1), (2) and (3) are listed in table 3. The standard errors expressed as percentage of average tree volume ranged between 28.0% for equation (2) and 28.5% for equation (1). The coefficients in every equation are significant. The R^2 values in all cases are greater than 85 percent. Plots of

Table 3: Regression Coefficients, R^2(adj) and Standard errors for Local and Standard Volume Functions.

Equation	Coefficient			R^2	Se	Ranking
	b_0	b_1	b_2			
1	-0.078296	+8.8397E-4		86.6%	0.06959	9
2	+0.05503	-0.013596	1.2072E-3	86.9%	0.06869	8
3	-4.[illegible]63	+2.66947		86.6%*	0.06964*	10
4	+7.869E-3	+3.085E-5		95.7%	0.03926	5
5	-4.35193	+0.96242		95.7%*	0.03950*	6
6	+3.05088E-5	+1.73292	1.27843	96.3%	0.03665	1
7	+4.52659E-5	-0.245086	0.127899	96.1%*	0.03779*	2
8	+3.14905E-5			95.7%	0.03956	7
9	+4.174868E-5	+0.970716		95.8%	0.03915	4
10	-4.34442	+1.75657	1.12342	96.0%*	0.03830*	3

* empirically computed R^2 and standard error.

residuals versus predicted volume from equation (1) and (2) indicated variance of volume increased with increasing tree sizes. The logarithmic transformed equation (3), yielded a more constant variance with no obvious systematic trend.

Equation (3) showed a standard error and R^2 nearly the same as that of equation (2), but its residual plot showed a better distribution and at zero diameter, unlike the other, predicted no volume. (See appendix 1a for a comparison of residual plots from equations (2) and (3)).

Equation (2) had an intercept term of 0.05503 m³, hence the equation overestimated the volume of small trees and is not very reliable. With equation (3) passing through the origin, it gives a reasonable prediction for small trees. The fact that the standard error is larger than that of equation (2) may imply that equation (yields a poorer prediction for large trees, although this was not determined. The question of which equation is most appropriate depends on the trees being considered, but from a practical point of view, either of these two could be applied.

To evalaute how well equations (2) and (3) predict volume, both equations were used to predict volume for the trees in the independent data set. These predicted values were compared to actual tree volumes and were evaluated based on R^2 values and standard errors (table 4). The values of these two statistics again indicated that equation (2) was more appropriate than equation (3), although the

Table 4. R^2 and Standard error for equations (2), (3), (6), (7) and (10) on independent data.

Equation	R^2	Standard error
2	78.00%	0.08808
3	77.75%	0.08939
6	96.30%	0.03804
7	95.98%	0.03964
10	95.89%	0.04008

difference was relatively very small.

Standard Volume Functions

The regression results for the seven standard volume functions, (4) to (10) are listed in table 3. All of the equations performed well based on standard error and R^2. The standard errors of the seven equations expressed as percentage of average tree volume ranged from 15.0% to 16.7%. R^2 values for all equations were greater than 95%. The ranking of the equations based on both standard errors and R^2 values is shown in table 3.

Comaprison of the three nonlinear equations, (6), (7) and (9) indicated that equation (6) was the most appropriate with the lowest standard error and highest R^2 value, although the difference of these two statistics between equations (6) and (7) was quite small. Comparing the plot of residuals and assuming the same assumptions hold as for linear relationships, all equations, with an exception of (7), showed increasing variance. Equation (9) also had a larger standard error and smaller R^2 than the other two.

Equations (4) and (8), the linear equations, were ranked lower than the others and suffer from increasing error variance with tree size. Among the two, equation (4) was more appropriate with a lower standard error and higher R^2 than equation (8). However, equation (8) was more realistic in that it has no intercept.

The two logarithmic linear equations were such that equation (10) had both lower standard error and higher R^2

than equation (5). The difference was however very small, as can be seen in table 3, and their plot of residuals are similar.

The three best ranked equations, (6), (7) and (10), are essentially the same model and differ mainly in that (6) is nonlinear, (7) is weighted and (10) is a logarithmic transformed equation. While equation (6) was ranked as the best, among the three equations, its plot of residuals suffers from increasing variance (see appendix 1b). Plotting the residuals against predicted volume when both equations (7) and (10) were used to estimate actual volume, an increasing varianee trend similar to that of equation (6) was observed (appendix 1c). Therefore, the statistical benefits of weighting and logarithmic transformation to equalize the variances do not improve prediction capability.

Analogous to the local volume functions, the three equations, (6), (7) and (10) were tested on the independent data. Based on both computed standard errors and R^2, the same ranking for these equations was obtained, with equation (6) having the lowest standard error and highest R^2 followed by equation (7) and finally (10). Therefore, among the individual tree volume functions, (6) [illegible] the most appropriate for prediction purposes. Table [illegible] shows the results of these comparisons.

If weights are not applied and the assumption is made that variances are equal, when in fact they are not, the regression technique will place more emphasize on large residuals and result in a good fit for those trees associated with the large variances and *vice versa* for small trees (Honer 1965). This is, however, consistent with the useage of tree volume functions, which are typically for larger trees associated with large variances.

Assuming the data used in this study are representative, then the conclusions drawn by Furnival (1961) and Cunia (1964) that increasing variance causes inefficient estimation of parameters apparently does not apply to the prediction capabilities of equation (6). Therefore, the weighting or the logarithmic transformation of equation (6) could be justified from statistical but not from a prediction point of view.

To carry out the second comparison, the values of coefficients for equation (10) and the currently used equation in Kenya listed below were compared. The coefficients are:

	equation (10)	existing equation
b_0	-4.34442	-4.3687
b_1	1.75657	1.8139
b_2	1.12342	1.1111

The differences between these coefficients are numerically small and when expressed as percentages are 0.56%, 3.26% and 1.11% respectively. However, when the two equations were used to estimate volume of an independent data set, a paired t-test revealed that the two were significantly different with a computed t-value of 12.959 compared to a tabular t-value of 2.009 at a 95% confidence level. A t-test between actual volumes and the estimated volumes from the existing equation showed a significant difference with a t-value of 3.41. The t-test between actual volume and equation (10) estimates was insignificant with a t-value of 0.013.

The equation developed in this study estimated a smaller volume than the currently used equation in all cases. The smaller volume, expressed as a percentage of the other, ranged between 91.0% and 96.0% with an average of 93%. The deviations from the actual volume were larger for the currently used equation than equation (10). Listed below is the total volume of 50 trees and estimates of the total from the two equations with their respective deviations.

	Total Volume (m^3)	Deviation (%)
Previous Equation	13.344	+7.3
Actual Volume	12.244	
Equation (10)	12.114	-1.1

D. Conclusion

Overall, standard volume functions are more accurate than local volume functions. Of the standard volume functions examined, the weighted nonlinear equation (7) or the logarithmic equation (10) were the best choice for volume prediction from a statistical point of view. If predictive power is of primary importance and increasing variance with tree size is ignored, the best choice among the functions fitted is equation (6), with the smallest standard error. It should, however, be noted that the differences among either local or standard volume functions considered separately is very small for all practical purposes.

The equations derived in this study are more accurate than the currently used tree volume equation. In the study region where plantations are currently being harvested at age 10, the derived equation should therefore be adopted if accurate estimates are to be obtained. Based on Bredenkamp's (1982) and Honer's (1965) studies, two points are noteworthy. The equations developed in this study are based on a well defined population and their utilization outside of this population should be verified. Also if applied to trees with DBH's greater than 30 cm, the equations may introduce some bias and thus should be applied cautiously.

IV. Estimation of Merchantable Volume

A. Introduction

Merchantable volume is the portion of the main tree stem volume within specified utilization limits. The relationship between merchantable volume and diameter and height differs from that of total volume and these same variables. Therefore, the equations derived in the preceding chapter cannot be applied without correction to the problem of merchantable volume estimation.

Four general methods have been used to estimate merchantable volume (Cao et al. 1980, Philips 1983):

1. Direct measurement, ie. ~~scaling,~~ of felled trees.
2. Integration of taper functions.
3. Regression of merchantable volume with DBH and height.
4. Adjustment of total volume using a ratio of merchantable to total volume. The ratio is estimated as a function of DBH and height, such as:

$$MR = f(dbh, ht) = \frac{\text{merchantable volume}}{\text{total volume}}.$$

The first method is usually too costly to apply routinely but is used to provide data required in the last two methods. The taper function method was not considered in this study even though it allows for any definition of merchantability. In Kenya, the limit of merchantability is fixed and unlikely to change.

This study deals, therefore, with application of the last two methods using several models for each and comparing the performance of the best models between the two methods. While the third method has been applied for other eucalypt species (Jacobs 1981), only the fourth method has been used for Eucalyptus grandis/saligna in Kenya (Wanene 1986). Unfortunately, the ratio that was derived may currently be of limited utility as it was based on data whose age range was above the normal current harvesting age.

To carry out the evaluation between the third and fourth method, the following comparisons were done:

Comparison 1: Compare the difference in accuracy of estimated merchantable volume among the merchantable ratio and merchantable volume equations.

Comparison 2: Compare the merchantable ratio and merchantable volume equations.

B. Methods

Based on past studies of eucalypts and, also, the literature concerned with volume estimation of a given portion of stems, several merchantable ratio functions were fitted to the sample data. These functions were:

$$MR = b_0 + b_1 e^{b_2 dbh} \quad \text{------------------------} (1)$$

(similar to the currently used ratio, Wanene 1986).

$$MR = (1 - b_1 dbh^{b_2}) \text{ ---------------------------------- } (2)$$

(Clutter et al. 1983)

$$MR = 1 - e^{b_1 dbh} \text{ ---------------------------------- } (3)$$

(Ratkowsky 1983)

$$MR = \frac{1}{1 + b_1 e^{b_2 dbh}} \text{ ---------------------------------- } (4)$$

(Logistic, Ratkowsky 1983)

$$MR = 1 + b_1 e^{b_2 dbh} \text{ ---------------------------------- } (5)$$

(restriction of (1) to $b_0 = 1$ and $b_1 < 0$ $b_2 < 0$)

where:

MR = merchantable ratio

dbh = diameter at breast height (cm)

b's = regression coefficients

e = base of natural logarithm.

Equations (1) and (5) are similar except that equation (1) has more flexibility than equation (5). The two are similar to an equation developed earlier for eucalypts in Kenya (Wanene 1986). In equation (1), b_0 should be close to 1 while b_1 and b_2 must be less than 0 if a ratio less than 1 is to be predicted. In equation (5), b_0 is equal to 1, and both b_1 and b_2 should be less than 0 to estimate a ratio less than 1.

Equation (2) is a rearrangement of an equation given by Clutter et al. (1983, page 9, equation [1.12]). Equation (3) and (4) are growth equations that have been applied in growth studies elsewhere (Ratkowsky 1983). While b_1 in equation (3) must be less than 0, in equation (4) b_1 must be greater than 0 and b_2 less than 0, if ratios between 0 and 1 are to be estimated. The testing of these two equations in this study was initiated because the merchantable ratio versus dbh plot was asymptotically approaching 1. Although the above restrictions are theoretical, no restrictions were applied when fitting the equations to the data, and therefore their values were empirically determined.

To estimate merchantable volume directly, use of merchantable rather than total height logically increases the precision of the estimates (Spurr 1952). However, there is usually more error associated with the determination of the merchantable height than total height on standing trees. Consequently, only total tree height was considered in this study.

The following merchantable volume equations were fitted to the data, mainly because of their better fit in total volume estimation:

$$Log(vol) = b_0 + b_1 log(dbh) + b_2 log(ht) \text{ ------------ (6)}$$

$$Vol = b_0 dbh^{b_1} ht^{b_2} \text{ ------------------------------ (7)}$$

where:

Vol = merchantable volume

ht = total tree height

log(vol) = logarithm to base ten of volume.

To carry out the first comparison, equations (1) to (5), and equations (6) and (7) were compared using standard errors, R^2 and analysis of residuals. In assessing the second comparison, the best equation from each of the two methods were compared. The regression coefficients of the two equations were used to predict merchantable volume of 50 randomly selected independent trees and their estimates compared using a paried t test (Freese 1967).

C. Results and Discussion

The ratio equations had very small differences in their merchantable ratio prediction. The actual merchantable to total volume ratios ranged from 0.905966 to 0.998756. Equation (1) had predicted ratios ranging between 0.919525 and 0.997521. Equation (2) had ratio values ranging from 0.920371 to 0.997878. Equation (3) ratios varied from 0.892485 to 0.999929 and those of equation (4) from 0.925988 to 0.999601. Finally equation (5) ratios ranged from 0.939349 to 0.999750 which is close to the range for equations (2) and (4). The regression results and parameter estimates of the five equations are given in table 5.

Among the five ratio equations, (1), (2), (4) and (5) are only slightly different. However, equation (1) is more precise than the rest as determined by the computed R^2 and standard error. Equation (3), is less precise but has the

Table 5: Regression results for the merchantable ratio and volume equations.

Equation	Coefficient			R^2	Se
	b_0	b_1	b_2		
1	0.997576	-0.516567	-0.228471	77.5%	0.0065813
2		21.347681	-2.598486	76.5%	0.006726
3		-0.273747		69.2%	0.007676
4		0.464744	-0.209027	77.0%	0.006644
5		-0.411710	-0.202457	77.1%	0.006633
6	-4.40822	1.79003	1.13563	96.0%	0.03813
7	2.850412E-5	1.74208	1.28893	96.3%	0.03691

least number of regression coefficients to work with. This may be the cause of the reduced precision.

The plot of residuals for both equations (4) and (5) are similar for all practical purposes. However, in the two equations, when both predicted and actual merchantable ratio were plotted against diameter at breast height, there was overestimation of ratios for trees with DBH greater than 24 cm. The plot of equation (3) showed a slight underestimation of the ratio for small trees and overestimation for larger trees similar to equations (4) and (5). The plots of equations (1) and (2) were similar and also acceptable, with no trend in overestimating or underestimating of the ratio, however, within the range of tree sizes in the data. Therefore, to choose from equations (1) and (2), both R^2 and standard error had to be rel[illegible]on, which led to the choice of equation (1) (table 5).

The merchantable volume equations used dependent variables with different scales and so could not be directly compared. Equation (7) suffers from an increasing variance trend, but has a higher R^2 and lower standard error than equation (6) (table 5). When using the results of these equations to predict merchantable volume of a set of independent data, equation (7) yields a lower sum of squares of residuals, which implies that it is more appropriate than equation (6). The fact that the two equations are the same, differing only in that one is nonlinear and the other logarithmic transformed, can be seen in the small differences between their R^2 and standard error values (table 5).

Predicted merchantable volume using equations (1) and (7) were computed for a set of independent data and R^2 and standard errors were calculated using the formulas given by Johnstone (1976). A paired t-test was also carried out between each of the two sets of estimated merchantable volumes and the actual merchantable volume of the independent data. The results from these comparisons are:

	St. error	R^2	t-value
Equation (1)	0.042875	95.09%	0.28 (ns)
Equation (7)	0.039028	95.93%	0.04 (ns)

Equation (1) is based on the estimates of both the ratio equation and total volume estimates from equation (6) of chapter 3.

From the above results, the difference between the estimates from the two equations are not significantly different from the actual merchantable volumes, although the merchantable volume equation is just slightly better than the ratio equation. This finding is not unexpected. The ratio equation is based on two approximations, whereby, the errors associated with the estimation of total tree volume are incorporated in the merchantable volume estimation using the ratio function. In contrast, the merchantable volume equation utilizes the actual values which have no previous estimation errors involved.

If the ratio function is utilized, it is appropriate since the merchantable volume is solely reliant on the total volume and therefore, will always be smaller than the total volume. This condition does not exist with the merchantable volume equations. Finally, the merchantable volume ratio method is currently used in Kenya for other species and, therefore, is more compatible with present volume estimation methods.

D. Conclusion

Although the accuracy in estimation of merchantable volume using a merchantable volume function should be higher with use of merchantable height (Spurr 1952), in the field its measurement is difficult (Husch et al. 1982) and usually not practical. Presently, the trend is towards constructing volume tables that predict total volume and deriving from these tables volume to specified top diameters (Philip 1983). This may suggest selection of a ratio equation instead of the merchantable volume equation. The comparison of ratio and merchantable volume equations indicated no significant differences.

Application of a merchantable ratio equation for merchantable volume estimation is an ongoing exercise in the Kenyan forest department. For other commercial species similar merchantable ratios have been in existence for the last 10 years (Wanene 1986). The current merchantable ratio equation for eucalypts in Kenya was based on this same data, collected on mature trees of different generations, species and from very diverse sites. The use of this function is consequently questionable and should be tested.

In this study, only a single top diameter was considered, which may appear as a drawback. However, different utilization standards are not anticipated for the following reasons. In the first place, higher utilization standards would mean total removal of the trees which may have detrimental effects on the sites when associated with the fast growth rate of the species. Secondly, considering that the growth rate is high, the top section of the tree is composed of very young material which is of little use except as fuelwood. Finally, it is the policy of the Kenya forest department that tree tops with diameters less than 5 cm should not be removed for any purpose from the logging site. Therefore, the ratio developed here is adequate and should be adopted in the study region.

V. Regional Differences

A. Introduction

One shortfall of the existing tree volume equation for eucalypts in Kenya has been the inclusion of data without validation from a variety of sources. So far, this study has assumed that all five forest regions from which the data were collected are similar. Bruce and Schumacher (1950) suggest that if the trees being estimated for volume are of the same form in all the forest regions concerned, then prediction of volume using standard volume functions should result in minimal errors. However, they also point out that this is rarely the case and experience elsewhere (Bredenkamp 1982) has shown that there may be significant differences between stands and/or regions.

Therefore, before a single equation can be adapted for the whole area, the similarity of the regions should be tested. To achieve this, the following hypothesis was advanced and tested:

> Hypothesis: There are no significant differences between the five forest regions once variation due to diameter and height has been controlled.

This hypothesis could be broken down into two questions:

1. Are separate equations fitted for each forest region the same?
2. If the above question is answered in the negative, where do the regional differences

occur?

B. Methods

The hypothesis that there were no differences between the forest regions was tested on the logarithmic function (equation (10) of chapter 3). Although the function was not the best as shown earlier, it was selected because it provided a better basis for statistical tests. To facilitate comparisons, indicator variables as defined below were introduced into the equation:

$$\text{Log(vol)} = b_0 + b_1\log(\text{dbh}) + b_2\log(\text{ht});$$

to include effects due to regional differences. The expanded form is:

$$Y = b_0 + \text{SUM}(b_i Z_i) + b_5 X_1 + \text{SUM}(b_{i+5} Z_i X_1) + b_{10} X_2 + \text{SUM}(b_{i+10} Z_i X_2)$$

where:

Y = log(vol)

X_1 = log(dbh)

X_2 = log(ht)

b's = regression coefficients

Z's = indicator variables such that

Z_1 = 1 when region 1, -1 when region 5, else 0

Z_2 = 1 when region 2, -1 when region 5, else 0

Z_3 = 1 when region 3, -1 when region 5, else 0

Z_4 = 1 when region 4, -1 when region 5, else 0.

With the indicator variables and the model as stated, each region has its own logarithmic function. The equation was fitted to the data using multiple linear regression procedures.

Three multiple partial F tests (Kleinbaum and Kupper 1978, Steel and Torrie 1980) were used to determine whether a single model could be used for the pooled data from the five regions. The null hypothesis was that no differences exist among the regions, while the alternative was that differences do exist.

To carry out the first test, that the equations for the five regions all have the same constant y-intercept, the parameters b_1, b_2, b_3 and b_4 in the expanded equation were set to 0. To test that the five regions have the same coefficient attached to log(dbh), the coefficients b_6 to b_9 were set to 0 and finally, to test for the coefficient attached to the log(ht), b_{11} to b_{14} were set equal to zero and the equation refitted with all of the other parameters. In each case, after assuming regional parameters were equal to zero, the equation was refitted and referred to as the reduced form, as opposed to the original equation which is referred to as the full equation. The F value was subsequently computed as:

$$F = \frac{\dfrac{\text{SSE(reduced equation)} - \text{SSE(full equation)}}{\text{number of b's put to zero}}}{\text{MSE(full equation)}}$$

This F value was compared with the critical tabular F value:

$F_{(m,\ n,\ a)}$'.

where: m = number of b's put to zero

n = degrees of freedom for the full equation

a = confidence level.

The coefficients for the different regions were significantly different if the computed partial F value was greater than the critical tabular F value.

If significant differences were found in the above tests, either Scheffe's or the Bonferroni method could subsequently be used to do pairwise comparison of the coefficients of the different forest regions. The choice of which test to use depends on which one provides the stricter limitations (Neter et al. 1985). These tests use the notation:

$$S^2 = (r-1)F_{(1-a,r-1,N-r)}$$

$$B = t(1-\frac{a}{2s},N-r)$$

where: S = Scheffe's constant

B = Bonferroni constant

r = number of independent populations

N = total number of observations

a = confidence level

s = number of comparisons being made.

While the two tests described above are generally conservative relative to other tests, they were preferred because of unequal sample sizes (Kleinbaum and Kupper 1978). To decide the test to apply, if necessary, both S and B were calculated using the individual tree volume data. At a confidence level of 95%, S was computed and found to be

3.079 while B was 3.612 which thus meant Scheffe's test was to be used if required. The difference between the coefficients is significant when:

$$\frac{| b_i - b_j |}{SQRT(S^2_{b_i} + S^2_{b_j})} \geq S \quad \text{(Neter et al. 1985)}$$

where: S = Scheffe's constant

b_i, b_j = coefficients to be compared

$S^2_{b_i}$, $S^2_{b_j}$ = the coefficients variances

SQRT = square root.

A confidence level of 95% was used in all the comparisons.

C. Results and Discussion

All the multiple partial F tests carried out were rejected implying some differences existed between each of the three coefficients among the five forest regions. The computed F values were 3.2097, 2.5934 and 8.6865 for a common intercept, common log(dbh) coefficient and a common log(ht) coefficient respectively. These F values were all greater than the critical F value 2.40. Therefore, pairwise comparison of the forest regions was required.

Kaptagat forest (region 4) had an intercept term that was barely significantly different from that of Penon forest (region 5) with an S value of 3.088. All the other pairwise comparisons of the the intercepts were not significantly different from each other. The slope coefficient attached to log(dbh) term was also barely significantly different between Sabor forest (region 3) and Penon forest with an S value value of 3.1165. Finally the coefficient attached to log(ht) term was found significantly different between Penon forest and three other forests. These are Turbo forest (region 2), Sabor and Kaptagat forests, with S values of 4.0199, 4.4121 and 5.5784 respectively. Therefore, except for the b_3 coefficient, which was significantly different between the three forest regions and one more (Penon), the other two coefficients were barely different at the 95% confidence level (compare 3.088 with 3.079 and 3.1165 and 3.079).

All the significant differences were between Penon and some other forest region. With no difference between the other regions, the pooling of their data may be acceptable, while Penon should have a separate tree volume function. Table 6 shows the statistical results of fitting data for each region.

The above results were not expected mainly because the regions are geographically close to each other. Similar results, however, have been reported elsewhere (Geary et al. 1983) where eucalypts are being grown as exotics. Geary et al. (1983) found that within short distances in the same stand, slight soil differences were responsible for the differences in growth rates which consequently may also have had some influence on the tree forms.

Table 6: Regression Results of equation (10) for separate forest regions.

Forest	Coefficients			R^2	Se
	b_0	b_1	b_2		
Kapsaret	-4.23294	1.67111	1.[illegible]	98.4%	0.02967
Turbo	-4.43593	1.77166	1.19[illegible]	99.5%	0.03039
Sabor	-4.27396	1.60493	1.24765	99.0%	0.03285
Kaptagat	-4.51218	1.72111	1.30128	97.1%	0.04801
Penon	-4.21004	1.92933	0.81264	93.1%	0.07220
Combined	-4.34342	1.75551	1.12367	96.7%	0.05829

D. Conclusion

After the variation due to diameter and height differences is accounted for, very little variance remains and, therefore, few regional differences exist. Based on the pairwise comparison of the forest regions, the first four regions could have a common tree volume estimating function. The tree volume function for Penon region. should, however, be separate.

Considering that other factors, such as seed source, silvicultural treatments and tending of the plantations in the first three years of establishment, on top of difference in soils, affect tree growth and form, further studies of these factors should be carried out to determine their effect and consequently reduce the unexplained, though small, variation.

With the availability of computers to estimate tree volumes, whether a single or several different equations for different forest regions are used depends on the accuracy required and the existence of such equations. Therefore, it is possible to estimate tree volume for each region based on an equation derived from data collected within its boundaries and within the harvesting age range, as in table 6.

VI. Stand Yield Prediction

A. Introduction

As yield prediction is required for planning at the forest level, estimates must be available for all significant species, sites and for the range of harvesting ages likely to be encountered (Johnstone 1976, Dempster and Goudie 1984). Future growth and yield of a given forest can be modeled based on two basic approaches: whole stand and individual trees (Clutter et al. 1983, Mathu 1983, Philips 1983). The approach used is largely dependent on the type of data available. In this study, the whole stand approach was considered mainly because there is no growth data for this species of eucalypt in Kenya.

The best way to collect growth data for an even-aged stand would be to monitor its developmental process by periodically taking measurements. An alternative to this is to carry out stem analyses. For this study, due to continuous growth experienced in the tropics and the lack of remeasurement data, the only possible means for obtaining reliable information was to survey stands at different stages of development (Sweda and Umemura 1979). This alternative is complicated by sampling variability and difference in stand characteristics such as density and productivity in addition to growth.

A wide variety of indirect prediction methods based on varying stand parameters has evolved to meet the range of conditions encountered in the forests (Spurr 1952). Among the stand variables applied, the most commonly used are age, site quality and stand density as well as interactions among these variables in a Schumacher type yield model (Curtis 1967b, Murphy and Sternitzke 1979, Murphy and Beltz 1981, Clutter et al. 1983, Borders and Bailey 1986). According to Pienaar and Shiver (1986), the Schumacher model is simple and eminently sensible as a yield function for unthinned stands.

The main difference between this study and others (Curtis 1967b, Borders and Bailey 1986, Pienaar and Shiver 1986) is that temporary plot data are being used. Therefore, projection of various variables in the future is not possible. Consequently, yield in this study will be estimated based primarily on age of the stand, but a stand yield equation based on other measured variables will be included to compare estimates with and without field measurements.

B. Collection of Stand Data

In each forest region, except Turbo, five representative, temporary, fixed area plots were sampled for each existing age class in the region. Age classes varied from 2 to 10 years. For the Turbo region, remeasurement data were used and treated as single-examination data. Fifteen plots were included in the Turbo region data and two measurement points (at least two years apart) were used even when more data was available. Twenty two plots were 0.015 and 8 were 0.04 hectares in this region. From the other 4 regions, 25 plots had an area of 0.02 hectares and the rest were 0.04 hectares. In total, from the five regions, 130 plots were sampled. The age distribution by region is shown in table 7.

The number of stems expressed on a per hectare basis ranged from 425 to 1400. Diameters at breast height (DBH) were measured to the nearest 0.1 cm for all trees within the plot and top height (height of 100 largest DBH trees per hectare - usually 2 or 4 trees per plot), was measured to the nearest 0.5 metres using a suunto clinometer.

The plot data, which were summarized on a per hectare basis, included number of trees, the average top height, age of the stand, basal area and total volume. Height was the average of 2 or 4 largest DBH trees, depending on the plot area. Age of the stand was accurately obtained from the plantation records. Basal area was plot basal area divided by plot area. Likewise, total volume was obtained by dividing plot volume by plot area. Since only a small number of trees were measured for height, a height-diameter relationship for each region was initially established (appendix 2), and applied to all trees in that region to estimate height. The individual tree volume function (equation (6)) developed in chapter 3 was used to estimate individual tree volumes.

Table 7: Plot of stand age distribution by region

	Age								
Region	2	3	4	5	6	7	8	9	10
Kapsaret			5	5	5		5		
Turbo	4	4	5		5	5	8		4
Sabor	5	5	5	5	5		5		
Kaptagat			5	5		5	5	5	
Penon		5	5		5	5	5		

C. Methods

One basic equation form that has been extensively used for yield estimation is the Schumacher-type variable density equation of the form:

$$\ln Y = b_0 + b_1(\frac{1}{A}) + b_2 f(S) + b_3 g(D) \text{ --------------- } (1)$$

where:

Y = yield per hectare

A = stand age

f(S) = some function of site quality

g(D) = some function of stand density

ln (Y) = natural log of Y

b's = regression coefficients

(Pienaar and Shiver 1986).

This equation forms the basis of this study.

Among the predictor variables, age was accurately known, but site quality was not. Owing to the similarity of soil types in the five regions, site quality was assumed to be the same in all regions. Stand density can be expressed in terms of number of trees or basal area per hectare (Bickford et al. 1957, Curtis 1967b). With the latter expression, additional field measurements are required since number of trees can be determined from the initial number of trees planted. Assuming constant planting density and little or no mortality, number of trees would be assumed constant. For these reasons, the initial efforts at modelling yield concentrated on volume as it relates to stand age.

Volume was fitted to age using two different models. Equation (1) was fitted to the data in the form:

$$Ln(Y) = b_0 + b_1(\frac{1}{A}) \text{ -----------------------------------(2)}$$

Equation (2) is based on the axiom from long term studies of plantation yield that have shown that yield increases asymptotically with age (Pienaar and Shiver 1986) and consequently the reciprocal of age. It is also the Schumacher model assuming that site and density are constant.

The second model was based on the Chapman-Richards growth model (Richards 1959):

$$Y = b_0(1 - e^{b_1A})^{b_2} \text{ -----------------------------------(3)}$$

Finally, a nonlinear equation:

$$Y = b_0BA^{b_1} H^{b_2} \text{ -----------------------------------(4)}$$

where:

BA = basal area,

H = top height,

was introduced to compare the strength of prediction relations with and without field measurements. Equation (2) was fitted to the data with the minitab statistical package (Ryan et al. 1976) while the nonlinear equations, (3) and (4) were fitted with the BMDP package (Dixon 1979). These equations were fitted to 105 sample plot data. Twenty five sample plots were withheld as a test data set. While the test data were composed of five randomly selected plots from each region, the age ranged from 2 to 8 years with 3, 9 and

10 year old plantations unrepresented. Also, age 2 was represented by only one plot.

The dependent variables in the equations were not of the same form and therefore both R^2 and standard errors from the transformed equation were directly computed to make them comparable with those of untransformed equations (Burley et al. 1972, Johnstone 1976).

D. Results and Discussion

Equations (2) and (3) provide reasonable predictions of stand yield with R^2 values of 60.6% and 65.8% respectively (table 9). Although the plot of residuals of the two equations indicated wide variation, the plot of equation (2) was more acceptable with less variation.

Considering that these are plantations of young trees, a logical question is: why isn't the relationship stronger? The data correlation matrix, table 8, and plots of volume, basal area, number of trees (density) and height, all related to age (figures 2 and 3) provide a partial answer. The plot of volume versus age (figure 2) shows substantial variability, particularly in the 7 and 8 year old plantations where the range in volume is 150 to 450 and 100 to 300 cubic meters per hectare respectively. Similar trends are evident in the plot of basal area versus age.

Height versus age (figure 3) shows much less variability, although the range increases somewhat in older planations. The surprising result, however, is seen in the

Table 8: Correlation coefficients of the stand variables.

	ln Vol	ln BA	$(\frac{1}{A})$	ln H	ln N	Vol	BA	A	H
ln Vol	1								
ln BA	0.984	1							
$(\frac{1}{A})$	-0.829	-0.784	1						
ln H	0.957	0.922	-0.864	1					
ln N	-0.014	0.121	0.301	-0.158	1				
Vol	0.863	0.840	-0.679	0.825	0.043	1			
BA	0.899	0.921	-0.685	0.840	0.181	0.951	1		
A	0.780	0.716	-0.901	0.813	-0.285	0.775	0.712	1	
H	0.915	0.870	-0.813	0.975	-0.160	0.878	0.860	0.828	1
N	-0.023	0.109	0.316	-0.171	0.988	0.029	0.166	-0.299	-0.176

Table 9 : R^2, standard error, parameter estimates of the yield functions, and their prediction suitability.

Equation	Coefficients			R^2(%)	Se (m^3/ha)	R^2(%)*
	b_0	b_1	b_2			
2	6.4211	-8.8515		60.6	69.92381	6.0
3	456.715093	-0.240674	4.020450	65.8	65.40642	0.0
4	0.512917	0.985742	0.887701	95.2	24.58658	89.0
5	5.5541	-9.4707	0.001072	66.5	64.71128	36.7
6	6.1424	-10.07877	0.000661	70.5	60.79474	26.0

* These are the computed R^2 values when the above results were applied on independent data.

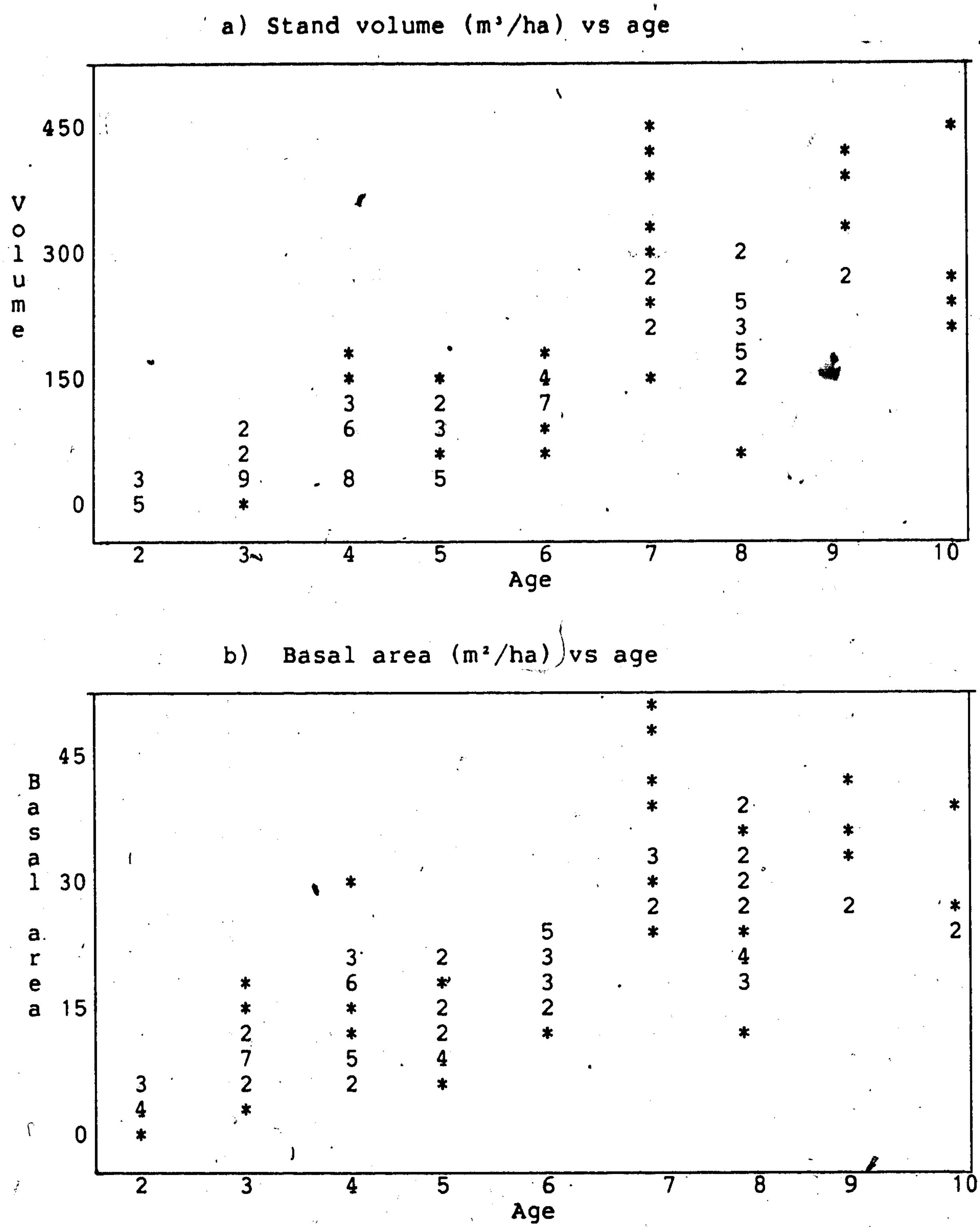
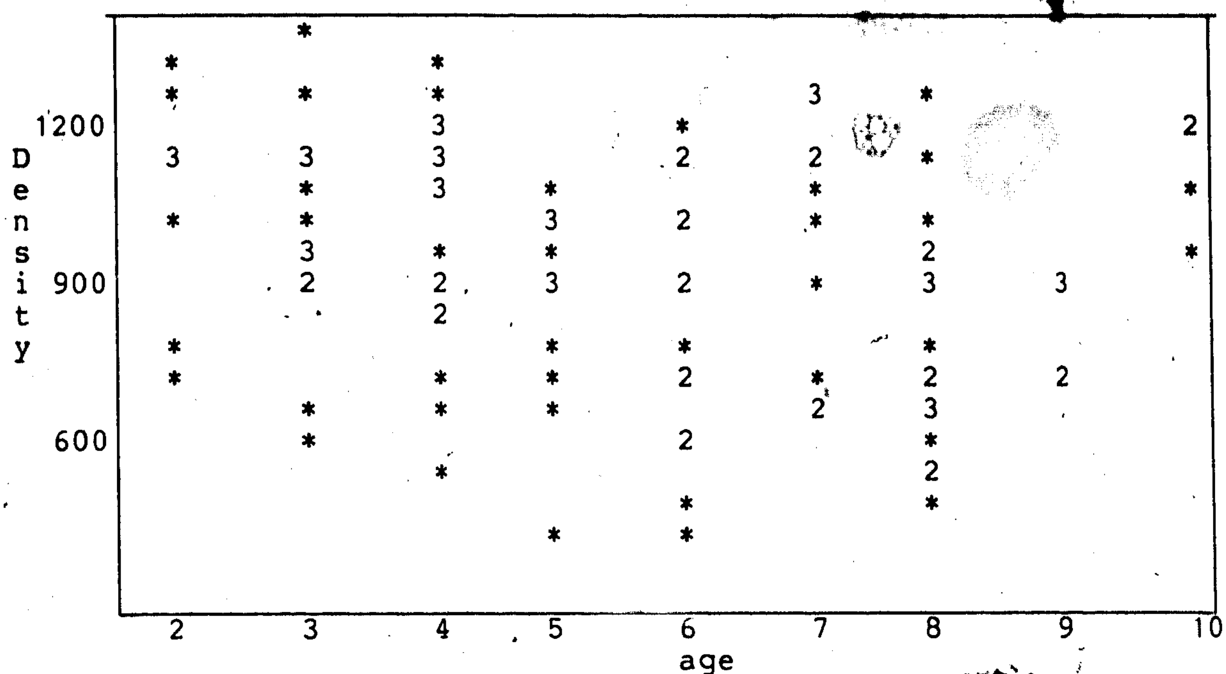


Figure 2. Stand volume and basal area versus age

(a) Density (number of trees/ha) vs age



(b) Height (m) vs age

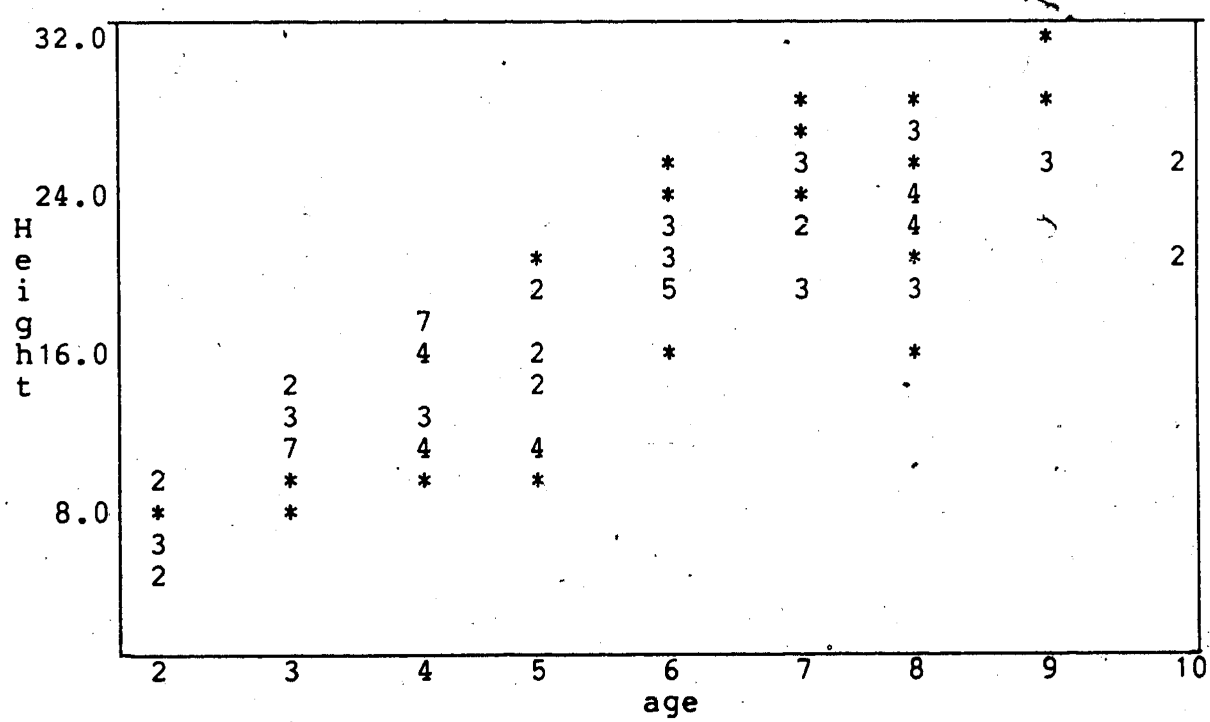


Figure 3: Plot of density and Height against age.

plot of number of trees versus age (figure 3). In spite of the assumption that initial density is constant, the actual density of plantations shows remarkable variability with a range of more than 600 trees per hectare at nearly every age from 2 to 8 years. This is a sharp contrast with what would theoretically be expected with an initial constant planting density of 1450 trees per hectare. This observation combined with the relatively less variability in height suggests that density variation is the major cause for the mediocre relation of volume (and basal area) with age.

As a result of these observations, the assumption of constant density was dropped and the Schumacher equation (both linear and nonlinear form) was fitted to the data including density as a predictor variable:

$$Ln(Y) = b_0 + b_1(\frac{1}{A}) + b_2N \qquad (5)$$

$$Y = e^{(b_0 + b_1(\frac{1}{A}) + b_2N)} \qquad (6)$$

Results in table 9 show only slight, though significant, improvement in the predictive model, since correlation of number of trees with volume is almost zero.

Figure 3 also suggests that height may be affected by density at ages 9 and 10 years. For age 9, the height is high and the density is low as compared with stands at age 10, which have high density and low height. A logical question then is: Is height affected by density? Taking data for age 8 which had the greatest variability, a simple linear relation between height and density was developed to answer the question posed above:

$$Ht = b_0 + b_1 N \quad b_0 = 20.358,\ b_1 = 0.003342.$$

The correlation was not significant between height and density at this age and thus the relation did not answer the above question. Although the correlation coefficient was insignificant, its positive value and therefore the positive slope coefficient (b_1) suggest that height is increasing with density though only marginally. This inference is contrary to accepted theoretical expectations and should be investigated further.

When equations (2) and (3), and (5) and (6) were used to predict yield for the test data, the linear forms of the two types of equations gave better predictions, with equation (5) giving the overall best estimate. This was, however, not expected and was probably due to problems with the test sample, such as, the variability in density, small size of the sample and the poor age distribution.

Equation (4), which was based on basal area and average top height, was far better than the other equations. However, unlike equation (3) which predicts yield with age only or (6) with both age and density, (4) cannot be directly used without field measurements and is thus of limited utility. Therefore, it is apparent that based on the data used, equations (3) and (6) can be used to obtain yield estimates depending on whether density is known or not.

Although the plot data used in deriving these equations originated from different forest regions, no attempt was made to fit separate equations for each region because:

1. The data are limited - 130 sample plots.
2. The data are from temporary sample plots and so the growth process is merely being approximated.
3. The forest regions are geographically close to each other and assumed similar.
4. Volume tables compared in chapter 5 were nearly similar.

E. Conclusion

Overall, the yield function based on age only (equation 3) gave predictions almost as accurate as the one based on both age and density (equation 6). Among these two equations, the first choice for yield estimation is equation 3. This is because, although equation (6) is better than equation (3), it requires a mortality function to estimate density at various ages and this could not be accomplished with the available data. In addition, equation (3) requires no field measurements once age is known and is thus easily applied.

Given physical stand measurements; basal area and top height, stand yield can be accurately predicted using stand volume equations (equation 4), or more directly from the field data itself without using equations. The essence of using equations is to obtain accurate estimates with minimum costs. Stand volume equations (eg. equation 4), although giving more accurate predictions (table 9), require field measurements and thus are not convenient in application.

Curtis (1967b) cited elimination of much time delay inherent in permanent sample plots and reduced costs as some of the possible advantages of applying temporary sample plots as compared to permanent ones. With the observed variation in yield estimation in this study, even with the equation based on measurements such as basal area and top height, the above advantages cannot be justified. Therefore additional work on expanding the permanent sample plot program, already underway, is desirable to obtain good growth data and also to explain or reduce any excessive variation in plantation densities and to quantify mortality relations. It should also form a fair background for studying the long term effect of coppicing the stands for several rotations.

The current management of eucalypts plantations involves planting 1450 seedlings per hectare (a constant density). Mortality after the first growing season is reduced through replanting any spots that have dead seedlings. However, based on the observations made (figure 3), density was highly variable even at age two which indicated a plantation management problem which requires further study. Extrapolation of the results beyond age 10 years is not recommended since the age of sample plots ranged between 2 and 10 years.

VII. General Conclusions and Recommendations

In the previous chapters, various methods for evaluating total volume, merchantable volume and stand yield were assessed. Although many other equations exist for each type of estimate, those presented here are the most common and the ones whose data requirement were met by the available information. Regional differences within the study area were also evaluated.

For total tree volume, standard volume functions, although demanding more field measurements, were more accurate in estimating volume than local volume functions. Among the standard volume functions tested, the nonlinear equation was considered more appropriate than either the nonlinear weighted equation or the logarithmic transformed one. However, differences were negligible and for all practical purposes any of them could be applied.

An evaluation of the accuracy of the existing volume equation for Kenya was carried out and compared to the equation developed in this study. The former was found to be less accurate, when applied to the data from the study area. The major reason for reduced accuracy stems from the data source on which the existing equation was based. On the other hand, the equation derived here may not be appropriate outside the study area without verification and/or modification. This is in conformity with Honer (1965) who indicates that when volume tables are constructed from sample trees that may have been truly representative of a specific tree population, and even when the volume relationship is established by minimizing the sum of squared residuals, the tables are biased by definition when applied to trees outside the specific population from which the sample was drawn.

Schönau (1971) found that bark thickness had a significant effect on the variation of tree volume for Eucalyptus grandis Hill ex. Maiden. He further noted that the difference in volume for the various bark thickness classes could be as large as 15%. A further observation in his study was that bark thickness varied with diameter, environment, age, stand density and seed source. In this study, only overbark measurements were considered. The effects of bark thickness, if any, in the light of the parameters shown by Schonau (1971) should be investigated.

With intensified management of eucalypt plantations, coppice regenerated stands will be a common feature in Kenyan forests in the near future. Although Bredenkamp (1982), studying Eucalyptus grandis Hill ex. Maiden, found there was no difference in form between seedling and coppice regenerated stems, separate individual tree volume functions should be developed for the two types of stems, and compared to justify their separation or pooling.

Merchantable volume was best estimated by a merchantable volume equation but the difference between the merchantable volume and ratio equation was insignificant. Based on the current system and convenience, the ratio equation should be continued as it is adaptable to the current method of volume estimation as done with other commercial species.

The regional differences were quite unusual. One of the regions was distinctly different from the others, although all the regions were close to each other. Based on Geary et al.'s (1983) observations, that significant growth differences were obvious within short distances in eucalypts plantations, and also considering Schonau's observations about bark thickness, further studies are necessary. Detailed soil studies in these and other forest regions are a prerequisite to a better understanding of the forests. Also, seed origin may have some effect on the growth of the various plantations and should, therefore, be incorporated as a predictor variable.

In deriving yield functions, wide variations were evident with all of the equations fitted. One conspicous observation was the wide variation in number of trees for plots at varying ages which could not be easily explained. Basically, this was a reflection of the management practices of eucalypts plantations. To overcome this obstacle, permanent sample plots should be established in young plantations, from which growth can be followed. On top of eliminating the assumed continuous growth process based on temporary plots, the permanent plots would facilitate the understanding of the effect of continued coppicing of the stumps as far as yields are concerned.

For all the equations derived in this study, extrapolation should not go beyond the age of 10 years. This limitation, however, may not presently be significant for most stands, since harvest is likely to occur prior to this age for the various possible end products.

Finally, Burley et al. (1972) point out that volume tables are not static and should therefore be periodically tested against measured trees. As such, during harvesting of the trees of this species, information concerning tree volume estimate and other tree parameters including age and seed source should be collected to facilitate continuous testing of the equations and making any necessary revisions as deemed essential.

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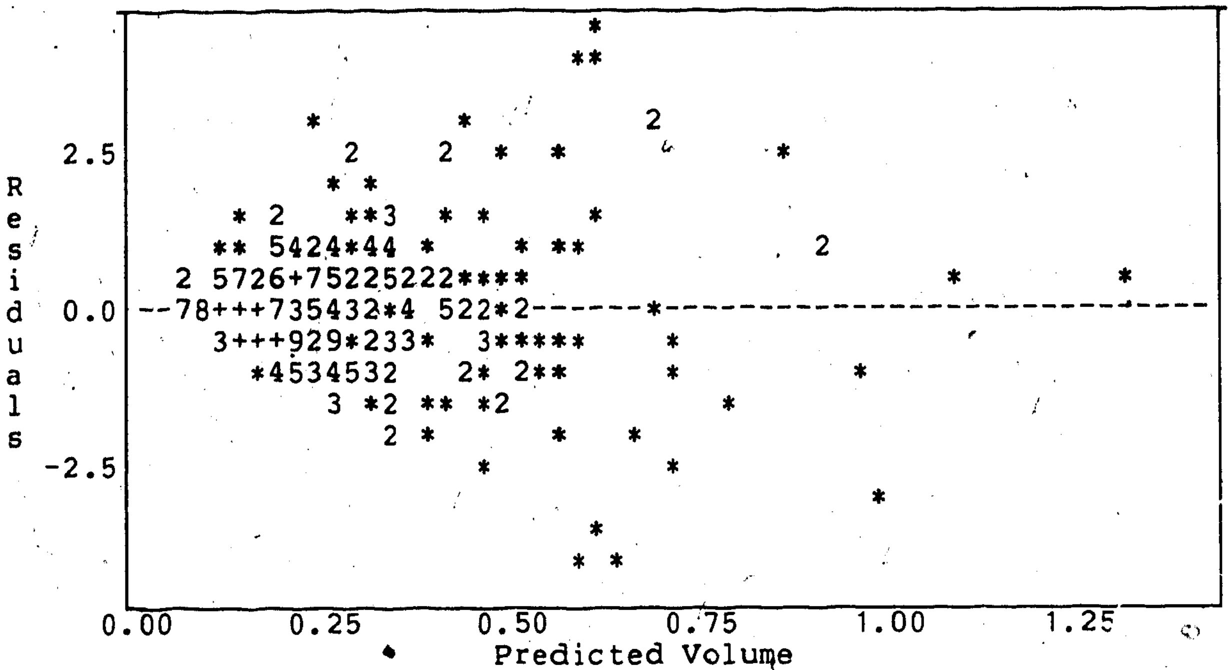
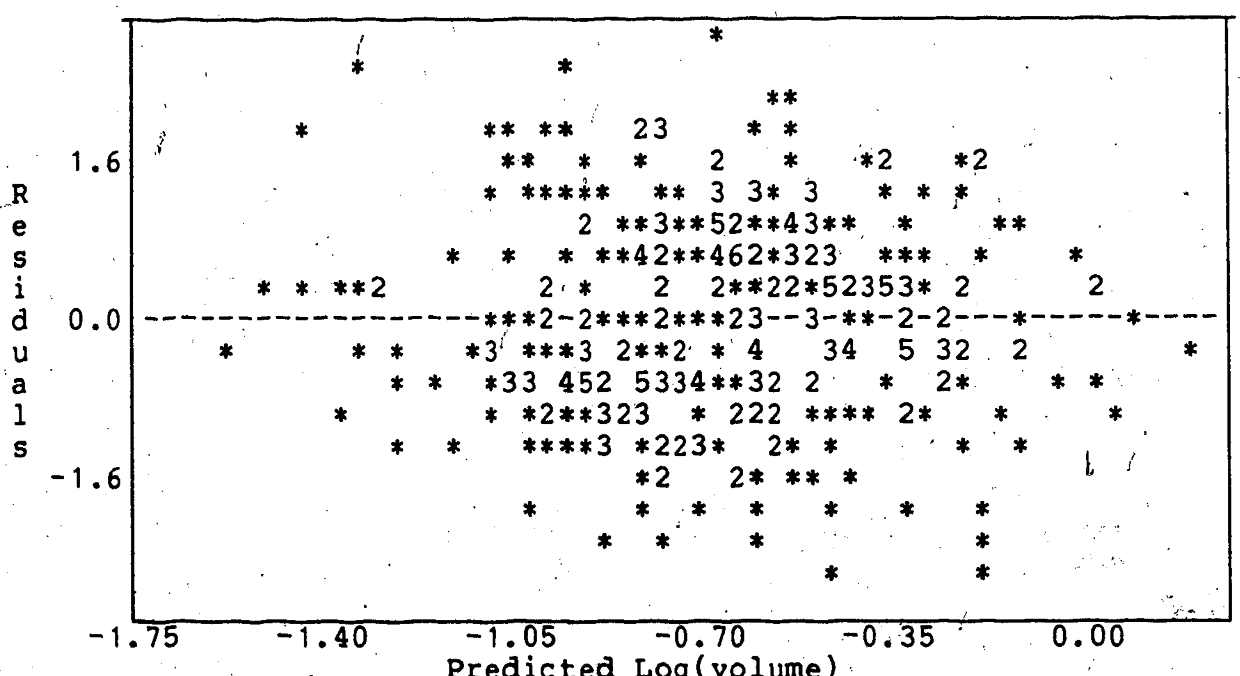
Appendix 1a. Residuals plots for local volume functions

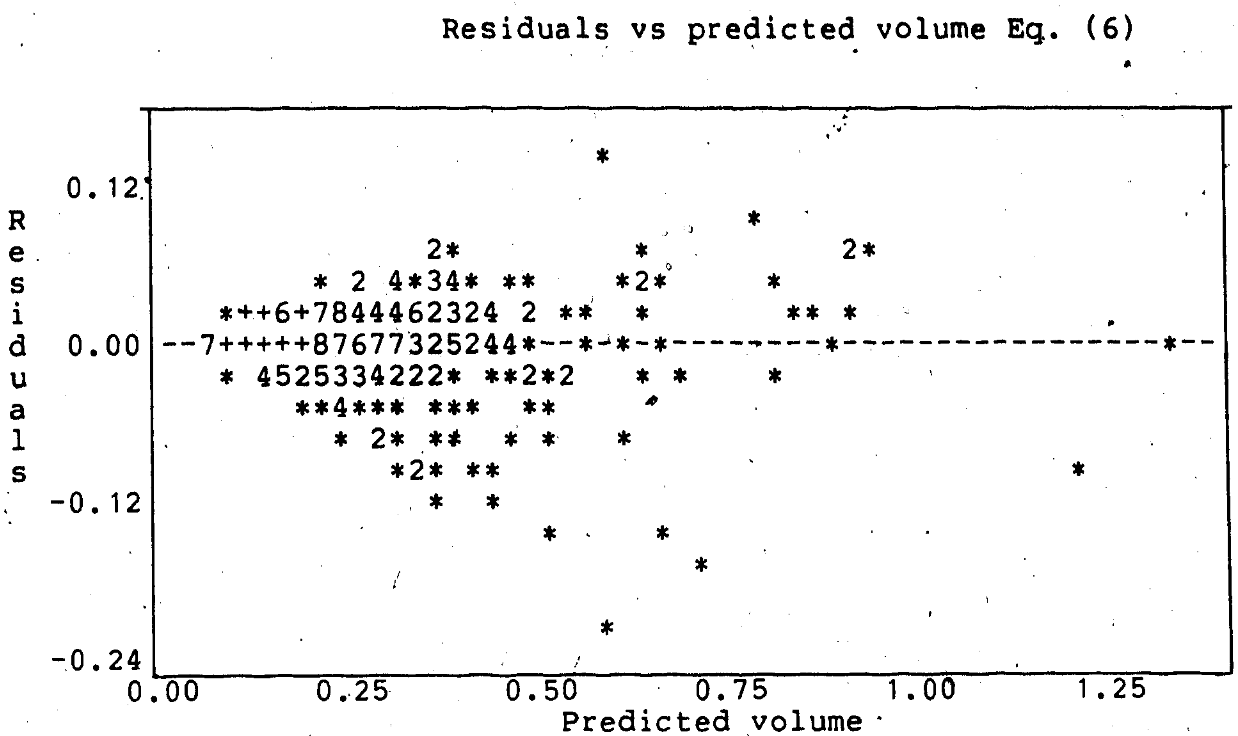
Residuals vs predicted volume Eq. (2)

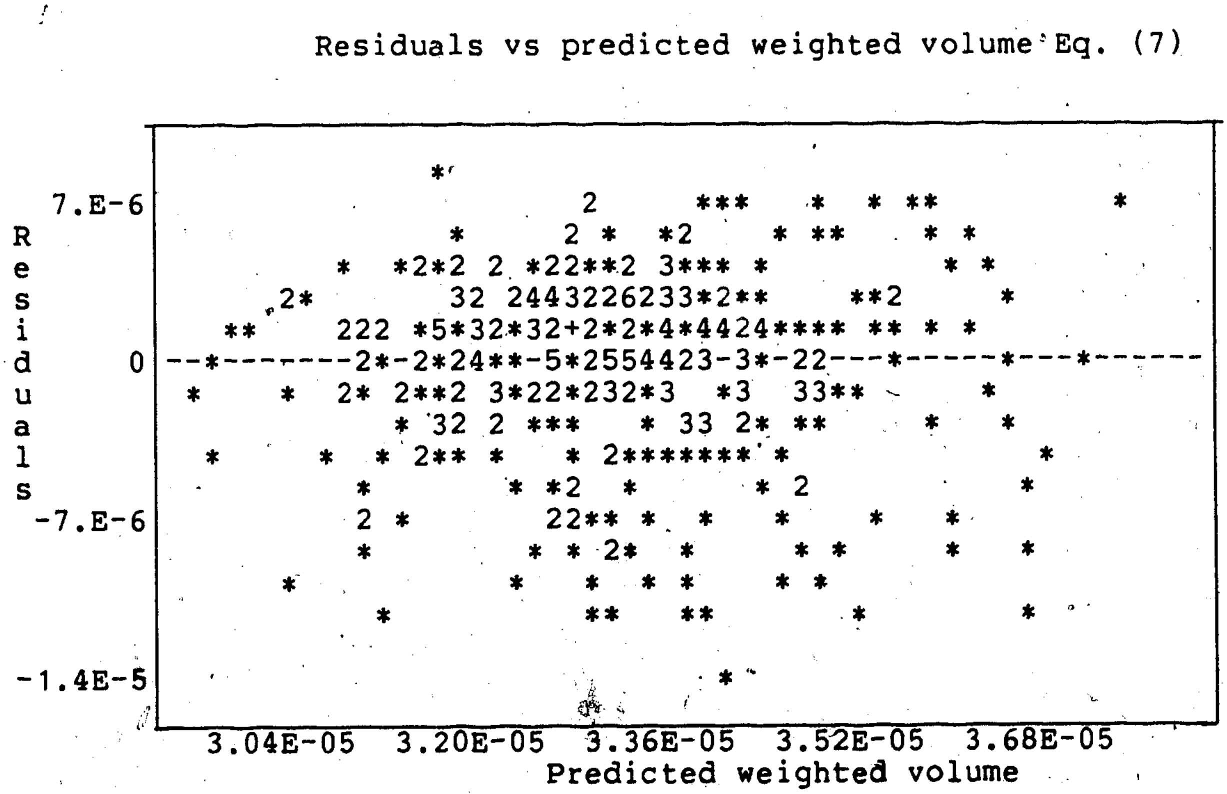


Residuals vs predicted log(volume) Eq. (3)

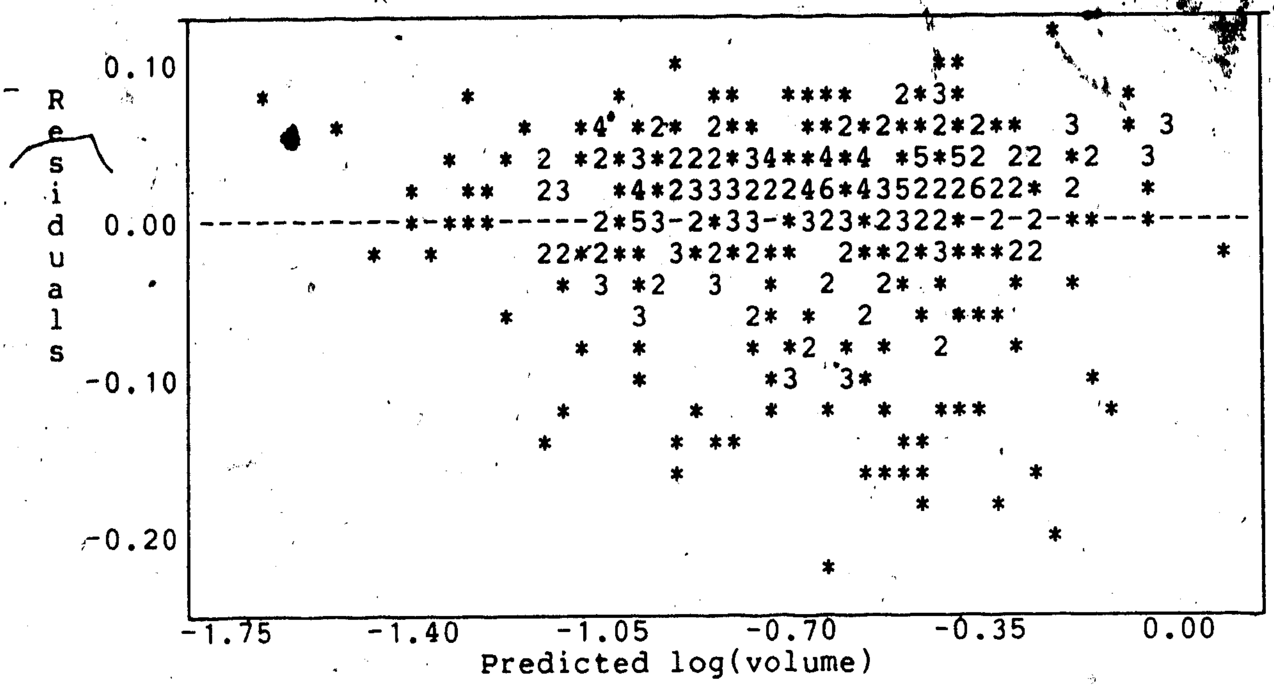


Appendix 1b. Residual plots for the standard volume functions

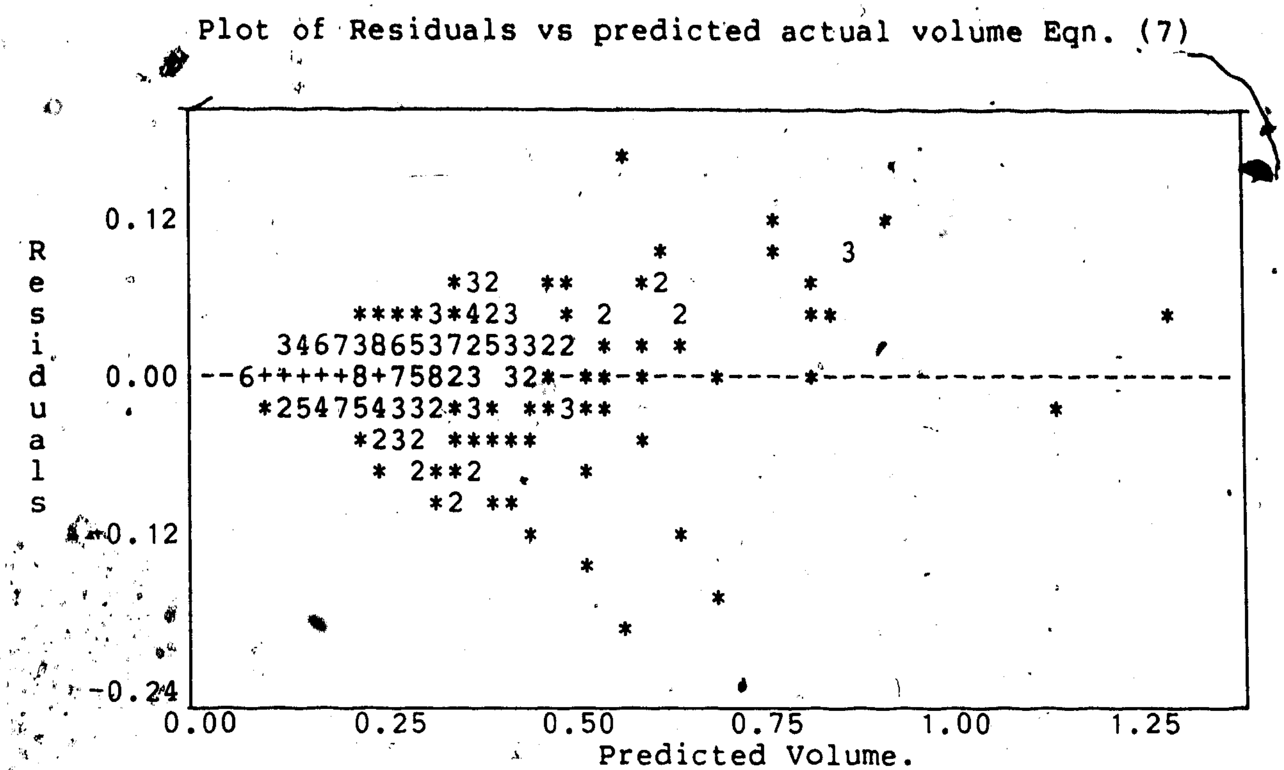


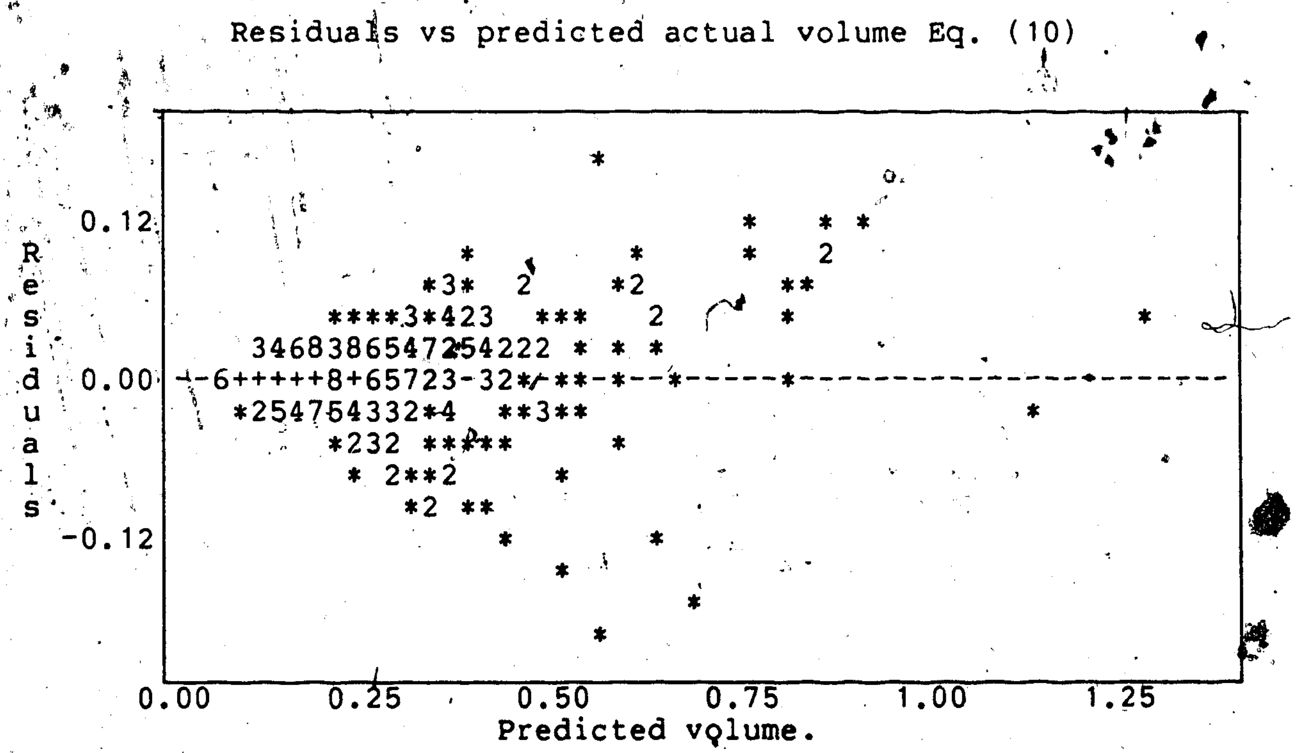


Residuals vs predicted log(volume) Eq. (10)



Appendix 1c. Plot of residuals for transformed equations





Appendix 2. Height-Diameter Relationship

A. Introduction

Height estimation in the field is a slow and expensive procedure and, consequently, it is not desirable to measure a large number of trees per unit area (Alder 1980). When stand volume is calculated from measurements of diameters for all trees on an area and estimates of height based on a sample of those trees, a common procedure is to relate height to diameter and then to obtain volume per tree by entering a standard volume table with the measured tree diameter and the estimated tree height given by a height-diameter function (Curtis 1967a, Hilt and Dale 1982, Clutter et al. 1983, Buford 1986).

Curtis (1967a) suggests that relating height to diameter may introduce erratic and illogical fluctuations into the estimates. He observed that this was mainly because the relationships are based on small samples and usually with measurements by different people. However, these fluctuations could be eliminated by inclusion of age as an independent variable. Alder (1980), however, suggests that data from stands of different ages and densities should never be pooled together as the resultant function is a poor height predictor for any individual stand.

Clutter et al. (1983) and Alder (1980) point out that a single height-diameter relationship should not be developed for different stands unless preliminary tests have shown the stands to be similar. Unfortunately, in some tropical species, there exists no strong relationship between height and diameter (Alder 1980). Also, no study known to the author has dealt with height-diameter relationship for eucalypts.

Meyer (1936) suggests that a height-diameter function should be moderately flexible and possess the following characteristics:

1. The slope of the function should always be positive, approaching zero as diameter becomes large.
2. The function should pass through the origin.

The objective of this appendix was to compare a number of alternative height-diameter and height-diameter-age functions. The selected function for each forest region was used in estimation of the individual tree volumes, to accomplish yield prediction.

B. Methods

In each plot, DBH was measured for all trees. However, only the heights of the dominant trees (100 trees with the largest DBH per hectare) were measured. As such the functions developed here are based on the dominant tree heights and DBH's.

A wide variety of equations have been used for the height-diameter relationship (Curtis 1967a, Alder 1980, Hilt and Dale 1982, Clutter et al. 1983). Most of the equations encountered in other studies are summarised in Curtis (1967a). The equations can be subdivided into two main groups. One group is for equations without transformation of height and the other has height transformed (logarithm or weighted). The equations below were fitted to the data of the five forest regions separately using the least squares technique and compared:

$$Ln(ht) = b_0 + b_1 dbh^{-1} \quad \text{------------------------------(1)}$$

(Clutter et al. 1983)

$$Ht = b_0 + b_1 dbh + b_2 dbh^2 \quad \text{---------------------------(2)}$$

(Staebler 1954)

$$Ht = 1.3 + b_1 dbh + b_2 dbh^2 \quad \text{-------------------------(3)}$$

(Trorey 1932, Ker and Smith 1955)

$$Ht = 1.3 + b_0 (1 - e^{b_1 dbh}) \quad \text{----------------------(4)}$$

(Curtis 1967a)

$$Ht = b_0 + b_1 dbh^2 + b_2 dbh^{0.5} + b_3 dbh^{-0.5} \quad \text{----------(5)}$$

(Curtis 1967a)

$$Log(ht) = b_0 + b_1 log(dbh) \quad \text{------------------------(6)}$$

(Curtis 1967a)

$$Ht = b_0 + b_1 log(dbh) \quad \text{------------------------------(7)}$$

(Myers 1966)

$$Dbh/ht = b_0 + b_1 dbh + b_2 dbh^{-1} \quad \text{--------------------(8)}$$

(Curtis 1967a)

where:

Ht = total tree height,

dbh = diameter at breast height,

Log = logarithm to base 10,

Ln = Natural logarithm,

e = base of natural logarithm,

b's = regression coefficients.

Of these equations, (1) has probably been the most frequently used in recent studies of height-diameter relationships (Clutter et al. 1983, Burk and Burkhart 1984, Buford 1986). In Buford's (1986) study, this equation was found appropriate when applied to an even aged plantation of loblolly pine at 15 years of age. Equations (2) and (3) have had considerable use in the Northwestern states (Curtis 1967a). Equation (4), like (1), is a realistic model which predicts breast height when diameter at breast height is zero. Equation (5) was initially fitted as a polynomial with several variables using stepwise techniques, while (6) and (7) have been used elsewhere (Myers 1966). Equation (8) is of the form:

$$H = \frac{D^2}{b_0 + b_1 D + b_2 D^2} \quad \text{(Curtis 1967a)}$$

and thus realistic in that it passes through the origin.

The linear equations were fitted to the data using the minitab package (Ryan et al. 1976) but equation (3) unlike the others was fitted with no constant term. Equation (4) being nonlinear, was fitted using the BMDP statistical package (Dixon 1979).

C. Results and Discussion

The results of fitting the eight equations are listed in table 10a to 10e, for each forest region separately. Equation (3) was fitted with (HT - 1.3) as the dependent variable, but with no constant term. As a result, its R^2 value was not comparable to that of the others and consequently was not computed. The same argument follows for equation (4). Therefore a comparison of these two equations was only possible using standard error.

Among the six equations whose R^2 were computed, equation (5) was the most appropriate in all cases. However, there is no consistency in ranking among the remaining five equations. Considering the standard error of all eight equations, equation (5) was ranked first for three forest regions. In the two cases where it was ranked differently, the difference between the best ranked and equation (5) was very small (0.48% and 0.51%). Equation (4) on the other hand had the highest standard error and thus was the least appropriate in all cases.

For consistency in estimation of heights given diameter, equation (5) was adopted for all forest regions. Age, as a predictor variable when introduced into equation (5), did not improve height prediction. Since both height and basal area are positively and almost equally correlated to age (table 8), this meant that the inclusion of age in height estimation after basal area was not significant.

Table 4[illegible]: Regression Results for Kapsaret Forest Region (Sample size = 74)

Eqn.	Coefficients				R^2	Se
	b_0	b_1	b_2	$b_{[illegible]}$		
1	3.77073	-18.265			63.2%*	2.717*
2	-0.584	1.0385	-0.007076		62.7%	2.715
3	0.98885	-0.006074				2.696
4		17.831079	[illegible].09879			4.446
5	234.5	0.03059	[illegible]8.01	-464.3	64.4%	2.709
6	0.1233	0.85275			6[illegible].5%*	2.706*
7	-30.116	36.626			[illegible]	2.698
8	0.4565	0.02058	5.993		[illegible]	3.5294*

* empirically computed R^2 and Standard error.

Table 10b: Regression Results for Turbo Forest Region (Sample size = 143)

Equation	Coefficients				R^2	Se
	b_0	b_1	b_2	b_3		
1	3.77058	-16.5321			83.0%*	2.619*
2	-8.250	1.8560	-0.02424		83.[illegible]	2.537
3	1.06084	-0.006632			[illegible]	2.701
4	18.146149	-0.09879				6.333
5	-251.20	-0.046733	45.549	380.[illegible]	85.9%	2.421
6	-0.042[illegible]	0.98732			79.9%*	2.865*
7	-29.166	37.098			82.8%	2.628
8	0.5816	0.01475	4[illegible]358		82.8%*	2.639*

* empirically computed R^2 and Standard error

Table 10c: Regression Results for Sabor Forest Region (Sample size = 83)

Equation	Coefficients				R^2	Se
	b_0	b_1	b_2	b_3		
1	3.52886	-15.1239			86.2%*	2.245*
2	-3.710	1.1582	-0.008451		90.7%	1.817
3	0.74147	0.001971				1.861
4	12.878312	-0.09879				5.972
5	-192.10	-0.04240	37.077	269.47	92.6%	1.656
6	-0.23436	1.09518			90.5%*	1.868
7	-25.241	32.117			87.6%	2.10[illegible]
8	1.3714	-0.004858	0.594		90.2%*	1.903

*empirically computed R^2 and Standard error

Table 10d: Regression Results for Kaptagat Forest Region (Sample size = [illegible])

Equation	Coefficients				R^2	Se
	b_0	b_1	b_2	b_3		
1	3.91083	-22.011			52.9%*	4.110*
2	-11.740	1.9002	-0.02322		52.5%	4.107
3	0.8386	-0.00032				4.310
4	18.437998	-0.09879				5.960
5	-424.4	-0.06191	68.01	722.5	53.8%	4.114
6	-0.1886	1.07136			52.0%*	4.151*
7	-38.652	42.760			52.8%	4.093
8	0.9366	0.00570	4.156		51.2%*	4.206*

*empirically computed R^2 and Standard error

Table 10e: Regression Results for Penon Forest Region (Sample size = 100)

Equation	Coefficients				R^2	Se
	b_0	b_1	b_2	b_3		
1	3.78039	-18.906			69.2%*	2.760*
2	-9.616	1.8794	-0.026304		68.6%	2.774
3	1.00585	-0.00767				2.830
4	16.964355	-0.09879				4.930
5	681.5	0.08248	-90.22	-1308.5	74.0%	2.564
6	0.04440	0.90139			66.1%*	2.894*
7	-28.055	34.794			69.1%*	2.749
8	-1.3479	0.06224	24.814		69.5%*	2.762*

*empirically computed R^2 and Standard error

Apparently, with the low values of R^2 and high standard errors of the equations fitted, every time an inventory is carried out, a height-diameter function should be fitted based on the data collected in that particular forest stand. Equation (7) could be easily fitted using a scientific calculator and thus is suitable whenever quick solutions are required. This is especially so where estimates may be required in the field. However, as pointed out by Curtis (1967a), the equation gives negative values for small trees and therefore is not reliable in such situations.

Equation (1) is asymptotic, passes through the origin and the slope is positive everywhere. Curtis (1967a), when discussing a similar equati[illegible]icated that powers other than -1 may give slightly better results in very young stands. However, with the possibility of using permanent plot data, an elaborate type of equation [equation (5)] should be fitted using the stepwise regression procedures with deletion of nonsignificant terms.

D. Conclusion

The poor height-diameter relationship pointed out in (Alder 1980) was observed in the functions fitted here. As a result, with the adoption of equation (5), the quantitative values of the pooled data were not appropriate and therefore data from each forest region were fitted separately. Unless an alternative method of estimating height is developed, probably using height-age relationships based on permanent sample plot data, the suggestion, that may be appropriate here, is that separate height-diameter relations should be derived at all times whenever yields of this species are being estimated in any specific region.

In cases requiring simple and easily computed estimates of height, two simple and generally accurate equations have been observed to be adequate. These are equations (1) and (7). Therefore, depending on the computing facilities available and the accuracy required, any of the three equations, (1), (5) or (7), may be applied.

When height-diameter measurements are available from successive remeasurements of a permanent plots, the equation obtained by fitting one of the three equations should provide more accurate and consistent estimates of height and consequently volume yield. However, until the availability of such data occurs, estimates based on single examination data should continue being applied.