Field document

Project report no. 25

GHA/74/013
The Development of Forest Energy Resources
GHANA

Stem volume and taper, and wood properties of *Gmelina arborea* plantations on Subri River Forest Reserve

by
Denis Alder
Forestry Officer (Inventory)

&

Kevin Stewart
Chemical Engineer (PCV)

UNITED NATIONS DEVELOPMENT PROGRAMME
FOOD AND AGRICULTAURE ORGANIZATION OF THE UNITED NATIONS
Takoradi, Ghana

December 1982

DISCLAIMER

This field document is one of a series of reports prepared during the course of UNDP/FAO Project GHA/74/013 "Development of Forest Energy Resources in Ghana". The conclusions and recommendations are those considered appropriate at the time of its preparation. As a field document, the contents of the report are the sole responsibility of the project; endorsement by FAO is not necessarily implied.

SUMMARY

Gmelina arborea volume taper and bark thickness functions are described based on 164 felled sample trees, on 30 angle count plots uniformly distributed in age classes 4 to 8. The taper functions employ a constrained cubic polynomial of relative height to predict relative sectional area; bark thickness is predicted by a homologous function of relative height giving bark sectional area relative to d.b.h. Underbark taper is estimated as the difference of the overbark and bark thickness taper models. A logarithmic volume equation and diameter-height function are also estimated and an algorithm presented for unbiased and compatible estimation of volume to different merchantable diameters from the taper and total volume functions. An appendix gives computer programs for calculating over and underbark volumes and log assortments from a stand table of diameters given different cutting constraints; the programs are in BASIC and for the HP-41C calculator.

Stacking factors for *Gmelina* cordwood in 1 m. lengths were estimated at 0.627 m^3/stere. Mean moisture content of felled trees was 166%; sample height affected moisture content which ranged from 210% at 1 m. to 110% at 25m. Wood density when fresh was independent of sample height with a mean of 0.990 Kg/dm^3; oven-dry density increased with sample height from 0.328 Kg/dm^3 at 1 m. to 0.483 Kg/dm^3 at 25 m. Mean oven-dry density was 0.3780 Kg/dm^3. Four sample stacks dried over 5 dry season months (October-March) showed exponential drying. After 3 months, mean moisture content was 70%; after 5 months, 30%. Piece size affected drying rates; 5cm diameter pices dried initially at 1.7% moisture content loss per day; 30cm pieces dried at 0.65% per day. Carbonisation yield at different moisture contents was calculated theoretically and related to actual characteristics of *Gmelina* wood.

ACKNOWLEDGEMENTS

The work described in this report was part of the project "Development of Forest Energy Resources in Ghana" financed by the United Nations Development Programme, and executed by the Food and Agriculture Organization of the United Nations through the agency of the Forestry Department of Ghana. The efforts of the project manager, Dr. D. E. Earl, and the poject co-managers, Mr.E.K. Afanyadey and currently Dr. E.Y. Djokotoe in initiating and supporting this work are very much appreciated; as are those of the Chief Conservator of Forests, Mr. J. Francois.

The United States Peace Corps Volunteers must be thanked for providing **personnel** for this work. The United States Agency for International Development also assisted in providing communications and evacuation facilities during a medical emergency resulting from a forest accident during the course of the sampling programme; this was deeply appreciated.

The staff members of the Forest Inventory Unit must be thanked for their dedication to duty during the physical execution of the work. The project Renewable Fuels Unit assisted with some of the wood property studies.

CONTENTS

APPENDICES

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Since 1971, there has been an interest in establishing exotic plantations in the Subri River Forest Reserve in the Western Region of Ghana, with a view to providing a raw material base for the establishment of a pulp mill at Daboase, some 10 to 15 km distant. During its early phase, this plantation establishment was carried out under the auspices of the Forestry Department of Ghana, and relied mainly on the so-called 'slash and burn' technique of salvage logging, followed by clear felling of the natural forest and its burning *in situ*; planting of *Gmelina arborea*, the principle species, was then carried out later in the season directly into the ashbed.

The 'slash and burn' technique was not very successful. Establishment was often patchy, and both yield and form were poor. This is principally due to the intense competition from Siam Weed, *Eupatorium odoratum*, whose growth is stimulated by burning. From 1977, the UNDP/FAO Project "Development of Forest Energy Resources in Ghana" pioneered a new method of establishing plantations, the Subri Conversion Technique. This has been documented elsewhere [1]. The essence of the Subri Conversion Technique is to offset plantation establishment costs against production of charcoal and fuelwood from the indigenous forest.

By 1980, the area of *Gmelina arborea* effectively established was 759 ha. At that time, little mensurational work had been conducted in the plantations, whilst there was intensified interest in the feasibility of the Daboase pulp mill.

The present author was therefore instructed to prepare volume and yield tables for the existing Gmelina plantations, that would provide a basis for future planning. Accordingly, felled volume sampling was carried out between September 1980 and February 1981; and a plantation inventory from July to October 1981. The results of this work have been partly reported in an earlier publication [2], which gives yield tables for *Gmelina*.

The present report is concerned with the detailed analysis of the volume and stem taper data gathered from the felled volume sampling, and also the wood density and moisture content studies conducted at the same time. It provides:

- A total volume tarif for Gmelina entered by diameter or diameter and total height;
- A stem taper model for derivation of form-factors for volume to different diameter limits;
- A bark thickness model, entered by sectional diameter;
- models relating drying properties, wood density and moisture content to mensurational parameters;
- estimated stacking factors for Gmelina shortwood.

2. SAMPLING METHOD

2.1 Location and demarcation of plots

Plots were located subjectively in the age classes, six plots per age class from P72 (8 years) to P76 (4 years). Constraints were placed on plot selection to avoid gaps and understocked stands, and locations within 50m of a road or 200 m of another plot in the same age class.

Plots were demarcated by Relascope using a metric angle count factor of 4 m^2/ha, i.e. two relascope bands. Those trees counted in from the plot centre were marked for felling.

The distribution of plots and trees by age classes is shown in Table 1 below.

Table 1 : Distribution of volume sample plots by age classes

Pyr	Age	No. Plots	No. trees
1972	8	6	33
1973	7	6	42
1974	6	6	30
1975	5	6	24
1976	4	6	35

The theoretical advantage of selecting the sample by angle count is that the sample will be biassed towards larger trees. In fact the probability of inclusion is proportional to D^2. Since the error variance for volume equations is also approximately proportional to D^2, this gives an optimum sample distribution for construction of total volume equations.

2.2 Felling and measurement of trees

The intention was to measure all trees in 1 metre sections from ground level, both over and under bark, to a practical limit of 5 cm diameter over bark. The continuity of the 1 metre sections would be maintained along the larger branches. A recording form was designed for this purpose, form inv/2, which is shown in Appendix B along with the field instructions to Technical Officers.

In practice trees were felled as close to the ground as possible, either by hand saw or axe. Before felling the 1 metre and 1.3 metre points were marked. The total height was then measured from the 1 metre point, and adjusted accordingly. Total height was measured to the point over the main bole, and not necessarily to the highest point of the crown.

The tree was marked into 1 metre sections. Forked sections were marked on both branches at 1 metres from the base of the section, with measurements then continuing along each branch. The trees were cross-cut by hand saw, and each log marked with the plot number, tree number, and section height. Diameter over bark was measured by tape at the top of each section; a strip of bark 2 cm wide was then removed, and diameter under bark recorded.

After measurement, all the wood from one plot was stacked into a rectangular stack which was measured in the vertical and horizontal dimensions three times on the front and back faces of the stack. The average length times the average depth gave stack volume in steres. The stack was assumed to be 1 metre deep since all pieces were 1 metre lengths.

3. TREE VOLUME TARIFS

3.1 Tree volume calculation

Tree volumes were calculated with a modified version of Smalian's formula suitable for the system of measurement adopted. This was:

$$V = \tfrac{1}{2}.k. \sum_{h=1}^{T} \left(\sum_{i=1}^{n_{h-1}} D^2_{i,h-1} + \sum_{j=1}^{n_h} D^2_{j,h} \right) \qquad - (3.1)$$

where:

V is tree volume to the measurement limit, in m^3.

k is the constant 0.00007854 to convert diameters squared in cm., to circular sectional area in m^2.

T is the total number of height sections measured.

h is the height in metres, of a given section.

n_h is the number of stems at height h.

$D_{i,h-1}$ is the diameter in cm. of the i'th stem at height h-1.

$D_{j,h}$ is the diameter in cm of the j'th stem at height h.

Note that the section length between h and h-1 is always 1 metre and so does not appear explicitly in the volume formula. The diameter at the base of the stem D_0, was not measured and was assumed to be 10% greater than the diameter at 1 metre, i.e.:

$$D_0 = 1.1\, D_1$$

The tree volume is overbark where diameters are overbark, and underbark volume when underbark diameters are used in the above equation.

3.2 Single-entry volume tarif

For practical purposes a single-entry volume tarif that gives tree volume from diameter at 1.3 m over bark is often the most convenient form to use. A logarithmic equation of the form:

$$\log_e V = a + b \log_e D \qquad -(3.2)$$

where V is total volume overbark in m^3 to a 5 cm measurement limit, D is diameter in cm. overbark at 1.3 m, was fitted with the coefficients:

a	-8.724
b	2.354

with an R^2 of 0.9479 and 164 sample trees.

3.3 Double-entry volume tarif

In situations where tree total height can be measured or estimated, then a double entry tarif is usually more precise than one entered by diameter alone. The logarithmic equation:

$$\log_e V = a + b_1 \log_e D + b_2 \log_e H \qquad -(3.3)$$

where V and D are as above, and H is tree total height in metres, was fitted with coefficients:

a	-9.800
b_1	1.966
b_2	0.800

with an R^2 of 0.9746 and 164 sample trees.

Figure 1 illustrates the single-entry volume tarif, together with the data.

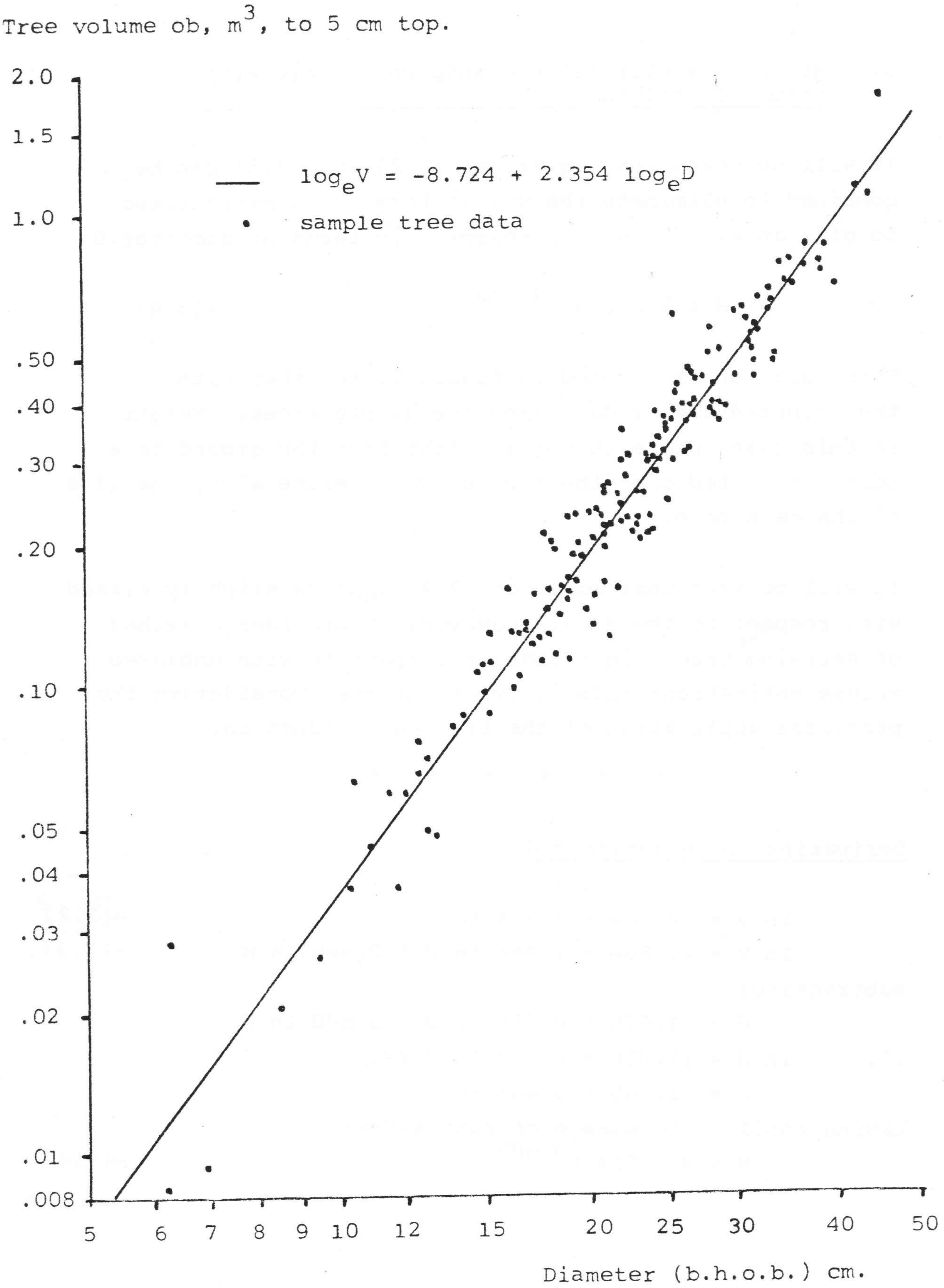


Figure 1 : Single-entry volume tarif for Gmelina arborea

Note that both axes are logarithmic. Volume is over-bark to a 5 cm diameter limit. Diameter is breast-height (1.3 m.) over-bark measurement.

3.4 Height-diameter relationship compatible with volume functions

It will be noted that equations (3.2) and (3.3) can be combined to eliminate the volume term V and manipulated to give an expression for height H in terms of diameter D:

$$H = 3.83814\ D^{0.485} \qquad -(3.4)$$

This equation is graphed in figure 2, together with the height-diameter data from the sample trees. Height in this case refers to total height from the ground to a point projected onto the tree crown envelope along the line of the main bole.

It will be seen that equation (3.4) appears slightly biased with respect to the data. However, it provides a method of deriving tree height that is compatible with unbiased volume estimation; this is important when considering the practical application of the tree taper function.

* * * * * *

Derivation of equation 3.4

$$\ln V = -8.724 + 2.354 \ln D \qquad -(3.2)$$

$$\ln V = -9.800 + 1.966 \ln D + 0.800 \ln H \qquad -(3.3)$$

subtracting:

$$0 = 1.076 + 0.388 \ln D - 0.800 \ln H$$

$$\therefore \quad \ln H = (1.076 + 0.388 \ln D)/0.800$$

$$= 1.345 + 0.485 \ln D$$

taking antilogs to base e of both sides:

$$H = 3.83814\ D^{0.485} \qquad -(3.4)$$

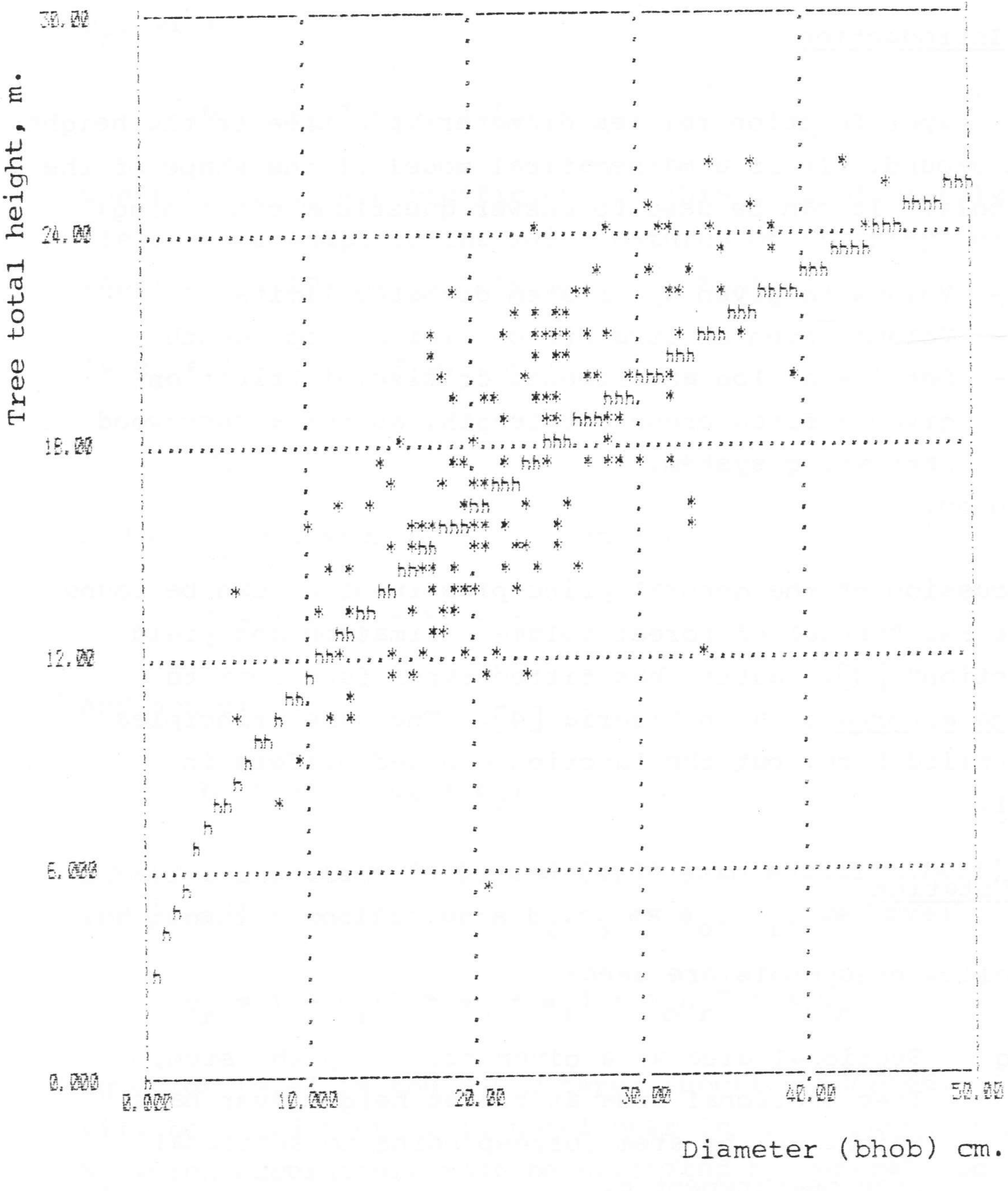


Figure 2 : Height-diameter function derived from volume tarifs

This computer-generated graph shows height-diameter data (*) from the volume sample trees, together with the derived height-diameter function described in section 3.4:

$$H = 3.83814\ D^{0.485}$$

which is plotted as (h).

4. TREE TAPER FUNCTION

4.1 Introduction

A tree taper function relates diameter up a tree to the height above ground. It is a mathematical model of the shape of the tree bole. It can be used to answer questions concerning:

- Volume to given upper stem diameter limits
- Volume given constraints on minimum log length
- Details of log assortments or size distribution given a fixed cross-cut length, as for a shortwood harvesting system,

and so on.

A discussion of the general principles involved can be found in the FAO "Manual of forest volume estimation and yield prediction" [3]. Sutter has fitted taper functions to Gmelina arborea data in Nigeria [4]. The same principles are applied here, but the function adopted differs in detail.

4.2 Notation

The following symbols are used:

g	Sectional area at a given height up the stem;
G	Tree sectional area at breast height over bark;
h	Height up the stem corresponding to sectional area measurement g.
H	Tree total height.
g_r	The ratio g/G;
h_r	The ratio $(h-1.3)/(H-1.3)$;

Note that at breast height, g_r is 1, h_r is zero. At the top of the tree, g_r is zero, h_r is one.

4.3 The basic taper model

The basic taper model was derived from a cubic polynomial of h_r, viz:-

$$g_r = b_o + b_1 h_r + b_2 h_r^2 + b_3 h_r^3 \qquad -(4.1)$$

where b_o to b_3 are coefficients. This is sufficiently flexible to adapt to the main features of the shape of the taper function, without being too complex.

As $g_r = 1$ when $h_r = 0$, then:

$$b_o = 1 \qquad -(4.2)$$

And as $g_r = 0$ when $h_r = 1$, then :

$$0 = 1 + b_1 + b_2 + b_3$$

and hence:

$$b_1 = -(1 + b_2 + b_3) \qquad -(4.3)$$

Substituting items (4.2) and (4.3) into equation (4.1) and renaming coefficients b_2, b_3 as a_o, a_1, we have:

$$g_r = 1 - h_r(1 + a_o + a_1) + a_o h_r^2 + a_1 h_r^3 \qquad -(4.4)$$

Equation (4.4) is the basic taper function adopted. It will be noted that it is non-linear in the parameters a_o and a_1 which accordingly must be estimated by generalized least squares methods.

It will be noted incidentally that the derivation of equation (4.4) can be applied to higher order polynomials, to give a general n'th order model of the form:

$$g_r = 1 - h_r(1 + \sum_{i=0}^{n} a_i) + \sum_{i=0}^{n} a_i h_r^{i+2} \qquad -(4.5)$$

4.4 Analysis of Gmelina taper data

On the 164 sample trees measured, there were 2447 upper stem diameter measurements not pertaining to forked stems or branches; these latter were omitted for purposes of analysis.

This data was initially grouped into classes of h_r and tree diameter/height ratio D/H, and the mean value of g_r for each class calculated. Average taper lines for each D/H class were plotted manually. There appeared to be no marked effect of D/H on tree shape.

Accordingly, all the data were pooled into classes of h_r only. The g_r values for each h_r class are plotted in figure 3. To this data, the model given in equation (4.4) was fitted using the generalized least squares program SNIFTA [5]. The resultant parameter values were:

a_o	2.59799
a_1	-1.16783

with a coefficient of determination of 0.9820. The function is shown in figure 3 as the heavier line.

4.5 Solving the taper function for merchantable height

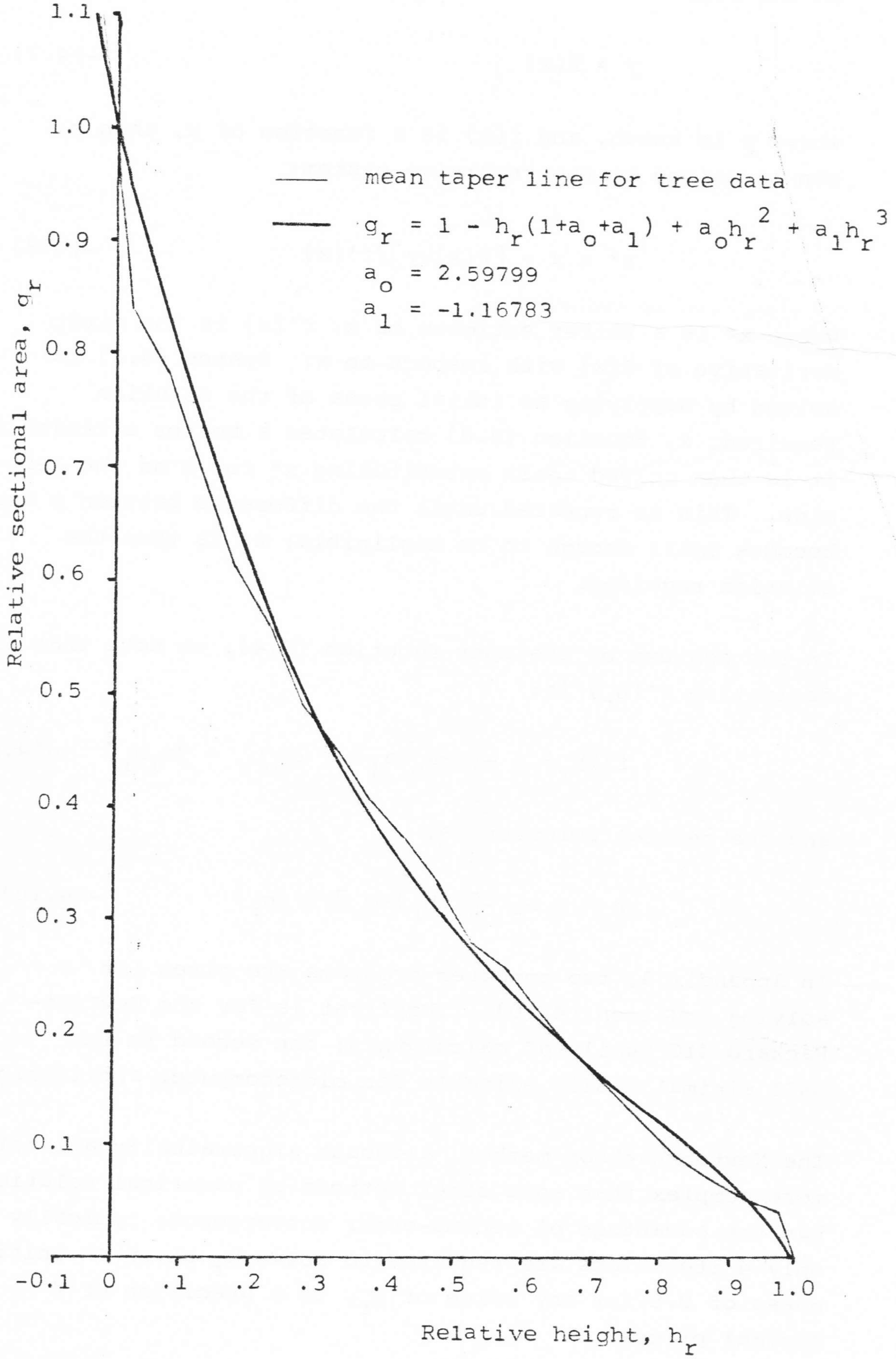
The taper model given in equation (4.4) gives a cross-sectional area for a given relative height. This is the most convenient form in which to express the model for integration to calculate volume. However, for most purposes, it is necessary to calculate a height up the tree for a given merchantable diameter limit. The merchantable diameter d can be converted to a value of g_r by noting that:

$$g_r = d^2/D^2 \qquad -(4.6)$$

where D is tree d.b.h.

Equation (4.4) cannot be solved for h_r by direct algebraic manipulation. It can however be easily solved by the Newton-Raphson iterative method. Given a general problem

Figure 3 : Taper function for *Gmelina arborea*



in the form:

$$y = f(x) \qquad -(4.7)$$

where y is known, and f(x) is a function of x, then x can be solved by the recursive system:

$$x^* = x - [f(x)-y]/f'(x) \qquad -(4.8)$$

where x^* is a better estimate of x. $f'(x)$ is the first derivative of f(x) with respect to x. System (4.8) is solved by supplying an initial guess of the solution required, x. Equation (4.8) calculates a better estimate x^*. It is then solved again substituting x^* for x on the left-hand side. This is repeated until the difference between x and x^* becomes small enough to be negligible; x^* is then the solution required.

In the context of the taper function (4.4), we note that the derivative $f'(h_r)$ is:

$$f'(h_r) = -(1+a_o+a_1) + 2a_oh_r + 3a_1h_r^2 \qquad -(4.9)$$

and the general solution is:

$$h_r^* = h_r - [f(h_r)-g_r]/f'(h_r) \qquad -(4.10)$$

In Appendix A, two computer programs are given for solving equation (4.10). The first is for the Hewlett-Packard 41C family of calculators; the second is in ANSI minimal BASIC, suitable for microcomputer applications.

The Newton-Raphson method, although algebraically a little more complex than some other methods of numerical solution, has the advantage of second-order convergence; typically only 4 iterations are required to solve h_r given an initial guess of 0.5 for any value of g_r, to a precision of 4 decimal places.

4.6 Calculation of tree volume from the taper function

Integrating equation (4.4) between height limits corresponding to stump height h_o and the height of the merchantable diameter h_m gives a form factor which can be used to calculate volume directly:

$$F_m = \int_{h_o}^{h_1} f(h_r).dh_r \qquad -(4.11)$$

where F_m is the form factor to the merchantable limit h_m. The height h_m will be determined for a given diameter limit using the procedure described in section 4.5, principally equation (4.10).

Volume is derived from the form factor in the usual way:

$$V_m = F_m GH \qquad -(4.12)$$

Note that the integral of the taper function is given by:

$$\int f(h_r).dh_r = h_r - \tfrac{1}{2}h_r^2(1+a_o+a_1) + \tfrac{1}{3}a_o h_r^3 + \tfrac{1}{4}a_1 h_r^4 \qquad -(4.13)$$

Appendix A gives computer programs for calculating equation (4.13) and the definite integral equation (4.11) for a specific form factor.

In practice, it is often found that volumes calculated directly from taper functions are somewhat biased when compared with a total volume equation such as (3.2). This arises because the least squares fit to taper data is unbiased only with respect to sectional areas, and not necessarily with respect to volume.

To avoid these problems, and also to provide a taper model which can be used when total height is unknown, the following procedure can be adopted for a tree of diameter D and merchantable diameter D_m:

(1) Calculate volume to a 5 cm measurement limit, V_5 from equation (3.2).

(2) Calculate total height H from equation (3.4).

(3) Calculate height to 5 cm limit, h_5; and height to the merchantable limit in question h_m from equation (4.10).

(4) Calculate form factor to the 5 cm limit F_5 and to the merchantable limit F_m from equation (4.11).

(5) Derive merchantable volume from:

$$V_m = (F_m/F_5).V_5 \qquad -(4.14)$$

This will always give volumes compatible with equation (3.2). It can be seen for example that when $F_m = F_5$ then equation (4.14) becomes an identity.

The subroutines for calculator and computer in Appendix A follow this procedure.

5. BARK THICKNESS AND UNDERBARK VOLUME

5.1 Compatible bark thickness and underbark taper functions

If bark thickness is expressed as sectional area of bark relative to tree basal area:

$$b_r = (d_o^2 - d_u^2)/D^2 \qquad -(5.1)$$

where d_o is overbark diameter, d_u underbark diameter, and D tree dbh over bark, then this can be plotted against relative height h_r as defined in section 4.2. The result is shown in figure 4 for Gmelina bark thickness data grouped into relative height classes.

If a cubic polynomial is fitted which is constrained to pass through the point (h_r=1, b_r=0), then one derives the function:

$$b_r = -(b_o+b_1+b_2) + b_o h_r + b_1 h_r^2 + b_2 h_r^3 \qquad -(5.2)$$

with:

b_o = -0.480301
b_1 = 0.667980
b_2 = -0.352390

This cubic polynomial is admittedly not the optimum model to fit the data in figure 4; a certain lack of fit is apparent in the graph. However, function (5.2) is sufficently satisfactory for practical purposes and has the important advantage that it can be combined directly with the overbark taper model to yield an underbark taper equation that yields consistent bark thickness estimates by subtraction.

Note that the overbark taper function is:

$$g_r = 1 - h_r(1+a_o+a_1) + a_o h_r^2 + a_1 h_r^3 \qquad -(4.4)$$

where:

$$g_r = d_o^2/D^2$$

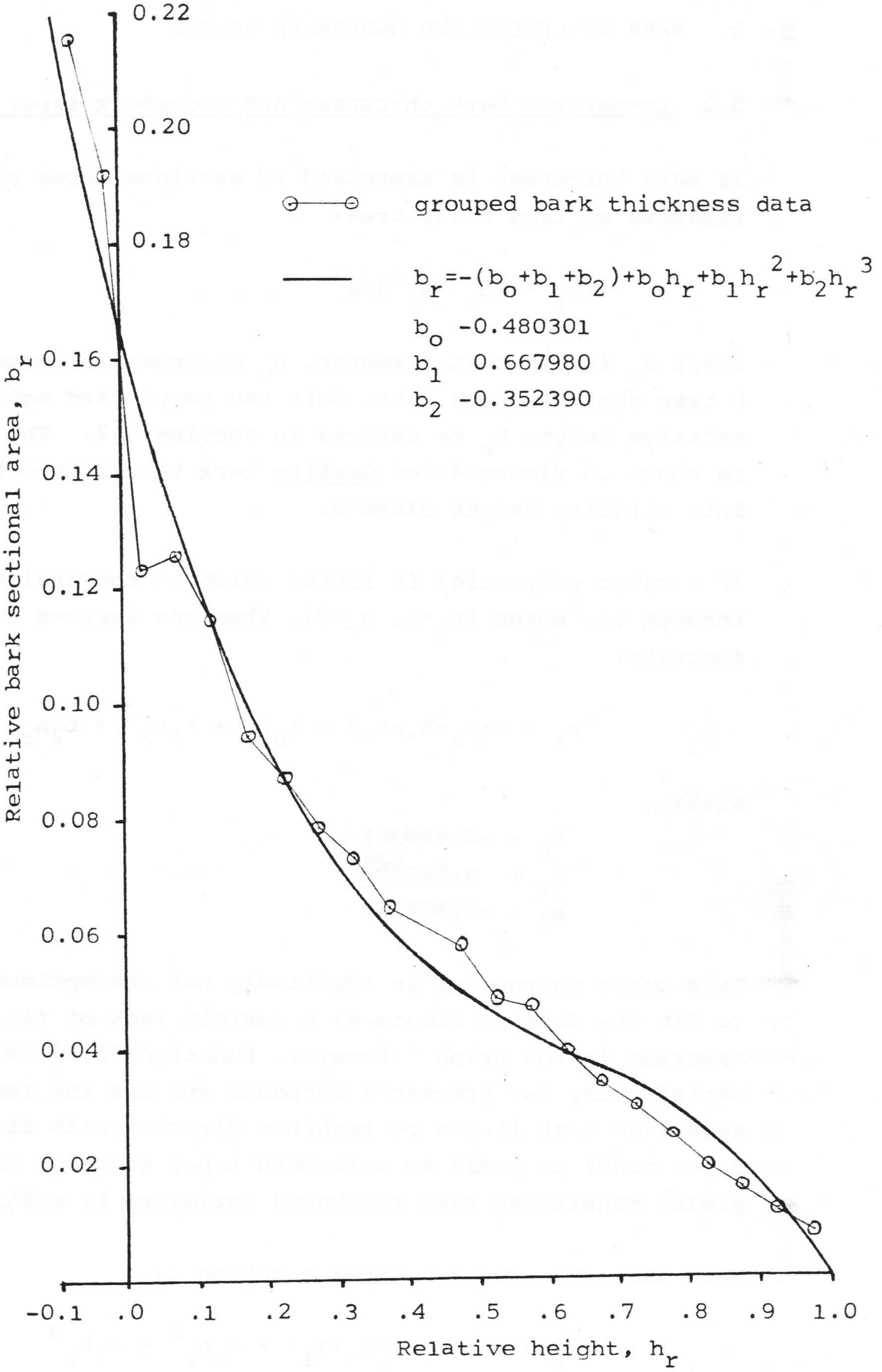


Figure 4 : Bark sectional area as a function of height

Subtracting equation (5.2) from (4.4), one derives an underbark taper function of the form:

$$d_u^2/D^2 = c_o + c_1h_r + c_2h_r^2 + c_3h_r^3 \qquad -(5.3)$$

where the coefficients c_o to c_3 are given by:

$$\begin{aligned} c_o &= 1 + b_o + b_1 + b_2 \\ &= 0.835289 \end{aligned}$$

$$\begin{aligned} c_1 &= -(1 + a_o + a_1 + b_o) \\ &= -1.949859 \end{aligned}$$

$$\begin{aligned} c_2 &= a_o - b_1 \\ &= 1.930010 \end{aligned}$$

$$\begin{aligned} c_3 &= a_1 - b_2 \\ &= -0.815440 \end{aligned}$$

5.2 Calculation of underbark volume to given diameter limits

As with the overbark taper model, an underbark form factor F_u is derived by integrating equation (5.3):

$$F_u = \int_{h_o}^{h_1} (d_u^2/D^2).dh_r \qquad -(5.4)$$

$$= \left[c_oh_r + \tfrac{1}{2}c_1h_r^2 + \tfrac{1}{3}c_2h_r^3 + \tfrac{1}{4}c_3h_r^4\right]_{h_o}^{h_1} \qquad -(5.5)$$

The limits of integration h_o and h_1 are estimated from, respectively, stump height and height to a given merchantable diameter limit. This latter is estimated as described in section 4.5. Note however that when using an under bark diameter limit, then equation (4.10) should be applied with the following substitutions:

$$g_r = d_u^2/D^2$$

$f(h_r)$ is equation (5.3)

$$f'(h_r) = c_1 + 2c_2h_r + 3c_3h_r^2 \qquad -(5.6)$$

Again, as in section 4.6, compatibility with total volume estimates and elimination of the necessity for a prior knowledge of tree total height can be achieved by using:

$$V_{u,m} = (F_{o,5}/F_{u,m}) \cdot V_{o,5} \qquad -(5.7)$$

where:

$V_{u,m}$	is underbark volume to a merchantable diameter limit m. This can be underbark or over bark diameter. If it is underbark, then equations (5.6) should be substituted into (4.10) when estimating merchantable height.
$V_{o,5}$	is total overbark volume to 5 cm diameter limit, estimated from equation (3.2).
$F_{o,5}$	is overbark form factor to a 5 cm diameter limit estimated from the taper function as described in section 4.6.
$F_{u,m}$	is underbark form factor to merchantable limit m, estimated from equation (5.5).

Computer and calculator procedures for these estimates are given in Appendix A.

6. SOME PROPERTIES OF Gmelina WOOD

6.1 Introduction

Density, moisture content, and drying characteristics of Gmelina wood were studied using sub-samples derived from felled volume trees. The results of these investigations are presented here. They provide some useful management information for the Gmelina planations with regard to reduction of haulage costs and maximization of fuelwood and charcoal calorific yields.

6.2 Conversion factor for stacked to solid wood

A total of 29 Gmelina stacks were measured, using piece lengths of 1 metre and diameters from 5 to 60 cm. overbark. The pieces were not split.

The mean stacking factor was 0.627 m^3/stere. The standard deviation was 0.053 m^3/stere, and the standard error of the mean 0.0098 m^3/stere. The reliable minimum estimate for the stacking factor at the 95% probability level is 0.607 m^3/stere.

It will be appreciated that this agrees very closely with stacking factors for indigenous wood given in [6] of 0.624 m^3/stere. Note that in both cases piece length is 1 m. A longer piece length wood probably be used in a real cordwood harvesting system, such as 1.5 or 1.8 m. In such a case the stacking factor would need to be re-assessed. Stacking factors for split wood, and for wood inside charcoal kilns at variable orientation would also be different.

6.3 Drying time of stacked wood

Four stacks from the volume sampling were transported to an open location near the Renewable Fuels Unit laboratory at Daboase for drying studies. The stacks were weighed initially on the day of felling, and then at intervals of one , three and five months, for three of the stacks. One stack was measured at two months only. The stack weights, There is a page numbering error, page 21 is used twice.

expressed as a percentage of their fresh weight are shown in figure 5 plotted against drying time. Note that the experiment was conducted between October and March, and therefore spans the main dry season. After March, the stacks began to suffer from termite attack, and the experiment was discontinued.

An exponential decay model was fitted to the data, in the form:

$$W = (100-a)e^{-rt} + a \qquad -(6.1)$$

with the coefficients r and a representing respectively drying rate and asymptotic stack weight. W is weight as a percent of fresh weight, and t is elapsed time in days. Coefficient values obtained were:

r -0.00894
a 40.0

with a coefficent of determination of 0.885 and 10 data points.

It should be appreciated that these stacks were dried in direct sunlight in an open location.

Note that the relationship between moisture content and the weight as apercentage of original weight, W, is as follows:

$$W = (100 + m_t)/(100 + m_0) \qquad -(6.2)$$

where m_t is moisture content % after t days, and m_0 is moisture content % at day zero. The moisture content percent scale shown on figure 5 is derived from this relationship, using an initial mean moisture content of 166.3%, based on 65 samples. As there is considerable variation in moisture content, and the drying stacks could not be sampled destructively, the scale shown on figure 5 should be regarded as indicative rather than absolute.

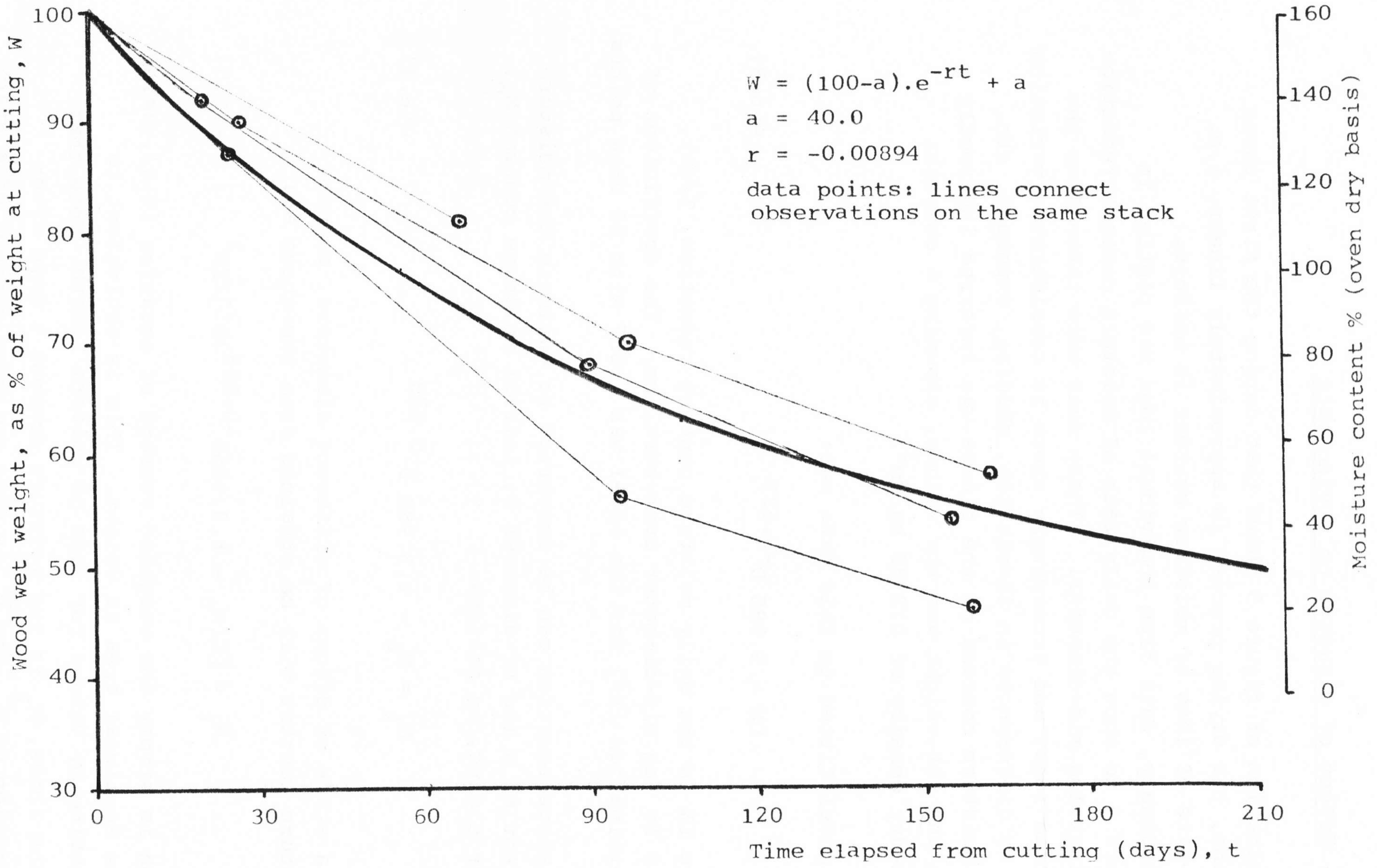


Figure 5 : Drying characteristics of stacked Gmelina during the main dry season

6.4 Effect of diameter on drying rate

Examination of figure 5 shows that during the first three months, the drying process is approximately linear, i.e. the rate of loss of moisture content is uniform. Accordingly, data from individual logs was plotted in figure 6 to show the daily rate of moisture content reduction against log mid-diameter. These data were taken from the stacked logs, and accordingly there is considerable variation due to differences in insolation, shading, exposure, etc. The moisture content of the pieces was inferred indirectly from the wet-weight and the volume, assuming a constant oven-dry density of 0.3780 kg/dm^3.

The model fitted to this data was:

$$L\% = 3.985\ D^{-0.523} \qquad -(6.3)$$

where L% is the daily moisture content reduction, %/day, and D is log mid-diameter over-bark, cm. The coefficient of determination (R^2) for the model was 0.557 with 88 data points.

The above equation can be converted to estimate the moisture content of a log of diameter D, initial moisture content M_o, after t days, as follows:

$$M_t = M_o - t.3.985\ D^{-0.523} \qquad -(6.4)$$

For a stack of pieces of different diameters, average moisture content will be obtained from the above as:

$$\bar{M}_t - [\Sigma(M_0 - t.3.985D^{-0.523})D^2]/\Sigma D^2 \qquad -(6.5)$$

which is simply the weighted average of equation (6.4), using piece sectional area as weight. This is equivalent to weighting by volume for logs of uniform length. Note that in the above, M_t is log moisture content t days after estimation of M_o, and $\bar{M}_t$ is mean moisture content of a stack after t days.

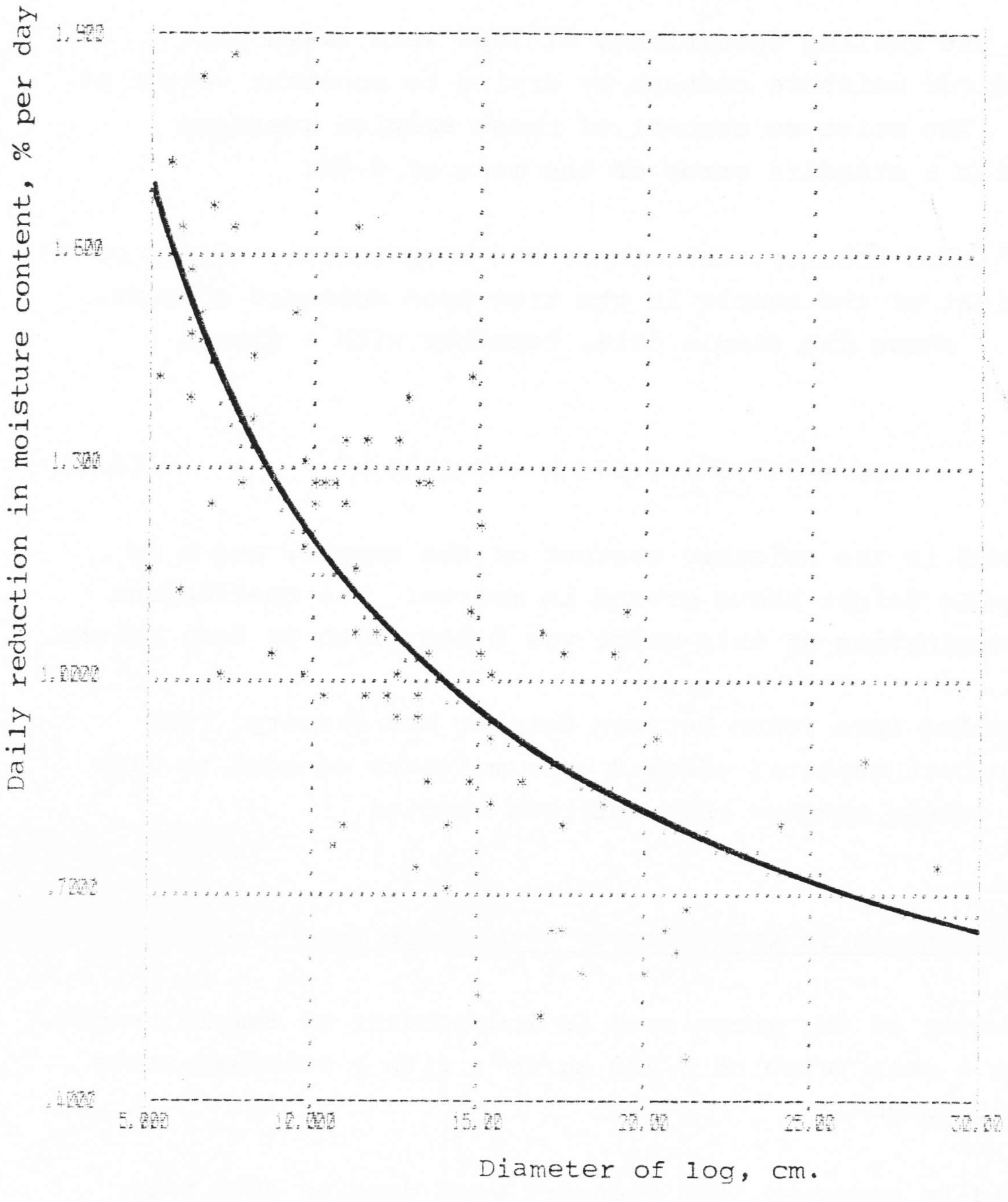


Figure 6 : Effect of piece size on rate of drying

This figure shows average moisture content loss per day for unsplit roundwood, with bark, during the months October-January, for the first three months of drying.

Data is shown by * for 88 logs.

The solid line represents the model:

$$\text{MC loss/day} = 3.985 \text{ Diam}^{-0.523}$$

6.5 Variations in moisture content within the tree

During the felling operations, 61 logs were taken and sampled for moisture content by drying to constant weight at 105°C. The moisture content of these samples averaged 166% with a standard error of the mean of 4.4%.

It was found however, that there was a systematic effect of the height of the sample in the tree upon moisture content. Figure 7 shows the sample data, together with a fitted model:

$$MC\% = 217.8 + 7.974\ h + 0.1559\ h^2 \qquad -(6.6)$$

where MC% is the moisture content of the sample, and h is the sample height above ground in metres. The coefficient of determination of this model was 0.650, with 61 data points.

The samples were taken between October and January. One would expect seasonal effects upon moisture content to also exist; these however have not been studied.

6.6 Variations in wood density within the tree

The density of the green wood is independent of sample height, and has a mean value of 0.990 kg/dm^3, with a standard error of 0.010 kg/dm^3.

As would be expected, the oven-dry wood density does vary with height, although the correlation is less strong than for moisture content. A linear regression of the form:

$$\text{Density(dry)} = 0.3212 + 0.006468\ h \qquad -(6.7)$$

had a correlation coefficient of 0.633 (R^2 0.4004). The mean oven dry density of all samples was 0.3780 kg/dm^3, with a standard error of 0.0074 kg/dm^3.

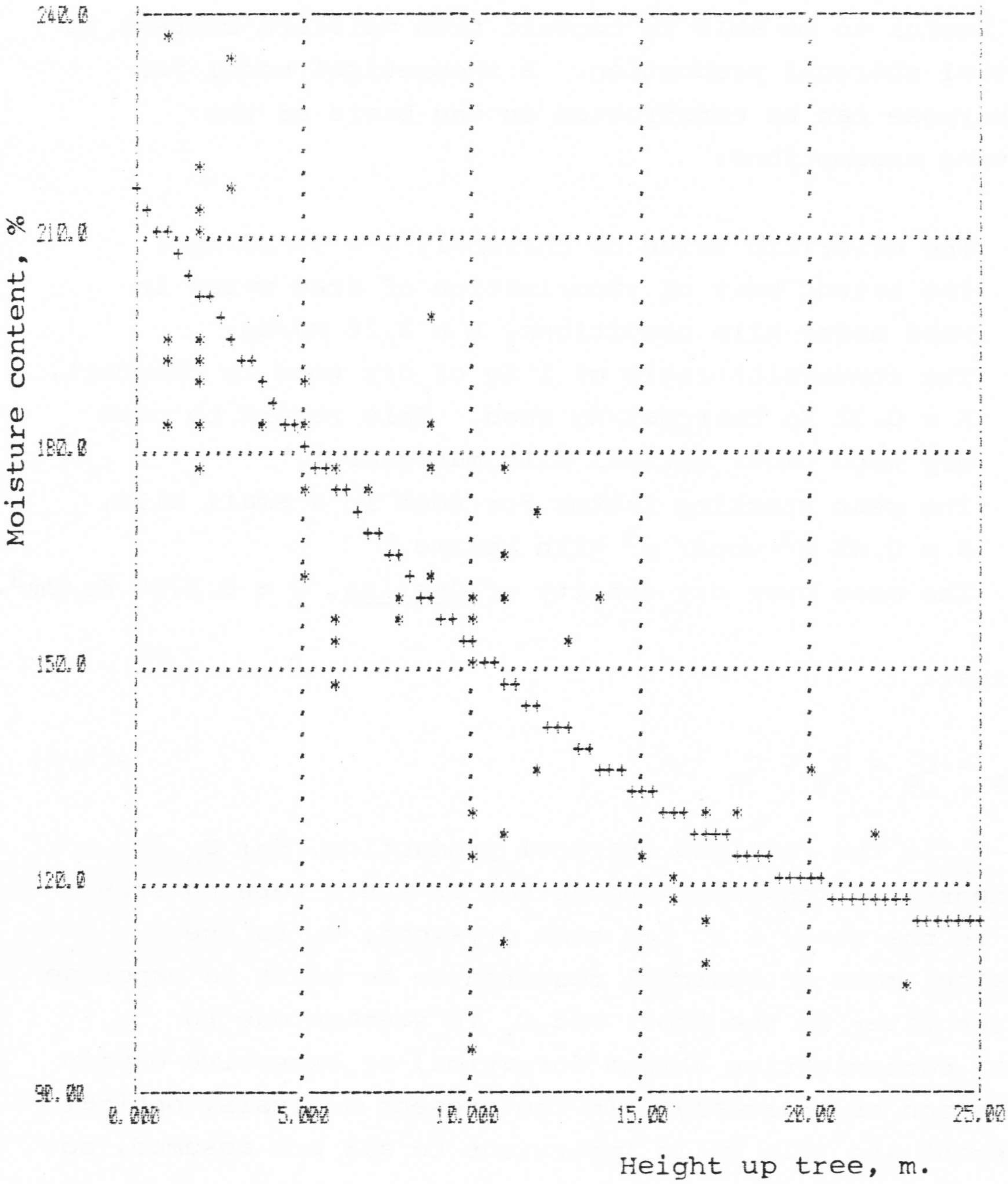


Figure 7 : Effect of sample height on moisture content

The figure shows the moisture content, % oven dry basis, of samples taken at different heights up Gmelina arborea trees. * are data points; + predicted values from the equation:

$$MC\% = 217.8 - 7.974\ h + 0.1559\ h^2$$

There are 61 sample points.

6.7 Relation between moisture content and charcoal production

It is useful to be able to convert from moisture content to potential charcoal production. A theoretical model for this purpose can be constructed on the basis of the following assumptions:

- The calorific value of charcoal, $V \approx 30$ MJ/Kg*;
- The latent heat of vaporisation of free water in wood under kiln conditions, $L \approx 2.26$ MJ/Kg;
- The conversion ratio of 1 Kg of dry wood to charcoal, $K \approx 0.32$ Kg charcoal/Kg wood. This refers to oven dry wood under optimal kiln management.*
- The mean stacking factor for wood in a small kiln, $S \approx 0.45$ m^3 wood/ m^3 kiln volume.*
- The mean oven dry density of Gmelina, $G \approx 0.3780$ Kg/dm^3.

Note that:

$$C_p = C_o - C_w - C_x \qquad -(6.8)$$

where C_p is the realised charcoal production, Kg; C_o is the theoretical charcoal production if there were no free water in the wood, i.e. for oven dry-wood; C_w is the equivalent mass of charcoal required to be burnt to vaporise the free water in the wood; and C_x is wastage due to partial carbonisation (brand formation) or excessive oxygen (combustion of charcoal). In the present analysis, optimal management and kiln walls impervious to air are assumed, so that C_x is negligible.

Theoretical charcoal production is determined from the conversion ratio of oven-dry wood to charcoal, K:

$$C_o = K.M_o \qquad -(6.9)$$

where M_o is the mass of oven-dry wood in the kiln, K_g.

---

* Data provided by J. Lejeune, project charcoal engineer.

The charcoal-equivalent used to drive off free water in the wood depends on the latent heat of vaporisation of water, the calorific value of charcoal, and the mass of water involved:

$$C_w = (L/V).(w/100).M_o \qquad -(6.10)$$

where w is the moisture content percent of the wood; the other variables are as defined above.

The production ratio, assuming wastage C_x is negligible, is therefore:

$$C_p/M_o = K - (L/V).w \qquad -(6.11)$$

This ratio is plotted on figure 8 agaist moisture content. Note that provided calorific value V and conversion ratio K are independent of species, as appears to be generally true, this ratio is also species independent, and applies to *Gmelina*, *Cassia siamea*, and indigenous hardwoods.

Actual yield of charcoal by weight per unit of kiln volume is also shown on figure 8 for *Gmelina arborea*, and is derived from:

$$C_v = (C_p/M_o).(S.G.1000) \qquad -(6.12)$$

where C_v is charcoal production per unit kiln volume, Kg/m^3. Note that the stacking factor may be as much as 20% higher or lower, depending on piece size, kiln shape, etc. A typical value of 0.45 is used for the above.

It will be interesting to plot data from actual kiln operating experience on the graph in figure 8 to compare the theoretical analysis and practical situation. Earl [7] shows a nonlinear yield function with moisture content from experience in Uganda; one may expect that at higher moisture contents the steam will interact with the carbonisation process, perhaps accounting for the departure from the theoretical linear model developed above.

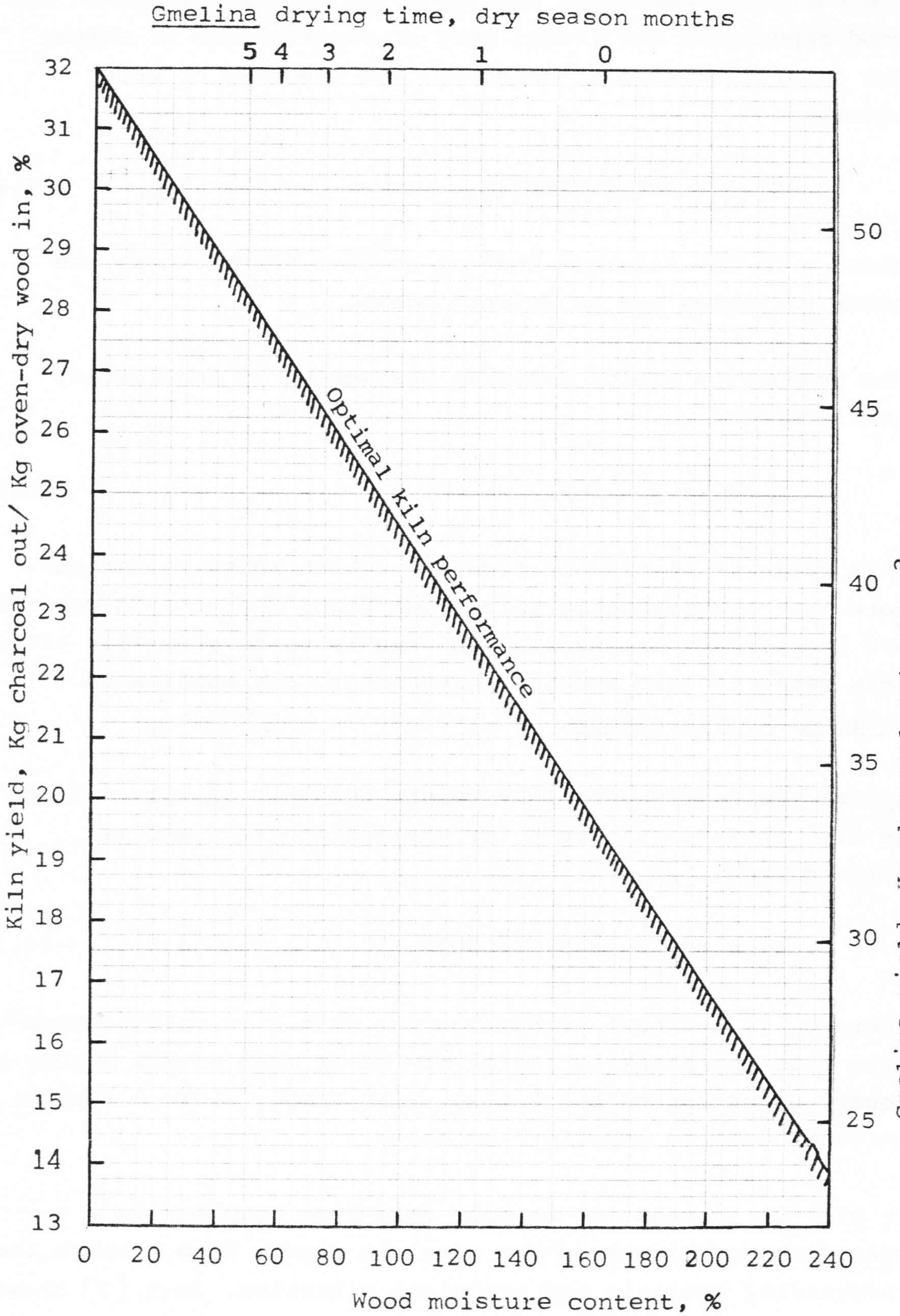


Figure 8 : Effect of moisture content on theoretical charcoal yields

The bottom and left scales are species independant; the scales at the top and right are for *Gmelina arborea*.

7. CONCLUSIONS

The stem taper functions presented here have a high order of flixibility in application, and provide a valuable tool for planning and operational analysis. Calculation of volumes with the taper functions are only readily practicable by computer or programmable calculator, and they will normally be used as part of a yield modelling system. Harvested volumes and size distribution of logs can be calculated on the basis of:

Inputs: Stem diameter distributions of Gmelina stand concerned.

Constraints: Fixed log-length piece size, or minimum and maximum log lengths. Minimum and maximum acceptable diameters, defined over or under bark.

The routines in Appendix A produce from the above the volume over and under bark, and a frequency distribution of log diameters for fixed-length harvesting; for variable log-length harvesting a size and length distribution table is produced.

The wood properties are of value in operational analysis of haulage costs, charcoal and fuelwood yields, and timing of operations. However, it should be noted that drying and moisture content studies need to be supplemented by wet season data. The drying curves are also based on an insufficient number of sample stacks and measurement points. The correlation of drying with thermohydrographic data in different situations (e.g. under forest canopy, at the roadside, and at open clearings) would be desirable.

It should also be noted that the results presented here are for first rotation Gmelina stands planted as seedlings or stumps. Coppice regeneration might well have different taper and wood density characteristics. This will require study if such a management practice is adopted.

Finally, it should be noted that the results here pertain to Gmelina arborea. However, the taper function procedures can readily be applied to other species; the programs in Appendix

A only require alteration of the coefficients. Note however that this does not apply to typically multistemmed species such as <u>Cassia siamea</u> under a coppice rotation.

REFERENCES

[1] Masson J.L. 1981 Subri conversion technique. UNDP/FAO project GHA/74/013 field document 7.

[2] Odoom F.K. 1981 A provisional yield table for <u>Gmelina arborea</u> plantations in Subri River Forest Reserve. UNDP/FAO Project GHA/74/013 field document 18.

[3] Alder D. & Cailliez F. 1980 Forest volume estimation and yield prediction. FAO Forestry Paper 22.

[4] Sutter H. 1981 A tree tariff table and a yield table for <u>Gmelina arborea</u> in the Omo and Oluwa Forest Reserves. UNDP/FAO Project NIR/77/008 field document 10.

[5] Alder D. 1982 SNIFTA nonlinear analysis documentation. Unpublished mimeo.

[6] Alder D. 1982 Forest inventory report for Subri River, Bonsa River, Neung and Pra Suhien Forest Reserves. UNDP/FAO project GHA/74/013 field document 21.

[7] Earl D.E. 1974 Charcoal : an André Meyer Fellowship report. FAO, Rome.

APPENDIX A

A.1 BASIC subroutines

The listing overleaf gives two subroutines in standard BASIC:

line 1000 Initializes the taper function module. Must be called once only from the main program before execution of subroutine 2000 below. No parameters are defined.

line 2000 Executes the taper function module. The following variables must be set on entry:

D	Tree diameter at 1.3 m., ob.
D1	Top diameter limit, cm. May be specified over or under bark, according to U below.
L	Length of logs, for pice size distribution analysis, in metres.
U	Set to 1 if D1 defines underbark top diameter; otherwise set to 0 for overbark top diameter.

On exit, the following values are returned:

V1	Overbark volume, m^3 to the top diameter limit.
V2	Underbark volume, m^3 to the top diameter limit.
N	Number of logs of fixed length L that can be cut.
L1	List of log mid-diameters, L1(1) to L1(N), in cm. overbark.

The following additional variables can also be referred to on exit:

H9	Tree total height, m.
V5	Tree volume to 5 cm ob from tree volume equation.
H1	Height to top diameter limit, m.
H0	Stump height, preset to 25 cm at line 2020

```
2240 REM compute over and underbark volumes
2250 P=1
2260 H2=(H0-1.3)/(H9-1.3)
2270 F1=FNV(H)-FNV(H2)
2280 P=3
2290 F2=FNV(H)-FNV(H2)
2300 REM convert form factors to volume relative to total volme eqn.
2305 P=1
2310 F5=FNV(H5)-FNV(H2)
2320 V1=F1/F5*V5
2330 V2=F2/F5*V5
2340 REM if fixed length cutting calculate log assortment
2350 IF L<=0 THEN 2220
2360 IF H1-H0<L THEN 2220
2370 P=1
2380 N=0
2390 FOR H3=H0 TO H1 STEP L
2400 REM count logs
2410 N=N+1
2420 REM calculate relative height of log mid-point
2430 H=(H3+0.5*L-1.3)/(H9-1.3)
2435 IF H>1 THEN N=N-1:GOTO 2470
2440 REM calculate diameter of log mid-point
2450 L1(N)=SQR(D*D*FNG(H))
2460 NEXT H3
2470 RETURN
3000 REM calculate merchantable height
3020 REM solve using Newton-Raphson iteration
3030 H=0.5
3040 G=D1*D1/(D*D)
3050 H8=H-(FNG(H)-G)/FND(H)
3060 REM test for convergence
3070 IF ABS(H8-H)/ABS(H)<0.0001 THEN 3100
3080 H=H8
3090 GOTO 3050
3100 RETURN
```

APPENDIX B

Field instructions and forms for volume sampling

Plantation Mensuration - Volume Sampling

Purpose

The purpose of the volume sampling in plantations is to provide data for a volume table of Gmelina arborea. The design of the sampling will permit volume tables to be derived using diameter, diameter and height, or stand basal area to predict solid wood volume to different top diameter limits, or stacked wood volumes, and obtain conversion factors from solid to stacked volume.

Location of sample plots

The sample plots will be located subjectively in areas indicated by the inventory officer. The objective is to place 3 to 4 plots in each age class, on different sites, to give a total of about 30 plots. The bearing and distance of theplot centre from the nearest road will be noted on the back of form 1. At the roadside a marker post will be placed indicating the plot number.

Measurement of the plot

(1) The plot centre will be marked by a short post. The exact location of the plot centre is chosen arbitrarily, but should be at least 1 metre from the nearest tree.

(2) The Relaskop is used, standing at the plot centre, to:

(i) Count all the trees that appear wider than one band at a height of 1.3 m. This count is entered on Form 1 as the Angle Count Factor.

(ii) Mark all trees that look wider than 2 bands. The diameter at 1.3 m. for the marked trees should be recorded. Each tree marked should be numbered with wax pencil or timber scribe.

(3) Each numbered tree is felled. On the felled tree, the following measurements are made and recorded on Form 2:

(a) The total length of the felled tree is measured to a point estimated as the top of the crown directly over the bole. This is added to stump height to give total tree height.

(b) The tree is marked with a cutlass at 1 metre intervals up the stem and along each side branch until a diameter limit of 5 cm is reached. The logs are numbered according to their height above ground. The bottom log is measured as 1 m from ground level, rather than from the top of the stump. It is more convenient to mark this point before the tree is felled.

(c) Logs are crosscut at the marked points. The top end of each log is marked with plot/tree/log no. Eg: The log from 3-4 m on tree 2 of plot 5 would be marked:

5/2/4

(d) The top diameter of each log is measured over bark and recorded. A thin ring of bark, not more than 1" wide is then removed, and the underbark diameter measured.

Form 1 Volume sampling in plantations

Reserve ....Compartment..........Pyear.........
Booker ....Date / / Plot ....
Angle count factor...........Main species.....................

Tree No.	Dbh (cm)	Height(m)	No. Stems	Species

Stacked weed volume ....Steres

Notes: 1. Height is total height
2. Record species only if different to main species
3. Treat trees branching below dbh as separate trees

Form: inv/2

TREE VOLUME SAMPLE (PLANTATION)

Reserve .... Compartment .... Plot ....
Booker .... Date / / Tree no. ......
Species .... Dbh .... cm Height .... m

Height from butt, m.	1st stem		2nd stem		3rd stem	
	Diam ob	Diam ub	Diam ob	Diam ub	Diam ob	Diam ub

Data processing section only

Recorded by .... Date / / Tape no. ....
File name .... File starts .... File ends ....

APPENDIX C

Gmelina volume tables

The volume tables shown on the following pages are produced using the subroutines in Appendix A.

The columes are as follows:

tree diam	Tree diameter overbark at 1.3 m, cm. This is the main entry for the table.
merch diam	The top diameter limit, cm. overbark. The zero top diameter gives totoal volume.
vol ob	Volume overbark, m^3 to the merchantable limit.
vol ub	" underbark " " " " " .
bark vol %	The percentage of the overbark merchantable volume comprising bark.
no. 1 m. logs	The number of 1 metre pieces in the tree, to the merchantable limit specified.
mean log diam	The mean overbark diameter of the 1 m. pieces.

The table is for trees from 6 to 60 cm dbhob, in 2 cm increments.

tree diam	merch diam	vol ob cu. m.	vol ub cu. m.	bark vol %	no. 1 m. logs	mean log diam
6	0	.0203	.0169	16.7	9	3.7
6	5	9E-03	7.5E-03	16.7	2	6.1
8	0	.0283	.0236	16.6	10	5
8	5	.0201	.0169	15.9	4	7.1
10	0	.0418	.0349	16.5	11	6.2
10	5	.035	.0294	16	7	7.7
10	10	2.5E-03	2E-03	20	0	0
12	0	.0601	.0501	16.6	13	6.9
12	5	.0545	.0458	16	9	8.6
12	10	.0226	.0188	16.8	2	12.1
14	0	.0838	.0699	16.6	14	8
14	5	.0793	.0665	16.1	11	9.4
14	10	.047	.0394	16.2	4	12.8
16	0	.1131	.0944	16.5	14	9.7
16	5	.1095	.0917	16.3	12	10.6
16	10	.077	.0647	16	6	13.5
16	15	.0161	.0134	16.8	0	0
18	0	.1482	.1237	16.5	15	10.8
18	5	.1453	.1215	16.4	14	11.3
18	10	.1131	.0952	15.8	7	14.8
18	15	.0511	.0426	16.6	3	17.4
20	0	.1892	.1578	16.6	16	11.8
20	5	.1867	.156	16.4	15	12.4
20	10	.1557	.131	15.9	9	15.4
20	15	.0919	.077	16.2	4	18.6
20	20	0	0	0	0	0
22	0	.2362	.1971	16.6	17	12.8
22	5	.2341	.1956	16.4	16	13.4
22	10	.2048	.1722	15.9	10	16.6
22	15	.1392	.1168	16.1	5	19.8
22	20	.0417	.0348	16.5	2	22.1
24	0	.2895	.2416	16.5	18	13.7
24	5	.2877	.2403	16.5	17	14.4
24	10	.2606	.2189	16	12	17.1
24	15	.1932	.1625	15.9	7	20.2
24	20	.0943	.0788	16.4	3	23.3
26	0	.3492	.2914	16.6	18	15.4
26	5	.3476	.2903	16.5	18	15.4
26	10	.3229	.271	16.1	13	18.2
26	15	.2544	.2141	15.8	8	21.3
26	20	.1536	.1286	16.3	4	24.4

tree diam	merch diam	vol ob cu. m.	vol ub cu. m.	bark vol %	no. 1 m. logs	mean log diam
28	0	.4155	.3467	16.6	19	16.3
28	5	.4141	.3457	16.5	18	17
28	10	.3917	.3285	16.1	15	18.7
28	15	.3229	.2718	15.8	9	22.4
28	20	.2199	.1845	16.1	5	25.5
30	0	.4886	.4077	16.6	20	17.2
30	5	.4873	.4068	16.5	19	17.9
30	10	.4671	.3914	16.2	16	19.7
30	15	.3989	.3358	15.8	11	22.8
30	20	.2936	.2467	16	6	26.5
32	0	.5686	.4745	16.5	20	18.8
32	5	.5675	.4737	16.5	20	18.8
32	10	.5492	.4599	16.3	17	20.7
32	15	.4825	.406	15.9	12	23.8
32	20	.3749	.3154	15.9	8	26.8
34	0	.6556	.5472	16.5	21	19.6
34	5	.6546	.5464	16.5	21	19.6
34	10	.6382	.5341	16.3	18	21.7
34	15	.5736	.4825	15.9	13	24.9
34	20	.4641	.3907	15.8	9	27.8
36	0	.7499	.6259	16.5	22	20.4
36	5	.749	.6252	16.5	21	21.2
36	10	.7341	.614	16.4	19	22.6
36	15	.6724	.5653	15.9	14	25.9
36	20	.5613	.4727	15.8	10	28.8
38	0	.8516	.7107	16.5	22	22
38	5	.8508	.7101	16.5	22	22
38	10	.8372	.7	16.4	20	23.5
38	15	.7788	.6542	16	15	26.8
38	20	.6668	.5616	15.8	11	29.7
40	0	.9608	.8019	16.5	23	22.8
40	5	.9601	.8013	16.5	23	22.8
40	10	.9476	.7921	16.4	20	25.1
40	15	.8926	.7494	16	17	27.1
40	20	.7806	.6574	15.8	12	30.7
42	0	1.0777	.8994	16.5	23	24.4
42	5	1.077	.8989	16.5	23	24.4
42	10	1.0656	.8905	16.4	21	26
42	15	1.014	.8507	16.1	18	28
42	20	.9029	.7602	15.8	13	31.6
44	0	1.2023	1.0035	16.5	24	25.1
44	5	1.2017	1.003	16.5	24	25.1
44	10	1.1911	.9952	16.4	22	26.8
44	15	1.143	.9583	16.2	19	28.9
44	20	1.0335	.8699	15.8	14	32.6

tree diam	merch diam	vol ob cu. m.	vol ub cu. m.	bark vol %	no. 1 m. logs	mean log diam
45	0	1.3349	1.1141	16.5	24	26.7
45	5	1.3343	1.1137	16.5	24	26.7
45	10	1.3245	1.1065	16.5	23	27.6
45	15	1.2796	1.0722	16.2	19	30.5
45	20	1.1726	.9865	15.9	15	33.5
48	0	1.4755	1.2315	16.5	25	27.4
48	5	1.4749	1.2311	16.5	25	27.4
48	10	1.4559	1.2244	15.5	23	29.1
48	15	1.4239	1.1926	16.2	20	31.4
48	20	1.3201	1.11	15.9	16	34.4
50	0	1.6243	1.3557	16.5	25	29
50	5	1.6238	1.3553	16.5	25	29
50	10	1.6153	1.3491	16.5	24	29.9
50	15	1.5761	1.3195	16.3	21	32.2
50	20	1.4709	1.2403	16	17	35.2
52	0	1.7814	1.4858	16.5	26	29.6
52	5	1.7808	1.4854	16.5	25	29.6
52	10	1.7729	1.4806	16.5	24	31.5
52	15	1.7363	1.453	16.3	22	33
52	20	1.64	1.3775	16	19	36.1
54	0	1.9468	1.6249	16.5	26	31.2
54	5	1.9463	1.6245	16.5	26	31.2
54	10	1.9389	1.6191	16.5	25	32.2
54	15	1.9046	1.5934	16.3	23	33.8
54	20	1.8125	1.5216	16	19	36.9
56	0	2.1208	1.7701	16.5	27	31.8
56	5	2.1203	1.7698	16.5	27	31.8
56	10	2.1134	1.7647	16.5	26	32.8
56	15	2.0811	1.7406	16.4	23	35.4
56	20	1.9933	1.6725	16.1	20	37.7
58	0	2.3034	1.9225	16.5	27	33.4
58	5	2.3029	1.9222	16.5	27	33.4
58	10	2.2964	1.9174	16.5	26	34.4
58	15	2.2661	1.8948	16.4	24	36.1
58	20	2.1825	1.8303	16.1	21	38.5
60	0	2.4947	2.0822	16.5	28	33.9
60	5	2.4943	2.0819	16.5	28	33.9
60	10	2.4881	2.0774	16.5	27	35
60	15	2.4596	2.0562	16.4	25	36.8
60	20	2.38	1.9951	16.2	22	39.3