Volume and growth models for some plantation species in Ecuador

A consultancy report for the Fundación Forestal Juan Manuel Durini prepared under contract through the United Kingdom Department for International Development by

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This report describes a visit to the Fundación Forestal Juan Manuel Durini (FFJMD) of a biometrics consultant sponsored by the United Kingdom Department for International Development. This is the third visit by this consultant to assist the Fundación in improving its techniques.

During the visit, a series of similar volume equations were developed for seven lowland tropical species (Laurel, Pachaco, Cutanga, Guayacan, Jacaranda, *Terminalia ivornesis, T. superba*). These equations give total volume, volume over-bark to 10 cm minimum diameter, volume under-bark to 20 and 35 cm , and under-bark volume for cylindrical sections of 2.6 m length to minimum diameters of 20 and 35 cm. General volume equations were also developed using pooled species data that could be applied to unsampled species as an interim measure.

With the volume equations, permanent and temporary sample plots from the lowlands were re-summarised in a compact format, to give for each plot stocking, Lorey's height, quadratic mean diameter, basal area, and the above-mentioned volumes on a per ha basis.

From the sample plot database, simple yield models were constructed for the most widely planted lowland species (Laurel, Pachaco, Cutanga, *T.ivorensis*, Coco, Jacaranda, Chuncho, Guayacan V.). These were based on mean height-age and volume-height curves for fully stocked plots, which were combined to give volume-age and mean annual increment on age. Curves of actual mean annual increments were also compiled directly from the plots.

A projection model called MOPP was developed from these yield curves which allows the whole plantation estate of FFJMD to be simulated. This gives production over the next 100 years using options for plantation mixture, new areas acquired, optimum rotation, and increased yields from genetic or silvicultural improvements.

Data for two seed orchards, for Laurel and Pinus patula, were also analysed. The families were ranked by growth performance to assist with roguing and selection.

A simple taper line method for constructing tree taper functions was demonstrated using data for Laurel.

Dynamic yield models developed during the last visit (1996) for Laurel and Radiata Pine were upgraded. In the Radiata Pine model, a function was added to show more realistically the relative adjustment of thinning and residual stand mean diameters due to the bias of thinnings to smaller trees. In the Laurel model, functions were added to give standing volume, thinning volume and MAI for under-bark cylindrical volumes to a 20 cm top.

Training and explanations were given for all the spreadsheet models produced. Several new techniques were demonstrated, especially the advantages of using Visual Basic versus traditional spreadsheet functions. Methods were indicated for more flexible regression analysis using arbitrary functions and non-linear coefficients. A technique for fitting curves by hand using the mouse was also explained that is useful for limit lines and other situations unsuited to regression analysis.

FFJMD has shown good absorption of training and techniques from past visits. Whilst it will take time for the several new techniques shown on this occasion to be fully mastered, the consultant felt that past precedents were a good indicator of probable success.

Contents

Abbreviations

Dbh...................Diameter at breast height (1.3 m).
DFID.................Department for International Development of the United Kingdom.
Excel ....*Microsoft Excel 97*. Registered trademark of Microsoft Corporation.
FFJMD ....Fundación Forestal Juan Manuel Durini
TSP ....Temporary sample plot.
PSP ....Permanent sample plot.
VBA ....Visual Basic for Applications. *Visual Basic* is a registered trademark of Microsoft Corporation.
TOR.................Terms of Reference

Acknowledgements

Disclaimer

This work is solely the responsibility of its author. Its conclusions and recommendations are those of the author, may not represent the formal view or policy of either the Fundación Forestal Juan Manuel Durini or of the United Kingdom Department for International Development.

Background This report forms part of a series of consultancies to the Fundación Forestal Juan Manuel Durini (FFJMD) involving both the present author and various other specialists. These visits have been supported by the United Kingdom Department for International Development (DFID) since 1975, with the objective of strengthening the capacity of FFJMD for forest management and research in the humid tropical and Andean zones.

The author has undertaken two previous visits. The first in February 1995 concentrated on training and assistance to transfer extensive sets of permanent plot data into computer formats. The second developed from the successful application of the fruits of the first visit. Site index curves and yield models were constructed for *Pinus radiata* and *Cordia alliodora* (Laurel), based on the plot data that had been entered into the computer since the first visit. A tree volume and taper function was also developed for *Pinus radiata*.

Terms of reference and activities undertaken The formal terms of reference (TOR) for the present assignment are given in Appendix A. Inevitably, priorities changed between the drafting of the TOR and the commencement of the assignment. Some of the issues listed have been addressed. A number of additional tasks were undertaken at the direction of FFJMD, whilst some items were not undertaken. The following list summarises the activities actually assigned to the consultant by FFJMD and described in the report:

> Volume equations for total volume and 10 cm, 20 cm and 35 cm diameter limits for seven tropical plantation species, including underbark measure and a scaling rule involving cylindrical measure on 2.6 m lengths for rotary veneer volumes.

> Yield models and MAI curves for eight tropical plantation species, both under conditions of optimal stocking, and for actual average production from plantations.

> Modifications to the simulation models developed previously (1996) for Laurel and Radiata Pine.

> Re-calculation of sample plot statistics for all temporary and permanent plot data, using the new volume equations and 'best practice' methods of calculation.

> Analysis of seed orchard measurements for Laurel and *Pinus patula* to rank families by performance and provide information on significant differences.

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Development of a planning model for the lowland tropical plantations, using the new yield and volume functions developed during the assignment.

Training to FFJMD's computer specialist in Visual Basic and various aspects of system use.

Assistance in upgrading of the ILWIS GIS software to Windows 95 compatibility.

Discussions and advice on natural forest growth and yield, forest inventory techniques, and various forest management issues arising from the growth and yield studies.

Table 1 : Species volume equations and yield models produced

Species	Volume equations	Yield models	Other
Pinus radiata	Variable top diameter limit completed 1996	Dynamic simulation model from 1996 improved	
Pinus patula			Seed orchard analysis as for Laurel
Laurel *Cordia alliodora*	Volume equations to 10, 20, 35 cm top, over and under bark, scaling rule for 2.6 m cylindrical sections	Dynamic model from 1996 modified to include volumes using 20 cm minimum diameter and cylindrical scaling. Height and yield curves developed from TSP/PSP data for average and optimal stocking.	Seed orchard analysis. Families ranked and significant differences tested.
Pachaco *Schizolobium parahybum*		Height and yield curves developed from TSP/PSP data for average and optimal stocking.	
Cutanga *Parkia multijuga*			
Guayacán V. *Cybistax donnell-smithii*			
Jacaranda *Jacaranda copaia*			
Chuncho *Cedrelinga cateniformis*	No individual volume equation. General volume equations developed for use with these species.		
Coco *Virola spp.*			
Paraiso *Melia azadiracta*			
Terminalia superba	Individual equations as for Laurel etc.		
Terminalia ivorensis			

Outputs produced The species-level studies are summarised in Table 1, showing for which species there are now local FFJMD volume equations and yield models. In all, volume equations have been developed for 7 species (Laurel, Pachaco, Cutanga, Guayacan, Jacaranda, *Terminalia ivorensis* and *T. superba*). Simple yield curves for both optimal and average growth have been prepared for 9 species (as above, but including also Chuncho, Coco, and Paraiso). Dynamic models which had been developed in 1996 for *Pinus radiata* and Laurel were modified to incorporate suggested improvements. Seed orchard analyses were carried out for *Pinus patula* and Laurel.

Table 2 Excel workbooks produced during the consultancy

Excel filename	Description of contents
Huerto Laurel	Data and analysis for Laurel seed orchard. Includes map of orchard and VBA programs for calculating means, standard deviations and studentized ranges for heights and diameters.
Huerto Pino patula	Similar to above, but with different data format and no map.
Sumario de parcelas	Summaries of all lowland permanent and temporary plots, one record per plot and year of measurement. Includes main species, stocking, quadratic mean diameter, Lorey's height, volumes to 10 cm top over bark, and 35 cm underbark cylindrical scale. Additional fields for stocking, 10 and 20 cm volume for whole stand including secondary plantings and natural regeneration. Includes VBA programs to summarise data from original plot measurement files.
Laurel Model (SIMOLA for Excel 5)	Yield model for Laurel developed during 1996 visit, with voumes and MAI added for 20 cm cylindrical volume measure modifications.
Radiata Model (SIMORA for Excel 5)	Yield model for Radiata, originally developed 1996 but modified to adjust residual mean diameter for distribution of thinnings.
PlanPlan	Average volume yields over time for eight most important plantation species in the lowlands. Includes VBA program to summarise data from plot summaries in *Sumario de Parcelas*.
Ecuvol	Volume equation analysis for seven species, including VBA program to analyse regressions for total volume, 10 cm volume, and ratio functions for 20 and 35 cm top, underbark conversion, and cylindrical scaling. Also includes general volume equations for all species combined designed for use with species for which no volume equation exists.
MOPP	A plantation planning program that includes a list of lowland forest areas under FFJMD management, yield tables for 8 species derived from the *PlanPlan* workbook, and a VBA program to project yileds over the next 100 years from the plantation estate.
MC-Chuncho MC-Cutanga MC-Jacaranda MC-Laurel MC-Pachaco MC-Paraiso MC-T.superba	A series of yield models for 7 species including in each one PSP and TSP summaries for the species, mean height curves, volume height curves for 10 cm overbark and 20 cm cylindrical underbark volume

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Table 2 lists the various Excel workbooks that have been developed for these analyses. Each workbook is available to FFJMD for modification or re-analysis. They also provide a training resource, as they contain various examples of common Excel methods for regression analysis and data summarisation. Most of them also include examples of Visual Basic code which should provide a basis for improving skills in this area. All the files were developed in Excel 97, but some were saved and tested also in Excel 5 for use on a portable computer (SIMOLA, SIMORA, MOPP).

Data collection and analysis with TAVOL

Since the author's previous visit in October 1996, the Fundación Forestal has made major efforts in the field of tree volume studies. Table 3 shows the data collected for various species, comprising in total some 399 sample trees for 7 major plantation species.

The Fundación has also developed a system for analysis in Excel called TAVOL. This undertakes the following functions:

- Provides a template for data entry of tree section measurements from tree forms.

- Calculates tree volume using a variety of standards and scaling rules (Huber's, Smalian's or Newton's formulae, cylindrical scaling on 2.6 m lengths (for rotary veneer), with top diameters of 10, 20, 25 or 35 cm).

- Fits regressions using the *Trendline* facility built in to Excel graphs. This allows many types of common regression with a single independent variable to be tested.

In discussions with the Fundación it was suggested that the kinds of volumes to be considered should be limited and standardised. There is in reality little difference in values calculated by the three common methods (Huber's, Smalian's or Newton's) over short sections (2-3 m length). It was agreed that Smalian's method be adopted as a standard. However, the cylindrical scaling using lengths of 2.6 m is important also because of its correspondence to the volumes that can be effectively processed for rotary veneer.

For the further analysis of volume, the following measures were therefore extracted from TAVOL:

- *Total volume overbark* (V_t), including both the cut stump volume, and the tip volume of the tree, calculated by Smalian's rule. This volume is in reality not of direct use for timber management, but has value for comparisons in other published literature.

- *Volume overbark of the stem to 10 cm minimum diameter* (V_{10}). This excludes the cut stump and a hypothetical tip, and corresponds to the maximum volume that is likely to be marketable to a integrated industry with a wood chip component.

- *Volume underbark using cylindrical measure over 2.6 m lengths to 20 cm minimum diameter* (V_{20}). The volume of each 2.6 m section is calculated as a cylinder from the small-end diameter. This

corresponds to the volumes actually useable in existing rotary veneer plants in Ecuador.

- *Volume to 35 cm minimum diameter using the same cylindrical scaling* (V_{35}). This represents and older standard for rotary veneer volumes that is still generally applicable to trees from the natural forest.

These data were extracted into an Excel workbook called Ecuavol, which contains all the volume equation models, graphs and summaries.

Comparison of total volume equations   For total volume, a set of equations was tested graphically for each species. These were as follows:

(i)   Form height: This is the simplest function for volume estimation, given algebraically as:

$$V_t = F_h.G$$

where V_t is total volume, F_h is the form height in metres, and G is the tree basal area in m²/ha. Form height is useful as a quick rule of thumb for estimating volume from basal area for a stand.

(ii)   Form factor: This incorporates information about tree height, and is therefore more accurate than form height. It is defined as:

$$V_t = F_f.G.H$$

where F_f is the form factor, and H is the tree total height.

(iii)   Diameter power function: This has the form:

$$V_t = a.D^b$$

This is a widely used model, especially in natural forests where heights are difficult to measure.

(iv)   Diameter and height power model: This is a logarithmic model in both diameter and height, and is accordingly more accurate than (iii). The form is:

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$$V_t = a.D^b H^c$$

This model is the preferred form, as it has the maximum flexibility compared with models (i)-(iii).

Figure 1 compares these models for Laurel. For comparison of the equations which include height, mean height is estimated from an average height diameter line. The workbook Ecuavol contains similar graphs for all the species analysed.

Figure 1 Various forms of total volume equations for Laurel
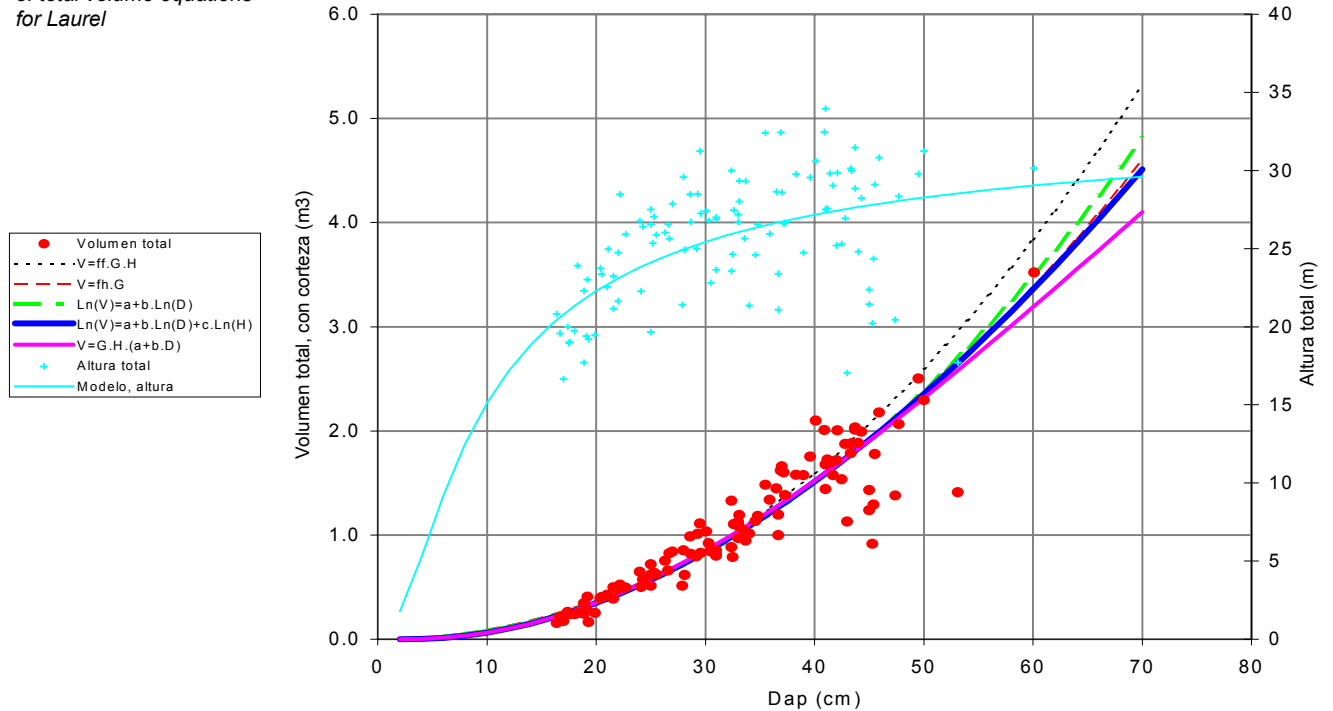
The purpose of these comparisons was primarily to demonstrate that the several possible forms of volume equations give similar results. The difference between the rather simple form factor model and the more complex logarithmic equation is very small.

Equations for over-bark stem volume   Two equations were fitted for volume overbark to a 10 cm minimum diameter. Both are variants of the logarithmic equation, and have the form:

$$V_{10} = a.(D-10)^b \qquad (1)$$

$$V_{10} = a.(D-10)^b H^c \qquad (2)$$

The first form is convenient for use in situations where height is unknown. The second can be expected to be more accurate. Figure 2 shows an example of form (1) for Laurel. It can be seen that the

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line has a typical logarithmic shape, but cuts the x-axis at 10 cm, instead of zero as would be the case with a simple power function

Figure 2 Over-bark volume equation to a 10cm minimum diameter
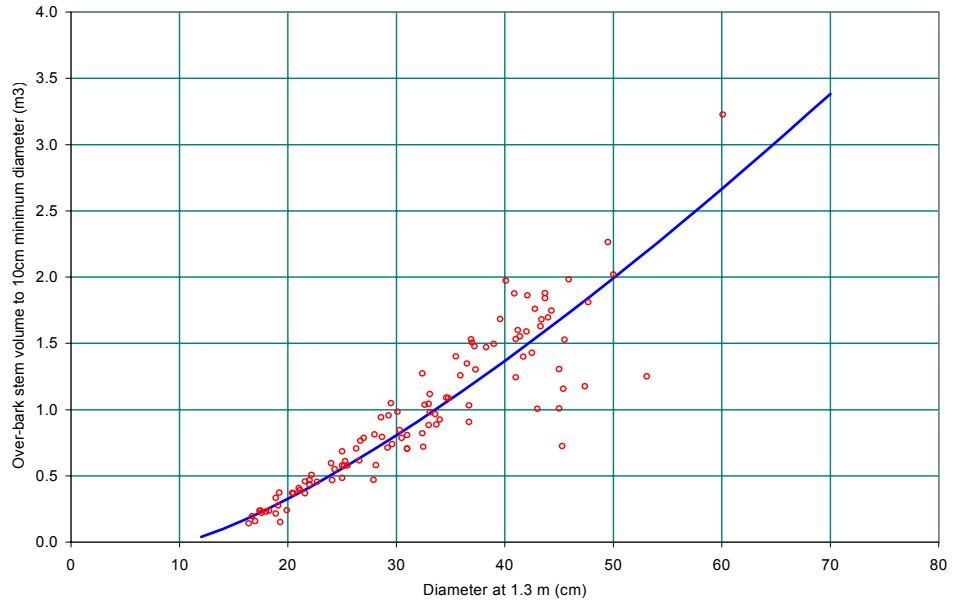
fitted using the Excel built-in trendline facility. The workbook *Ecuavol* contains similar graphs for all the species studied.

Volume ratios for upper stem diameter limits

Volumes to other top diameters are calculated using the ratio estimator. Figure 3 shows an example for Laurel data. For 20 cm top diameter, for example, the ratios are calculated between 20 and 10 cm volumes over-bark. These are then plotted against tree diameter. A strongly asymptotic relation exists which can be modelled by various functions. The consultant found that the best fit from easily linearized models was obtained with the relation:

$$R = 1 - exp(-a(D-D_{min})^b) \tag{3}$$

Here, R is the ratio of 20 or 35 cm volume to 10 cm volume, a and b are coefficients estimated by regression, D is tree dbh, and D_{min} is the diameter limit.. This equation can be transformed to fit the coefficients by linear regression using the form:

$$Ln(-ln(1-R))=ln(a) +b.ln(D-D_{min})$$

This is equivalent to the linear regression formula:

$$Y= \alpha + \beta. X$$

Here, Ln(-ln(1-R)) can be substituted for Y and .ln(D-D_{min}) for X. The coefficient a is calculated as exp(α); β is the same as b.

To use this equation, the 10 cm volume is first calculated using the equations (1) or (2) above. The ratio is calculated from equation (3). The volume to the 20 or 35 cm limit can then be calculated from:

$$V_{20} = V_{10}R_{20}$$

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Figure 3 Volume ratio functions to 20 and 35 cm top diameter for Laurel
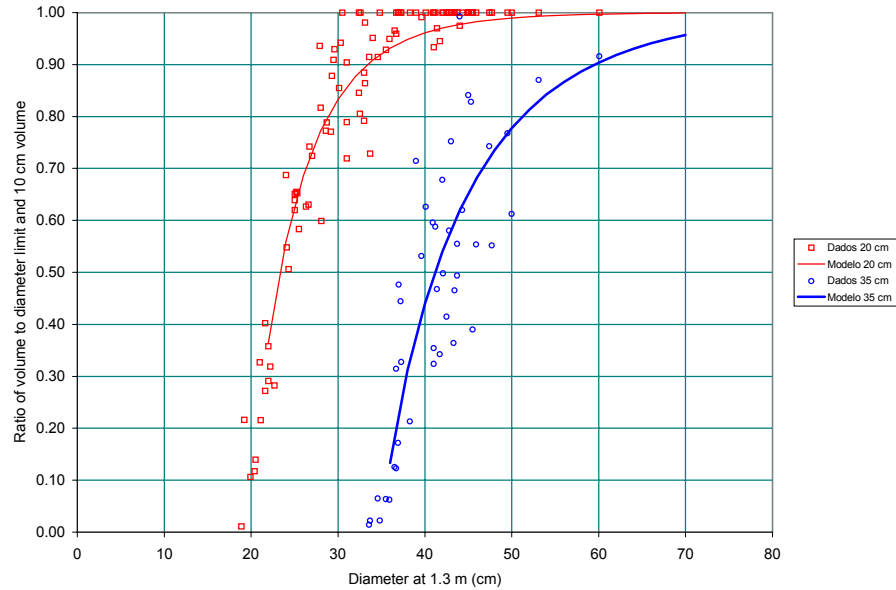
or $V_{35} = V_{10}R_{35}$

Under-bark and cylindrical volume conversion

Conversion from over to under-bark measure is also carried out using a ratio function, where:

$$V_{ub} = R_{ub}.V_{ob}$$

$$R_{ub} = a + b.ln(D) \tag{4}$$

Here, V_{ob} is the over-bark volume calculated from the preceding systems of equations (either V_{10}, V_{20} or V_{35}). V_{ub} is the corresponding under-bark volume to the same measurement limit. In the second equation, a and b are coefficients which can be fitted by regression, D is tree dbh, and R_{ub} is the ratio of under to overbark volume.

The same method is used to convert from stem over-bark volume calculated according to Smalian's rule to under-bark cylindrical measure for 2.6 m lengths. In this case, the conversion ratio can be written as:

$$V_{cil} = R_{cil}.V_{ob}$$

$$R_{cil} = a + b.ln(D)$$

Figure 4 shows these ratio models for data for Laurel sample trees.

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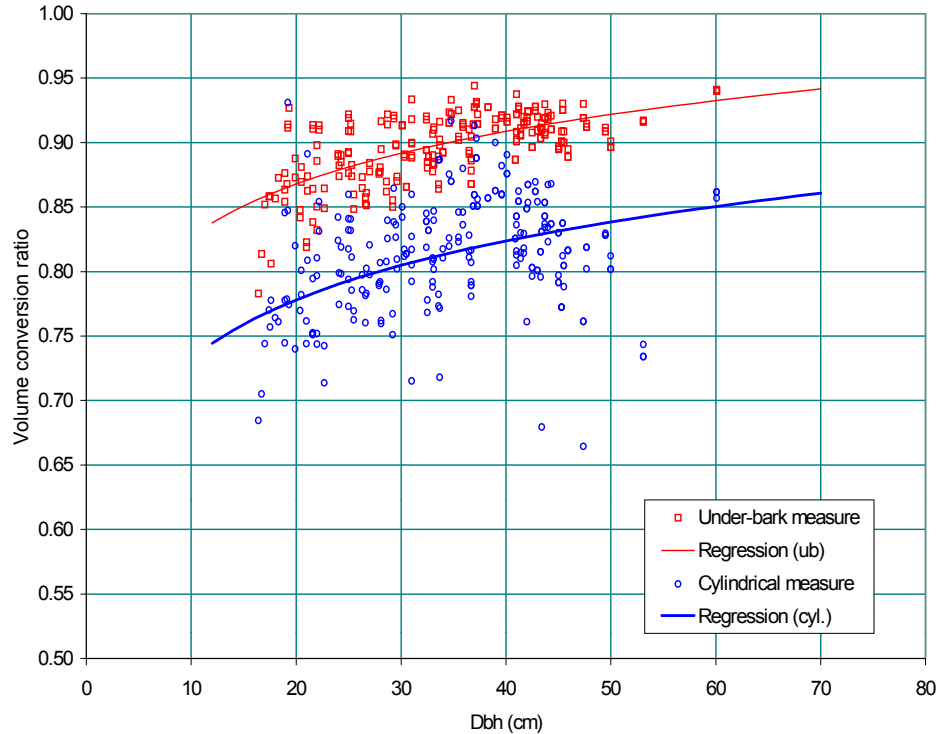
Figure 4 Under-bark and cylindrical conversion ratios

Example of volume calculation

The coefficients for the regressions for various species are shown in Table 3. The following example shows how the system can be used to calculate stem over-bark volume to 10 cm top, under-bark volume to 20 cm, and under-bark measure with cylindrical scaling, for a Laurel tree of 30 cm dbh and 25 m total height.

Stem volume over-bark is calculated using equation(2), which with the coefficients for Laurel is:

$$V_{10} = 0.0006041 \ (D\text{-}10)^{1.099} H^{1.209}$$

For the tree of 30 cm dbh and 25 m height this gives:

$$V_{10} = 0.796 \ m^3$$

The conversion ratios for 20 cm top diameter uses equation (3), which with the coefficients for Laurel is:

$$R_{20} = 1\text{-}exp(\ \text{-}0.2507 \ (D\text{-}20)^{0.8542})$$

This gives a ratio of 0.833, so that over-bark volume to 20 cm top diameter is:

$$V_{20,ob} = 0{,}663 \ m^3$$

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Table 3 Coefficients for volume equations for various species

Species		Cutanga	Guayacan	Jacaranda	Laurel	T.ivorensis	T.superba	Pachaco
No. trees	Total	49	30	20	107	35	42	124
	>10cm	49	30	20	107	35	42	124
	>20cm	46	29	17	93	31	38	124
	>35cm	20	10	5	42	15	11	98
Form factors								
	ff	0.447	0.488	0.463	0.467	0.515	0.485	0.430
	fh	11.73	10.92	11.57	11.95	13.04	10.93	15.88
Total volume over-bark								
$V=aD^b$	a	2.770E-04	6.381E-04	6.979E-05	6.978E-04	6.532E-04	4.240E-05	6.004E-04
	b	2.343	2.084	2.765	2.080	2.124	2.879	2.188
	R^2	0.95	0.93	0.98	0.91	0.91	0.92	0.96
$V=aD^bH^c$	a	2.539E-05	4.929E-05	5.165E-05	3.752E-05	6.334E-05	3.133E-05	3.530E-05
	b	2.049	1.691	2.130	1.764	1.684	1.943	1.795
	c	1.046	1.254	0.754	1.240	1.197	1.124	1.206
	R^2	0.98	0.97	0.99	0.97	0.98	0.99	0.98
f=a+b.D	a	0.430	0.604	0.504	0.560	0.651	0.476	0.492
	b	5.365E-04	-3.776E-03	-1.445E-03	-2.853E-03	-4.134E-03	2.782E-04	-1.261E-03
	R^2	0.01	0.28	0.10	0.20	0.38	0.00	0.19
Stem volume over-bark to 10 cm top diameter								
$V=a(D-10)^b$	a	0.00759	1.402E-02	5.782E-03	1.613E-02	1.564E-02	3.039E-03	5.823E-03
	b	1.54973	1.320	1.662	1.306	1.348	1.828	1.690
	R^2	0.95	0.92	0.98	0.91	0.90	0.91	0.96
$V=a(D-10)^bH^c$	a	0.00044	5.262E-04	1.584E-03	6.041E-04	6.407E-04	4.471E-04	2.744E-04
	b	1.34953	1.051	1.292	1.099	1.047	1.185	1.399
	c	1.06	1.313	0.733	1.209	1.276	1.234	1.138
	R^2	0.97621	0.97	0.99	0.96	0.98	0.99	0.98
Conversion ratio for various top diameter limits $\{r=1-\exp(-a(D-Dmin)^b)\}$								
20:10 cm diam.	a	0.21	0.5696	0.2108	0.2507	0.2139	0.5334	
	b	0.91518	0.5203	0.8480	0.8542	1.0275	0.6464	
	R^2	0.90768	0.59	0.93	0.90	0.94	0.79	
25:10 cm diam.	a							0.9492
	b							0.4048
	R^2							0.70
35:10 cm diam.	a	0.20	0.1958	0.1284	0.1435	0.1341	0.2105	0.1801
	b	0.72338	0.8540	0.6717	0.8675	1.0082	0.6130	0.7577
	R^2	0.87735	0.56	0.73	0.66	0.85	0.68	0.85
Conversion ratio for under-bark Smalian's volume								
r= a + b.ln(D)	a	0.83654	0.6553	0.7097	0.6920	0.8545	0.8101	0.8390
	b	0.02811	0.0601	0.0585	0.0587	0.0210	0.0346	0.0211
	R^2	0.29	0.43	0.64	0.42	0.31	0.33	0.16
Conversion ratio for cylindrical 2.6 m under-bark volume								
r= a + b.ln(D)	a	0.59842	0.5397	0.2904	0.5806	0.6713	0.5212	0.6622
	b	0.07	0.0691	0.1499	0.0659	0.0495	0.0931	0.0473
	R^2	0.18581	0.03	0.52	0.08	0.16	0.28	0.11

The volumes under-bark with Smalian or 2.6 m cylindrical scaling are given from equation (4), which with the Laurel coefficients substituted become:

$$R_{ub} = 0.6920 + 0.0587 \ln(D)$$

$$R_{cil} = 0.5806 + 0.0659 \ln(D)$$

This gives ratios as follows for a tree of 30 cm dbh:

$$R_{ub} = 0.892$$

$$R_{cil} = 0.805$$

The ratios for the diameter limits and under-bark or cylindrical scaling are combined for a final conversion of the 10 cm over-bark volume:

$$V_{20,ub} = V_{10}.R_{20}.R_{ub}$$

$$V_{20,cil} = V_{10}.R_{20}.R_{cil}$$

This gives final results for the volumes of:

$$V_{20,ub} = 0.796 \times 0.883 \times 0.892 = 0.626 \ m^3$$

$$V_{20,cil} = 0.796 \times 0.883 \times 0.805 = 0.566 \ m^3$$

Although the method may seem complicated, it can be applied quite easily within a spreadsheet analysis.

The alternative method to the use of ratios is to fit volume equations directly for different categories of volume against tree diameter and tree total height. However, this has the disadvantage that inconsistencies arise because regressions for different types of volume do not have any mathematically constrained relationship. The ratios are also themselves useful management information, showing that for example, 20 cm cylindrical volume is 71% of 10 cm stem volume for a 30 cm tree (ie. 0.883 x 0.805). This indicates approximately the waste available for boiler fuel, etc.

General volume equations Table 3 shows the 7 lowland species for which volume equations were fitted individually. In addition, during the previous visit, a variable top diameter volume equation was developed for *Pinus radiata*. However, there remain a number of species managed by FFJMD for which there are as yet no volume functions. To cater for these, general functions were developed using pooled data for all the lowland tropical species.

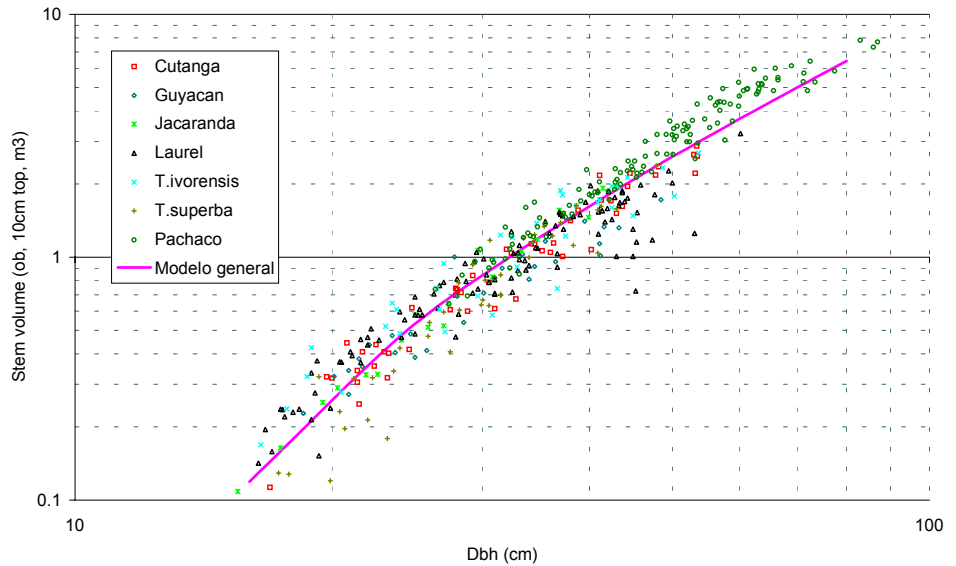*Figure 5 General volume equation, plotted on logarithmic axes*

Figure 5 shows the data for the seven species plotted on logarithmic axes, with the fitted function for equation (1). The general function is quite representative except for the larger Pachaco, which tend to be under-estimated. The pooled coefficients for the key equations are shown in Table 4.

Table 4 General volume equations for lowland tropical species

(i)   <u>Stem volume to 10 cm top diameter over-bark</u>

$V_{10} = 0.0006472 (D-10)^{1.624}$ *(Dbh only)*

$V_{10} = 0.0005874 (D-10)^{1.200}H^{1.128}$ *(Dbh and total height)*

(ii)   <u>Conversion ratio for 20 and 35 cm top diameter limits</u>

$R_{20} = 1 - exp(-0.3222 (D-20)^{0.7636})$

$R_{35} = 1 - exp(-0.1830 (D-35)^{0.7550})$

(iii)   <u>Conversion ratios for under-bark and cylindrical scaling</u>

$R_{ub} = 0.7841 + 0.0357 ln(D)$

$R_{cil} = 0.6124 + 0.0606 ln(D)$

Tree taper functions   The consultant's terms of reference make specific mention of tree taper functions. However, the consultant advised FFJMD's management that this is a relatively complex issue that could not be dealt within the limitations of a short assignment. Taper functions cannot be used as easily as volume functions, and require programmed subroutines within specific forest planning programs in order to be useful for calculating, for example, log assortments based on diameter and length specifications. This is somewhat beyond FFJMD's current method of operation, and consequently, had most of the time been devoted to developing taper functions, they would have been of little use.

However, in order to demonstrate the techniques and principles a preliminary analysis was made for Laurel using the simple taper line principle. For most tree species, there is a proportional relationship between sectional area up the tree, and height above ground. This is due to the fact that most tree boles are approximately paraboloid in shape over their main part. This relation breaks down within the crown, where the form may be excurrent (multiply branched) or tapering in a conical fashion. It also is untrue close to the ground, normally below dbh. This part of the stem is typically neiloid in shape.

Data for upper stem measurements for Laurel were extracted from TAVOL to an Excel workbook called *Taper Laurel*. In this, diameter and height for each sample tree were converted to relative measurements using the following transformations:

$$h_r = (h – 1.3)/(H – 1.3) \qquad \textit{(relative height)}$$

$$g_r = d^2/D^2 \qquad \textit{(relative diameter)}$$

Here, h is height above ground for a sectional diameter measurement d, D and H are tree dbh and total height respectively. These transformations are conventional in tree taper studies, and give values with relative sectional area 1 at tree dbh, and zero at the tip of the tree. Relative height is zero at 1.3 m, 1 at the tip, and negative below dbh.

Figure 6 shows these sectional measurements plotted graphically for the various sample trees. The taper line is shown formed by the equation:

$$h_r = 1 - d_r \qquad \textit{(taper line)}$$

This gives a good approximation to tree taper for Laurel, although a better model could be fitted using a constrained polynomial. A simple polynomial or other unconstrained regression is not suitable as it would not automatically pass through the points (1,0) and (0,1) at dbh and the tip of the tree respectively.
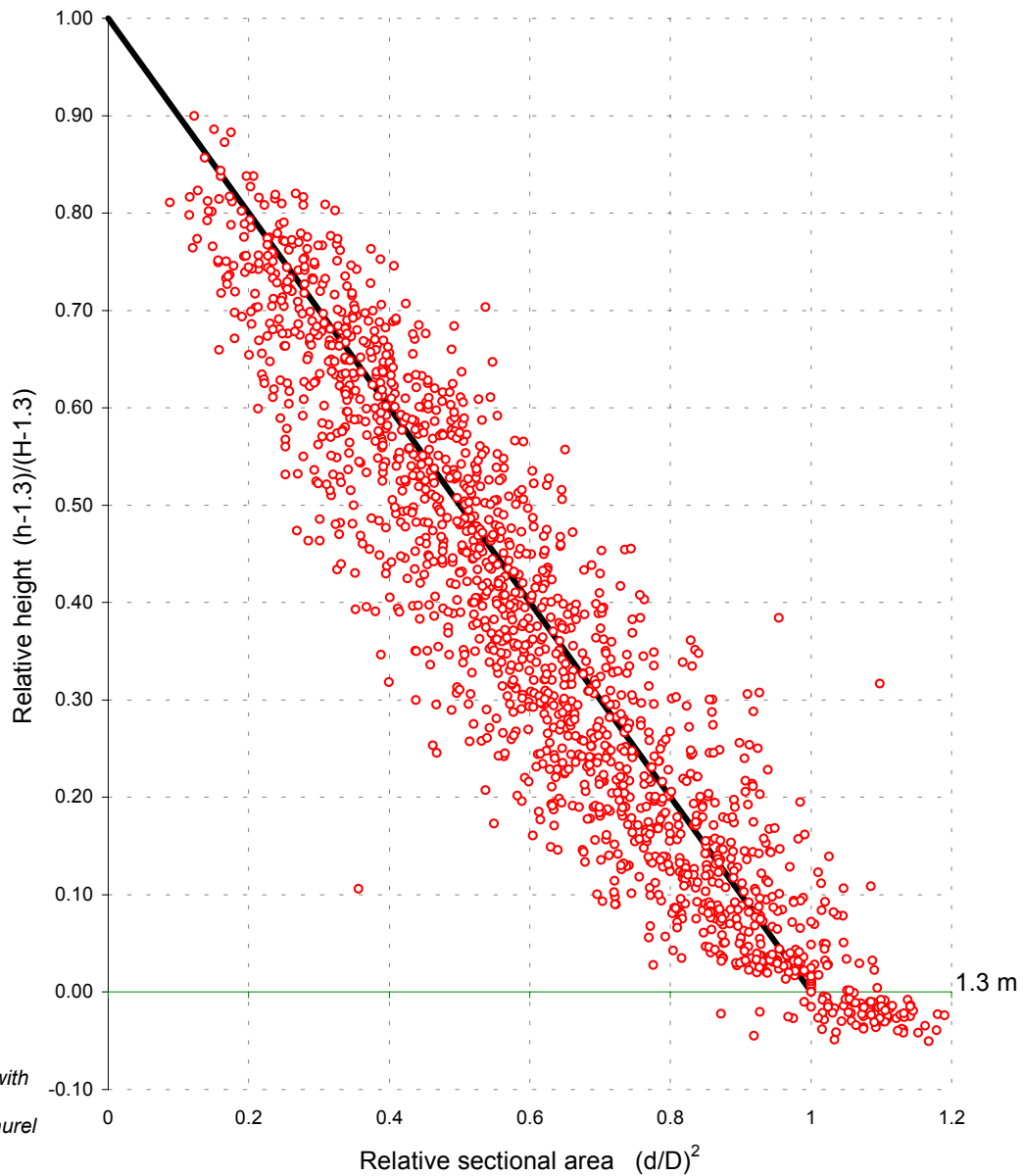
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Figure 6 Taper line with upper stem measurements for Laurel

The height of a point corresponding to a given diameter can be calculated from:

$$h = (1 - d^2/D^2)(H - 1.3) + 1.3 \qquad \textit{(height to a top diameter)}$$

For example, with a tree of 30 cm dbh and 25 m total height, the height to a 20 cm top would be 14.5 m.

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Improvements to dynamic yield models

During the 1996 visit, dynamic yield models were developed for Radiata Pine and Laurel. The current terms of reference provided for some upgrades to these models, which were duly made. The Radiata Pine model was amended to show the effects of thinning on the residual diameter distribution. The Laurel model was extended to incorporate 20 cm volumes using the under-bark cylindrical scaling rule. Three columns were added to the tables: (1) standing volumes to 20 cm top, (2) thinned volumes, and (3) MAI of 20 cm volume, including accrued thinnings.

Formats on both models were changed, and the Radiata model tables and graph captions were translated into Spanish. Both models were tested on Excel 97 and Excel 5 in different versions, as noted in Table 2.

Sample plot summaries

As a precursor to the development of further yield models, data from temporary and permanent sample plots were summarised in a standard format in the workbook *Sumario de Parcelas.* FFJMD had digitised data from all temporary and permanent plots, and developed a series of summaries using a variety of methods of calculation. However, volumes were based on assumed form factors applied to stand basal areas or mean trees. The summaries were also based on Excel functions applied to the raw data, resulting in workbooks that were very large and slow to open or update.

The consultant's approach was slightly different. The original raw data files were stripped of all worksheet functions and simplified into two series of files, each containing only raw data. The first series, comprising only temporary plot data, have names such as PMT-R1.XLS, PMT-R2.XLS, etc. The secondary series for permanent plots are grouped by species, and have names relating to the species, such as PP-LAUREL.XLS, PP-JACARANDA.XLS, etc. The data were then summarised in a separate file (*Sumario de Parcelas*) by a Visual Basic program embedded in the latter workbook. This is considerably faster and avoids creating very large files.

The summary process used the new volume equations described in previous chapter to calculate volumes tree by tree for each plot. As the plots were read, a height-diameter regression was built using the available sample tree data. This is done stand by stand, or in cases were there are more than 20 sample trees in a plot, plot by plot. The resulting height diameter regression is more accurate than the method used in FFJMD's summaries. This was based on overall

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height-diameter regressions for all data from each species, and was not sensitive to local variation in site, age, and stand density.

Volumes for each tree were calculated using the power model in tree total height and diameter (equation 2, page 7). Heights used were either those recorded, for height sample trees, or estimates from the local height-diameter regression.

Volumes of secondary plantation and natural forest species were estimated using the general volume equations shown in Table 4.

The summaries for each plot included the stocking, basal area, diameter of mean basal area tree, Lorey's height[*], 10 cm over-bark volume, 20 cm and 35 cm cylindrical volumes for the main plantation species. For the whole stand including secondary species (re-plantings) and natural regeneration, total stocking and 10 cm over-bark and 20 cm cylindrical volumes were calculated as well.

Details of the calculations can be reviewed in the workbook *Sumario de Parcelas* by examining the macros SumPP and SumPMT through the Visual Basic editor.

Method for yield model construction

Yield models were constructed for eight species for which sufficient sample plot data existed. These included:

Chuncho	*Cedralinga cateniformis*
Cutanga	*Parkia multijuga*
Jacaranda	*Jacaranda copaia*
Laurel	*Cordia alliodora*
Pachaco	*Schizolobium parahybum*
Paraiso	*Melia azadiracta*
	Terminalia superba

The method is illustrated using the data for Jacaranda. For each species, a curve of Lorey's height on age was constructed as shown in Figure 7. A second pair of curves was constructed for stand volume against Lorey's height (Figure 8). For this curve, the upper limit of the trend was estimated to indicate the volume development of fully stocked stands. Combining height-age and volume-age allows an MAI curve to be drawn (Figure 9).

This method is based on the assumption that at least some of the plots represent fully stocked stands. It also assumes the tendency of the height-age curve to reach a limit at full stocking which is closely definable by a logarithmic curve.

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[*] Lorey's height is mean height weighted by tree basal area, or $(\Sigma d^2 h / \Sigma d^2)$.

Two volumes are shown: the 10-cm over-bark stem volume, and the 20 cm under-bark volume based on scaling to 2.6 m cylindrical lengths. The 20-cm volume is the most important figure for commercial production.

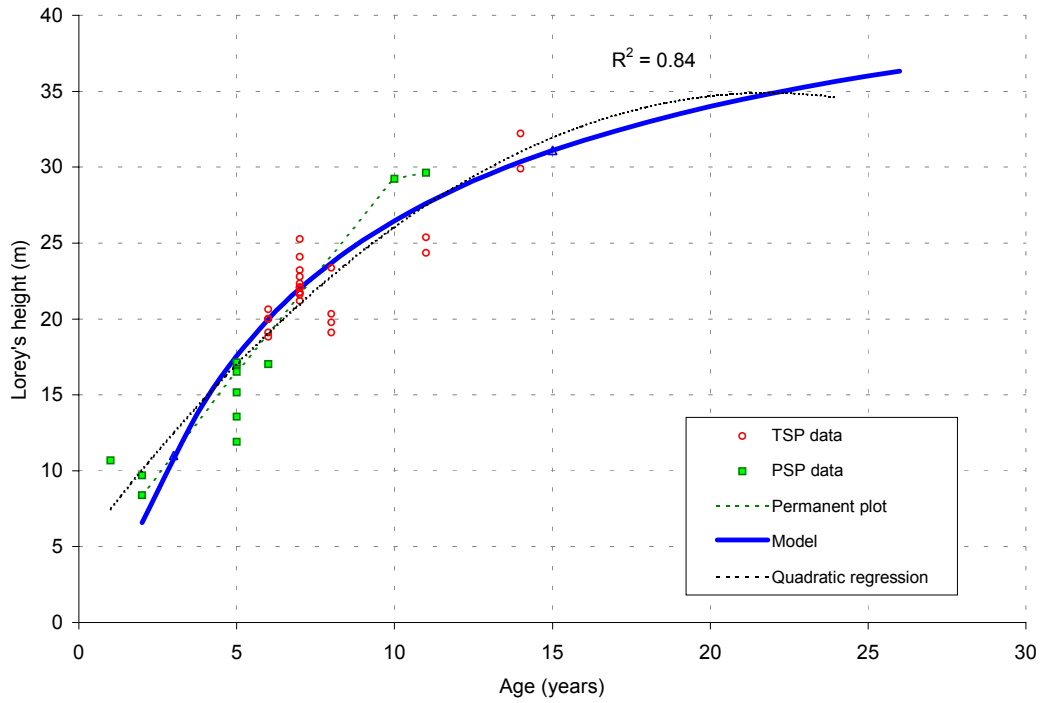*Figure 7 Stand height on age for Jacaranda*

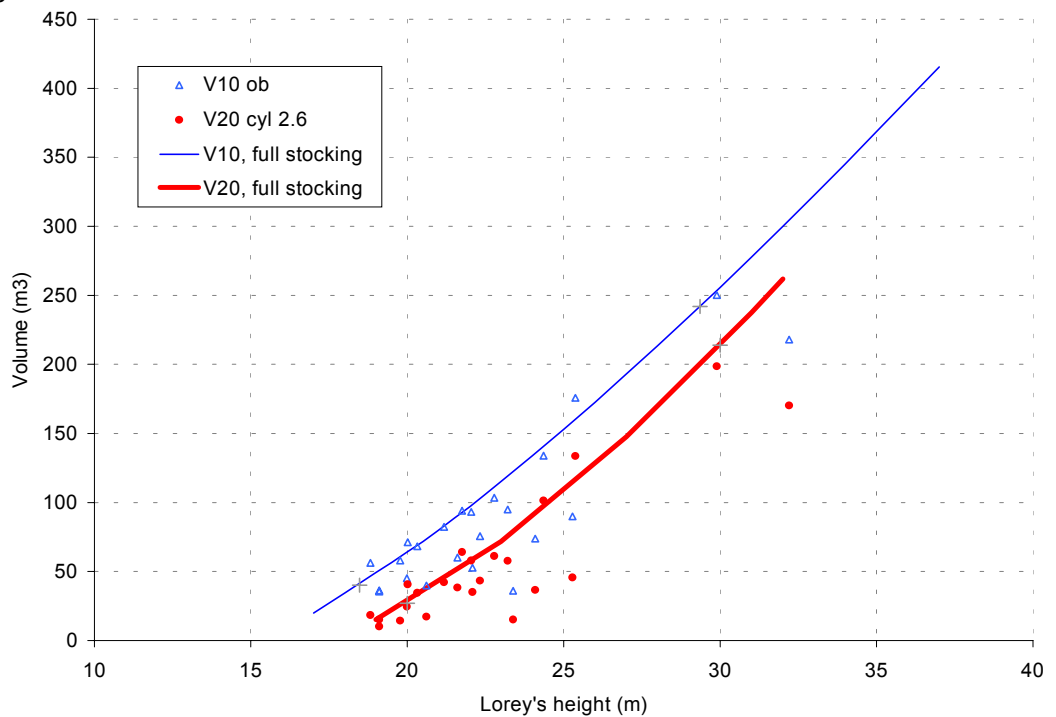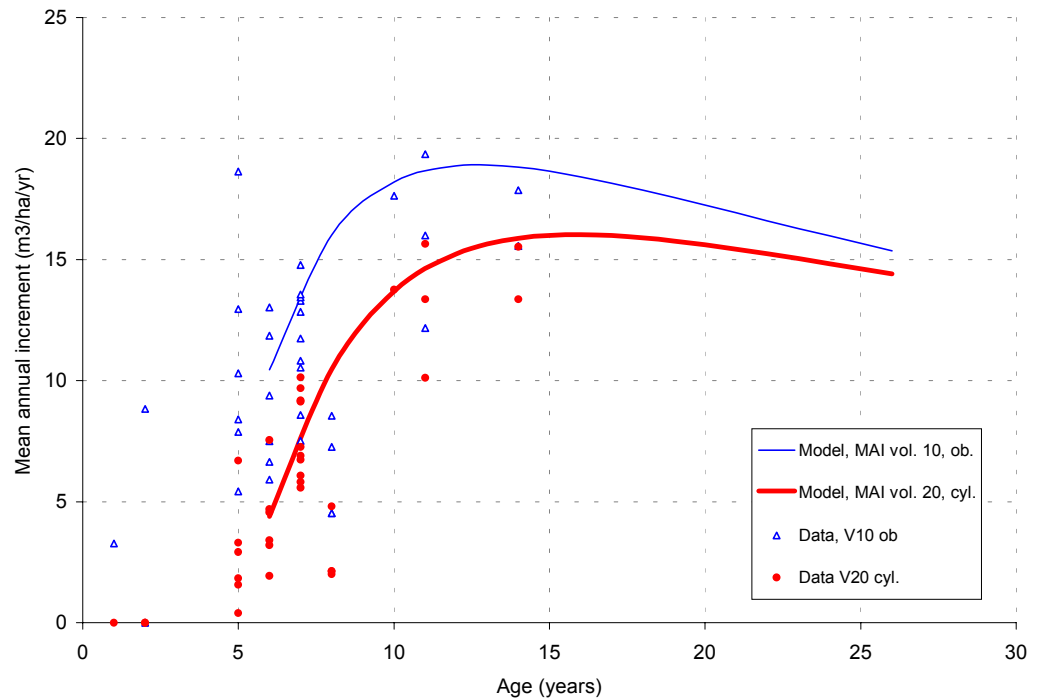*Figure 8 Stand volume-height curve for Jacaranda*

Figure 9 MAI curves for Jacaranda at full stocking

Actual MAI curves   The curves constructed by the above method show the potential of species at full stocking. However, many stands are under-stocked for a variety of reasons. For planning purposes, actual MAI curves are also needed. These were constructed by directly summarising mean volume-age trends for the 8 most widely planted species. These comprised:

		% area
Laurel	*Cordia alliodora*	22.1
Pachaco	*Schizolobium parahybum*	20.8
Cutanga	*Parkia multijuga*	19.7
T.ivorensis	*Terminalia ivorensis*	9.6
Coco	*Virola spp.*	5.9
Jacaranda	*Jacaranda copaia*	5.4
Chuncho	*Cedralinga cateniformis*	4.7
Guayacan V.	*Cybistax donnell-smithii*	4.3

These species comprised 92.7% of the planted area of about 7,000 ha at various locations, but principally Rio Pitzara, Rio Sabalo, and Rio Silanchi .

The analysis of these actual MAI curves are contained in a workbook called PLANPLAN.XLS. Figures 10 and 11 show the actual and fully stocked MAI curves for the various species studied.
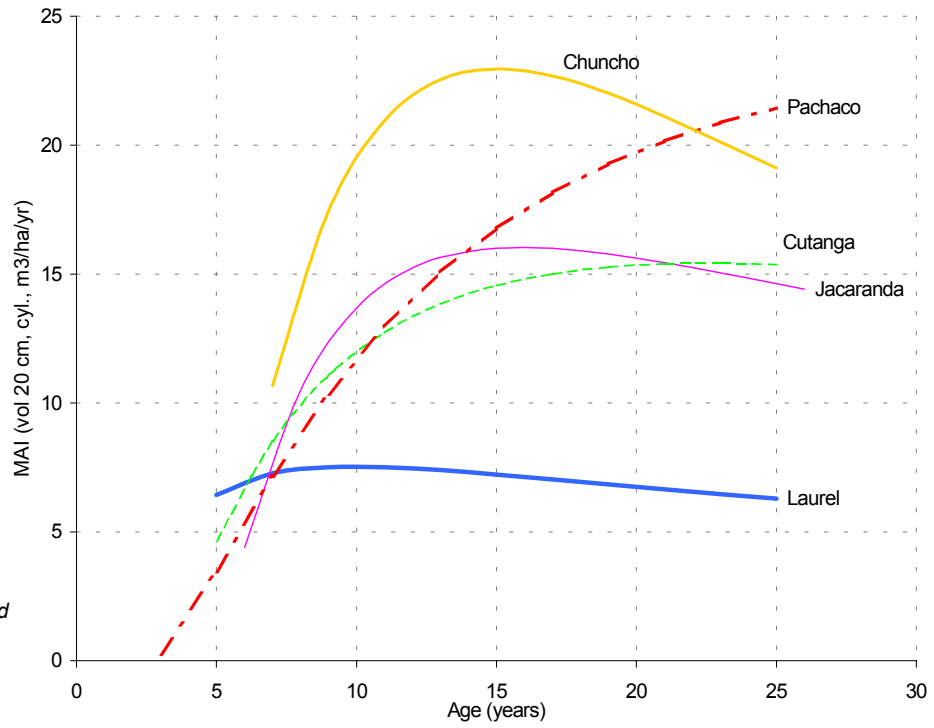
19

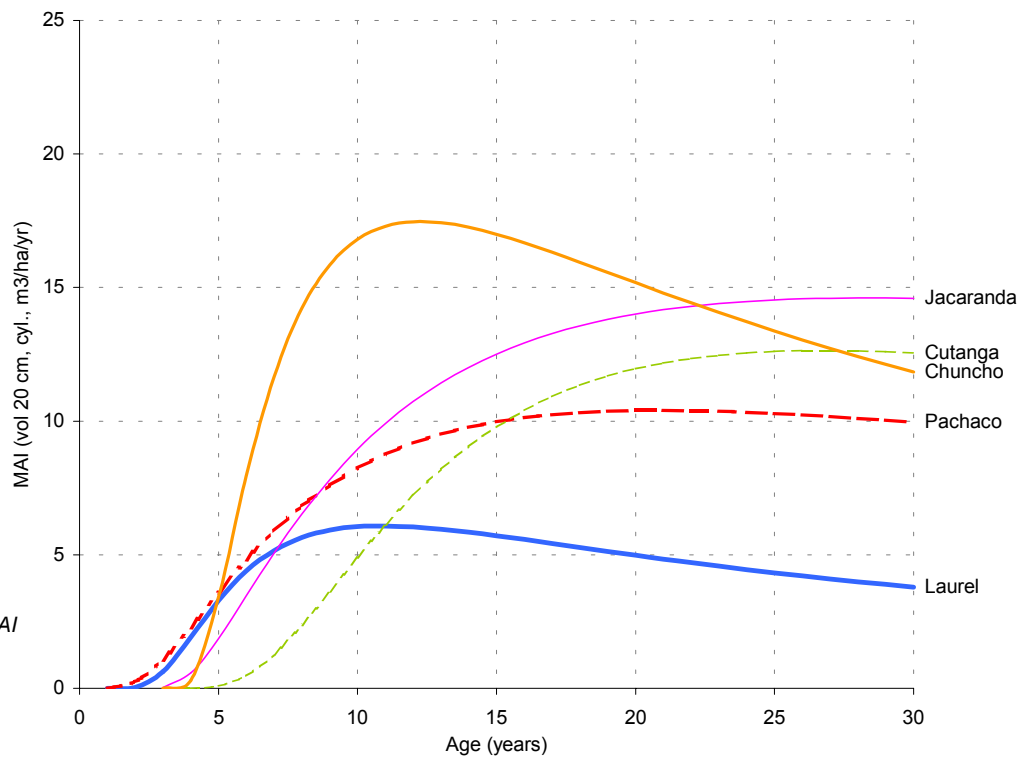*Figure 10 Estimated MAI curves for fully stocked stands*

Figure 11 Actual MAI curves for main plantation species

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Figures 10 and 11 compare these curves for 5 species common to both (Laurel, Pachaco, Cutanga, Chuncho and Jacaranda). They are similar, with actual MAI curves generally 10-20% below the fully stocked models. The exception is Pachaco, which as a result of the early death syndrome occurring in many stands, has much lower actual than potential MAI.

These figures all relate to volume measured under-bark to a 20 cm top using cylindrical scaling, and are thus commercial volume MAIs. It is apparent that the peak MAI for Laurel occurs at about 10 years of age. Chuncho appears to peak at about 12-15 years. Other species may have optimum rotations about 20 years but the data is as yet weak. The natural optimum for healthy Pachaco is later than 25 years, but under current conditions occurs at about 15 years due to excessive mortality and under-stocking on older stands.

Plantation planning Using the actual volume yields summarised from sample plots, a plantation planning programme was written called MOPP.XLS*. This combines forest area information with yields in order to project production from the plantation estates over time. The model allows the future species mix to be varied, and additional areas of land to be purchased progressively. The preferred rotation for each species is designated manually. Only average site class and stand densities are used.

MOPP is a demonstration of the type of planning system which FFJMD should maintain and develop. One difficulty the author found is that existing inventories do not cover many stands, so that there are age-classes and localities that are presently unsampled.

Although MOPP is written in Visual Basic, it is a simple to understand, as it contains little mathematics. It operates by multiplying the tabulated yields for each species by the areas to obtain standing volume. Yields are estimated by considering only stands above the minimum rotation, and limiting felling to a volume defined by the AAC, calculated as discussed below. The oldest stands are felled first until the AAC limit is reached.

AAC, or annual allowable cut, is calculated as the MAI for the species at the designated rotation age, times the total plantation area. This is a correct calculation for a normal plantation (one with equal areas in each age class). For a non-normal forest, it is an approximation which will, if applied, lead eventually to normalisation of the age-class structure.

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* MOPP :is an acronym for _Modelo para planificación de plantaciones_

Outputs from MOPP include standing areas and volumes by species and year, felled volumes by year, and areas re-planted with species, by year. These outputs are shown both graphically and in tabular form, and can be used for an economic evaluation of the plantations given average prices per m³ by species, and average management costs per ha for each species.
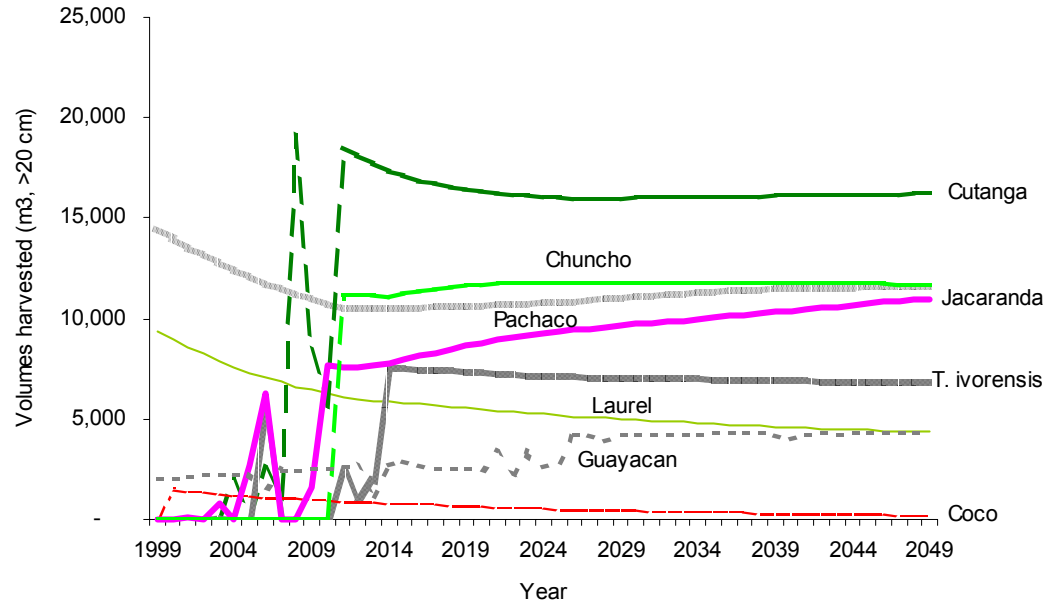

Figure 12 Future plantation production simulated by MOPP

Figure 12 shows a typical simulation of production over the next 50 years for the existing plantations. This scenario assumes rotations of 10 years for Laurel, 15 years for Pachaco, Chuncho, Jacaranda and Guayacan, and 20 years for T. ivorensis, Cutanga and Coco. Species are re-planted in equal proportions except for Coco, which is not replanted.

Total production and areas re-planted annually are shown in another graph from this model, illustrated in Figure 13. These show some fluctuations until the areas established become normalised around the year 2020. Initial production is mainly from felling older Laurel and Pachaco stands, and totals around 30,000 m3/year (from some 6,500 ha). This rises to some 60,000 m3/yr as current younger stands attain maturity, and the species mixture become more varied, with Laurel and Pachaco diminishing in importance. Re-plantings eventually stabilise at 300 ha/yr, or around 5% of the total area annually.

This is clearly only one of a wide range of possible scenarios, and probably not an especially realistic one. MOPP itself is partially intended as a demonstration of technique, although it can serve an

Figure 13 Total yield
and areas re-planted,
simulated by MOPP

Figure 13 — Total yield and areas re-planted, simulated by MOPP
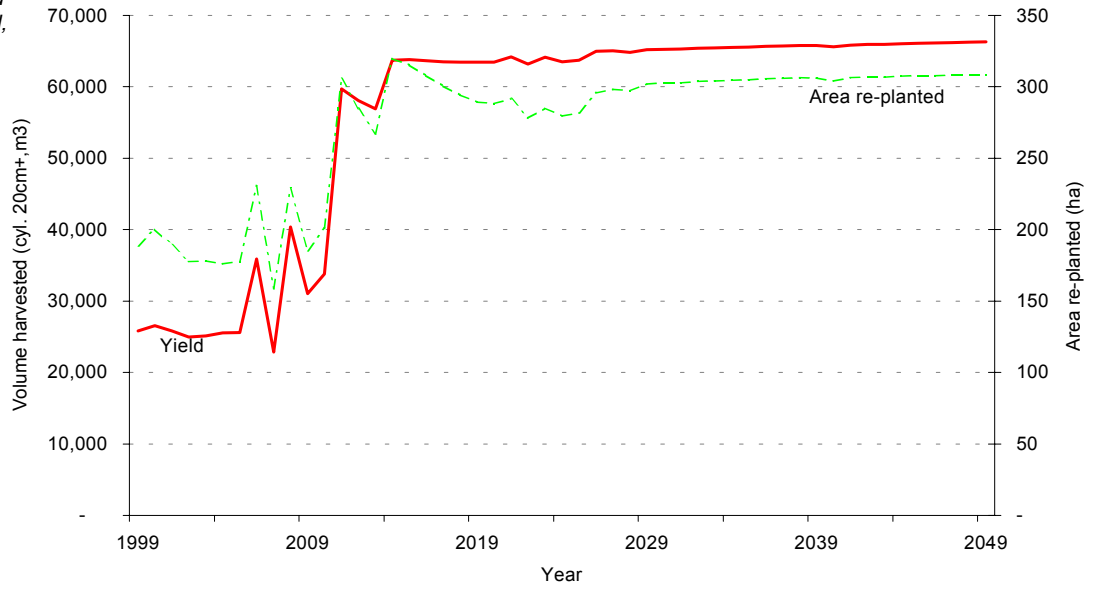
immediate purpose in assisting in the valuation of current worth of
the plantations, by indicating future yields by species.

Progress by FFJMD in data processing

Since the author's first visit under the project in February 1995, the culture of FFJMD with regard to data processing has changed greatly. Field sampling for inventories, permanent plots, volume studies etc. are now recorded using forms designed in Excel, and digitised immediately into Excel with the same form.

FFJMD has shown a good capacity for more or less complex analyses using spreadsheet functions and uses Excel quite efficiently for many studies.

Previous work by the consultant has also been well-absorbed into day-to-day use. This has resulted in more efficient inventory programs and tree volume analysis, and better forest planning using the yield models for Laurel and Radiata Pine developed in 1996.

The next steps

The present visit has emphasised that Visual Basic can be used to by-pass the bottlenecks that develop when Excel is used to process large masses of data. Spreadsheet functions are relatively slow, and this becomes obvious with large amounts of data. They are also limited in some respects, whereas Visual basic programs are limited only by the technical skills of the programmer.

For regression methods, FFJMD has been using the various 2-variable functions that can be fitted directly on Excel graphs using trendlines. The consultant has demonstrated and provided numerous examples of more powerful techniques which include:

- The LINEST function for multiple linear regression analysis using any user-defined transformations for the x and y variables.

- The graphing of sets of lines representing calculated curves from 2 and 3-variable functions fitted by LINEST.

- Using LINEST with artificial control points to produce curves that can be fitted and shaped by eye with the mouse.

- Using the SOLVER function to fit regressions that include a non-linear parameter.

All these methods were used for the Radiata and Laurel yield models produced for the 1996 visit, but more attention has been given on this occasion to re-iterating, explaining and demonstrating them as key methods for yield model and volume equation analysis.

FFJMD needs to study and work through the various spreadsheet programs that are listed in Table 2, especially the Visual Basic components. Given the past record, the author has little doubt that this will be done, and the benefits incorporated into the organisation's work.

Definition and prioritisation of objectives

The author has noted the tendency at FFJMD for much work to be undertaken on what appears to be a momentary whim. This has applied during this consultancy, where several items of the pre-agreed TOR's were set aside in favour of spontaneously arising issues during the course of discussions.

There is also a tendency for discussions and meetings to continue endlessly without clear objectives or results, wasting much valuable time.

The author would recommend that FFJMD try to:

- Identify clear objectives for each task and meeting undertaken.

- Define the time the task or meeting should be allowed.

- Prioritise tasks by establishing formal categories of urgency.

- Not initiate new tasks of lower or equal priority until those of higher priority are completed.

- Maintain a whiteboard with current tasks and the responsible person.

In the author's opinion this would result in a more efficient use of time and resources, and reduction in stress.

Conclusion

This third visit to FFJMD has continued the policy of earlier assignments, of providing example programs and methods which can be adapted and absorbed by the organisation. It has been rewarding to see that this policy has clearly been successful through the application of earlier biometric inputs. At the same time, these consultancies have sought to meet immediate needs in data management, analysis, and planning information. In the current visit, this has comprised mainly the development of species volume equations and yield functions that are immediately required for critical forest planning decisions.

FFJMD is a dynamic organisation that has made excellent use of the modest inputs provided under the DFID project. The author does not doubt that it will make good use of the work briefly described in this report, and through it, further strengthen the capacity for

sustainable forest management and economic growth in the forestry sector in Ecuador.

The following publications contain further details of the methods used in this report:

Alder, D & Cailliez, F (1980) Forest volume estimation and yield prediction. FAO Forestry Paper 22..

Alder, D (1976) Report on a consultancy to the Fundacion Forestal Juan Manual Durini, Ecuador on behalf of the Overseas Development Administration of the United Kingdom, 15th September to 16th October 1996. Unpublished consultancy report.[*]

Clutter, JL; Fortson, JC; Pienaar, LV; Brister GH; Bailey RL (1983) Timber management: A quantitative approach.   John Wiley & Sons, pp. 333.

Philip, MS (1983) Measuring trees and forests. University of Dar-es-Salaam Press. (2nd edition available from CAB International).

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[*] Copy available from d-alder@eurobell.co.uk

The following terms of reference were provided for this consultancy mission:

(i)   To construct taper functions and/or volume tables for Pinus radiata, Cordia alliodora and pachaco, ensuring that the procedures are well documented;

(ii)   To carry out further analysis of the pachaco mortality data;

(iii) To provide training in the use of computer software for
       a)   simple statistics (sampling, regression)
       b)   use of the yield models for management purposes

(iv)   To review and consolidate procedures for natural forest permanent sample plot analysis as future input for the growth model CAFOGROM

(v)   To draft contributions to the relevant species Technical Notes

(vi)   To review and ensure that plantation temporary sample plot and permanent sample plot procedures for data storage/analysis and their use in yield model construction/modification documented; consider design of an Access database linking site, species and assessment data to answer queries such as what is average growth for a specific species on specific sites

(vii) To check the existing yield tables for Pinus radiata and Cordia alliodora for different merchantable diameter limits and the effect of the stocking level of the residual stand

(viii) To ensure that all computer programs and procedures are documented for handover.

(ix)   To provide further assistance as required by the FD Executive Director

(x)   submit a report to DFID within three weeks of completing the assignment in Ecuador