Volume equations and yield models for *Pinus radiata* and *Cordia alliodora* in Ecuador

Edited extracts from a 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

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Summary

This report describes work to develop yield models for *Pinus radiata* and *Cordia alliodora* (Laurel) based on data from temporary and permanent sample plots established by the Fundacion Forestal Juan Manuel Durini. Both models use similar methods. Site index, volume-height-stocking, and derived diameter-height-stocking models are the basic components. For *Pinus radiata*, merchantable volume to 20 cm top diameter was also derived. For Laurel, there is no Ecuadorean volume equation, and only total volume was estimated using a function developed by CATIE in Costa Rica. The models have immediate application for forest management, but are also intended as training tools. The methods are provided as Excel workbooks, and can be studied and adapted to other species. A merchantable volume equation system proposed by JL Clutter was also applied to *Pinus radiata* tree volume data to provide a simpler set of equations than those currently existing, from which height-diameter taper functions can be derived algebraically. It is recommended that this method is used to produce merchantable volume equations for *Cordia alliodora*.

The yield models for *Pinus radiata* and *Cordia alliodora* also indicated how the management of these species might be improved. There are indications that many *Pinus radiata* stands are over-thinned, leading to loss of volume and revenue. There is a need to exercise more disciplined and planned forest management in this area. For *Cordia*, current assumptions are too optimistic with respect to potential diameter growth and proposed rotations are too long. The tree is naturally slender, and achieves maximum total volume MAI at about 12 years. Heights above 30 m, and mean diameters above 35 cm are likely to be exceptional. It is suggested that management can be improved by planting at 800 stems/ha, pre-commercial thinning to 400 stems at age 3, a commercial thinning at age 9 down to 250 stems per ha. This will give a final crop on typical sites of 250 m3/ha with a mean diameter of 30 cm at age 16. Many existing stands should be harvested and re-planted with improved seed.

Contents

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Disclaimer

This report is based upon analyses by the author of data supplied by the Fundacion Forestal. The methods employed, and their correct application, are the sole responsibility of the author, as are any errors or omissions that may have occurred. This consultancy report is not edited, reviewed, or approved by any third party. The analyses, opinions, and conclusions presented are solely those of the author and do not constitute any statement of policy, or imply any acceptance or agreement, by either the Fundacion Forestal or the Overseas Development Administration.

Yield model for Radiata Pine

Sources of data

The data for the Radiata Pine yield model was based on the inventory of the ACOSA plantations undertaken in 1994 by the Fundacion Forestal[1]. This provided 210 rectangular plots of variable size, but typically around 500 m^2. In addition, 37 other plots of varied design were added from older files and sources.

This data already existed as Statistica and Excel files, but without diameter distribution information. For this reason, it was re-entered using an Excel format which is contained in the file INVRADP.XLS. This workbook contains a sheet for each plot, using a standard format, a program in Visual Basic to summarise the plots, and a sheet of plot summaries.

Site index curves

All the data analyses were undertaken using Excel, and were carried out in the workbook file &P-RAD1.XLS. The method was based on the polymorphic base-age invariant site index equation proposed by Bailey & Clutter in 1974[2].

The basic equation for this model is:

$$H = a.\exp(\beta.A^{-k}) \qquad \{eqn.1\}$$

where H is stand height, A is age, and a, β, and k are coefficients. For the *Pinus radiata* analysis, dominant height was used as the indicator of stand height. Dominant height is defined by the Fundacion Forestal according to international conventions as the mean height of the 100 largest diameter trees per hectare. For stands with less than 100 trees per hectare, dominant height is identical to the arithmetic mean height by definition.

This equation was fitted as a regression to the height-age data to determine a mean line. Sets of site index curves were then constructed using both the common slope and common intercept transformations. For the common slope method, the *a* coefficient is calculated for each site index value at a chosen base age. For the common intercept method, the β term depends on site index.

It was found that the common intercept method gave better results for *Pinus radiata.* This accords with the author's previous experience in the use of this function. The data together with fitted mean regression line, and constructed sets of site index curves, are shown in Figure 1.

The coefficients for the model were:

$$H = 74.47 \exp(\beta.A^{-0.506}) \qquad \{eqn. 2\}$$

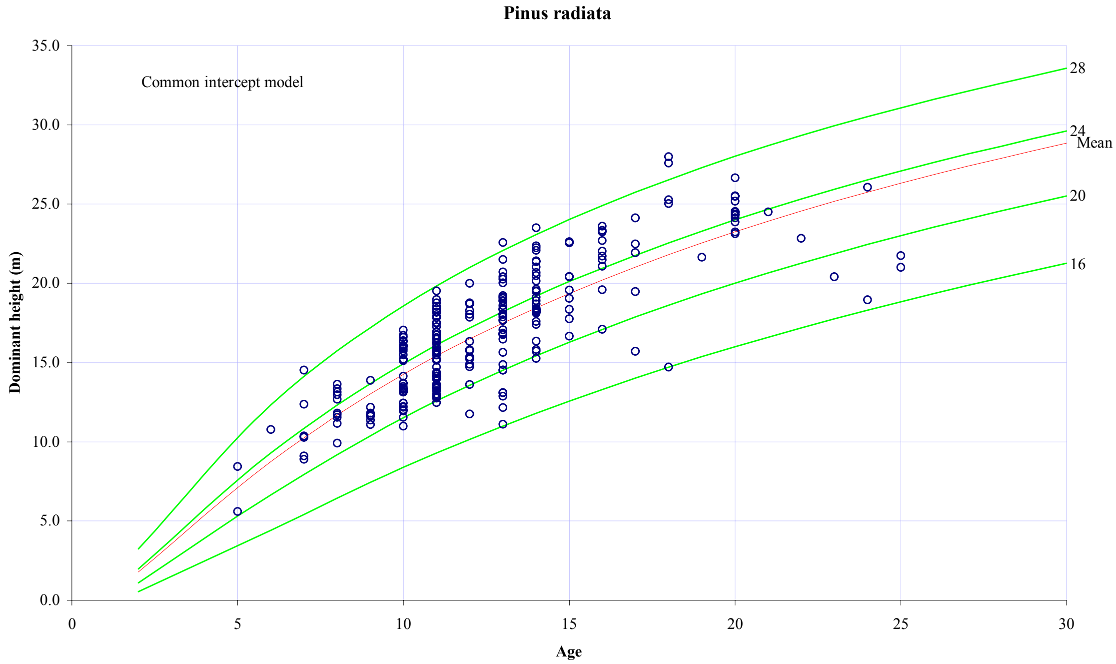


Figure 1 Site index curves for *Pinus radiata*

The coefficient β depends on site index, and can be calculated from the following equation:

$$\beta=(\ln(H_o)-\ln(a)).A_o^{k} \qquad \{\text{eqn. 3}\}$$

where H_o is the site index value, and A_o is the base age chosen. In the case of the curves illustrated, 20 years has been chosen as the base age, for reasons of international standardization.

The relation between site index and altitude was also calculated, as shown in Figure 2. This has a coefficient of determination (R^2) of 29.9%, indicating that some 30% of the variation in site index can be accounted for by altitude. The linear increase of site index at lower altitudes must be weighed against the increasing prevalence of *Dothistroma pini* and other pathogens. These are considered to be contra-indications for the use of *Pinus radiata* below about 3100 m in Ecuador. Conversely, current tree improvement programs of the Fundacion Forestal may improve the performance at higher altitudes.

The regression equation for site index at a base age of 20 years from altitude in metres above mean sea level was given as:

$$\text{Site Index} = 79.63 - 0.017\ \text{Altitude} \qquad \{\text{eqn. 4}\}$$

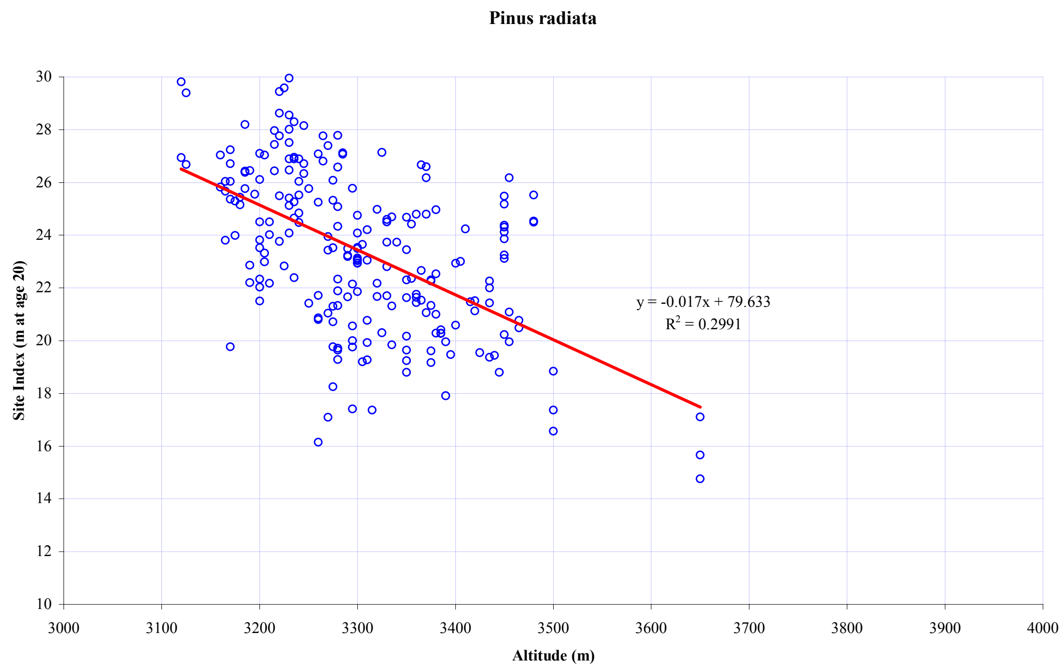


Figure 2 The relation between site index and altitude for *Pinus radiata*

Volume, height and stocking

A logarithmic function relating total volume with height and stocking provides a robust and simple method for constructing variable density yield tables[3].

For the present data, total volume over bark (V_t) was related to dominant height H and stocking in trees per hectare, N with the equation:

$$V_t = a.H^b.N^c \qquad \{eqn.5\}$$

where a, b and c are coefficients that can be fitted by regression. The data and fitted model are illustrated in Figure 3. The R^2 for the regression was 89.2%. Coefficient values were:

a	0.003519
b	2.5223
c	0.5596

On the graph, a line labelled *Excess stock* is shown for the maximum volume attainable at high stockings. This is a hypothetical line that has been drawn through the most densely stocked plots.Another line, shown as *Crown closure*, indicates a limit below which the logarithmic function in equation {5} is no longer valid. Below this point, crown closure has not occurred.

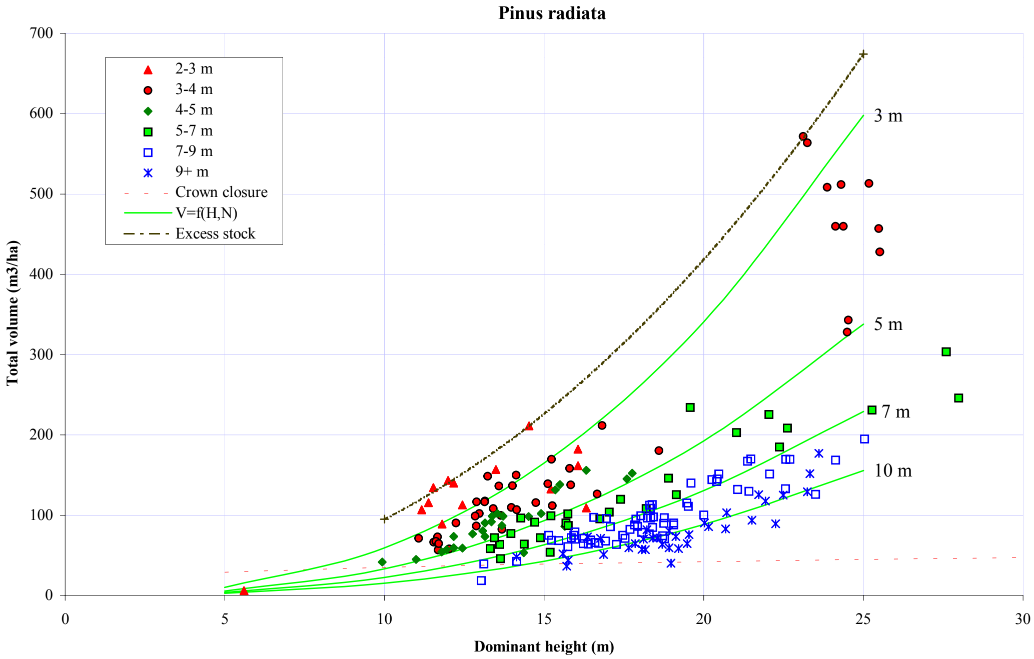


Figure 3 Volume-height-density function for *Pinus radiata*

Mean diameter from the volume function

With a logarithmic tree volume equation in the form:

$$V_a=pD^qH^r \qquad \{eqn.6\}$$

Stand volume can be calculated approximately using dominant height and quadratic mean diameter for D and H. The assumption is made that:

$$V_t \approx V_a.N \qquad \{eqn.\ 7\}$$

Given this relation, it is possible to combine equations {5} and {6} algebraically and solve them for quadratic mean diameter D in terms of H and N. The combined equation is:

$$D \approx (a/p)^{1/q}.H^{((b-r)/q)}.N^{((c-1)/q)} \qquad \{eqn.\ 8\}$$

For *Pinus radiata*, as discussed on page 10, a logarithmic overbark volume equation for total volume was obtained with coefficients:

p	0.00009766
q	1.663
r	1.024

The values substituted into equation (8) gives a predictive function for quadratic mean diameter of:

$$D = 8.631\ H^{0.9016}\ N^{-0.2648} \qquad \{\text{eqn. 9}\}$$

A graph of this function is shown in Figure 4. The line marked as *Open Canopy* is estimated manually and indicates the diameter development of a stand prior to canopy closure. Equation (9) is applicable only to stands with closed canopy. The open canopy line is given by the equation:

$$D=0.07477H^{2.2463} \qquad \{\text{eqn. 10}\}$$

An algebraic solution is possible to combine equations {9} and {10} to solve for stocking at which the diameter indicates incipient canopy closure. Using the following notations for the coefficients:

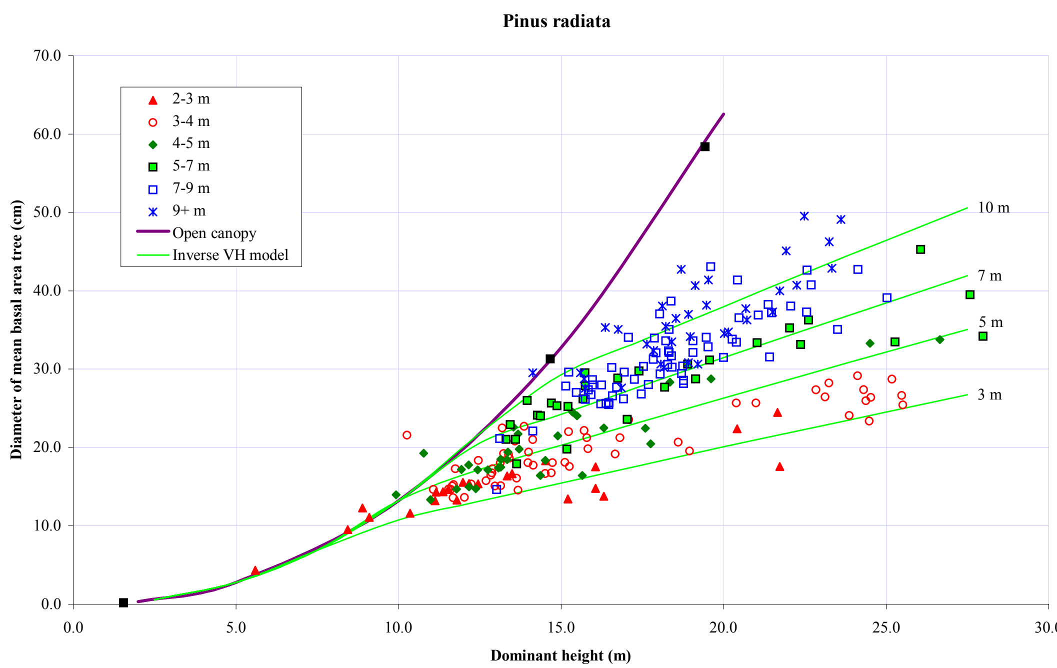
$$D=aH^{b}N^{c} \qquad \text{for equation (9)}$$
$$D=pN^{q} \qquad \text{for equation (10)}$$

Then a crown closure model for diameter and stocking will have the coefficients:

$$D=a^{\gamma}.p^{-\gamma b/q}.N^{c\gamma} \qquad \{\text{eqn. 11}\}$$
$$\gamma=1/(1-b/q)$$

which with the equations for *Pinus radiata* simplifies to the empirical function:

Figure 4 Quadratic mean diameter for *Pinus radiata* derived from the stand volume model



$$D = 208.47\ N^{-0.4424} \qquad \text{\{eqn.12\}}$$

Total and merchantable volume conversion

A function was developed to relate plot over bark volume per hectare to a 20cm top diameter to plot total volume, depending on plot quadratic mean diameter. This allows the yield model to be used to predict merchantable volumes, to a 20 cm top. In principle, the same method could be applied to other volume limits such as 10, 15 or 30 cm. However, due to limited time, this was not attempted.

After some experimentation with appropriate scales and transformations, it was found that the ratio of merchantable over total volume could be related to mean diameter with the regression:

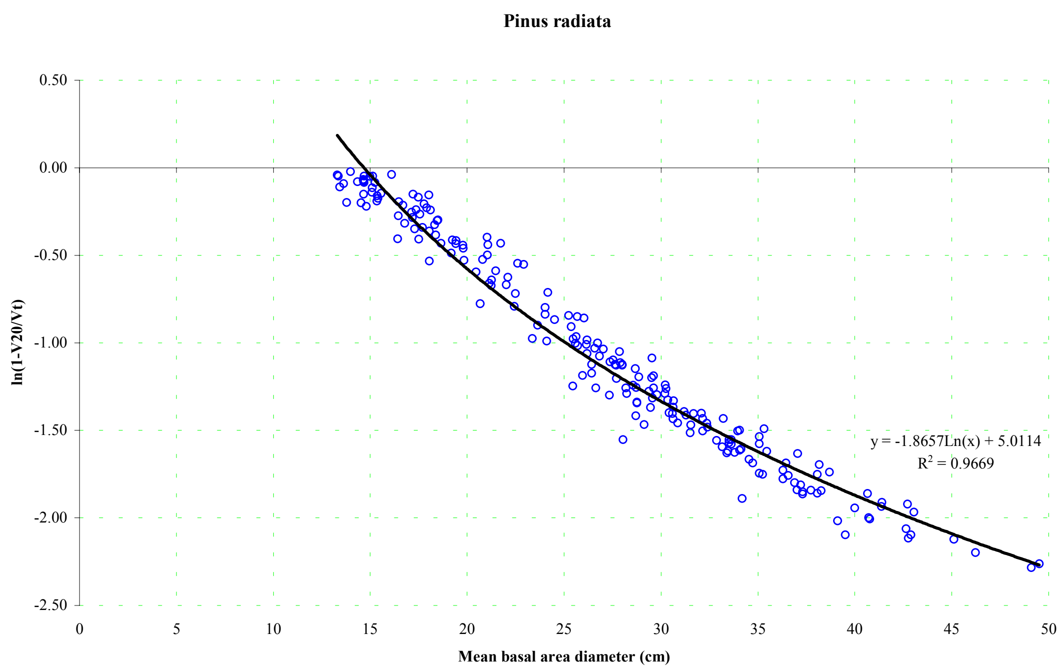
$$\ln(1-V_{20}/V_t) = a + b.\ln(D) \qquad \text{\{eqn.13\}}$$

This equation was fitted with an R^2 of 96.7%, as shown in Figure 5 with coefficient values for *a* and *b* of 5.0114 and -1.8657 respectively. It can be transformed into a more direct form as follows:

$$V_{20}=V_t.(1-150.11D^{-1.8657}) \qquad \text{\{eqn.14\}}$$

Here, the value 150.11 is exp(*a*) from equation 13. Coefficient *b* is not transformed.

Figure 5 Merchantable volume ratio and stand mean diameter, *Pinus radiata*



Integrated yield model for **Pinus radiata**

The equations discussed in the preceding sections have been integrated into a dynamic model in the workbook YT-PRAD.XLS. An example of the appearance of this model is shown in Figure 6. The user can enter site index, the initial mean spacing of the plants, and thinnings as may be required. The model then calculates other stand variables year by year.

The equations in this model for diameter and volume employ the derivatives of equations (5), (9) and (10) with respect to height to calculate increments directly. This is necessary as the original, static models cannot be accurately applied to varied thinning regimes.

The model also includes assumed values for the Reineke Line for density dependent

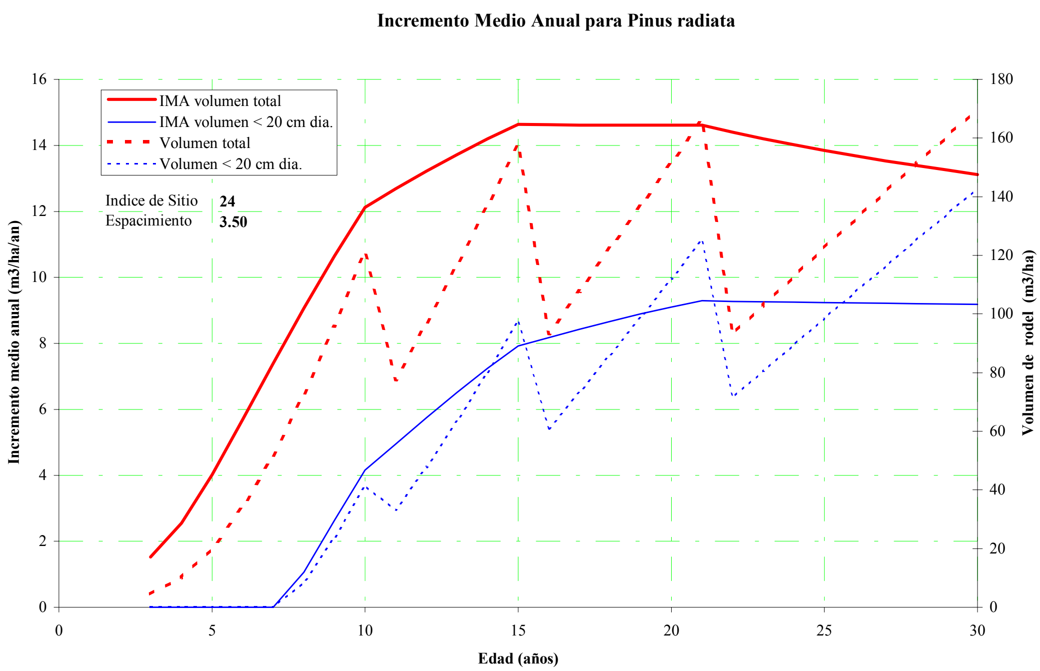
Figure 6 Integrated yield model for Radiata Pine

Tabla para calcular crescimiento y aprovechamiento - *Pinus radiata*											
Indice de Sitio			**24**				**Espaciamiento**		**3.50**		
Edad	Densi-	Altura	Diam.	Area	Volumen		Raleo			IMA	
	dad	superior	AB	basal	total	ϕ>20 cm	N/ha	Vt	V20	Vt	V20
Años	*N/ha*	*m*	*cm*	*m²/ha*	*m³/ha*	*m³/ha*		*m³/ha*	*m³/ha*	*m³/ha/an*	
3	816	3.9	1.6	0.16	4.6	0.0		.	.	1.52	0.00
4	816	5.8	3.7	0.87	10.2	0.0		.	.	2.55	0.00
5	816	7.6	6.4	2.62	20.1	0.0		.	.	4.02	0.00
6	816	9.3	9.9	6.34	34.1	0.0		.	.	5.68	0.00
7	816	10.9	14.2	12.89	51.7	0.0		.	.	7.39	0.00
8	816	12.3	15.7	15.79	72.5	8.5		.	.	9.06	1.07
9	816	13.7	17.1	18.71	95.8	23.7		.	.	10.65	2.63
10	816	14.9	18.4	21.63	121.3	41.5	616	91.5	31.3	12.13	4.15
11	200	16.1	24.1	9.13	42.1	25.4		.	.	12.15	5.16
12	200	17.2	25.7	10.38	55.1	35.7		.	.	12.22	5.58
13	200	18.2	27.2	11.61	68.6	46.8		.	.	12.31	6.01
14	200	19.2	28.6	12.84	82.4	58.6		.	.	12.42	6.42
15	200	20.1	29.9	14.04	96.5	70.9		.	.	12.54	6.81
16	200	21.0	31.1	15.22	110.9	83.6		.	.	12.65	7.18
17	200	21.8	32.3	16.37	125.4	96.5		.	.	12.76	7.52
18	200	22.6	33.4	17.51	139.9	109.7		.	.	12.86	7.83
19	200	23.3	34.4	18.61	154.6	123.0		.	.	12.95	8.12
20	200	24.0	35.4	19.70	169.2	136.4		.	.	13.03	8.39
21	200	24.7	36.3	20.76	183.8	149.9	100	91.8	74.8	13.11	8.63
22	100	25.3	37.4	11.02	101.9	84.2		.	.	12.96	8.65
23	100	25.9	38.4	11.64	111.8	93.2		.	.	12.83	8.67
24	100	26.5	39.4	12.24	121.6	102.3		.	.	12.70	8.69
25	100	27.1	40.4	12.83	131.3	111.4		.	.	12.58	8.70
26	100	27.6	41.3	13.41	141.0	120.5		.	.	12.47	8.72
27	100	28.2	42.1	13.98	150.5	129.5		.	.	12.36	8.73
28	100	28.7	43.0	14.54	160.0	138.4		.	.	12.26	8.74
29	100	29.1	43.8	15.09	169.4	147.3		.	.	12.16	8.74
30	100	29.6	44.5	15.62	178.7	156.2		.	.	12.07	8.74

mortality. In fact none of the stands in the sample appear sufficiently dense for mortality to occur. However, a model of this nature will inevitably be tested by running it at, for example, 2500 trees/ha without thinning. To avoid absurd or excessive values for volume and basal area, some assumed function for mortality is necessary. The sheet named *ReinGraf* in the workbook &P-RAD1.XLS gives this function.

The yield model is on sheet *TabCresc* of workbook YT-PRAD.XLS. The graph on sheet *IMAgraf* shows total standing volumes, standing volumes to a 20cm top, and mean annual increments for these volumes, as illustrated in Figure 7 below. In this graph, the Mean annual Increment figures use the left-hand axism and the standing volumes use the right hand axis. The regime illustrated in the figure is different to the one shown in the table output in Figure 6, and involves three thinnings.

Figure 7 Volume and MAI graph produced by the *Radiata Pine* yield model



Volume taper function for Radiata Pine

Data sources and input

The tree volume data used was that collected for the ACOSA inventory. This has been used previously to devise separate volume equations for total volume and to limits of 5,10, 15 and 20 cm over- and underbark[1]. In order to calculate taper function coefficients, the data was re-entered using data forms devised in Excel. The format is illustrated in Figure 8.

Figure 8 Form used for entering tree volume data

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	**Arbol**	**Rodal**	**Edad**	**DAP**	**Altura**											
2	1	47	14	46.7	23.06											
3																
4	**Medidas de troza**						**Limitas de diametro**						**Volumen hasta diametro**			
5	*Nr.*	*L*	*Dm*	*Da*	*Czm*	*Cza*	*L*	*Dm*	*Da*	*Czm*	*Cza*		*Dm*	*Hm*	*Vc*	*Vs*
6	*tocon*	0.22		55.7		27							*t*	23.06	1.5727	1.3879
7	1	2.44	46.0	44.6	18	14							5	21.07	1.5645	1.3810
8	2	2.44	41.4	39.4	13	9							10	19.94	1.5600	1.3772
9	3	2.44	36.7	25.1	9	7							15	16.90	1.5204	1.3424
10	4	2.44	31.7	29.7	7	6							20	14.36	1.4587	1.2874
11	5	2.44	27.6	25.0	5	5							30	7.02	1.0197	0.8857
12	6	2.44	21.8	18.9	5	5	1.94	22.2	**20**	5	5		40	4.73	0.7751	0.6653
13	7	2.44	16.5	15.1	5	4	2.04	16.8	**15**	5	4					
14	8	2.44	12.0	10.3	4	4	2.64	12.2	**10**	4	4					
15	9	3.32	7.9	0.0	3	0	1.33	8.5	**5**	3	3					
16	10															
17	11															
18	12															
19	13															
20	14															
21	15															

The workbook used for entering this data is called ARBVOL.XLS. Each tree is entered as a separate sheet in the workbook. A blank form is contained in a page called *Arbol(0).* This is copied for each new tree, automatically acquiring the names *Arbol(1), Arbol(2)* and so on. The volumes are calculated by a Visual Basic program called VOLARB, which is located on the sheet *Programas*. Once the data is entered on a sheet, VOLARB is called up via the Excel Tools Macros menu. It then calculates and fills in the diameters required. By editing the merchantable limits on the grey area of the volume section of the form (preferably on the base form *Arbol(0)*), calculations can be made to any limits required.

Two other programs then summarize the data from the separate volume sheets into a single summary table in columnar format, on sheet *VmData*. VTEQN summarizes total volumes, and VMEQN summarizes merchantable volumes. The two functions could be easily combined into a single program but were separated in the development phase to simplify the work. VTEQN also recalculates volumes for each sheet in order to take account of any edits to the data that may have been made.

Method of analysis

The method chosen is that described in Clutter et al. (1983)[4]. This provides for one equation for total volume, using the conventional logarithmic model:

$$v_t = ad^b h^c \qquad \{eqn. 15\}$$

where v_t is tree total volume, d is tree dbh, h is tree total height and a,b, and c are regression coefficients. A second equation is then fitted which relates total volume to merchantable volume using the following function:

$$v_m = v_t(1 - a d_m^{\,b} d^c) \qquad \{eqn. 16\}$$

where v_m is merchantable volume to top diameter d_m, and a,b,c are regression coefficients.

These equations were fitted to the over- and underbark volumes separately, using in both cases overbark top-diameter limits. The regression coefficients obtained for *Pinus radiata* are shown in Figure 9.

Figure 9 Regression coefficients for total and merchantable over and underbark volumes for *Pinus radiata*

Total tree volume equations for Pinus radiata

Form of equation: $V=aD^bH^c$

Regression analysis

	(1) Overbark volume			*(2) Underbark volume*		
c,b,ln(a)	1.024	1.663	-9.234	1.073	1.658	-9.510
σ_β	0.035	0.029	0.042	0.036	0.031	0.044
R^2, σ_y	99.7%	0.081		99.6%	0.086	
F, df	19167.6	132		17681.7	132	

Merchantable volume equations for Pinus radiata

Form of equation: $R=ad^bD^c$ where $R=1-V_d/V_t$

Regression analysis

	(1) Overbark volume ratio			*(2) Underbark volume ratio*		
c,b,ln(a)	-2.6056	3.0357	-1.7650	-2.6513	3.1517	-1.9390
σ_β	0.0322	0.0221	0.1029	0.0355	0.0243	0.1134
R^2, σ_y	97.2%	0.329		96.8%	0.362	
F, df	10108.8	590		8918.4	590	

This figure is taken directly from sheet *VolEqn* of the workbook ARBVOL.XLS . It will be seen that the R^2 for the total volume equation is 99.7%, and for the merchantable volume ratio, 97.2%.

To test this model, the ratio of merchantable to total volume was plotted for the 6 diameter limits used with both the original data and the fitted functions. The results are shown in Figure 10. There is some evidence of bias in the ratio at higher diameters, and some lack of fit to the bole shape below the line of dbh, but generally for a single equation which caters for any top diameter limit, it seems to be quite effective.

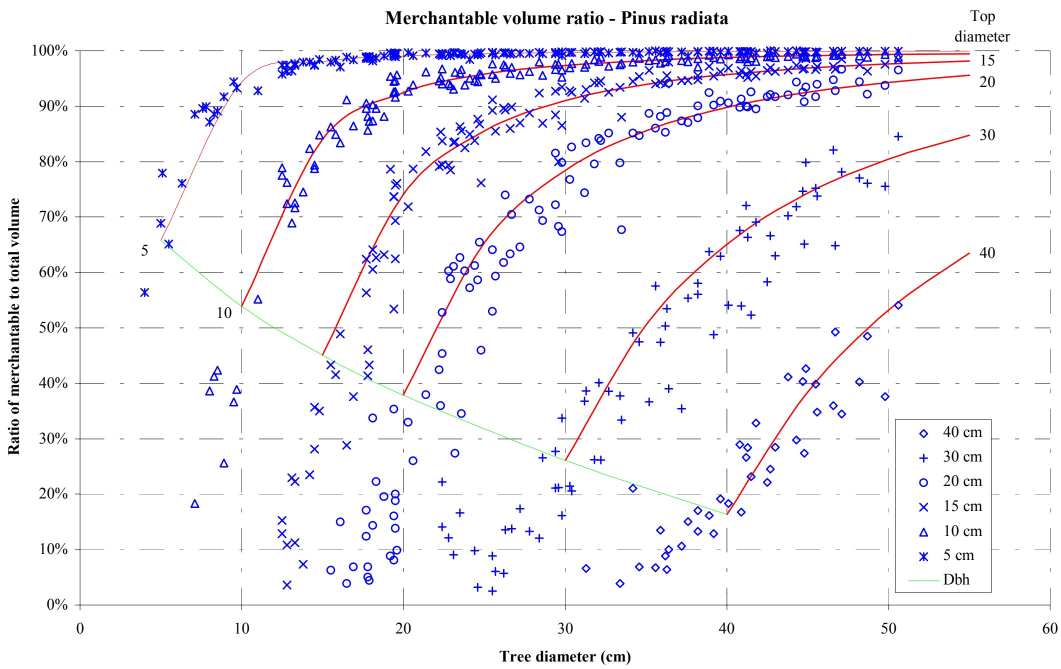


Figure 10 Comparison of merchantable volume ratio equation with data for *Pinus radiata*

This method also allows the direct derivation, by calculus, of a height-diameter taper function. Unfortunately, Clutter's textbook[4] does not give complete details of the transformations of the coefficients in equations (15) and (16) required. It is necessary to refer to the original article in *Forest Science* on the subject[5]. This was not available during the consultancy, although it is hoped to provide the Fundacion Forestal with more information by correspondence.

Applications of the method

There already exist merchantable volume equations for *Pinus radiata* which appear quite adequate for the moment[1]. The method demonstrated here is mainly provided to show a technique that is simpler and more direct in providing equations for any top diameter limit. These equations also give directly, height-diameter taper functions which can be very useful for volume calculations where both diameter and length are constraints on merchantability, as for example in estimating volumes of peeler logs.

As the workbook ARBVOL.XLS provides a complete set of procedures for data entry, volume calculation, and coefficient analysis, it is recommended that it is used for future volume studies. Volume equations are needed for Laurel (*Cordia alliodora*) and can developed using this method. However, the format and method is not suitable for trees with a well-defined crown break. In that case, measurements should be made up to the point of crown break, and a logarithmic model developed for bole volume based on dbh and merchantable height. It is possible to develop within-crown taper functions for multi-branched hardwoods, but both the forms and the field procedures need to be carefully considered[6].

Yield model for Laurel

Sources of data and methods of input

A data entry form was developed in Excel that is suitable for many types of permanent or temporary plots. It is illustrated in Figure 11. This was used to input data for all permanent plots having some Laurel, usually in mixtures with Pachaco (*Schizolobium parahybum*) and indigenous natural regeneration.

The form provides for plot identification data, age of planting and measurement, plot size and shape. For the main plot, tree number, species, diameter, height and codes or notes can be entered. There is also a provision mainly designed for the older plots, for a separate height sample, which in the early years was often taken outside the main plot and some months after the initial enumeration.

As with the data entry schemes for the *Pinus radiata* inventory plots and the volume sample trees, the procedure was followed of using a separate sheet of the workbook for each plot. However, several workbooks were used, with separate files for each locality with permanent plots. A single workbook, &LAUREL2.XLS, contains the program to summarize the data and calculate stand statistics.

For *Pinus radiata*, dominant height was used as the indicator of stand height. In the Laurel plantations, the mixture of species present makes it difficult to apply a clear definition of dominant height. For this reason, Lorey's height, or height of the mean basal area tree, was used. This was calculated by first defining a height-diameter regression within each plot, and then estimating the height of the tree of mean basal area.

For tree volumes, a volume equation developed by CATIE for *Cordia alliodora* in Costa Rica was used[7]. This was re-parameterized from their formulation as a multivariate model in d^2, d^2h and h into a conventional logarithmic equation with the form:

$$v_t=0.00004789d^{1.766}h^{1.135} \qquad \text{\{eqn. 17\}}$$

This equation is also practically identical to a simple form factor of 0.432 based on total height and tree basal area. The re-parameterization method will be found on sheet *VolEqn* of the &LAUREL2.XLS workbook.

Figure 11 Data entry form used for Laurel and other sample plots

Descripción de parcela			**Archivo/pagina**	1,1
Predio	Rio Pitzara			
Rodal	418		**Fecha de medición**	22-Apr-95
Tipo	circular	*(circ./cuad./linea)*	**Fecha de plantación**	00/00/83
Area, m^2	1000		**Espacimiento**	5x6

Arbole	**Especie**	**Diam.**	**Alt.**	**Cualidad**	**Apuntes**
1	lau	25.2	24.2		
2		33.3	21.5		
3		34.6	25.3		
4		36.5	24		
41	mata	37			
5	lau	27.5	21.8		
6		40.1	26		
7		27.7	21.2		
8		32.8	25.2		
9		27.5	24.6		
10		39.7	23.3		
11		14	11.7		
12		38.5	23		
13		38.9	22.8		

Muestra de altura		*Fecha*
Especie	*Diam.*	*Alt.*

Manejo y observaciónes

Plot summaries are contained in the sheet *PlotSum*, and are produced by running the program PLOTSUM in the workbook. The summary contains one line for each plot, including location, plot identification, age, number per hectare, mean basal area diameter, Lorey's height, percentage of total basal area comprising Laurel, and tree numbers by 10 cm diameter classes. All the statistics relate to Laurel only: Other trees are ignored in this analysis. The percentage basal area allows the competitive influence of other species on each plot to be assessed.

Site index curves

The basic function used was the same as for *Pinus radiata*, as discussed on page 1. However, it was found that neither the common intercept nor common slope forms of this model were ideal, and a new variant was developed in which both slope and intercept are fixed for the system of curves, and instead the shape coefficient k varies with site index.

This gave a general model:

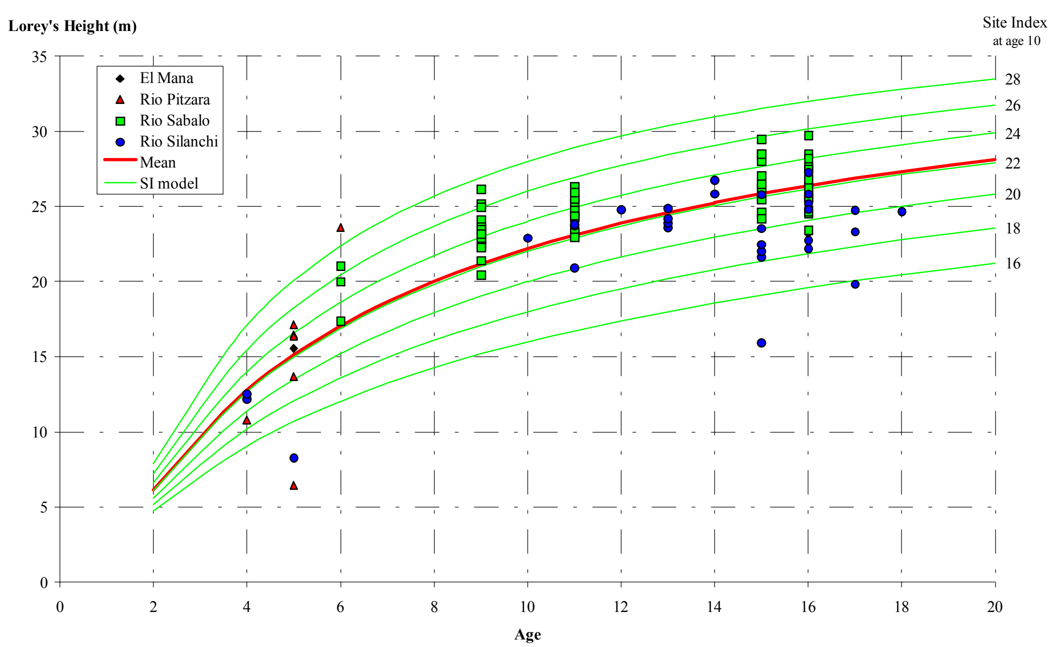
$$H = \alpha.\exp(\beta.A^{-k}) \qquad \text{\{as for eqn. 1\}}$$

with H as Lorey's height and A as stand age. The coefficients α and β were 41.05 and -3.084 respectively. The coefficient *k* depends on site index, and can be calculated as:

$$k=[ln(-\beta)-ln(-\{ln(H_o/\alpha)\})]/ln(A_o) \qquad \text{\{eqn. 17\}}$$

where H_o is site index in metres at a base age of A_o. The curves from this model are

Figure 12 Site index curves for Laurel (Cordia alliodora)



shown in Figure 12 using a base age of 10 years.

The mean height-age curve corresponds to a site index of nearly 22 m. Rio Sabalo plots are generally above this, with a mean of about 24 m. Other plots are generally below, with a mean curve around 20 m. Several Rio Silanchi plots show very low height development. This was considered to correspond with site conditions. Rio Sabalo is said to have a loamy soil and less extreme rainfall than Rio Silanchi, where the soil tends to an extreme clay and rainfall to some 4000 mm per annum. It may be these conditions are too extreme for Laurel.

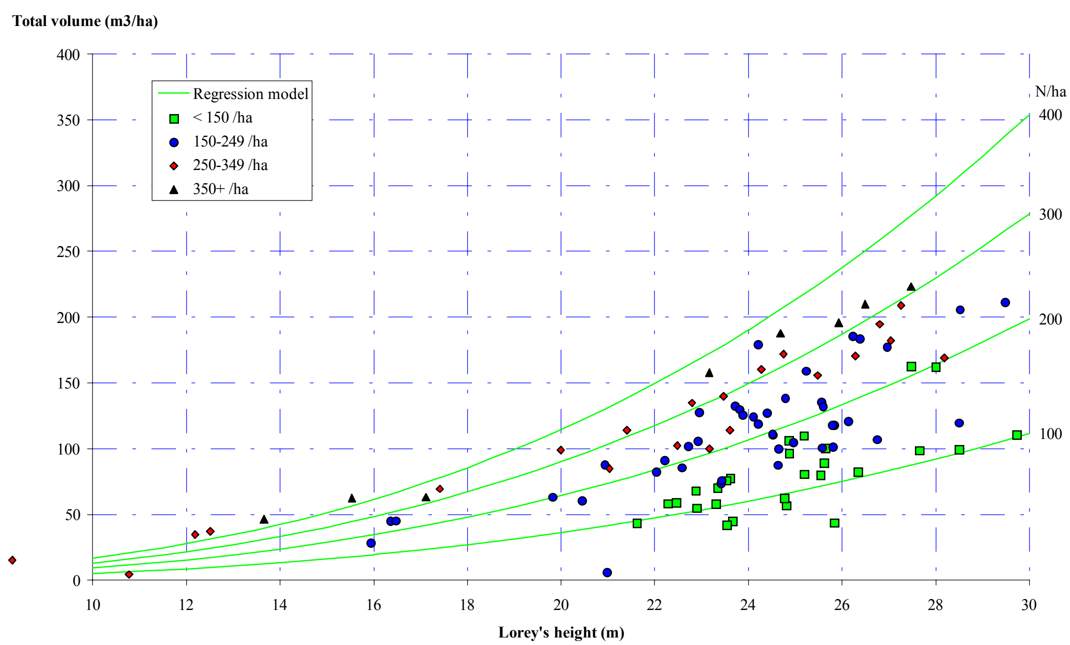
Volume, height and stocking

To provide a variable-density yield table for total volume, the same procedure was followed as has been described for Radiata Pine (see page 3). The logarithmic volume-height-stocking model was:

$$V = 0.00001882\ H^{2.7820} N^{0.8320} \qquad \text{\{eqn. 18\}}$$

where V is total volume over bark, as estimated from the re-parameterized CATIE equation, H is Lorey's height, and N is the stocking in trees per hectare. This regression fitted the data with an R^2 of 80.1%. The regression model, together with the sample plot data, is shown in Figure 13.

Figure 13 Volume-height-density function for Laurel (*Cordia alliodora*)



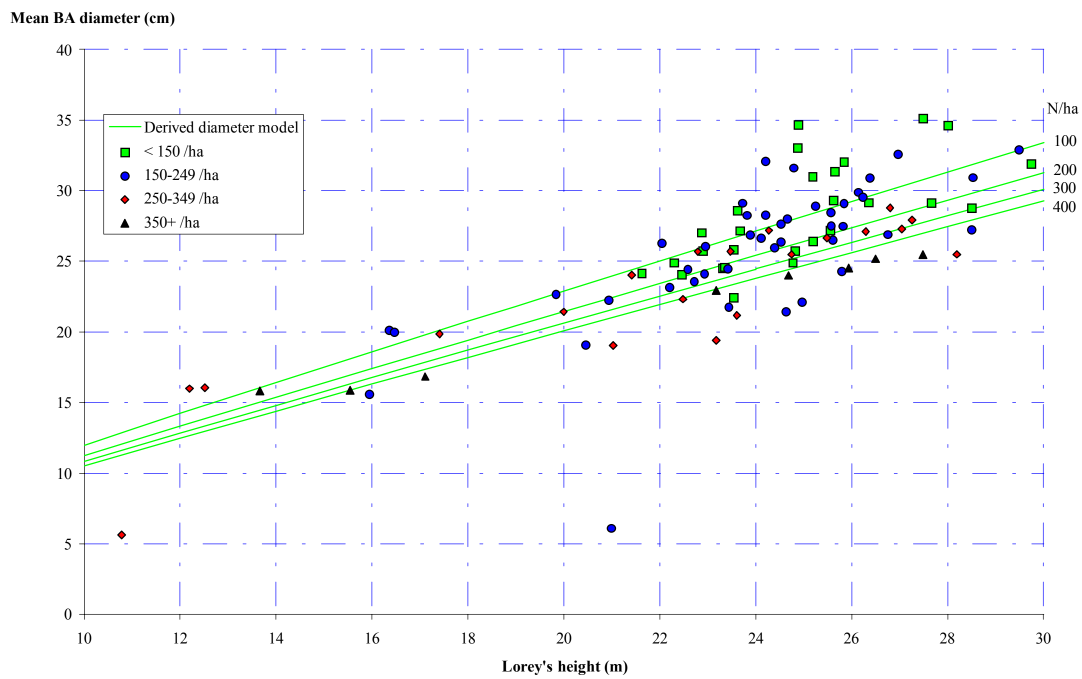
Diameter development of Laurel

As discussed previously (page 4), the stand volume-height-stocking function can be combined with a tree volume equation to estimate mean basal area diameter from height and stocking. Using the transformation in equation (8), the coefficients for Laurel were:

$$D = 2.1706\ H^{0.9326} N^{-0.09515} \qquad \text{\{eqn. 19\}}$$

When the data for mean basal area diameter and Lorey's height is plotted with this function for the typical range of stockings found for Laurel, the results are as shown in Figure 14. Unlike the equivalent model for *Pinus radiata* (see page 5), the diameter

Figure 14 Mean diameter with Lorey's height and stocking for Laurel



development appears quite unresponsive to increases in spacing, with only a 4 cm difference in mean diameter at 30 m height between stands grown at 400 trees/ha and those at 100 trees/ha. This may not be completely realistic. The functions shown are derived from stands which include typically 20-30% of non-Laurel basal area, so that there is much hidden competition. Most of the stands have been thinned down to their final spacing, and may not have had the possibility of developing the typical size that they would have reached under conditions of constant spacing. However, at the same time the contrast with the same model for *Pinus radiata* is very clear, and there is nothing to indicate that *Cordia alliodora* can respond to wide spacings through rapid diameter growth.

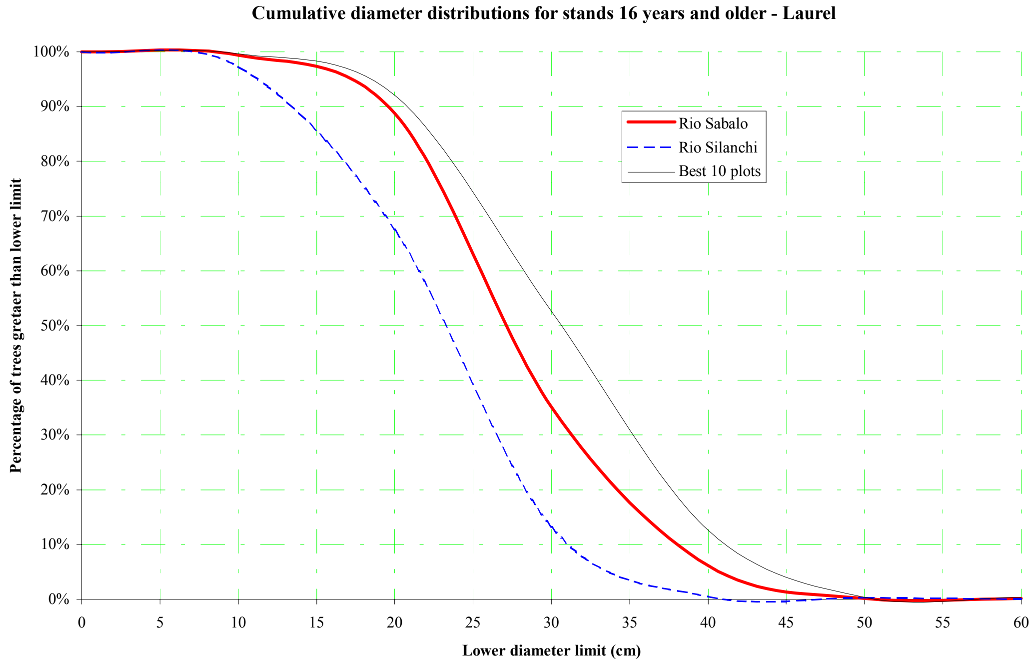


Figure 15 Cumulative diameter distributions for Laurel from stands 15 years and older

Figure 15 shows the mean diameter distributions that occur on older stands of Laurel in Rio Silanchi and Rio Sabalo. In each case, the average was taken of stands 15 years and older, with a mean age of 16 years in both cases. To show the most optimistic case, the mean for the largest 10 plots is also shown. The mean basal area diameter is close to the median, or 50% point on these distributions. It can be seen that for the best stands with mean diameters around 30cm, some 13-14% of the trees are over 40 cm diameter. There is a considerable difference between the mean diameters for Rio Silanchi and Rio Sabalo, and between the mean and 10 best plots in Rio Sabalo. This goes beyond any obvious effect of spacing or site index. It is probable that the diameter growth of Laurel can be improved though a combination of tree improvement and careful site selection.

Optimum thinning regimes and rotation for Laurel

The age for maximum mean annual increment for total volume in Laurel appears to be about 12 years, more or less independently of site index. The age for maximum MAI of merchantable volume to 20 cm top diameter is likely to occur a few years later, but it is very unlikely to be later than 18-20 years of age. By 20 years, even on the best sites and at wide spacings, diameter increment is of the order of 0.5 cm/yr and falling rapidly, whilst height growth is practically static. Mean annual volume increment will be past its maximum.

Because Laurel does not show a strong response to spacing through improved diameter growth, closer spacings with commercial thinnings are likely to give the maximum volume and financial return. The use of wider spacings results in lower volume which is not compensated for by corresponding gains in diameter growth.

To explore regimes for Laurel, a model was designed similar to the variable density yield table for *Pinus radiata* discussed on page 7. It is simpler, in that no information is available about volumes to a 20 cm top diameter. Unlike the *Pinus radiata* model, it attempts to simulate the direct effect of thinnings on diameter distribution. Correctly done, thinning from below will shift up the mean diameter of the residual crop. This is particularly important in the case of Laurel, as the diameter increment function is otherwise fairly unresponsive to thinning.

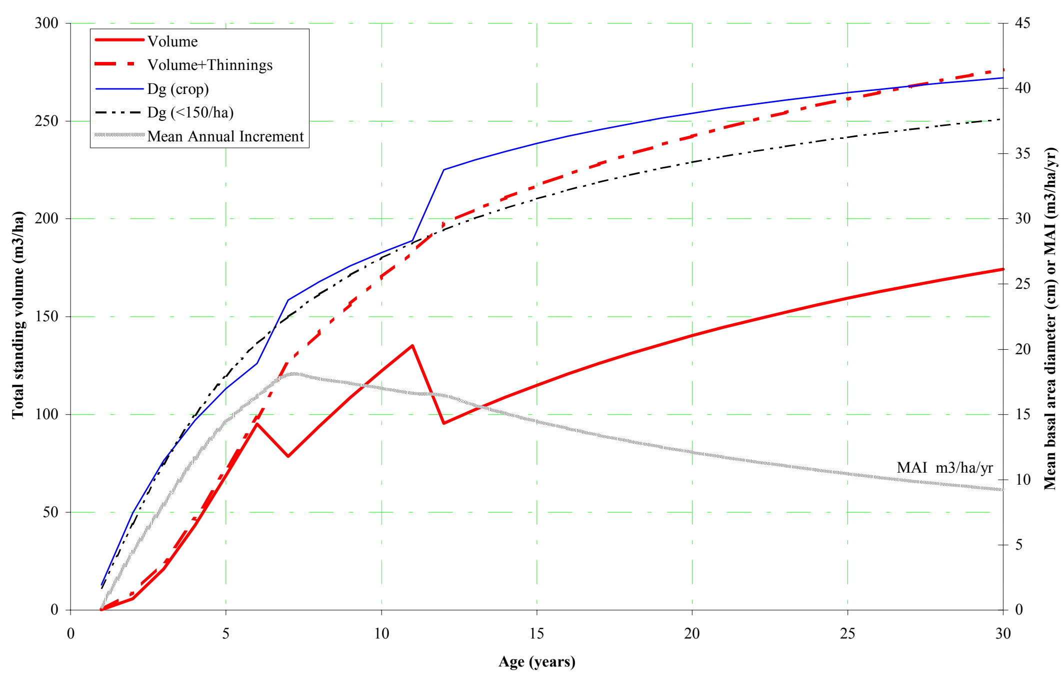
The model is contained in the sheet *YldModel* of the workbook &LAUREL2.XLS. The method employs the derivative of equation {19} with respect to height, and a finite difference estimate of height increment with respect to age, to estimate growth following thinning. In plain language, diameter increment is calculated in each year, and added to the accrued diameter of the residual stock. However, it is assumed that the ratio of thinned to original quadratic mean diameter is given by the function:

$$D_t/D_g = (N_t/N_b)^r \qquad \{eqn. 20\}$$

where D_t is the quadratic mean diameter of thinnings, D_g is the quadratic mean diameter the crop would have had without thinning, N_t is the number of trees thinned, and N_b is the number before thinning. *r* is an empirical coefficient, which was estimated by inspection of diameter distributions to be about 0.25.

Thus thinning exerts two effects in the model:

Figure 16 Volume, MAI and mean diameter outputs from the Laurel yield model for a regime with several thinnings



- It results in increased diameter growth through reduced competition. For Laurel, this effect seems to be weak with the available data.

- It results in increased mean diameter of the crop by selectively removing smaller trees. The larger trees that are left will also tend to be the faster growing ones.

The model calculates standing volume and quadratic mean diameter, as well as volume and diameters for thinnings. It calculates mean annual increment as the total accrued volume, including thinnings, divided by the stand age. As a comparison for diameter development, it shows the mean diameter achieved by the low density stands in the data (less than 150 trees/ha) as a regression line.

These outputs are displayed in the form of a graph, as shown in Figure 16. This example is for a regime where the Laurel is planted at 800 stems/ha, pre-commercially thinned to 400 stems at age 2, and then thinned at 20 m and 25 m height (ages 7 and 12) to 200 and 100 stems respectively. The graph shows the gain in mean diameter due to thinning. With this example, a site index of 24 is used (typical for Rio Sabalo), and the stand reaches about 38 cm at age 20. This is about 4-5 cm better than the mean for actual low density stands.

The author favours a regime of this type as a management prescription for Laurel. Planting at higher density (eg. 5 x 3) and then thinning every second plant pre-commercially at 2-3 years old has several advantages:

- The problem of gaps and the costs of re-stocking are mostly avoided.

- Weed competition will be less serious in the first two years.

- The pre-commercial thinning will exercise strong selection pressure in favour of faster growing individuals.

The model provides a basis for examining these questions, and also provides more realistic estimates of achievable diameters and volumes for Laurel than some of the estimates that are in current circulation.

Notes and references

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