A yield model for *Cordia alliodora* plantations in Ecuador

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SUMMARY

A yield model for *Cordia alliodora* plantations in the Pacific lowlands of Ecuador is described. The data base comprises 73 permanent sample plots and 479 temporary inventory plots on 1600 ha of plantation. The oldest stands were 19 years in 1997. Site index curves are developed to predict Lorey's height from age. The Schumacher equation is used with a polymorphic form. Volume is calculated from a logarithmic function of stocking and Lorey's height; functions for volume to 10 cm top diameter overbark and 20 cm top diameter underbark are given. Mean annual volume increment curves are presented for a range of site index values and stockings. Maximum MAIV to 10 cm overbark is around 16 m^3 ha^{-1} y^{-1} at age 3, and 9 m^3 ha^{-1} y^{-1} at age 11 for 20 cm underbark volume for typical site index of 24 m (age 10) and 300 trees ha^{-1}.

Keywords: *Cordia alliodora,* Ecuador, plantation, site index, yield model.

INTRODUCTION

Cordia alliodora (commercially known as Laurel or Salmwood) is a plantation species of moderate importance in the lowland humid tropics. In Ecuador, it has been extensively planted for timber production by the Fundación Forestal Juan Manual Durini (FFJMD), which has directly established some 1,600 ha since 1978 and assisted private growers to plant additional areas. During this process various sample plots, both temporary and permanent, have been established to evaluate growth and yield. The present paper describes a yield model for pure plantations that has been developed from these data.

In spite of its worldwide use, both in pure plantations and as a cover crop for coffee and cocoa, there are few published studies of the growth and yield of *Cordia alliodora* as a plantation tree. Information on the species has been reviewed by Greaves and McCarter (1990), and earlier by Johnson and Morales (1972). Its genetic and reproductive aspects have been recently discussed by Boshier and Lamb (1997). It is widely planted in Costa Rica and elsewhere in central and southern America as a shade tree with coffee, and its potential for timber production in this context has been analysed by Somarriba and Beer (1987) and Somarriba and Somarriba (1990). The species has been noted in these and other reports as having very rapid early height and diameter growth, but many estimates of later growth have been extrapolations. Some studies have been made of the sensitivity of the species to site, especially in the agrisilvicultural context in association with coffee, and it has been noted that it grows best at a pH of about 5.5, with declining growth on more acid soils (Giraldo *et al.* 1981), and is demanding of nutrients (Bergmann *et al.* 1994). Haggar and Ewel (1995) have analysed crown dimensions, leaf area, tree architecture, root biomass and growth of young trees. *Cordia alliodora* is reported as producing reliable growth rings (Tschinkel 1966) which correlate with mean annual temperature and rainfall (Devall *et al.* 1995). The phenology of the species is peculiar, the tree having a tendency to lose its leaves in the wet season. In Costa Rica, the timing of leaf growth in relation to rainfall correlates significantly with increment, may be genetically determined, and is a factor in site variation and productivity (Blake *et al.* 1976). It is considered to be a light-demanding early successional species, and occurs naturally as a common element of secondary forests on abandoned agricultural lands in Costa Rica (Gerwing 1995).

In Ecuador *C. alliodora* is native to the lowland tropical forests both east and west of the Andean Cordillera. It commonly occurs to altitudes up to 900 m above mean sea level, with occasional individuals being found up to 1200 m, and is found in rainfall zones varying from 1000 mm to 4500 mm per annum (Montenegro and Veloz 1999). The plantations formed by FFJMD and discussed in this paper have all been established with seed selected from these native trees.

SOURCES OF DATA

Some 73 permanent sample plots (PSPs) have been established by FFJMD in its *Cordia* plantations, with an average density of about one per 20 ha. These are mostly of a square design, of approximately 30 x 30 m (900 m^2), comprising a block of 6 x 6 trees planted at an average spacing of 5 m. To compensate for variations in distances between rows in the plantation, actual plot dimensions were recorded corresponding to the estimated mid-point between

between rows in the plantation, actual plot dimensions were recorded corresponding to the estimated mid-point between adjacent trees, so plot size varies a little around the planned size. In all, the PSPs give 151 plot measurements. However, 31 of these are single measurements, 20 plots have two measurements, and only 22 plots have three or more measurements.

In addition, an inventory of the plantations during late 1997 and early 1998 provided data from an additional 479 temporary sample plots (TSPs) of circular design, 600 m^2 in area. These plots were established systematically to give a sample of about 2.35% by area, and represent the current condition of the plantations at the time of the inventory. The plantations are divided into three main blocks, known as Rio Pitzara, Rio Sabalo, and Rio Silanchi. The respective areas and distribution of temporary and permanent plots by 3-year age classes are shown in Table 1.

The majority of the temporary plots are in older stands from 12-18 years old. The younger stands are sampled principally by a relatively small number of PSPs. It will also be noted that the Rio Sabalo block is more strongly represented amongst the PSPs than the other two blocks. There is only one sample in stands younger than 4 years.

For both types of plots, a standardised database was compiled from the original measurements, which included plot location, age, stocking in trees per ha and basal area, Lorey's height, diameter of the mean basal area tree, and plot volumes calculated according to various volume equations. These included overbark volume to 10 cm top diameter, underbark volume to 20 cm top diameter, and scaled peeler volume to 20 and 35 cm diameter limits. The latter measure is based on 2.6 m length cylindrical sections within the taper of the bole. The volume equations were derived from work described in Montenegro and Montenegro (1999).

TABLE 1 *The distribution of temporary and permanent sample plots by age classes and locality*

Age class	Pitzara (526 ha)		Sabalo (267 ha)		Silanchi (425 ha)		Total (1218 ha)	
	TSPs	*PSPs*	*TSPs*	*PSPs*	*TSPs*	*PSPs*	*TSPs*	*PSPs*
1-3		1						1
4-6		3		13		8		24
7-9		7		27		1		35
10-12	6	6		11		5	6	22
13-15	154	16	3	13	34	12	191	41
16-18	42		83	17	139	11	264	28
19-21					18		18	
Total	202	33	86	81	191	37	479	151

Note: the TSP figure indicates the actual number of temporary plots. The PSP figure indicates the number of plot measurements in each age class, which may be successive measurements on the same plot in different age classes.

Lorey's height was adopted as a measure of stand height for this and other work conducted by the FFJMD in 1995 after considerable discussion of alternatives. Simple mean height is sensitive to stand density and the effect of thinning on height distribution. Dominant height, which is usually defined as the mean height of the 100 largest diameter trees per ha, is a widely used standard in plantation yield studies. However, many of FFJMD's plantations are of low density, below 100 trees per ha, due to the use of very wide crowned species such as Pachaco (*Schizolobium parahybum*), and it was felt that dominant height, under such circumstances, becomes a confusing concept as it equates to mean height at low density. Lorey's height, which is a stand mean height weighted by tree basal area, is less influenced by stand density or low thinning than simple mean height, and has a consistent definition for both low and high density stands, unlike dominant height. It also has useful properties when calculating stand volumes using tree volume equations (Philip 1983).

Many of the stands in the sample were lightly mixed with other species, including Pachaco (*Schizolobium parahybum*) and pole-sized indigenous regrowth. Total basal area and stocking of all species was calculated for each plot and used to filter out from the plot database those stands in which Laurel constituted less than 70% of the stock.

SITE INDEX CURVES

The patterns of height growth observed are presented in Figure 1. The permanent plot data are shown as connected lines, whilst the temporary plots appear as discrete points. Different point and line symbols are used for the three localities. The plantations show a number of distinctive features with respect to height growth. It will be noted firstly that early height growth is very rapid, with heights between 16 and 25 m being achieved during the first five years of growth. Thereafter, the different sites show broadly parallel curves. The asymptotic region of the growth is not well shown by the PSPs, as most have only two measurements and appear as simple straight lines, but it is apparent that height growth has substantially slowed down by age 15.

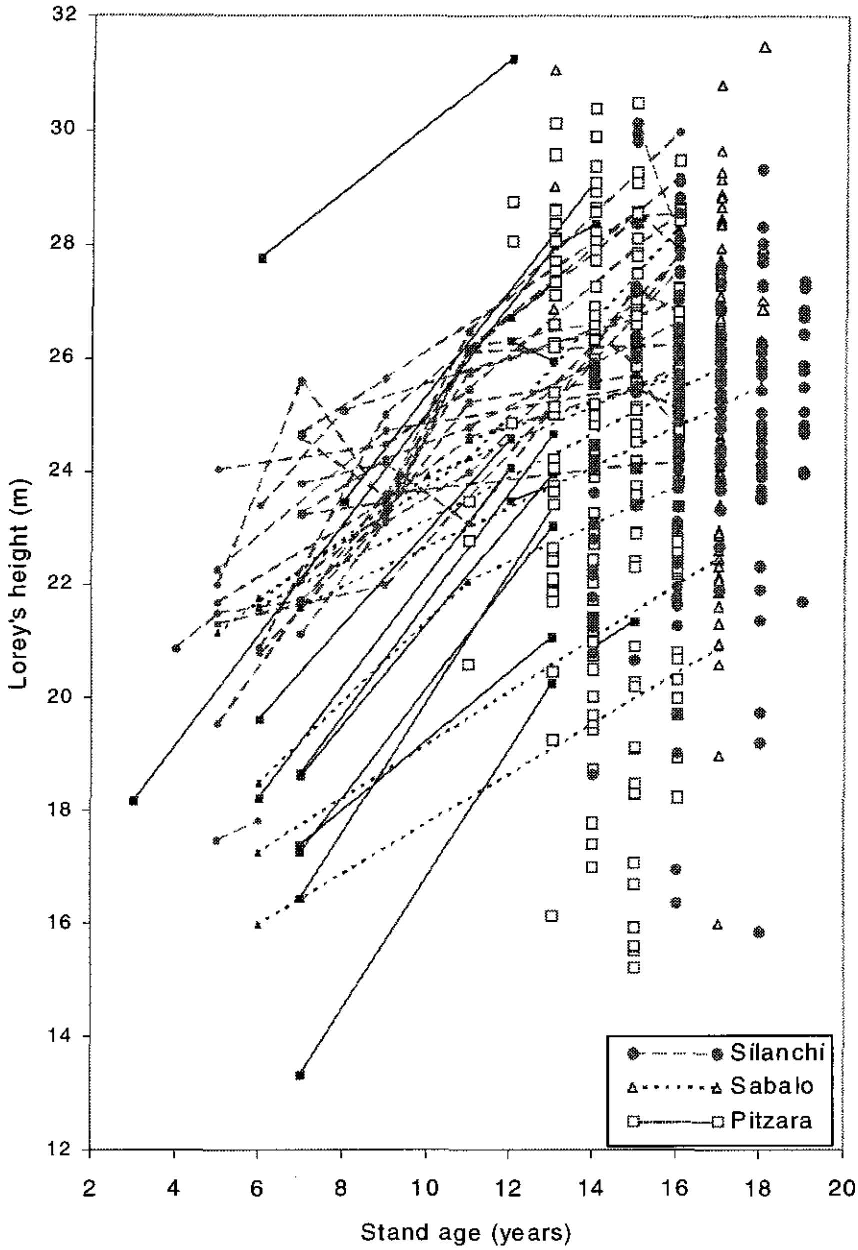

FIGURE 1 *Height growth patterns for* Cordia alliodora *permanent and temporary plots at three localities in Ecuador*

The three localities distinguished on Figure 1 (Rio Silanchi, Rio Sabalo and Rio Pitzara) show a somewhat different pattern of growth. The Rio Pitzara PSPs show a very wide range of initial heights by age 5, from 13 to 28 m, but thereafter growth in all these plots is nearly parallel and tends to have a slightly steeper slope, or rate of height growth, than the other two areas. The temporary plots from this location show the widest range of distributions, from virtual failures at the low end of the scale, to heights of about 30 m on the best sites.

The Rio Silanchi PSPs have a much less dispersed variation, ranging initially from 19 to 24 m and with many of the plots showing the characteristics of being near their asymptotic height, with fluctuating and nearly flat growth. Others however show continued growth, but with a distinctly gentler slope than for Rio Pitzara. The TSPs for these plots are relatively well grouped with a mean value around 25 m at age 16. All the Rio Silanchi PSPs have better sites, appearing in the upper part of the data, but this tendency is not confirmed by the TSPs, which overlap, and do not differ significantly in their mean (around 25 m) between the three localities.

Site index curves were developed for the data shown in Figure 1 which were based on the Schumacher (1939) equation:

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

In this equation, H is stand height in m, H_{max} is a theoretical asymptotic stand height, A is stand age in years, and β and k are parameters. Stand height in all cases is measured as Lorey's height as previously discussed. Alder (1980) describes principles for developing site index curves and presents step-by-step calculation forms. Philip (1983) and

Clutter *et al.* (1983) also provide expositions of methods for site index analysis. Bailey and Clutter (1974) have discussed how equation (1) may be fitted using a covariance analysis to take account of the within-plot and between-plot information available from sequential measurements on permanent plots.

In the present case, because the PSP data include neither the foot of the growth curve nor the asymptotic region, tests with Bailey and Clutter's (1974) method did not provide the optimum results. Curves fitted using their common slope or common intercept estimators tended to be too straight and fan-shaped, and under-estimated early growth on the better sites. However, it was found that equation (1) can provide for a good representation of the data if both the H_{max} and the β parameter can depend simultaneously on site. After some investigation, it was found that a suitable system of curves could be produced if the coefficient in equation (1) was assumed to be a linear function of site index:

$$\beta = a + b\,S \qquad (2)$$

Here, S is the site index, which was taken as the stand height at age 10, and a and b are coefficients. The asymptote H_{max} can also be derived from site index by manipulating equation (1), and substituting the index age (10 years):

$$H_{max} = S / exp(\beta . 10^{-k}) \qquad (3)$$

By combining equations (1) to (3), a single function is obtained containing three coefficients which describe a system of site index curves in a flexible and efficient manner:

$$H = [S / exp\{(a + b\,S).10^{-k}\}].exp\{(a + b\,S).A^{-k}\} \qquad (4)$$

Figure 2 shows the site index curves developed using equation (4). A graphical method was developed to fit equation (4) using Microsoft Excel. The data from Figure 1 and the curves in Figure 2 were overlaid on a single graph. The curves were produced by a model based on equation (4) whose shape was controlled by four graphical handles. These could be manipulated interactively with the mouse to change the shape of the curves until the best match with the underlying data was obtained. The graphical fit was tested by comparing site index values estimated for each PSP by direct interpolation with those derived from the fitted system of curves. This allowed bias to be observed and an approximate estimate of R^2 to be made from a regression between observed and estimated site index values for the PSPs. For the best model, this R^2 value was 0.81, and the coefficient values were:

k = 0.25; a = -3.496; b = 0.073.

Equation (4) with the above coefficients is plotted in Figure 2 using the same scales as for Figure 1. The curves provide a good representation of the mean slope observed in the PSPs and the spread of data indicated by the PSPs and TSPs.

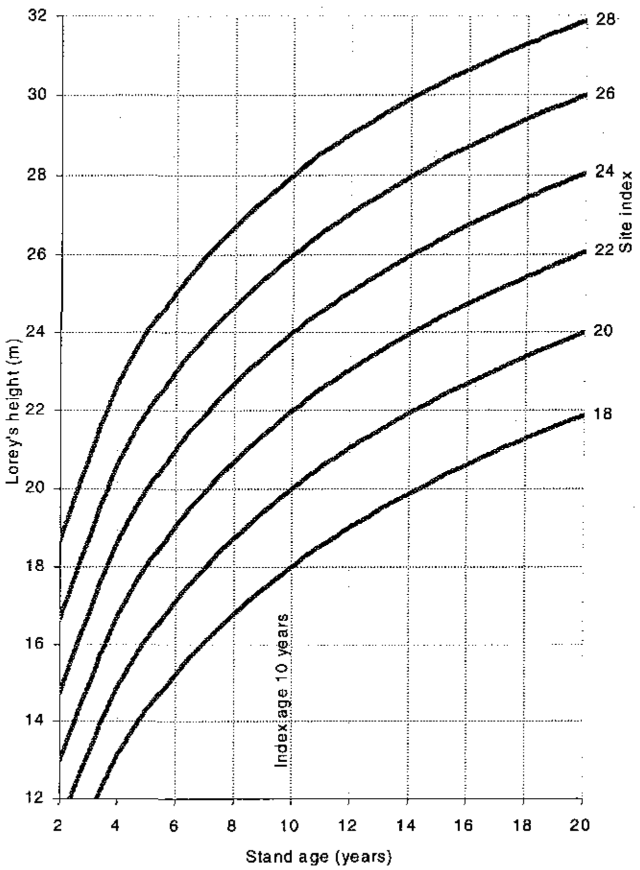

FIGURE 2 *Site index curves for* Cordia alliodora *in Ecuador based on equation 4*

To calculate site index for a plot given any single height and age measurement, equation (4) needs to be rewritten in the form S*=f(S):

$$S^* = [H / exp\{(a + b\,S).A^{-k}\}].\ exp\{(a + b\,S).10^{-k}\} \qquad (5)$$

This type of equation can be solved by direct iteration (Stark 1970). An initial guess at site index (*e.g.* 20) is substituted into the right-hand side and used to calculate a better estimate of site index S*. The process is repeated until convergence to the desired accuracy occurs. This typically requires 4-5 iterations for an accuracy of ±0.05 m. Using this method, site index was calculated for all the plots. It was found that the mean site indices for Silanchi, Pitzara and Sabalo were respectively 22.0, 22.2 and 23.2 m. A Tukey HSD test suggested that Silanchi and Pitzara did not differ significantly, whilst Sabalo differed at the 5% but not 1% probability level. In practice it can be stated that there are no large differences in average site index between the plantations, and the overall mean site index was 22.3 m.

VOLUME AND STAND DENSITY

Eichorn proposed in 1904 that the standing volume of a species at a specified stand height is independent of the site index, as noted in Assmann (1970, p.161). This empirical rule has been used as the basis for constructing yield tables by a number of authors. These include the yield tables of Hamilton and Christie (1971) for a variety of species in Great Britain. When the total volume of fully stocked stands is plotted against stand height (whether mean, dominant or Lorey's height), then curves of a typically logarithmic form ($y = ax^b$) are obtained. The dependence of these curves on stocking or stand density is discussed in Alder (1980). From Eichorn's rule, height may be substituted by age and site index to give a variable density yield table. Skovsgaard (1995) gives a recent application of this method to Norway spruce (*Picea abies*).

Figure 3 shows the data for *C. alliodora* stand volume to a 10 cm top diameter overbark plotted against Lorey's height. The variation in a vertical direction is mostly associated with differences in stocking. This is indicated for example in Figure 4, which shows stand volume against stocking only for plots between 23 and 27 m height.

A multiple regression model was fitted having the form:

$$V_{10} = \alpha . H^{\beta} . N^{\gamma} \tag{6}$$

In this equation, V_{10} is stand volume to 10 cm top diameter overbark, H is Lorey's height, and N is stocking in trees per ha. The resulting function is shown in Figure 3 as curves for different values of stocking. On Figure 4, the same fitted model is shown as a curve of volume against stocking for two values of height. Figure 4 also shows the simple regression $V_{10} = a.N^b$ for comparison, fitted to the data actually graphed. The coefficient of determination (R^2) for equation {6} was .889, and the fitted model was

$$V_{10} = 0.0000411\ H^{3.152}\ N^{0.889} \tag{7}$$

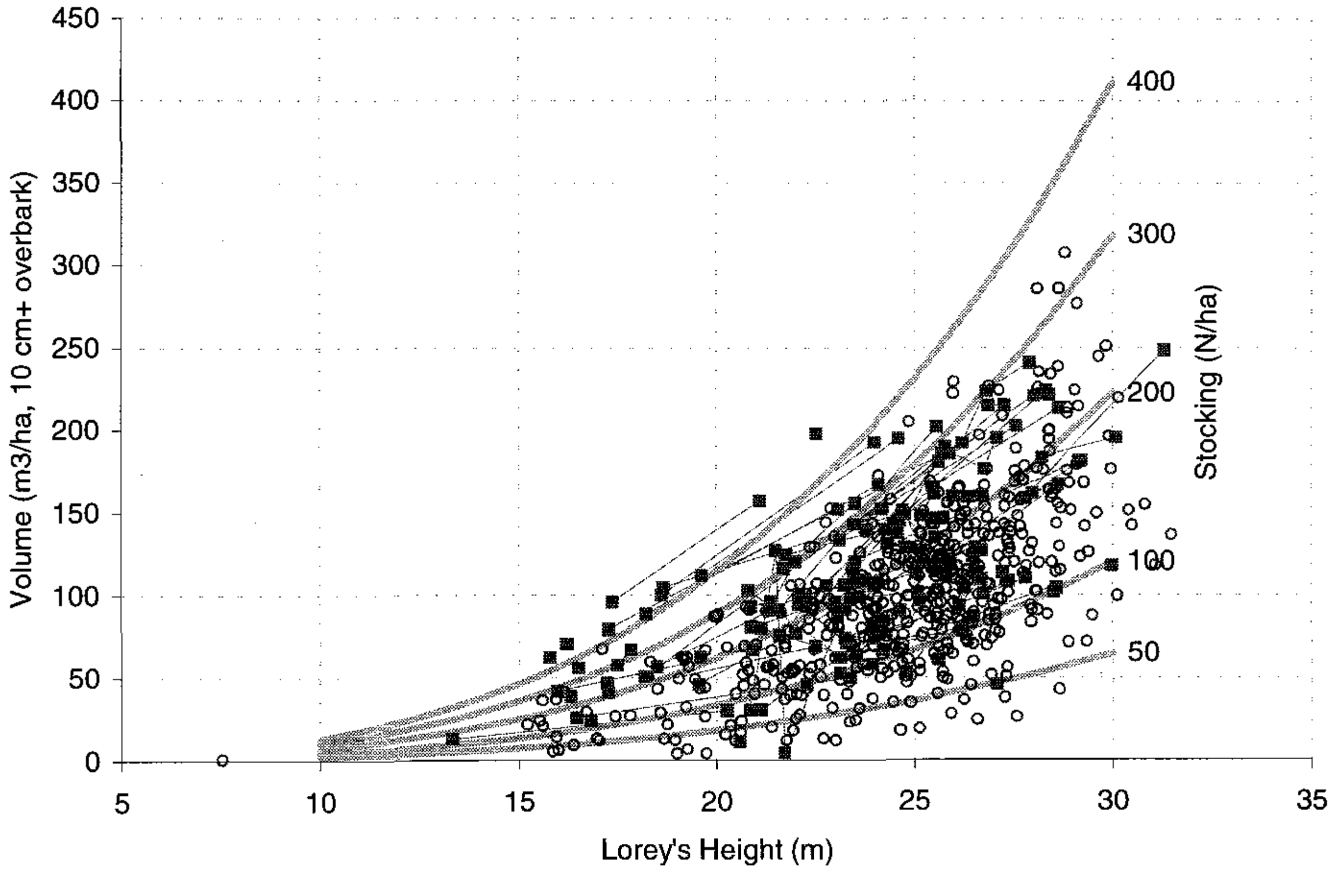

FIGURE 3 *Model relating stand volume, Lorey's height and stocking*
[TSPs shown as circles, PSPs as connected squares, model as thick lines]

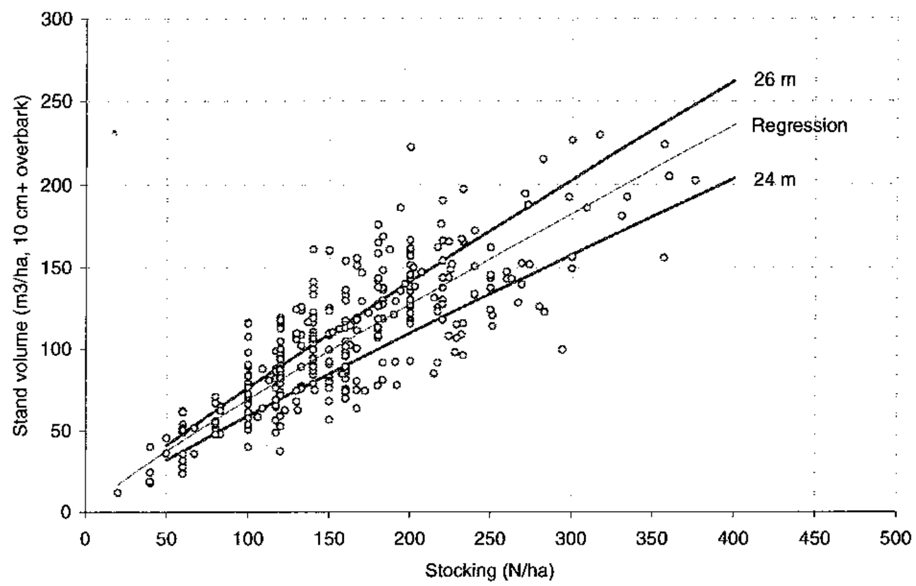

FIGURE 4 *Stand volume against stocking for plots with Lorey's height between 23 and 27 m* [The thick lines are calculated from equation {7} for heights of 24 and 26 m. The thin line is a regression fitted to the data shown.]

A similar logic was used to develop a function for the commercial volume, or volume underbark calculated to a minimum top diameter of 20 cm. In this case, the shape of the curve cannot be represented by a simple logarithmic model, as shown in equation {7}, as there is a definite intercept on the height axis, below which commercial volume is zero. A modified form was used with an additional non-linear k parameter to allow for the intercept, as shown in equation {8}:

$$V_{20} = \alpha . (H-k)^{\beta} . N^{\gamma} \quad (8)$$

This equation was fitted by regression analysis as the linear form:

$$ln(V_{20}) = ln(\alpha) + \beta . ln(H-k) + \gamma . ln(N) \quad (9)$$

The non-linear k value was estimated by using the *Solver* function within *Microsoft Excel* to maximise R^2. The resulting equation was:

$$V_{20} = 0.01187 \, (H-13.5)^{1.961} \, N^{0.7527} \quad (10)$$

The R^2 of this equation was .736 with 631 degrees of freedom. Figure 5 shows the values from this function plotted as solid lines for various stocking levels, from 50 to 400 trees per ha. The data are also shown on the graph, with different symbols according to plot stockings.

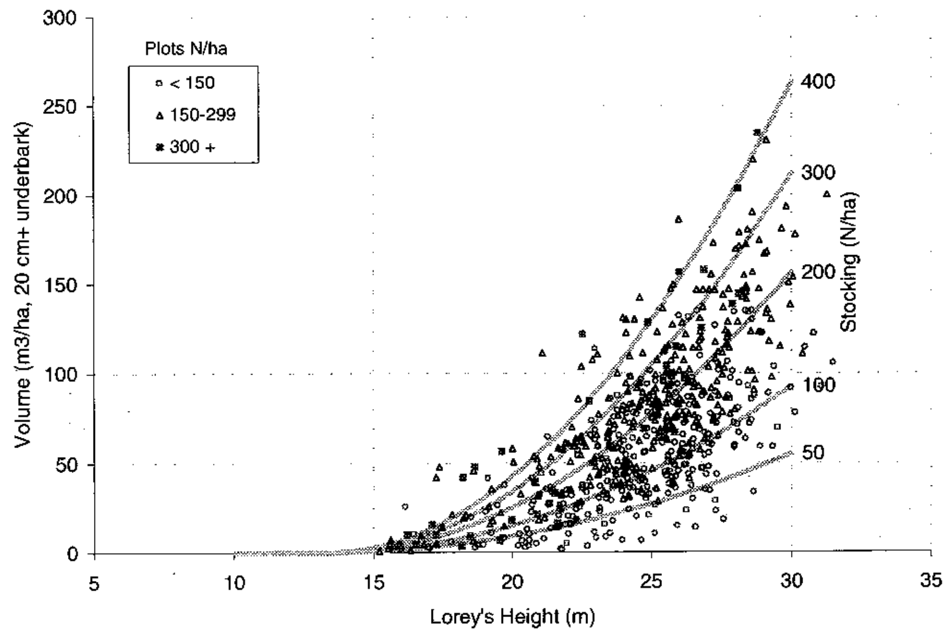

FIGURE 5 *Model of volume underbark to 20 cm top diameter as a function of stocking and height*

MEAN ANNUAL INCREMENT

Mean annual increment (MAI) curves over time can be produced for given site index values and constant stockings by combining equations (4) and (7) for total volume (over bark, 10 cm top diameter), or equations (4) and (10) for commercial volume (under bark, 20 cm top diameter). This can conveniently be done within a spreadsheet program such as *Microsoft Excel*. Figure 6 shows curves for total and commercial MAI at different site indexes and a constant stocking of 300 trees ha^{-1} (Figures 6a and 6b), and at a constant site index of 24 m for several stocking levels (Figures 6c and 6d).

The fine line on these graphs joins the points of maximum MAI, which could be taken as optimum rotations if there are no other constraints. The age of maximum MAI varies with site index, becoming higher at lower values. It is constant however for different stockings. For a typical site index of 24 and stocking of 300 trees ha^{-1}, maximum MAI of total volume is 16.5 m^3 ha^{-1} y^{-1} for 10 cm volume overbark, and 8.8 m^3 ha^{-1} y^{-1} for 20 cm volume underbark.

On the best sites, age of maximum MAI for commercial volume occurs at 5 years, whilst on the worst sites, it is as late as 30 years. For the more typical site index values of 22 to 24, maximum MAI occurs at from 11 to 16 years.

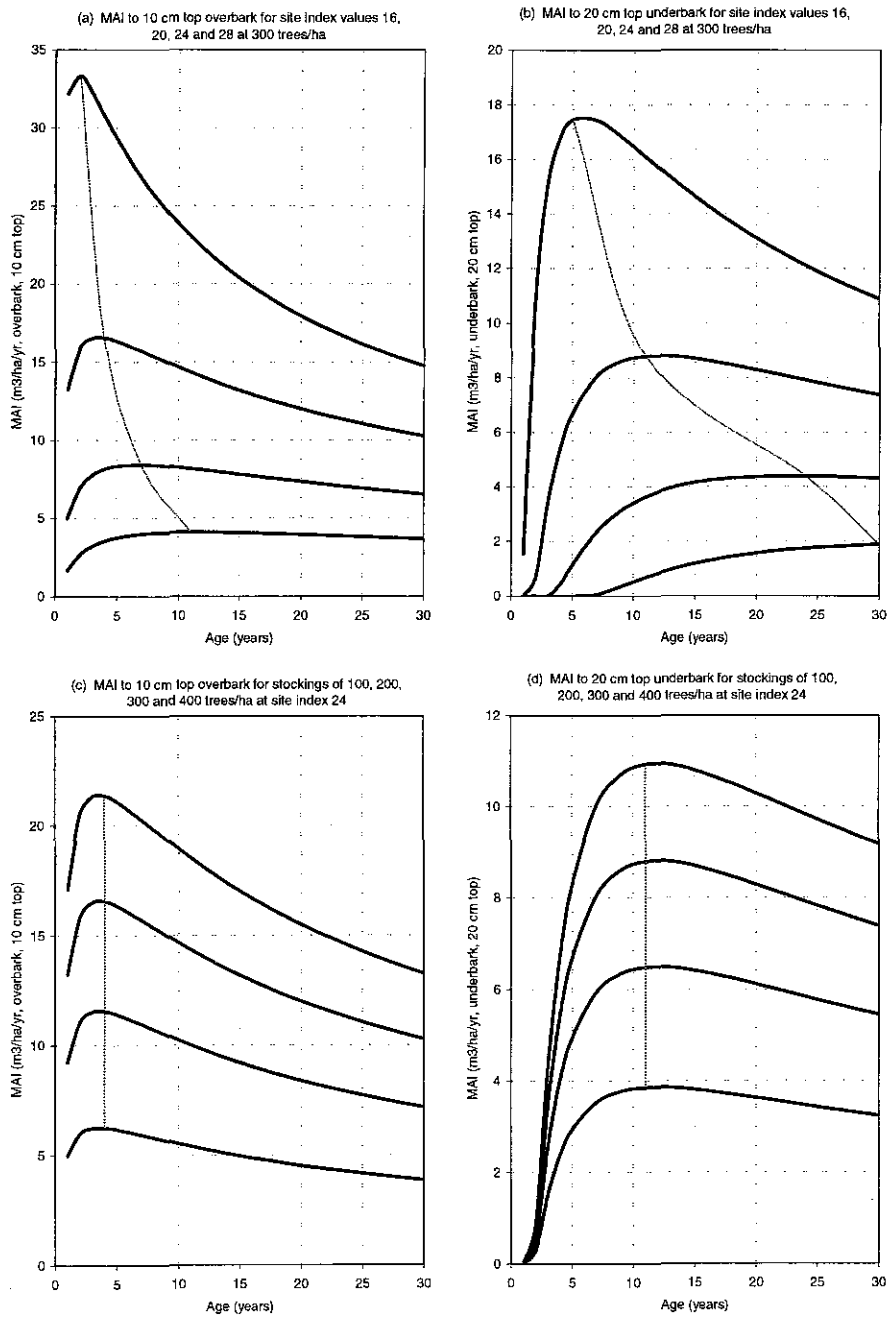

FIGURE 6 *MAI curves for different site indexes and stockings, for volume to 10 cm top overbark (left) and 20 cm top underbark (right)*

DISCUSSION

The present analysis shows that on average sites of about 22 m height at age 10, and with current average stockings of the order of 200 trees per ha, volume yields underbark above 20 cm diameter are about 6 m^3 ha^{-1} y^{-1} occurring at about 18 years. Volume yields increase markedly with higher stockings and improved site index. Volume production is more or less proportional to stocking over the range of densities investigated (up to 400 trees per ha) as Figure 4 shows. This indicates that it is important to employ a planting density and re-stocking method that will ensure at least 300 trees per ha in the established stand. It was hitherto believed that *C. alliodora* required wider spacings to maintain maximum diameter increment. It is now apparent that at least for these wild genotypes, diameter growth will taper off rapidly at about 5-6 years irrespective of spacing, and volume production can be improved through higher densities.

It is also clear that it is inefficient to plant *C. alliodora* on the poorer sites. The rotation for maximum production increases rapidly with decreasing site index, from 5-6 years on the best sites, to more than 20 years on the poorest sites as shown in Figure 6b. In economic terms, the discounted revenue of a stand on site index 24 is likely to be more than double that on site index 22. This assumes a 10% interest rate, a rotation of 12 years and production of 9 m^3 ha^{-1} y^{-1} at site index 24, and a rotation of 18 years and production of 7m^3 ha^{-1} y^{-1} at site index 22 (Figure 6b). The development of methods for identifying suitable sites for planting should therefore be a priority for future study. The existing database of inventory plots provide a complete coverage of the plantations with several plots in each compartment. It should be possible to characterise the compartments in terms of their average site index, and to correlate this with factors relating to soil, climate, hydrology and previous land use.

The model presented describes two technical standards for volume, namely 10 cm overbark volume based on Smalian's formula, and underbark volume to a 20 cm top diameter using 2.6 m cylindrical sections, corresponding to current wood processing standards in Ecuador. In another study (Alder 1998), volumes to a 35 cm top diameter for similar sections were also considered, and show production levels which are half again those for 20 cm volume. At a site index of 24 and stocking of 300 trees per ha, MAIs to 10 cm overbark and 20 and 35 cm underbark are approximately 17, 9 and 4 m^3 ha^{-1} y^{-1} respectively. There is therefore a very strong incentive to process the smallest diameter material possible. In this paper, 20 cm underbark volume has been described as commercial volume because it is technically feasible to process this size for veneer production with existing equipment installed in Ecuador. However, any improvements in the conversion and marketing of smaller sized material will clearly be strongly advantageous in terms of available volume production which will otherwise be wasted.

The above points regarding the strong gearing between site index, stand density, technical size limits for utilisation and production volume also imply that major economic gains may be made through quite modest progress in tree breeding. The existing plantations were established from selected trees in the natural forest, and more recently, from plus trees in the plantations. However, a seed orchard for Laurel based on the best plantation trees has been established by FFJMD and will be producing seed in two to three years. This may lead over the next decade to a great improvement in yields, especially if applied jointly with better management practices in terms of site selection and stand density.

The yield model presented here is comparatively simple, using only two basic functions (height-age-site index and volume-height-stocking) to derive mean annual increment curves to estimate technical rotation and plantation production over a range of stockings. The method has been applied to a number of species planted by FFJMD including *Cedralinga cateniformis* (Chuncho), *Parkia multijuga* (Cutanga), *Jacaranda copaia* (Jacaranda) among others (Alder 1998, 1999). For most of these latter species the data is too limited to develop anything beyond a mean and a tentative optimum model, whereas the *Cordia alliodora* data are more extensive and lends itself to a complete exposition of the technique. It can be applied to questions of economic analysis and plantation planning, as shown in Alder (1998), but does not include the facility for predicting the effects of thinning. The model has been based on data for densities up to 400 trees per ha, and should not be applied to higher stockings, as it is likely that inter-tree competition, suppression and mortality effects may occur which are not accounted for in equations (7) or (10).

An improved model requires better information on height growth from an earlier age, and more frequent annual measurements. This may be accomplished for new plantations with PSPs established at the time of planting and monitored annually for the first 5 years, and, thereafter biannually. An alternative approach which may be possible with *C. alliodora* is to use stem analysis to reconstruct height growth curves for younger trees in the existing stands. Tschinkel (1966) reports the occurrence of growth rings, but it is not known if these may be reliable or clear enough to permit stem analysis, especially under the seasonal conditions occurring in Ecuador. Another aspect of sampling that is important relates to spacing. Existing stands are all of low density, and it is important to know the growth characteristics of the species at higher densities to develop a fully efficient yield model. It is desirable to establish a spacing experiment, replicated on a number of sites, to provide this information in future.

Cordia alliodora itself is an important plantation species in Ecuador. It has proved itself to be one of a small number of species that can be generally planted in the lowland tropics. It has remained healthy under plantation conditions over 20 years. The wood is valuable for decorative veneers and quality joinery timber and has a strong international market. Production on typical sites is comparable with other tropical plantations (30 m^3 ha^{-1} y^{-1} over bark volume to a 10 cm top by age 4 on the best sites, and 16 m^3 ha^{-1} y^1 on average sites at 300 trees ha^{-1}). First generation improved seed orchard seed will shortly be available in Ecuador that will further increase yields. It requires careful management, as growth is sensitive to site and optimum spacing, but the yield model presented in this paper should assist in this process and contribute to the further development of the species' use.

ACKNOWLEDGEMENTS

The work described in this report is based on research undertaken and supported by the Fundación Forestal Juan Manual Durini and its President, Manuel Francisco Durini. The United Kingdom Department for International Development has also provided support for data processing and analysis. Special thanks are due to Forest Engineer Leno Veloz who has supervised the sample plot operations over many years. Forest Engineers Armando Chamorro, Venicio Meneses and Freddy Tandazo have contributed to the field work at various stages. Maria Christina Marcayuta has assisted with translation and secretarial support. Cristobal Montenegro undertook the volume equation analysis that was the basis of plot volume calculations, whilst Marco Cantuña did much of the basic data processing.

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