Analysis of the 2006 forest inventory for the Laos Industrial Tree Plantation Project

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on behalf of
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Executive Summary

This report analyses inventory data collected between May and September 2006 from *Eucalyptus camaldulensis* plantations established in Laos under the ADB Industrial Tree Plantation Project (ITPP) between 1997 and 2001. In all, 309 inventory plots of 0.012 ha (10 x 12 m) were established in 65 villages in 5 provinces. The sampling design recorded areas of failed or previously felled plantations, as well as those inventoried. GPS transects were made of sampled plantation boundaries to calculate actual planted areas. From this it was possible to relate reported/planned areas, totalling 3,398 ha, to actual established areas, estimated at 51% or 1,732 ha, and currently remaining fully stocked areas on the ground, which were estimated to be 1,153 ha. Total standing volume on this remaining area was 42,178 m^3. Mean annual increment averaged 5.1 m^3/ha/year. Of the area actually established, it was estimated that 21% were lost for silvicultural reasons, 12% were harvested prior to inventory, and 67% remained as at 2006.

Several volume equations were tested from the data. The best was a simple form factor of 0.454, used to calculate all volumes overbark to a top diameter of 2 cm, as measured on 114 felled sample trees. These ranged in height from 6 to 19 m, and in diameter from 4 to 17 cm.

Sample plot stand parameters were calculated for all inventory plots. Lorey's height (height of mean basal area tree) was used as a substitute for dominant height, as plots were small, all trees had been height-measured, and there was no agreed dominant height standard.

Site index (SI) curves were borrowed from work of Tewari (2002) in India for *E. camaldulensis*, and found to fit the data satisfactorily. A base age of 7 was adopted for site index. 90% of plots had SI's between 8 and 16 m. Mean SI tables for villages, districts and provinces were produced. This should aid the development of site selection decision tools. Overall mean site index was 10.9 m at age 7, but satisfactory MAI's (above 10 m^3/ha/yr at culmination only occur above SI 13, which is recommended as a lower limit for future planting selection for *E. camaldulensis.*

A yield model was developed using a logarithmic function of stand height and stocking to predicted volume. The self-thinning curve was explored and incorporated into a worksheet function for yield modelling. Management tables were produced that allow quick lookup of all stand parameters from basic information on age, stocking and height.

Mean stocking and spacing varied widely, but the majority of plots were well stocked, with 80% in excess of 800 stems per ha (less than 3.5 m average spacing). Overall mean stocking was 1242 sph.

The yield models showed that MAI culminates between 22-35 years for SI's 13 and 9 m respectively. Analysis of optimum financial rotation suggest that for SI 13, it would be 5 years at 7% interest, 4 years at 9%, or 7 years at 5%. Optimum rotation is not sensitive to stumpage or stocking, although profitability is very much so.

Recommendations were that the site index results should be used to develop a site selection tool; for new inventories, techniques and mensurational standards should be reviewed, as the present methodology had some weak points; and the project monitoring and management systems should be more rigorously designed at the outset, to provide more robust and less fragmented project information.

Contents

Acknowledgements

The inventory described here was conducted by a team from the University of Laos which were supervised in the field by a consultant, Mr. Thongthanh Southitham and a WWF staff member, Mr. Somphone Bouasavanh. Preliminary analysis of much of the data, and its organisation and preparation into tables for the consultant's review and further analysis was carried out by Alastair Fraser, consulting for Asian Development Bank, also with the involvement of Mr. Somphone Bouasavanh of the WWF. Alastair Fraser has also coordinated supporting work in the preparation of this report, especially in the provision of additional or revised datasets where requested. The consultant has also been assisted by the advice of Dr. VP Tewari of the Arid Forest Research Institute, India regarding the growth and yield of *E. camaldulensis* in that country. He would also like to thank Scott Geller of LTS international Ltd, who has coordinated this project.

Introduction

This report is the consultant's analysis of inventory data collected between May and September 2006 from *Eucalyptus camaldulensis* plantations established in Laos under the ADB Industrial Tree Plantation Project (ITPP) between 1997 and 2001.

The report is divided into three main sections, covering the development of a suitable tree volume equation, analysis of growth and yield models, and total volumes and areas for the inventory zone.

Three supporting workbooks are provided, corresponding to these areas of analysis and containing all the data and models used. This includes the originals for all the tables and figures in this report.. They are *VolumeEquations.xls*, *YieldModels.xls*, and *InventoryAnalysis.xls*. Copies of these workbooks, and an electronic copy of this report, can be downloaded from http://www.bio-met.co.uk/laos.

The analysis in this report takes forward and extends prior work that has been done by project staff and consultants, as noted in the **Acknowledgements**. This has covered the field work and planning, data entry, and preliminary analysis.

This report has a provisional status, as some information regarding the plantation total areas has yet to be verified. It will be updated with a final version as soon as that data is available.

Inventory design

This section describes the inventory design, and is paraphrased from background documents provided to the consultant.

The sample consisted of 143 household plantations from a total of 2513 households that borrowed funds under the ITPP. The samples were stratified according to province (six provinces) and year of establishment (1997-2002). As plantations were not established in all provinces in all years, the stratification resulted in 21 province-age groups.

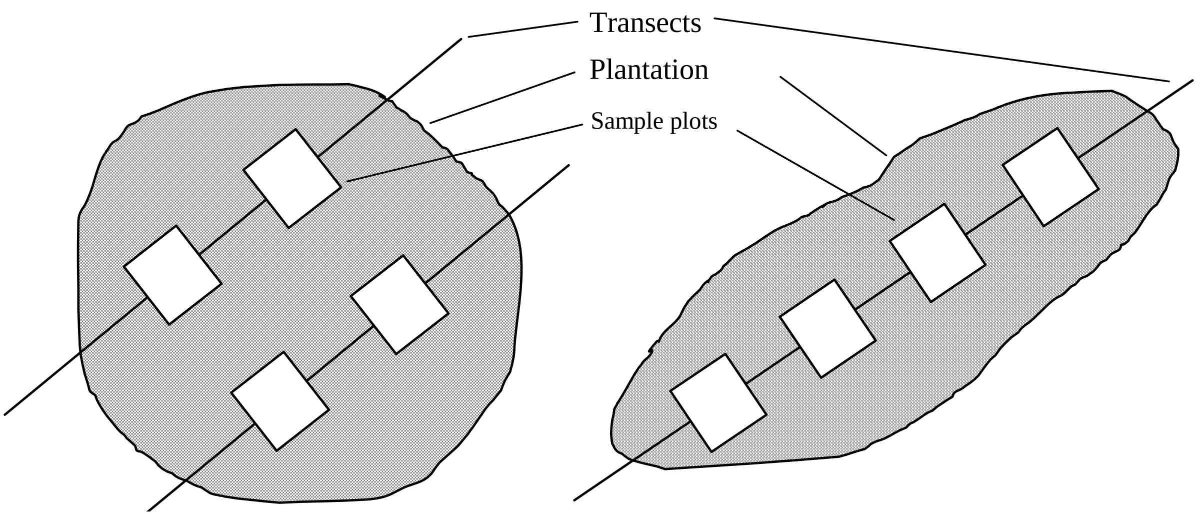
Within each farmer's plantation block, four 12x10m plots per hectare were systematically selected after measurement of the total planted area by GPS. In broad plantation blocks, the plots were located equidistantly along two transects running across the block at equal spacing as shown in Figure 1 for a ~1 hectare plot. In narrow plantation blocks, plots were established equidistantly along a transect running centrally through the block. In larger blocks the design was replicated according to the size of the block, for example, in an area of 1.5 ha, six 12m x10m plots would be systematically laid out.

The distance between line transects was maintained at a minimum 12 m while the distance between plots was kept at a minimum 10 m to avoid overlapping of plots. The line transects were planned to run across the fertility gradient (or the drainage pattern) rather than along it. Within each plot, tree diameter at breast height (dbh) and tree height were measured for every tree and entered into a the tally sheet.

One sample plot was chosen from the laid out plots in a plantation block for tree volume sampling. On this plot, three dominant or co-dominant trees were selected and felled. Dbh, total height were recorded for each of these felled trees. Diameter outside bark (d.o.b) was recorded at 30 cm. intervals for these trees from the but to a 2 cm top diameter.

Two bolts, each 30 cm long, were sawn off from stump-end and the tip-end of the cut trees from the sample plot, their cut-end diameters and weights. These data were to be used to determine volume to weight conversion factors. A small number of samples, approximately 20 in all, of 2 metre length were set aside for reweighing after air-drying for one month to reassess the changes in weight on account of drying.

Figure 1 : Layout of inventory plots



Tree volume equations

In the data sets provided to the consultant, measurements for 114 felled sample trees of *Eucalyptus camaldulensis* were found. These were cross-checked for calculation and data entry accuracy, and a number of minor corrections made. Table 1 shows the height and diameter distribution of the sample trees.

Table 1 : Height and diameter distribution of volume sample trees

Tree diameter (dbh, cm)	Tree height, m														
	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Total
4		4													4
5	1	1	1												3
6			1	2											3
7				1	2	2	1								6
8			1	2		4	2	1							10
9					2	2	3	3	2						12
10					2	2	2	5	4	1					16
11						3	5	6	3	2		2			21
12							1	1	3	5	2	1			13
13							1	1	4	2	1	1	1		11
14									1	1	1	2	1		6
15										1	1		3		5
16											1		1		2
17												1		1	2
Total	1	5	3	5	6	13	15	17	17	12	6	7	6	1	114

Tree volumes were calculated for each tree and tabulated in an Excel workbook called *VolumeEquations.xls.* The data is in the sheet labelled *Voltrees*. A number of possible regression models were tested to determine the best volume equation. These are shown in Table 2 below together with the corresponding sheet names in the workbook and a comment on their suitability. The symbols used in the equations are:

- d tree dbh in cm
- h tree height in metres
- g tree basal area, in m2
- v tree volume in m^3
- k the constant $\pi/40{,}000$, or 0.00007854 . Note that by definition $g = k.d^2$

The recommended volume equation, from those tested, is the form factor model. An average form factor of 0.454 is calculated from the felled sample trees, and predicts volume as well as any other equation. It is simple to understand – most professional foresters are familiar with the concept of a cylindrical form factor as a way of measuring tree volume – and in this case particularly suitable because :

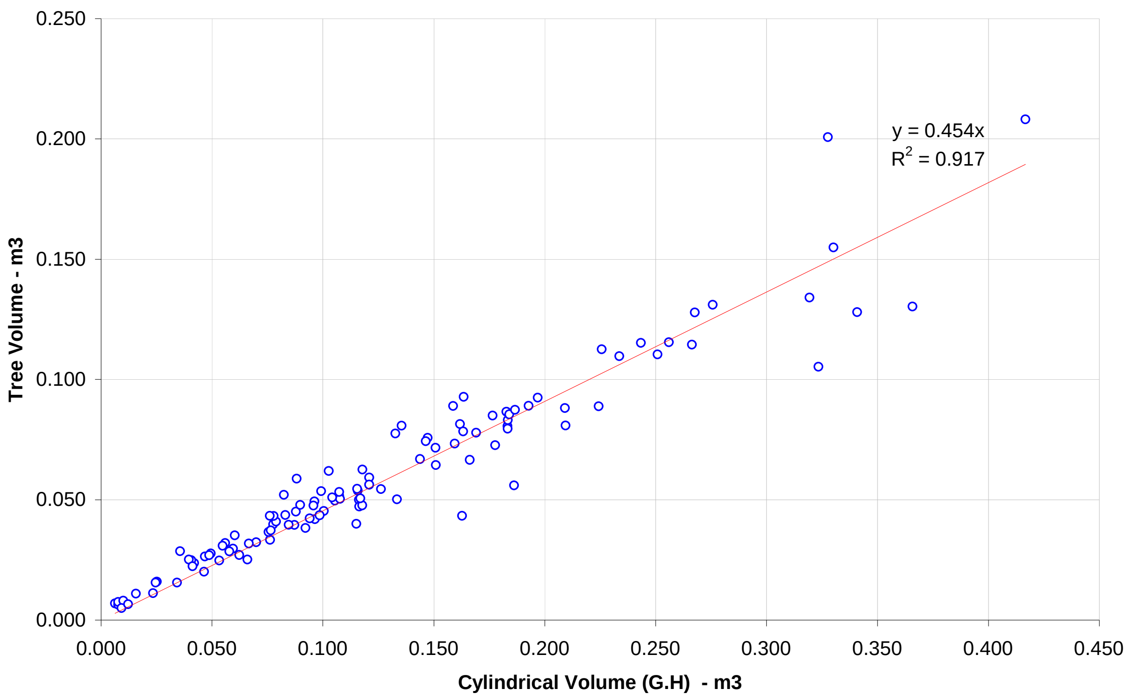
- A robust equation is needed that will behave well if used to extrapolate to larger trees. It is almost inevitable that any volume model derived from this study will continue to be used as the trees grow, and this robust quality is therefore an important criteria.

- As all the trees have already been measured for height, there is no extra cost to using such an equation. The consultant would not normally recommend measuring all tree heights, as it is slow procedure, but once it has been done, it makes sense to take advantage of the information.

Table 2 : Volume equations tested for young *Eucalyptus camaldulensis* in Laos

Equation type	Fitted model	Worksheet name	Comment
Form Factor	$v = 0.454\ kd^2h$	Formfactor	*Fitted with an R^2 of 0.92, simple to understand (0.454 is the form factor, or ratio of tree volume to cylindrical volume), robust for extrapolation, easy to calculate in field, **recommended**.*
Volume-Diameter	$v = 0.000734\ d^2 - 0.002431\ d$	Vol-Diam	*Fitted with R^2 of 0.89. Less accurate than form factor, but suitable for use where height data lacking or unreliable. Less robust than form factor for extrapolation, should limit it to trees below 20 cm dbh.*
Logarithmic Volume-Diameter	$v = 0.000282\ d^{2.239}$	Vol-Diam	*Widely used as a natural forest model where height measurement difficult. Gives seemingly better fit (R^2 0.94) but this is a statistical artefact because fit is to ln(v) not to v. Biased - tends to slightly underestimate volume (Meyer's correction should be applied, see Alder ,1980, p.139 or other textbooks).*
Form Height	$v/g = 0.2719\ h + 2.8058$	FormHeight (chart, equation) FormHt Test (goodness of fit)	*Has some significant advantages in biometrically designed plantation inventory to reduce costs and allow error partitioning between sample and volume equation. Here R^2 is 0.92 for predicted volumes. Conceptually simple: a form height (tree volume/tree basal area) that varies with stand dominant height. Robust for extrapolation. However, not preferred for present context as form factor better if all trees measured for height.*

Figure 2 : Volume sample trees with Form Factor model used as the volume equation



Stand growth and yield

Calculation of sample plot stand parameters

The consultant was provided with data collected from 309 sample plots. Full details of the plots are given in the workbook *YieldModels.xls*. The worksheet *InvData* lists original tree measurements for each plot. These are summarised to give the stand parameters for each plot listed in Table 3.

Table 3 : Stand parameters calculated for sample plots

Parameter	Symbol	Units	Notes
Location			Province, District and Village.
Plantation area, nominal	A_n	ha	Intended planting area declared by owner
Plantation area, actual	A	ha	Perimeter measured by GPS waypoints
Stand age	T	years	Inventory date (2006) – Planting year.
Stem numbers	N	stems per ha	No of trees on plot ÷ plot size in ha (0.012 ha)
Basal area	G	m^2/ha	Sum of diameters^2 on plot, x (π/40000) , or in algebraic terms, $G = k.\Sigma d^2$
Mean basal area diameter	D_g	cm	Square root of sum of the diameters squared, also known as quadratic mean diameter. Algebraically, $D_g = \sqrt{(\Sigma d^2)}$
Lorey's mean height	H_g	m	Sum of (tree heights x diameter squared), all divided by sum of diameters squared. Algebraically: $H_g = (\Sigma d^2 \cdot h)/ (\Sigma d^2)$
Volume per ha	V	m^3/ha	Given a form factor f (here 0.454), stand volume per ha is calculated by summing tree cylindrical volume x form factor, and dividing by plot size p in ha. Algebraically: $V = f.(k\Sigma d^2 \cdot h)/p$. It can also be calculated from G and H_g with: $V = f.G.H_g$. These formulae are algebraically equivalent.
Site Index	S	m	Estimated stand height at age 7 years, based on the provisional site index curves discussed below.

The workbook *YieldModels.xls* contains a macro, or computer program, which automatically processes the plot heading and tree data information on the *InvData* sheet, and generates the plot summary listing on sheet *PlotSum*. This program can be re-run by using the Alt-F8 key and selecting the macro *MakePlotSum*. Its program code can be examined using the Alt-F11 key to bring up the Visual Basic editor.

Site index curves

Figure 3 shows the stand height H_g of the inventory plots graphed against their age. Superimposed on this data are a set of site index curves derived from the equations of Tewari *et al* (2002) for *Eucalyptus camaldulensis* plantations in Rajasthan, India. The curves appear to be reasonably representative of the Lao inventory plots, although without permanent sample plots (PSPs) to validate height growth patterns, and plots of a sufficiently great age as to verify the asymptotic region of the curve, it is impossible to be sure. However, these curves are adopted here on a provisional basis for the further yield calculations.

Tewari's model is base-age invariant: That is any convenient age can be adopted as the site index age. For the present study, 7 years is used as it is the median age of the inventory data set, and therefore reflected in real observations of stand height.

A user-defined function to do site index and height age calculations has been added to the workbook *YieldModels.xls*. This is used within Excel in the form:

HtFn(*age1*, *height1*, *age2*)

where *age1* and *height1* are a known height-age point, and *age2* is the age at which a subsequent (or earlier) height is to be calculated. To calculate site index, *age1* and *height1* should be actual plot age and height, and *age2* should be 7 (the chosen base age). The site index will then be the returned value. To calculate height at a given age when site index is known, *age1* should be 7, *height1* should be the site index, and then height will be returned for *age2*.

The form of the equation, which was originally proposed by Payandeh & Wang (1994) is:

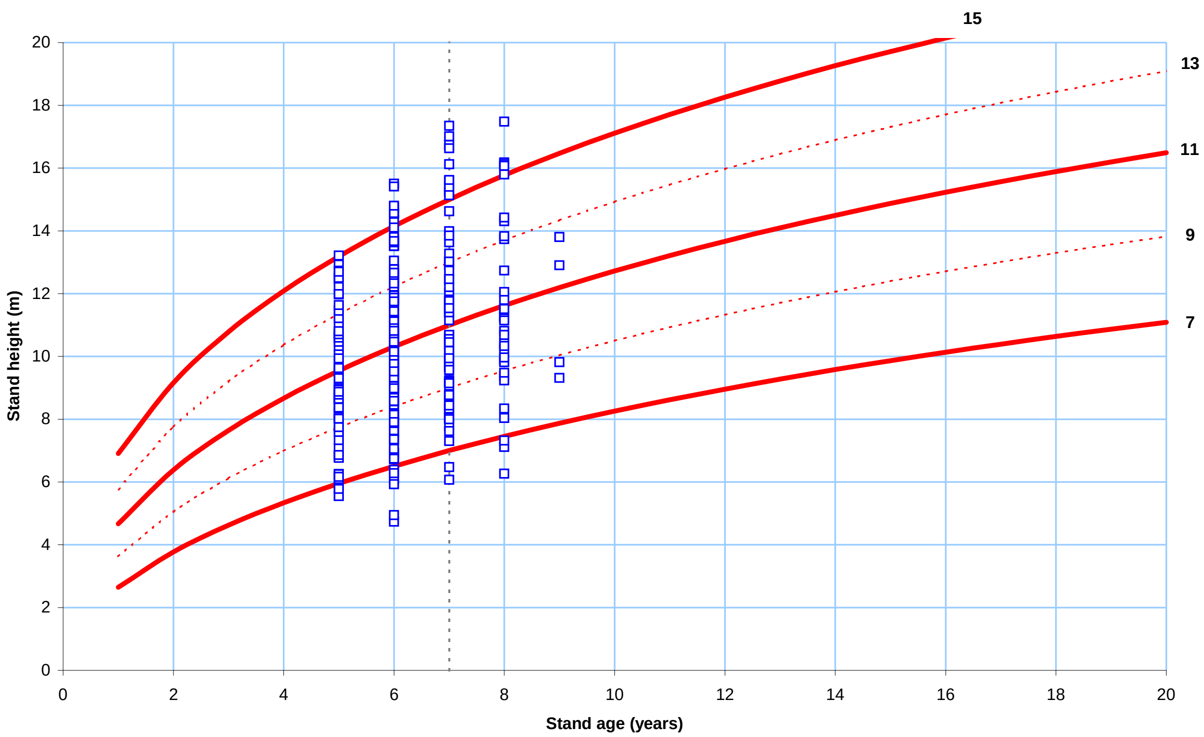
$$H_2 = a.\ H_1^{b}.[1 - exp(-c.t_2)]^{d} \qquad \text{\{eqn.1\}}$$

$$d = ln[H_1/(a.H_1^{b})]/ln[1-exp(-c.t_1)] \qquad \text{\{eqn.2\}}$$

where H_1, H_2 are the *height1*, *height2* as per the usage above, t_1 and t_2 are *age1* and *age2*, and *a, b* and *c* are the coefficients 3.95687, 0.75844 and 0.0278 respectively.

Figure 3 : Inventory plots with Tewari et al (2002) site index model

A base of 7 years has been denominated for site index curve values shown at the right



A yield model for volume, height and stocking with self-thinning rule

A yield model was fitted by regression analysis to sample plot standing volumes, with stand height and stocking as the independent variables. The regression had the linear form:

$$ln(V) = -10.208 + 3.2990\ ln(H_g) + 0.7863\ ln(N) \qquad \text{\{eqn.3\}}$$

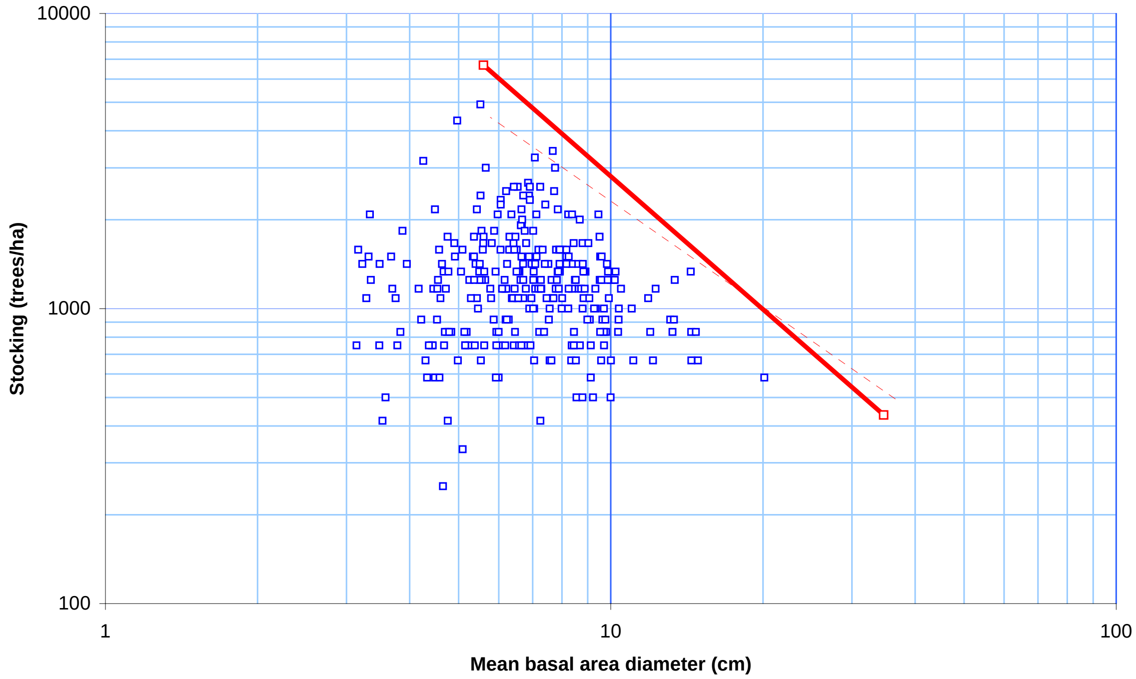
This fitted to the 299 stocked plots (10 were empty plots) with an R^2 of 92%. The antecedents of this model are discussed at some length in Alder et al (2003). It allows standing volume to be calculated when stand height and stocking are known. Stand height itself can be determined from age and site index, and hence we have an almost complete yield model given basic site and initial stocking information.

However, for stands planted at closer spacings, it is also essential to have a self-thinning function. This is conventionally devised in forestry by plotting stocking against mean diameter, although similar results occur plotting stocking against stand basal area, volume, or even height, as all are allometrically related to biomass (Zeide, 1987).

Figure 4 shows the inventory plots with stocking (N) graphed against mean diameter (D_g). The dotted line shows the self-thinning line determined empirically by Tewari (2007, *in press*) for *Eucalyptus camaldulensis* in Rajasthan. This line was too severe a cut-off when examined empirically for the Laos data in terms of the volume-height plot (see Figure 5). A more relaxed line was estimated visually, as shown by the heavy line. This gave results consistent with the data in Figure 5. This line has a slope close to –3/2, as expected by the normal self-thinning rule (Zeide, 1987).

Figure 4 : Estimated self-thinning line for *E. camaldulensis* in Laos

Dotted red line after Tewari (2007), India. Bold red line estimated for Laos. Axes are logarithmic.



The self-thinning rule shown in Figure 4 has the equation:

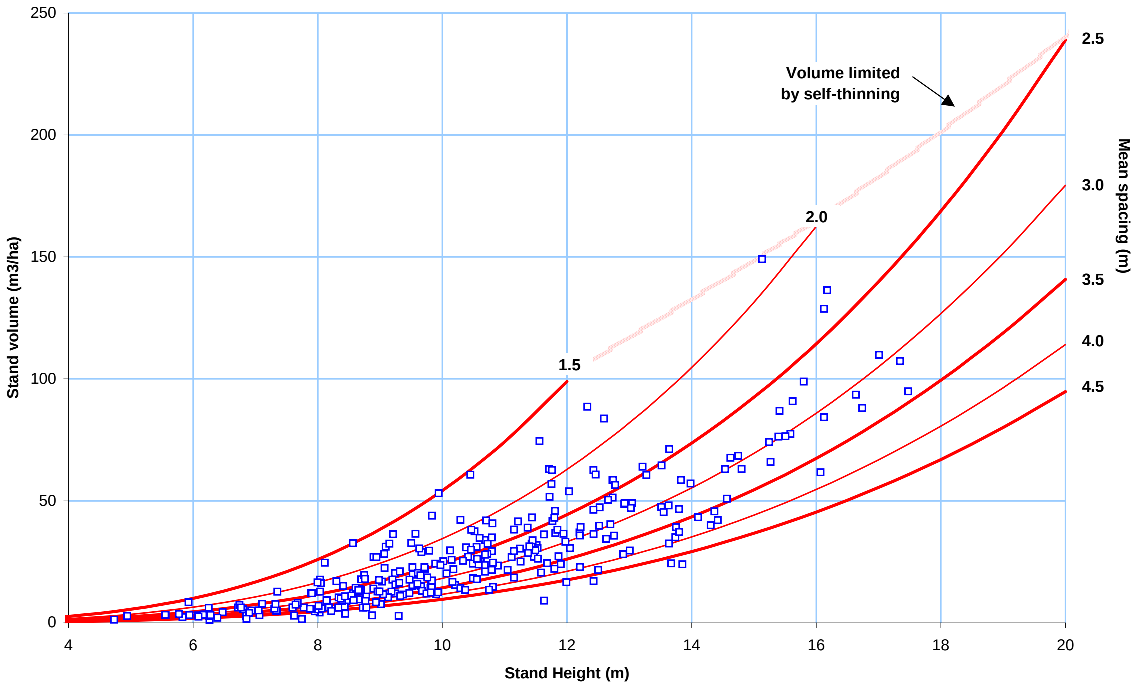
$$N = 88127.43\ D_g^{-1.4975} \qquad \{\text{eqn. } 4\}$$

It can be seen that the exponent (-1.4975) is very close to the theoretical value of –3/2.

As is also noted in Alder et al (2003) for *E. grandis*, self-thinning in Eucalypts is often more chaotic and irregular than in denser crowned species such as pines, *Acacia mangium*, or Teak, and it is hence difficult to identify exactly the self-thinning line, as stands show self-thinning behaviour before apparently reaching their density limit, especially under conditions of drought stress in low-rainfall years. PSPs would again be useful here in identify self-thinning behaviour more clearly.

Figure 5 combines equations {3} and {4} to produce a series of volume-height lines for stands at different stockings, but with the self-thinning limits incorporated to avoid predicting unrealistic values.

Figure 5 Inventory data with volume-height-stocking model



An Excel worksheet function called *YieldFn* is also included in *YieldModels.xls* workbook that incorporates the above models. It is used with two parameters, in the form:

YieldFn *(Height, Stocking)*

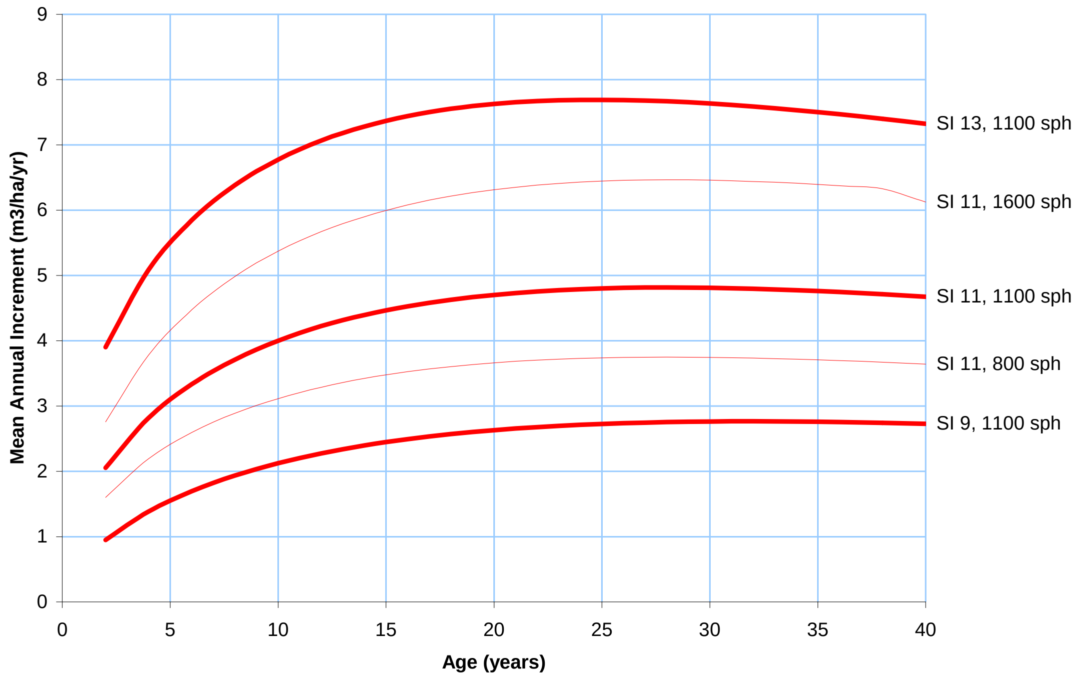
and returns standing volume in m^3/ha, limited by self-thinning if applicable.

Mean Annual Increment curves

The above functions can be combined to calculate standing volume (yield) with age and Mean Annual Increment (MAI), but there are many possible combinations of site index and stocking involved, so it is difficult to represent these completely on simple graphs. Figure 6 shows MAI curves plotted for a range of moderate site index and stocking values, over a period long enough (40 years) to show the likely maximum MAI, which is generally around 25-30 years.

These show that the age of maximum MAI depends on site index, but is insensitive to stocking. The actual level of MAI is very sensitive to both, and it is critical to good management to plant only the better sites, and to maintain optimum stocking.

Figure 6 : Mean Annual Volume Increment (MAI) curves for several site index-stocking combinations



Management Tables

Table 3 shows the above functions in tabular form, for ease of reference. Given age and site index, height can be looked up from the left-hand table. This can then be combined with stocking to look up volume in the right hand table.

Table 3 : Yield tables for unthinned *E. camaldulensis* in Laos

Height growth and site index

Age	Site index 7	9	11	13	15
	Lorey's mean height in metres				
1	2.6	3.6	4.7	5.8	6.9
2	3.8	5.1	6.4	7.8	9.2
3	4.6	6.1	7.6	9.2	10.8
4	5.3	7.0	8.7	10.4	12.1
5	6.0	7.7	9.5	11.4	13.2
6	6.5	8.4	10.3	12.2	14.1
7	7.0	9.0	11.0	13.0	15.0
8	7.5	9.5	11.6	13.7	15.8
9	7.9	10.0	12.2	14.3	16.5
10	8.3	10.5	12.7	14.9	17.1
11	8.6	10.9	13.2	15.5	17.7
12	9.0	11.3	13.7	16.0	18.3
13	9.3	11.7	14.1	16.4	18.8
14	9.6	12.1	14.5	16.9	19.3
15	9.9	12.4	14.9	17.3	19.7
16	10.1	12.7	15.2	17.7	20.1
17	10.4	13.0	15.6	18.1	20.5
18	10.6	13.3	15.9	18.4	20.9
19	10.9	13.6	16.2	18.8	21.3
20	11.1	13.8	16.5	19.1	21.6

Stand volume given stocking and height

Height m.	Stocking *(N/ha)* 494	625	816	1111	1600	2500	4444
	Stand total volume overbark, m3/ha						
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.1	0.1	0.1	0.1	0.2	0.3
3	0.2	0.2	0.3	0.3	0.5	0.6	1.0
4	0.5	0.6	0.7	0.9	1.2	1.7	2.6
5	1.0	1.2	1.5	1.9	2.5	3.5	5.5
6	1.8	2.1	2.7	3.4	4.5	6.4	10.0
7	3.0	3.6	4.4	5.6	7.5	10.6	16.7
8	4.6	5.6	6.8	8.7	11.6	16.5	26.0
9	6.8	8.2	10.1	12.9	17.1	24.4	38.3
10	9.6	11.6	14.3	18.2	24.3	34.5	54.2
11	13.2	15.9	19.6	25.0	33.2	47.2	74.2
12	17.6	21.2	26.1	33.3	44.3	62.9	98.9
13	22.9	27.5	34.0	43.3	57.7	81.9	111.3
14	29.2	35.2	43.4	55.3	73.7	104.6	119.9
15	36.7	44.2	54.5	69.4	92.5	131.4	128.4
16	45.4	54.6	67.4	85.9	114.4	162.5	137.0
17	55.5	66.7	82.3	104.9	139.8	176.6	145.6
18	67.0	80.6	99.4	126.7	168.8	186.9	154.1
19	80.0	96.3	118.8	151.4	201.7	197.3	162.7
20	94.8	114.1	140.7	179.3	238.9	207.7	171.2

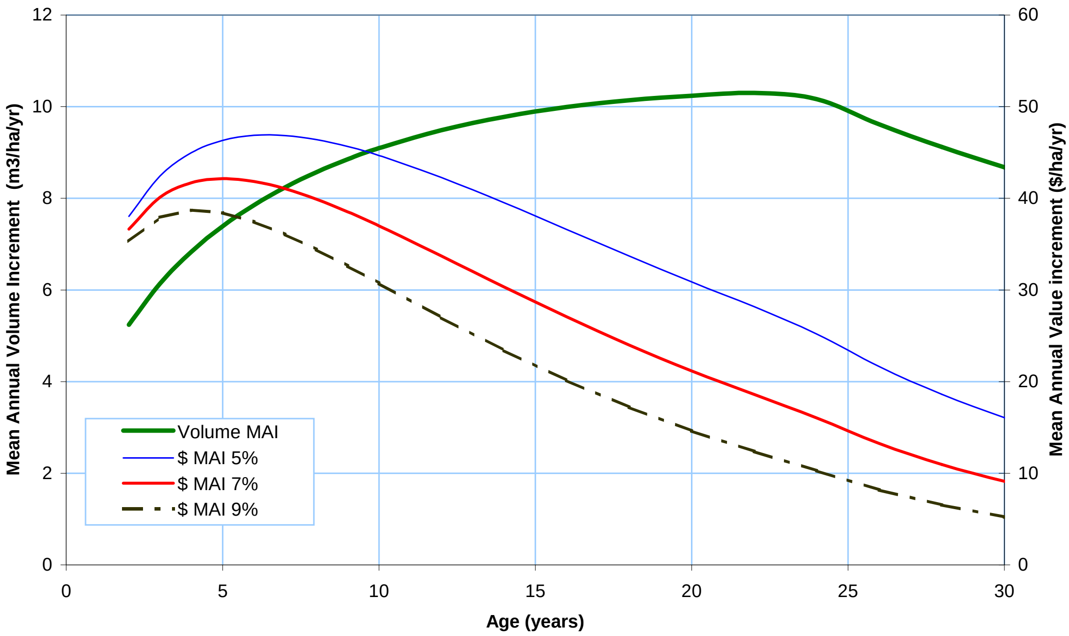
self-thinning limits volume

Optimal rotation

Figure 6 shows that optimum rotation is sensitive to site index, but not to stocking, except at higher densities where self-thinning occurs. Maximum MAI occurs at ages from 20 to 25 years, longer for lower site indices. For an established, normal plantation (one with equal areas in each age class) the rotation of maximum MAI is also the one which maximizes total production.

However, the rotation which maximizes the discounted net worth (DNW) of the plantation will be shorter than that of maximum MAI, and will depend on interest rate. The workbook *YieldModels.xls* contains a model of this situation on sheet *OptFR*, which can be used to compare the baseline technical rotation (0% interest) with that for other interest rates. Figure 7 below illustrates results for 5%, 7% and 9% interest rates, assuming site index 13, a stocking of 1600 trees/ha, and a wood value of $8 per m^3.

Figure 7 Comparison of optimum financial rotations at 5%, 7% and 9% interest rates
for site index 13, established at 1600 trees/ha



The solid green line is for volume MAI, read from the left axis. This peaks at 22 years for site index 13, at about 10 m^3/ha/year. When the value increment is considered, calculated as discounted worth at the time of planting, optimum rotation is much shorter, and depends sensitively on interest rate. At 5% interest, optimum rotation is 7 years; at 7%, it is 5 years, and at 9% it is 4 years. Optimum rotation does not depend on stumpage, although this is of course critical to the profitability of the plantation.

It should also be noted that this analysis is for a fully stocked stand at 1600 stems per ha. Lower stocking produces proportionately lower yields and net worth, but do not result in a change in rotation except for very dense stands which are undergoing self-thinning. The model on the sheet *OptFR* in *YieldModels.xls* can be used to explore the effect of different site index value and stockings.

Project area and volume

Planned project areas

Provisional total project areas reported as planted with *Eucalyptus camaldulensis* are shown in Table 4. They are shown in the Excel workbook *InventoryAnalysis.xls*, sheet *InvSum* as table A. At the time of writing these figures remain subject to revision, but the calculations in *InventoryAnalysis.xls* will cascade through and update automatically if these figures are changed.

Table 4 Total reported Eucalyptus plantings based on farmers loan application data

PROVINCE	1997	1998	1999	2000	2001	TOTAL
Bolikhamxay	105	98	118	152	220	691
Champassak		37	174	258	26	495
Salavan		6	109	35	101	251
Savannakhet	157	145	301	200	49	850
Vientiane Municipality	57	30	183	37	73	380
Vientiane Province	99	84	275	208	64	730
TOTAL	417	399	1160	889	533	3,398

Inventory sample areas

The provinces and age classes sampled in the inventory are summarised below in Tables 5a and b (these are tables B and C on worksheet *InvSum*). Table 5a shows the reported (planned) area in the loan application. Table 5b shows the areas established on the ground, as measured by GPS.

Table 5a : Planned areas included in the inventory sample, ha

PROVINCE	1997	1998	1999	2000	2001	TOTAL
Bolikhamxay		4.5	10.3	20.8	19.7	55.3
Champassak		6.4	7.5	19.0		32.9
Salavan		2.8	4.2	3.0	3.0	13.0
Savannakhet	8.5	6.5	6.0	5.0		26.0
Vientiane Municipality			2.0			2.0
Vientiane Province			10.0	8.5	5.5	24.0
TOTAL	8.5	20.2	40.0	56.3	28.2	153.2

Table 5b : Actual area of the same plantations as measured by GPS, ha

PROVINCE	1997	1998	1999	2000	2001	TOTAL
Bolikhamxay		3.2	6.4	4.8	11.0	25.3
Champassak		3.4	3.2	4.5		11.1
Salavan		1.4	1.9	1.8	3.8	8.9
Savannakhet	3.7	6.0	2.5	5.4		17.6
Vientiane Municipality			2.0			2.0
Vientiane Province			5.7	2.2	5.2	13.2
TOTAL	3.7	14.0	21.7	18.7	20.0	78.1

Areas lost to prior felling or plantation failure

Clearly, the inventory plots represent a biased sample, in a technical statistical sense, in that they can only be laid out in plantations which exist. In order to extrapolate inventory results to the whole area, it is necessary to know what proportion of the originally planned areas were lost before the inventory as a result of prior harvesting or due to termites, disease, unsuitable soils, fire or other mortality factors.

A planning schedule for the inventory was available to the consultant, which shows plantations not inventoried because of these various causes. Unfortunately, this schedule was not a complete list of all inventoried areas, but it is sufficient to provide a reasonable basis for estimation. It is included in the *InventoryAnalysis.xls* workbook as sheet *Schedule.* From this, Table 6 summarises proportion of established areas remaining intact at the time of inventory. Province-planting year combinations occurring in Table 4 above but not present in this summary were interpolated using the overall average value, shown as shaded yellow cells.

Table 6 : Proportion of surviving plantations
(based on actually established areas, interpolations shaded in yellow)

PROVINCE	1997	1998	1999	2000	2001	TOTAL
Bolikhamxay	62%	39%	37%	88%	67%	60%
Champassak		60%	37%	83%	62%	62%
Salavan		67%	74%	27%	24%	42%
Savannakhet	62%	100%	64%	100%	62%	87%
Vientiane Municipality	62%	62%	13%	62%	62%	13%
Vientiane Province	62%	62%	59%	49%	52%	55%
TOTAL	62%	73%	47%	80%	55%	62%

Reasons for areas being lost included prior felling, amounting to some 36% of the losses, and silvicultural failures (64%) mainly due to termites and wood caterpillars, but with fire, poor maintenance, and stony ground also commonly cited. Applying these ratios to the above average rate of loss, it is estimated that 21% of all established plantations were lost due to silvicultural failure, of which termites was probably the single most important factor (see summary Table 11).

Estimated actual areas

Taking into account the ratios between planned and established areas on the plantations sampled, as measured by GPS (Table 5), and the proportion of planned area lost prior to the inventory (Table 6), it is possible to derive multipliers for the originally planned areas (Table 5) to provided estimates of the actual areas still remaining. These are shown in Table 7.

Table 7 : Actual plantation areas remaining in 2006, by planting year, ha

PROVINCE	1997	1998	1999	2000	2001	TOTAL
Bolikhamxay	33	27	27	31	82	199
Champassak		12	27	51	8	97
Salavan		2	37	6	31	75
Savannakhet	42	134	80	215	15	487
Vientiane Municipality	18	9	23	12	23	85
Vientiane Province	31	27	93	26	32	209
TOTAL	125	211	287	340	191	1,153

Estimated standing volume

Standing volume per ha, as measured directly in the inventory, are summarised in Table 8 to give weighted means by province and age class. Additionally, for those provinces not sampled directly, the yield model described on page 5 *ff* has been used to estimate mean volume/ha. These cells are shown shaded in yellow. Mean site index and stocking values

Table 8 : Standing volume from the inventory (m^3/ha)

Yellow shaded values are interpolated from the yield model using province mean site index and stocking

PROVINCE	1997	1998	1999	2000	2001	Mean SI	Mean N/ha
Bolikhamxay	34	27	18	28	19	11	1,188
Champassak		28	70	28	18	11	1,234
Salavan		54	15	19	6	9	1,032
Savannakhet	24	62	35	52	30	12	1,902
Vientiane Municipality	37	32	35	21	17	11	1,125
Vientiane Province	42	36	32	20	22	11	1,220

used to estimate these volumes are shown for each province at the right of the table. Multiplying the per ha volumes in Table 8 by the actual plantation areas in Table 7 gives the total standing volume shown in Table 9 for the project as a whole.

Table 9 : Total standing volumes for Eucalyptus camaldulensis in the project area

All volumes in m^3, overbark, to a 2-cm top diameter measurement limit

PROVINCE	1997	1998	1999	2000	2001	TOTAL
Bolikhamxay	1139	715	488	858	1,561	4,761
Champassak	0	330	1870	1419	149	3,768
Salavan	0	107	549	106	177	939
Savannakhet	996	8352	2793	11204	466	23,811
Vientiane Municipality	673	302	819	251	384	2,429
Vientiane Province	1320	959	2964	524	704	6,470
TOTAL	4128	10765	9482	14361	3442	42,178

Table 10 : Districts ranked by site index, as an indicator of suitability for *E. camaldulensis*

		Inventory sample		*Productivity*	
Province	**District**	**Plots**	**Area**	**SI**	**MAI15**
Savannakhet	Champhone	2	0.42	16.3	17.0
Salavan	Lao Ngaam	1	0.20	15.4	7.4
Champassak	Phonthong	1	0.10	15.2	11.0
Champassak	Bachieng	15	3.05	15.2	11.3
Savannakhet	Xayphouthong	2	0.74	13.5	8.9
Salavan	Khongxedon	6	0.80	13.3	10.5
Vientiane Province	Keo Oudom	8	2.50	13.2	8.1
Savannakhet	Outhomphone	3	2.08	13.0	11.7
Vientiane Province	Thoulakhom	17	5.40	12.1	5.4
Bolikhamxay	Thaphabaath	59	15.34	11.4	4.9
Vientiane Municipality	Xaythany	8	2.02	11.2	4.8
Savannakhet	Xaiphouthong	4	0.28	10.7	9.2
Bolikhamxay	Bolikhan	16	3.17	10.3	4.4
Savannakhet	Champone	4	0.84	10.1	3.4
Champassak	Pathoumphone	39	5.65	10.0	4.3
Vientiane Province	Phonhong	24	4.72	9.7	4.2
Savannakhet	Kaisone	15	2.38	9.6	4.3
Bolikhamxay	Paksan	21	4.53	9.4	3.5
Salavan	Salavan	40	7.87	8.7	2.3
Savannakhet	Xaybouly	5	0.89	8.7	2.5
Champassak	Xanasomboune	16	2.29	8.7	3.2
Savannakhet	Khanthabouly	2	0.00	0.0	0.0

Site suitability

Table 10 shows the inventory data summarised by districts within provinces, with number of inventory plots, area of plantation inventoried, mean site index of plots, and estimated mean annual increment at age 15, in m^3/ha/yr (MAI_{15}). Number of plots and inventory area are indicators of data reliability and robustness, whilst site index and MAI_{15} are indicators of productivity and suitability for planting in those districts. The districts are ranked from best to worst in terms of site index.

It should be desirable to investigate what environmental factors predispose to a more favourable performance of *E. camaldulensis*. The consultant would suggest that it should really be seen as unsuitable for planting in areas where the site index is likely to be below 13, as single figure MAI_{15}'s are unlikely to be economic on any criterion.

Conclusions and recommendations

Main conclusions

From a planned area 3,398 ha of *Eucalyptus camaldulensis* plantations, it is estimated that **1,153 ha** have been successfully established and remain fully stocked at the time of inventory (2006). The total standing volume is estimated at **42,178 m^3**. It is estimated that only 51% of the planned area was actually established on the ground (see table 11). The reasons for this should if possible be identified in order to guide future projects, but it seems probable that actual input costs were higher than anticipated, so that smaller areas were established by growers than were anticipated.

Of this established area of 1,732 ha, some 33% was lost before the 2006 inventory. The losses are estimated from partial lists of scheduled inventory areas and may require refinement with updated information. They appear to comprise 21% which failed for silvicultural reasons, of which the most common was termites, and 12% which were harvested prior to inventory. Losses totalled 579 ha. This leaves the currently extant area of 1,153 ha.

Table 11 : Area summary for the inventory

	ha			
Planned area	**3,398**			
Established area	1,732		*51%*	*of area stated as planned that was planted*
Losses prior to inventory	579		*33%*	*of area planted that was lost prior to inventory*
of which		*ha*		
termites, fire etc.		371	*21%*	*of planted area lost due to silvicultural factors*
harvesting		209	*12%*	*of planted area harvested prior to inventory*
Net area at inventory	**1,153**		*67%*	*of actual established area*

Growth rates are mostly quite low, with a **mean MAI of 5.1 m^3/ha/yr**, although on fully stocked stands on the better sites, yields above 10 m^3/ha/yr are being achieved. As noted above, the inventory also showed a relatively high failure rate at or after establishment, with termites being a commonly cited cause, although not the only one.

Yield models for the plantations have been produced from the inventory data. Site index curves adapted from India, based on the work of Tewari (2002) appear suitable as a provisional basis. Site index curves are shown in the report as a graph and table, using age 7 as a base age, and Lorey's height as the measure of stand height.

A yield function based on the inventory data itself has also been developed. From this work it has been possible to examine potential rotations, and undertake a site classification of all the villages in the survey. It should be possible to use this as the basis for a site suitability guide that will focus planting of the species in the most appropriate localities.

From the yield models, it is clear that the optimum technical rotation (maximum MAI volume) is from 25 to 35 years, being shorter on the better sites, and longer on the poorer ones. However, the optimum financial rotation is shorter, and depends on the interest rate applied. At 5% interest, it is about 6-7 years. At 1½ %, it is 13-15 years.

Recommendations

- Site selection and good extension support are critical to successful establishment and good yields. **The information and tools provided in this report should be applied to developing a practical set of site selection guidelines**. *Eucalyptus camaldulensis* should not be planted on unsuitable sites.
- Inventory methods used in this study could be improved. Measuring all trees for height is relatively costly, and is unnecessary. Only a sub-sample of trees should be measured for height. Small square plots are more likely to be biased and suffer edge effects than larger circular ones. **The consultant recommends a review of inventory techniques and mensurational standards if any major new inventory is planned**.
- Project monitoring systems have also clearly been somewhat fragmented. It has been difficult to establish clearly total planted areas, factors causing losses, inventory sampling framework and so on. **Future projects should give stronger attention to the information system for project monitoring, evaluation and control at the outset**, to ensure that it uses good relational database design and software, with links to GIS capability, is well-integrated, whilst remaining robust and appropriate to the circumstances. Forms, indicators and criteria need to be better designed to enhance quantification, classification, and analysis, rather than relying on wordy questionnaires that are very difficult to evaluate and of little use for monitoring.

Notwithstanding the above points, the consultant feels that the inventory work and the associated plantation project have clearly been conducted with the highest degree of professionalism, which will certainly contribute to further successful outcomes in the forestry sector in the future.

References

Alder, D (1980) Forest Volume Estimation and Yield Prediction : Vol. 2 – Yield Prediction. *FAO Forestry paper* 22/2. 194 pp.

Alder, D; Drichi, P; Elungat, D (2003) Yields of Eucalyptus and Caribbean Pine in Uganda. Uganda Forest Resources Management and Conservation Programme, Technical report, 52 pp.

Payandeh, B; Wang, Y (1994) Relative accuracy of a new base-age invariant site index model. *Forest Science* (40) 341-348.

Tewari, VP (2007) Stand density and basal area prediction of unthinned irrigated plantations of *Eucalyptus camaldulensis* in the hot desert of India. *Bioresource Technology* 98 (5) 1106-1114.

Tewari, VP; Verma, A; Kishan Kumar, VS (2002) Growth and yield functions for irrigated plantations of *Eucalyptus camaldulensis* in the hot desert of India. *Bioresource Technology* 85(2) 137-146.

Zeide, B (1987) Analysis of the 3/2 power law of self-thinning. *Forest Science* 33(2)517-537.