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OPTIMUM ROTATION FOR *EUCALYPTUS CAMALDULENSIS DEHNH.* IN NORTHEAST THAILAND

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ABSTRACT

Based on dominant height/age relationship of *Eucalyptus camaldulensis* Dehnh. in Northeast Thailand, and on earlier stand models of eucalypts in Ethiopia, provisional yield tables for Northeast Thailand were prepared. Dominant height growth in Thai lowlands is fast for the first 10 years and notably slower thereafter. For the maximum mean annual volume increment the optimum rotation is about 10 years for fully stocked plantations and about 12 years for the commonly used spacing of 3 x 3 and 2 x 4 meters. Continuing the rotation from 5 to 10-12 years may increase the annual timber supply from the plantations by 30-50 %. Denser village woodlots (2 x 2 m spacing) may be harvested about two years earlier than the industrial (3 x 3 or 2 x 4 m) plantations, for the same volume production.

INTRODUCTION

Determination of the optimum rotation length is a central task in the growth and yield studies of plantation forests. Usually the plantation forests, like for *Eucalyptus camaldulensis* Dehnh. in Thailand, are grown at regular spacing with rather short rotations, just to maximize the pulp fibre yield. As thinnings are not needed in pulp fibre production, optimization of rotation length leads to studying the Mean Annual Increment (MAI) and Current Annual Increment (CAI) curves. For a particular spacing, the optimum rotation with respect to wood yield is defined by the maximum of the MAI curve.

The growth models needed for the determination of the MAI and CAI curves, and for the preparation of yield tables, are commonly based on the relationship between dominant height (mean height of 100 largest trees per hectare) and stand age (e.g. Stage, 1963; Bailey and Clutter, 1974). The dominant height at a certain age is an indicator of site quality.

The dominant height has not been regularly determined in the growth and yield studies of *Eucalyptus camaldulensis* in Thailand. The mean stand height, which is usually measured routinely, cannot be directly used as a site quality indicator, as it is much affected by small trees, the number of which varies rather broadly according to stand density and silvicultural operations. To establish a firm base for growth and yield studies, as well as for site classification in Thailand, additional studies on the relationship between stand age and dominant height of *Eucalyptus camaldulensis* are needed.

The reference rotation for *Eucalyptus camaldulensis* in Thailand, at which the yield and profitability calculations are done, is usually 5 years (e.g. Jeeranantasin, 1987). Five years' rotation is also commonly used for village woodlots. This rotation length is based on various field trials, but not necessarily on careful scientific analyses. Economically optimal rotations, taking into account the costs, benefits and the rate of interest, tend to be shorter than the biological optimum (e.g. Pohjonen and Pukkala, 1988). Satitwibon (1985) concluded that, for Thailand, the optimum rotation in agro-

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forestry systems, with fuelwood as the main product, would be as short as 3 years.

The optimum rotation for pulp fibre from eucalypts is also affected by the fibre quality, which depends on the volume ratio of bark, sapwood and heartwood. Based on the analysis of fibre yield on one hand, and fibre dimension, the sulphate pulping process and chemical consumption in bleaching, on the other hand, Rativanich *et al.* (1987) concluded that an appropriate rotation for pulp production of *Eucalyptus camaldulensis* should be 3-6 years rather than 10-15 years.

The purpose of this study was to reassess the optimum rotation for *Eucalyptus camaldulensis* in Northeast Thailand. The assessment was based on studying the relationship between stand age and dominant height in the existing plantations. This relationship was amalgamated with previously prepared stand models for Ethiopian highland eucalypts (including *Eucalyptus camaldulensis*) (Pukkala and Pohjonen, 1989*b*). The models were used to simulate provisional yield tables for industrial and village woodlot plantations.

MATERIAL

For the analysis of dominant height/age relationship in *Eucalyptus camaldulensis* plantations, 15 sample plots were measured in Northeast Thailand (Table 1). Most of the plots belonged to the reforestation programme of the Forest Industry Organization. One of the plots (number 6) was a village woodlot plantation established at the school of Ummao village (between Kalasin and Ubon Ratchathani). Another plot (number 3) belonged to the demonstration farm of Phoenix Pulp & Paper Co. in Khon Kaen.

The *Eucalyptus* plantations in Northeast Thailand had earlier been established at a spacing of 2 x 8 meters (plots 2, 5, 8, 10 and 13 in the material), as a part of the Forest Village Agroforestry Programme (Mehl, 1990). The cash crop in the alleys, over the first 1-3 years after planting, was either cassava or sesame. Later plantings had been established at a spacing of 3 x 3 or 2 x 4 meters, as for plots 1, 4, 7, 12, 14 and 15 in the material.

In all plantations, a sample plot was delineated inside the stand, by measuring the trees over a certain length along the regularly spaced rows. Every tree was tallied to an accuracy of 1 mm. Altogether 17 sample trees (breast height diameter from 1.7 to 32.6 cm, height from 2.7 to 26.5 m) were measured to find the dependence of tree height on diameter (Pukkala and Pohjonen, 1988*a*). The Nalsund's (1936) height curve was used to describe this relationship :

$$h = 1.3 + d^2 / (a + db)^2$$

where h = height (m), d = diameter at 1.3 m level (cm), and a and b are coefficients ($a = 1.54$, $b = 0.16$).

The resulting model was used for calculating the tree height in each diameter class. The estimated heights were used for calculating the mean height (H_n) and dominant height (H_{dom}) of the plot. For the determination of stem volume, Örlander's (1986) formula for *Eucalyptus camaldulensis* was used.

RESULTS

Development of dominant height

The relationship between age (T) and dominant height was determined from the data in Table 1 (Figure 1). Plot number 13 was excluded from this analysis because it was growing on an exceptionally rocky site, far poorer than the majority of the current *Eucalyptus* plantations in the Northeast.

A declining exponential curve (Mitscherlich, 1919) (Equation 2) was fitted to the data. The degree of determination (R^2) of the fitting was 74.5 %.

$$H_{dom} = 25.5 (1-e^{(0.169 T)})$$

Table 1. Stand characteristics in the *Eucalyptus camaldulensis* sample plots measured in Northeast Thailand. (Stock = number of stems per hectares; basal area = stand basal area, m^2/ha)

No, Site	Age (years)	H_{dom} (m)	Ave D (cm)	Stock. (stem/ha)	Basal area (m^2 /ha)	Volume m^3 /ha	MAI m^3 /ha/a
1 Manjak	1.8	9.5	5.40	1061	2.6	10.0	5.56
2 Manjak	9.0	17.1	10.10	575	5.4	34.0	3.78
3 Khon K	7.0	19.6	13.10	1167	16.9	114.0	16.29
4 Somdet	12.0	23.9	18.30	1022	29.5	231.0	19.25
5 Somdet	7.0	17.7	14.30	556	9.1	62.0	8.86
6 Ummao	7.0	13.8	6.20	2319	8.5	40.0	5.71
7 Pibulm	5.0	16.3	11.40	969	10.5	65.0	13.00
8 Pibulm	13.0	21.9	16.70	564	13.6	103.0	7.92
9 Pibulm	2.0	4.7	2.10	2500	1.0	2.0	1.00
10 Khunha	4.0	17.4	12.90	625	8.6	57.0	14.25
11 Buri R	3.0	11.7	7.70	918	4.6	23.0	7.67
12 Buri R	7.0	15.9	11.50	1159	12.4	76.0	10.86
13 Dankhu	12.0	15.8	10.10	387	3.5	21.0	1.75
14 Dankhu	6.0	12.2	6.40	885	3.2	15.0	2.50
15 Dankhu	3.0	7.6	3.50	959	1.2	4.0	1.33

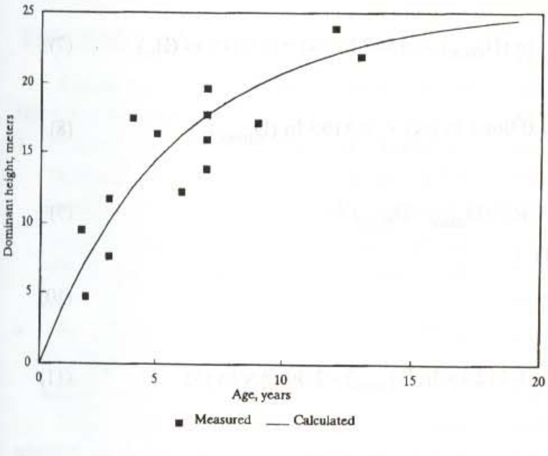

Figure 1. Dominant height/age relationship in the *Eucalyptus camaldulensis* sample plots measured in Northeast Thailand.

The dominant height approaches asymptoticaly the upper limit of 25.5 m as the stand approaches full maturity. Equation 2 can be regarded as a provisional guide curve for the dominant height/age relationship. In this study, it was used in the preparation of yield tables for average plantation sites of *Eucalyptus camaldulensis* in Northeast Thailand.

Simulation of growth and yield

The method of predicting the growth of *Eucalyptus camaldulensis*, and consequently constructing the provisional yield tables, was based on the prediction of the gradual change in the diameter distribution over time. Using the allometric relationships of the stand characteristics, the diameter distribution can be calculated from stand age and dominant height. From the diameter distribution it is possible to derive all the stand characteristics needed in the yield tables (Pukkala and Pohjonen, 1989*a*).

The beta function was used for estimating the distribution of stems into different diameter classes (Loetsch *et al.* 1973) :

$$f(d) = c\,(d-D_{min})^{A}\,(D_{max}-d)^{B}$$

where f (d) is frequency of diameter d, D_{min} is the minimum, D_{max} the maximum of the diameter distribution, and c is a scaling factor to obtain a specified total number of stems. A and B are constants that can be calculated from the mean and variance of diameter (Loetsch *et al.*, 1973).

The diameter distribution for the simulation of growth was computed through the following sequence of equations (Equations. 2-9), originally constructed for Ethiopian highland *Eucalyptus* plantations (combined modelling of *Eucalyptus globulus*, *E. camaldulensis*, *E. saligna* and *E. grandis*, see Pukkala and Pohjonen, 1989*b*) :

Stocking (N) :

$$\ln(N) = 7.7080 - 0.0317T - 0.0694\ \ln(H_{dom}) \quad (4)$$

Mean height (H_n) :

$$\ln(H_n) = -0.0727 - 0.0041 + 1.201\ \ln(H_{dom}) - 0.0658\ \ln(N) \quad (5)$$

Mean diameter (D_n) :

$$\ln(D_n) = 1.7470 + 0.1509\ \ln(T) - 0.2716\ \ln(H_{dom}) - 0.1567 \times \ln(N) \quad (6)$$

Maximum diameter (D_{max}) :

$$D_{max} = 1.4008 + 0.0171T + 0.3975\ \ln(H_{dom}) - 0.1567\ \ln(N) + 0.9019\ \ln(H_n) \quad (7)$$

Minimum diameter (D_{min}) :

$$D_{min} = 1.9940 + 1.4133\ \ln(H_{dom}) - 0.0661\ \ln(N) + 0.3195\ \ln(D_{max}) \quad (8)$$

Variance of diameter (VAR) :

$$VAR = -0.9674 + 0.2009H_{dom} + 0.0467\ (D_{max} - D_{min})^2 \quad (9)$$

Parameter *b* of the height curve (Equation 1) :

$$\ln(b) = -0.2862 - 0.4788\ \ln(H_{dom}) \quad (10)$$

Parameter a of the height curve :

$$\ln(a) = -1.0461 + 0.2124\ \ln(T) - 1.1129 \times \ln(H_{dom}) - 2.3013 \times \ln(b) \quad (11)$$

Equations 4 to 11 follow a logical sequence. The basic information comes from the age (T) and dominant height (H_{dom}) of the plantation. Finally, all the necessary stand characteristics will become known.

In the simulation, 20 sample trees at equal intervals between D_{min} and D_{max} were sampled from the simulated distribution to represent the stand. Each sample tree was described by diameter, height, stem volume, and number of trees per hectare. The stand characteristics for the yield tables were computed from this theoretical tree population.

To test the applicability of the Ethiopian models in Thailand, stand volumes, computed through the beta distribution that was predicted from H_{dom}, T, and N, were compared to the measured volumes (Figure 2). The correlation between the measured and

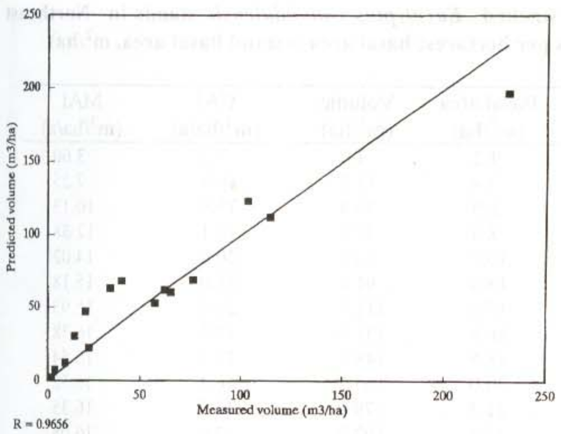

Figure 2. Correlation between the measured stand volume and the volume predicted with the models 1-11 for the sample plots measured in Northeast Thailand.

calculated volumes was 0.966 which means that the Ethiopian models quite well describe the allometric relationships among stand characteristics in Thailand 's *Eucalyptus camaldulensis* plantations.

Yield tables

Calculation of the tables was based on the following assumptions :

- In average site conditions of Northeast Thailand the dominant height/age relationship of average *Eucalyptus camaldulensis* plantations, follows Equation 2, which has been determined in the local conditions.
- The allometric relationships in planted *Eucalyptus* forests are similar in Thailand and in Ethiopia.

Table 2 shows a yield table for fully stocked plantations. The plantation is regarded fully stocked if it, after the establishment phase, has an initial density of over 2,000 trees per hectare. This spacing is normally produced by planting spacing of 2 x 2 meters (2,500 seedlings per hectare), followed by some initial mortality. In Thai plantations of fully stocked evenaged *Eucalyptus camaldulensis*, regular self-thinning due to competition is found (Thoranisorn *et al.* 1990). Sapling mortality rates similar to Ethiopian models are assumed here.

Table 3 shows data for mild understocking. The stands had been established at spacings of 3 x 3 meters or 2 x 4 meters. The initial stocking was therefore 1,111 or 1,250 trees per hectare, respectively. In the simulation, it was assumed that there was a slight seedling mortality at the planting; the initial density was reduced to 990 trees per hectare. Thereafter, no sapling mortality was assumed.

The rotation length that maximizes the yield from a forest plantation is defined by the maximum of the Mean Annual Increment curve. This is based on the assumption that there are no thinnings. The stand is harvested by clearcutting. The optimum rotation for a fully stocked plantation is 11 years (Figure 3). For the spacing of 3 x 3 meters, or 2 x 4 meters, the optimum rotation is 13 years (Figure 4).

DISCUSSION

According to this study the optimum rotation in stem biomass production for *Eucalyptus camaldulensis* in Northeast Thailand is 10-13 years. This is considerably longer than the generally applied 5 years. The

Table 2. Provisional yield table for fully stocked *Eucalyptus camaldulensis* stands in Northeast Thailand (Stock=- number of stems per hectares; basal area = stand basal area, m^2/ha)

Age (years)	H_{dom} (m)	Ave D (cm)	Stock. (stem/ha)	Basal area (m^2/ha)	Volume (m^3/ha)	CAI (m^3/ha/a)	MAI (m^3/ha/a)
1	5.5	2.62	1885	1.2	3.6	3.6	3.60
2	8.7	4.50	1808	3.4	14.5	10.9	7.25
3	11.2	6.07	1741	5.9	30.4	15.9	10.13
4	13.4	7.42	1680	8.4	49.5	19.1	12.38
5	15.1	8.60	1623	10.7	70.1	20.6	14.02
6	16.6	9.64	1568	13.0	91.1	21.0	15.18
7	17.9	10.58	1517	15.0	111.5	20.4	15.93
8	19.0	11.42	1564	16.9	131.0	19.5	16.38
9	20.0	12.18	1420	18.5	148.9	17.9	16.54
10	20.8	12.88	1375	20.0	165.2	16.3	16.52
11	21.5	13.52	1330	21.2	179.9	14.7	16.35
12	22.1	14.12	1288	22.4	192.9	13.0	16.08
13	22.5	14.67	1248	23.4	204.4	11.5	15.72
14	23.0	15.19	1208	24.2	214.5	10.1	15.32
15	23.3	15.68	1170	24.9	223.3	8.8	14.89
16	23.7	16.14	1133	25.6	230.8	7.5	14.43
17	23.9	16.58	1098	26.1	237.2	6.4	13.95
18	24.2	16.99	1063	26.6	242.7	5.5	13.48
19	24.4	17.40	1030	26.9	247.3	4.6	13.02
20	24.6	17.79	998	27.3	251.2	3.9	12.56

Table 3. Provisional yield table for fully stocked *Eucalyptus camaldulensis* stands in Northeast Thailand planted at spacing 3 x 3 m and 2 x 4 m. (Stock = number of stems per hectares; basal area = stand basal area, m^2/ha)

Age (years)	H_{dom} (m)	Ave D (cm)	Stock. (stem/ha)	Basal area (m^2/ha)	Volume (m^3/ha)	CAI (m^3/ha/a)	MAI (m^3/ha/a)
1	5.5	3.18	990	0.9	2.8	2.8	2.76
2	8.6	5.34	990	2.5	10.8	8.1	5.41
3	11.2	7.09	990	4.4	23.0	12.2	7.67
4	13.3	8.57	990	6.4	38.1	15.1	9.52
5	15.1	9.83	990	8.4	54.9	16.8	10.98
6	16.7	10.92	990	10.3	72.6	17.7	12.10
7	18.0	11.86	990	12.1	90.45	17.8	12.91
8	19.1	12.69	990	13.8	107.9	17.5	13.48
9	20.0	13.42	990	15.4	124.7	16.8	13.85
10	20.8	14.07	990	16.9	140.6	16.0	14.06
11	21.5	14.64	990	18.3	155.6	15.0	14.14
12	22.0	15.15	990	19.6	169.6	14.0	14.13
13	22.5	15.61	990	20.8	182.5	13.0	14.04
14	23.0	16.02	990	21.9	194.6	12.0	13.90
15	23.3	16.39	990	22.9	205.7	11.1	13.71
16	23.7	16.73	990	23.9	216.0	10.3	13.50
17	23.9	17.04	990	24.8	225.5	9.5	13.27
18	24.2	17.32	990	25.6	234.4	8.9	13.02
19	24.4	17.58	990	26.4	242.6	8.2	12.77
20	24.6	17.82	990	27.2	250.3	7.7	12.51

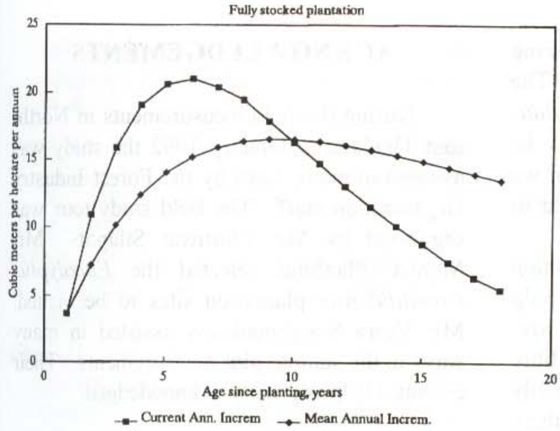

Figure 3. Development of current annual increment and mean annual increment for fully stocked *Eucalyptus camaldulensis* plantations in Northeast Thailand.

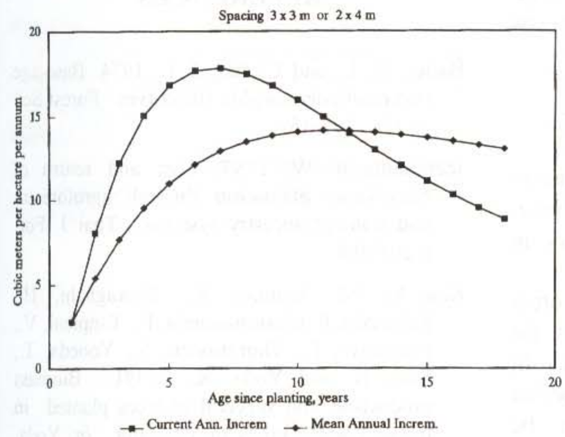

Figure 4. Development of current annual increment for *Eucalyptus camaldulensis* plantations in Northeast Thailand, planted at spacing of 3 x 3 meters or 2 x 4 meters.

growth rate of dominant height slows down earlier than, for instance, in Ethiopia, but the trees continue their diameter growth. The course of diameter growth has been recorded also in a comprehensive study of Kanzaki *et al.* (1991).

The optimum rotation for *Eucalyptus* in the Ethiopian highlands, determined using the same techniques as in this study, is 14 to 21 years, depending on the site class (Pukkala and Pohjonen, 1989*b*). If economic optimum is sought for and various levels of interest rate are used, the optimum rotation is between 12 to 20 years for seedling rotations and between 8 to 16 years for coppice rotations (Pohjonen and Pukkala, 1988).

In Aracruz Floresta, Brazil, the optimum rotation for *Eucalyptus* is only 7 years. In Aracruz, however, the height growth is 5 times faster than in Thailand and the growth results are not directly comparable. Experience for shorter *Eucalyptus* rotations can also be found in Kenya. Shriver and Brister (1992) studied the growth of *Eucalyptus saligna* in western Kenya and found that the mean annual increment is maximized in various site classes between 5-6 years.

The growth results of this study are more comparable to Ethiopian than to Brasilian or Kenyan results. Even if the results are still provisional and should be verified at larger scale and over longer periods in the field, there is no justification from a mere biomass production point of view, to apply rotations shorter than 10 years.

Higher pulp fibre quality of the young plantations may justify shorter rotations. The Thai finding that young *Eucalyptus camaldulensis* trees yield better pulp should now be related to the yield level. How much can we allow the quantity of the pulp fibre yield to drop for the improved pulp quality ?

The matter of fibre quality is a function of tree size rather than tree age. If the pulp fibre quality can be related to tree size, oversized logs are culled out from the fibre market. This, however, will not necessarily shorten the optimum rotation time, as there are other uses for the large *Eucalyptus* logs, for instance poles, lumber and a future saw milling industry.

CONCLUSIONS

The provisional yield tables give raise to the following practical conclusions for *Eucalyptus camaldulensis* plantation forestry in Northeast Thailand :

- The rotation time of 5 years often recommended is obviously too short for the maximum pulp fibre production. In the applied spacing of about 1,000 trees/ha the mean annual increment can be increased from 9 to 13.5 m^3/ha, by increasing the rotation from 5 to 12 years. The productivity would increase by 35 %.
- The denser the stand, the shorter the rotation. The difference in the optimum rotation time between 2 x 2 spacing and 3 x 3 (or 2 x 4) spacing is about 2 years in favour of the denser planting.
- The denser the stand, the higher the pulp fibre yield. The difference in the maximum mean annual increment is about 2 m^3/ha, in favour of the denser planting.
- In alley cropping applications of *Eucalyptus* agroforestry, where a spacing of 2 x 4 meters is applied, a rise of one year in the rotation, for the common 5 years to 6 years, would raise the wood productivity by 1.4 m^3/ha/a, or by 15 %.

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