OPTIMIZING MANAGEMENT OF EVEN-AGED TEAK STANDS USING GROWTH SIMULATION MODEL: A CASE STUDY IN KERALA

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JAYARAMAN, K. & RUGMINI, P. 2008. Optimizing management of even-aged teak stands using growth simulation model: a case study in Kerala. A growth simulation model was developed for even-aged teak stands to derive optimal density management plans. The optimal rotation age and effects of understorey species on the growth of teak were ascertained. The growth model consisted of five modules, i.e. effects of site index, unrestrained growth, ageing, density of teak and density of miscellaneous species. The model was calibrated based on data gathered from 69 permanent sample plots established in teak plantations in Kerala, India. A model was developed in order to identify the optimum density trajectory that maximized the net present value (NPV) of cash flows. Optimum density regimes were worked out for different interest rates in all the site quality classes, with and without miscellaneous species (understorey) in the stands. The relative initial density that maximized the NPV varied from 0.41 for site quality I to 0.21 for site quality IV regardless of interest rate. The rate of increase in initial density required for attaining the optimum was 3% every five years. For any particular interest rate, the optimal rotation age remained the same under all site quality classes. However, the optimal rotation age changed from 65 to 40 years as the interest rate changed from 2 to 5%. Understorey species in teak plantations had a significant effect on the growth of teak trees. The percentage increase due to the absence of miscellaneous growth was about 16% for crop diameter and 23% for mean annual increment of volume over a rotation period. Consequently, there was an increase of 56% in NPV for all the site quality and interest levels.

Keywords: Rotation age, index of self tolerance, density

JAYARAMAN, K. & RUGMINI, P. 2008. Mengoptimumkan pengurusan dirian pokok jati yang sama usia menggunakan model simulasi pertumbuhan: kajian kes di Kerala. Satu model simulasi dibangunkan untuk pokok jati berusia sama untuk merancang pengurusan kepadatan yang optimum. Usia giliran yang optimum dan kesan spesies tingkat bawah kanopi terhadap pertumbuhan pokok jati ditentukan. Model pertumbuhan terdiri daripada lima modul iaitu kesan-kesan indeks tapak, pertumbuhan tak dikawal, penuaan, kepadatan pokok jati dan kepadatan spesies beraneka. Model ditentu ukur berdasarkan data yang diperoleh daripada 69 plot sampel kekal yang didirikan di ladang-ladang pokok jati di Kerala, India. Model dibangunkan untuk menentukan lengkungan kepadatan yang optimum yang memaksimumkan nilai semasa bersih (NPV) bagi aliran tunai. Kepadatan optimum dikira untuk kadar faedah berlainan dalam semua kelas kualiti tapak, sama ada dengan atau tanpa spesies beraneka (spesies tingkat bawah kanopi) dalam dirian. Kepadatan awal relatif yang memaksimumkan NPV adalah antara 0.41 untuk kualiti tapak I hingga 0.21 untuk kualiti tapak IV tanpa mengira kadar faedah. Kadar pertambahan kepadatan awal yang diperlukan untuk mencapai nilai optimum ialah 3% setiap lima tahun. Usia giliran optimum kekal sama di bawah semua kelas kualiti tapak untuk sebarang kadar faedah. Bagaimanapun, usia giliran optimum berubah daripada 65 tahun ke 40 tahun apabila kadar faedah berubah daripada 2% ke 5%. Spesies tingkat bawah kanopi di ladang pokok jati mempengaruhi pertumbuhan pokok jati. Pertambahan peratusan disebabkan ketiadaan spesies beraneka adalah kira-kira 16% untuk diameter pokok jati dan 23% untuk purata pertambahan isi padu tahunan selepas suatu tempoh giliran. Terdapat pertambahan 56% dalam NPV untuk semua kualiti tapak dan kadar faedah.

INTRODUCTION

Control of stand density by initial spacing and subsequently by thinning helps to increase tree growth on a sustainable basis in forest plantations. Density is one of only a few things that we can control efficiently and often profitably. Consequently, relating growth and density is a principal problem in forestry. Particularly important is one special point of this relationship at which the output reaches maximum. Density at this point is called optimal density.

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Stand density management is important in teak plantations. It generates intermittent yields and also allows proper growing space for the residual stand. The basis of the current prescriptions in this regard in India is the All India Yield Tables for teak derived in 1959 (FRI 1970). However, information on optimal stand density management is lacking for teak.

Research on thinning in teak stands have been few. Perhaps the first of its kind, Hellinga (1939) made the following observations on natural thinning in unthinned teak plantations. The initial number of trees per hectare in plantations of different spacing varied from 2500 to 5000. After a period of 20 years, natural mortality had reduced these numbers to approximately 1300–1800 trees per hectare. At the same age, the better sites tended to grow relatively fewer trees than the poor sites. Yield studies of 21 teak sample plots, which were left unthinned since their establishment 20 years ago, showed that the mean basal area diameter was only 70 to 95% that of normally thinned plantations. The number of trees per ha was 50 to 250% more, and the total basal area per ha, 50 to 100% more than under normal conditions of thinning. The total tree volume per ha of unthinned plots was 20 to 80% more than that of the remaining stand and 5 to 25% less than the total tree volume of the total stand (remaining stand plus thinnings) of normally thinned plantations. There was very little difference (only 2 to 10%) in the weighted mean height of the thinned and unthinned plantations.

Khlail (1943) advocated delayed thinning in teak plantations by stating that heavy early thinnings are inadvisable for the following reasons, *viz.* (i) Teak responds well even to late thinnings, (ii) Opening up a young crop will cause trees to become branchy, (iii) Pruning would prove too expensive in teak plantations (iv) Weed growth can be kept suppressed only as long as the canopy is closed, (v) The thinnings of the first four years are too small to be merchantable, (vi) Heavy early opening of the crop may lead to storm damage among the young shallow-rooted trees thus exposed and(vii) Drastic opening of the canopy produces an exposure of site that may result in the conversion of good productive soil into hard, unproductive laterite.

Tint and Schneider (1980) reported dynamic growth and yield models for Burma teak. A computer simulation model in FORTRAN was developed for analysis of stand basal area and volume growth as functions of diameter class distribution and site class. Examples of output were presented, consisting of growth and yield tables for a natural teak selection forest in central Myanmar and for teak plantations, giving stand statistics, by 5-year age intervals, including mensurational and yield data for main crop and thinnings, mean annual increment and current annual increment.

Abayomi *et al.* (1985) reported results of analyses of variance of diameter and height increments of 12 teak thinning trials at six sites in Nigeria, comparing four treatments: no thinning and thinnings down to residual stockings of 800, 400 and 250 stems per ha. Diameter increment tended to increase with thinning intensity, while height increment and basal area were less affected by thinning treatment. It was recommended that teak plantations be thinned at ages 5, 10, 15 and 20 years to residual stockings of 800, 600, 400 and 300 stems respectively to produce a good stocking of large-sized timber stems by age 50–60 years.

Gonzales (1985) presented growth and yield prediction model for teak plantations in the Magat Experimental Forest in Philippines. Bermejo *et al.* (2004) reported yield tables for teak plantations in Costa Rica based on data from permanent sample plots in the region.

All past studies on the subject were related to how teak trees respond to either natural or artificial thinning in terms of physical characteristics but no economic studies were attempted. The density was expressed in terms of number or basal area, which were found to be inadequate measures by later workers (Zeide 2002). The need for more systematic studies on the topic led to the present investigation. The major objective of the study was to develop a growth simulation model for even-aged teak stands. The developed model was used to determine the optimal density to be maintained in teak plantations during different stages and also to develop guidelines on control of understorey growth and economic rotation age.

MATERIALS AND METHODS

Methodology

The study was conducted in the State of Kerala, India. The data were obtained from permanent sample plots laid out in teak plantations in different parts of the State. The plots were 50 × 50 m in size except for a few which were 20 × 20 m.

Altogether, there were 69 plots established and remeasured between 1993 and 2004 with an interval of two to four years. Girth at breast-height (1.37 m above ground) was recorded on all the trees in the plots. Height was measured on a sub-sample of less than 10 trees covering the range of diameters in each plot. Site index was calculated using the equation reported by Jayaraman (1998).

$$\ln S = \ln H - 7.41014\left(\frac{1}{A} - \frac{1}{50}\right) \tag{1}$$

where S = site index (top height at the base age of 50 years)
H = top height of the stand (m)
A = age of the stand (years)

Volume was computed using the volume prediction equation reconstructed from Chaturvedi (1973).

$$v = 9.175\,D^{2.235} \tag{2}$$

where v = volume of timber and smallwood (m^3)
D = diameter at breast-height (m)

The mean diameter in the 69 plots ranged from 2.48 to 45.83 cm. The number of trees varied from 72 to 2088 trees ha^{-1} and the basal area from 0.49 to 33.10 m^2 ha^{-1}. The range of site index was from 6.67 to 36.62 m.

Growth model

The diameter growth function used was as below.

$$\frac{dD}{dt} = Z = a_2 H^{b_3} D^p e^{-qt} e^{-S_t/c_2} e^{-S_m/c_3} \tag{3}$$

where Z = mean annual increment in diameter at breast-height (cm)
H = top height at the base age of 50 years (m)
D = quadratic mean diameter of teak (m)
t = age (year)
S_t = density of teak as measured through modified Reineke's index
S_m = density of miscellaneous species including teak coppice similar to S_t
a_2, b_3, c_2, c_3, p and q are parameters

The modified Reineke's index is

$$S = N\left(\frac{D}{25.4}\right)^b \tag{4}$$

where b = is a measure of self-tolerance of a species, i.e. the ability of trees to compete with or tolerate conspecifics (Zeide 1985).
N = number of trees per ha

Further, the following thinning impetus module (Zeide 2005) was included in Equation (3) in multiplicative mode.

$$\text{impetus, } Z(m) = 1 + mMe^{-M} \tag{5}$$

where M = $(S_b - S_a)/S_b$
S_b = stand density before thinning
S_a = stand density after thinning.

The volume growth model was of the following form, which included the effect of miscellaneous species on growth of teak trees.

$$\frac{dv}{dt} = v' = a_1 b_1 D^{b_1 - 1} Z e^{S_t/c_1} e^{S_m/c_4} \tag{6}$$

where v′ = mean annual increment in tree volume (m^3/year)
Z, D, S_t and S_m as defined earlier
a_1, b_1, c_1 and c_4 are parameters

Estimation of parameters of growth model

The parameters of Equation (3) including the impetus module and Equation (6) were estimated simultaneously using PROC MODEL of SAS (1993), assuming an additive error term. In the SAS programme, the parameter q was constrained by the following relation, $q = \ln(1/(1-p))/t_\$$ where $t_\$$ is the age inflection point estimated independently through stump analysis. The parameters were estimated using iterated generalized method of moments (ITGMM option of SAS), which allows unstructured covariance matrix of residuals. The instrumental variables used were site index, plantation age, mean diameter of teak and understorey species, and number of trees of teak and understorey species.

Optimum thinning schedule and rotation age

The current optimal density index, S_c is defined as the density index at which current volume growth reaches maximum, which is at c (Zeide 2004) given by,

$$c = 1/(1/c_2 - 1/c_1)$$

where c_1 and c_2 are parameters. Any density value can be expressed in relative terms by dividing that value by c.

Investigations on optimum thinning schedule and rotation age were carried out using a growth simulator written in SAS language. All the simulations were started with an initial stand of five years of age. The initial crop diameter at five years was obtained using the following equation estimated from the data collected from 1170 temporary sample plots laid out to estimate the productivity of teak plantations in the State (Nair *et al.* 1997).

$$D = 6.7404H^{0.6731}(1 - e^{-qt})^{(1/(1-p))} \quad (7)$$

where D = quadratic mean diameter of teak stand (cm)
H = top height at the base age of 50 years (m)
t = age (year)
p and q are parameters of diameter growth equation, i.e. of Equation (3).

The corresponding volume was predicted using the following equation estimated from the same dataset of Nair *et al.* (1997),

$$V = 0.00044D^{2.09554}e^{-0.00029S_t} \quad (8)$$

where V = volume of tree (m^3)
D = diameter of tree (cm)
S_t = density of teak stand

As the change in diameter over years could occur due to diameter jump as a consequence of thinning (Zeide 2005) other than due to growth, the following module for diameter jump was incorporated in the simulation.

$$D_a = D_b (1 + Z/D_b)^{b_4} \quad (9)$$

where D_b = diameter before thinning (cm)
D_a = diameter after thinning (cm)
Z = diameter increment (cm)
b_4 is a parameter to be estimated

The estimate for b_4 of Equation (9) had come to 0.464247 (± 0.0524). This was estimated using the same dataset used for estimating the parameters of the diameter increment function.

Net Present Value (NPV) as shown in Equation (10) was used as a financial criterion in the optimization.

$$V_0 = \sum_{t=0}^{n}(B_t - C_t) / (1+i)^t \quad (10)$$

where V_0 = present value of the cash flows
B_t = benefit in year t
C_t = cost in year t
n = number of years over which costs/benefits accrue
i = discount rate (interest rate)

Standing volume at any age was predicted from the accumulated volume computed by the simulator using the following equation,

$$V_{st} = 1.073V_{ac}^{0.4147} D^{0.7184} \quad (11)$$

where V_{st} = standing volume (m^3 ha^{-1})
V_{ac} = accumulated volume (m^3 ha^{-1})
D = mean diameter (cm)

The coefficients of Equation (11) were obtained using data from yield table for teak (FRI 1970). Thinned volume at any age was computed utilizing the successive differences of accumulated thinned volume. For the calculation of NPV, average cost of operations (excluding the cost of thinning and final felling operations) was obtained from approved Schedule Rate during 2000–01 of Kerala Forest Department. The land rent of Rs. 1300 ha^{-1} $year^{-1}$ was added to the actual cost of operation every year to obtain the total cost corresponding to each operation.

In the simulation, the runs 'with miscellaneous growth' had the corresponding miscellaneous density level as per the modified Reineke's index set to 60 which was the average miscellaneous density found in the permanent sample plots from which data on increments were gathered. The absence of miscellaneous species was achieved by setting the miscellaneous density to zero. Keeping the miscellaneous growth to this level will require additional weeding. These additional expenses were considered while computing the NPV for simulation runs 'without miscellaneous density'. For calculating the price of timber and input costs that vary with the size of trees, two corresponding equations were established. Data on price and girth at breast height of trees were collected from the Felling/Thinning Registers maintained by the Kerala Forest Department.

RESULTS

Growth model

The age at inflection point, $t_\$$, worked out using stump analysis on 57 trees was 8 years. The estimate of parameter p was 0.188 (± 0.0234). The estimate of q worked out to 0.026 ($q = \ln(1/(1-p))/t_\$$). The index of self-tolerance b was estimated as 1.2773 (± 0.3820). The estimate of the site index parameter b_3 was 1.0616 (± 0.2751). The parameters c_2 and c_3 were 829 (± 670) and 428 (± 215) respectively. The density of teak, although had a depressing effect on individual tree growth, had complementary positive effects on overall stand growth by the larger number of trees with higher density. On the contrary, the effect of miscellaneous species on teak growth was one-sided and was very serious as the coefficient ($1/c_3$) was higher than ($1/c_2$).

The estimate of impetus parameter turned out non-significant in trial runs and so was omitted in the final model. The parameter a_2 was 0.0731 (± 0.0544). The adjusted r^2 for the model was 0.38. The residuals did not show any unsatisfactory pattern when plotted against predicted values of diameter increment.

Equation (6) when simultaneously estimated with Equation (3) produced the following estimates. The estimates were a_1= 0.140851 (± 0.00877), b_1= 2.777254 (± 0.0739). As the parameters c_1 and c_4 were non-significant, they were dropped from the model. These parameters were non-significant as neither teak density nor understorey density had direct effect on volume increment. Both of these variables had high influence on diameter growth (Z) but as Z was already present in Equation (6) as a predictor variable, the teak and miscellaneous density became redundant. The value for a_1, the coefficient of proportionality and b_1, the power coefficient of tree volume equations were realistic. The adjusted r^2 for the fitted model was 0.96. The residuals did not show any distortion when plotted against the predicted values of volume increment.

Current optimum density

The formula for finding optimal density for maximizing current volume growth suggested by Zeide (2004) is $S_c = 1/(1/c_2 - 1/c_1)$. Since the parameter c_1 was not included in the model, the value of S_c turned out to be just c_2 which was nearly 830.

Estimation of price–size gradient for teak trees

The equation for predicting the price of trees from diameter at breast height worked out to be the following.

$$\ln y = \underset{(\pm 0.230)}{-3.492} + \underset{(\pm 0.069)}{3.406} \ln x \qquad (12)$$

where y = total price (Rs)
x = diameter at breast height (cm)

Mean error sum of squares = 0.559, Adjusted r^2 = 0.778.

The figures in parentheses in Equation (12) are standard errors of the coefficients.

The adjusted r^2 was around 0.78 indicating a satisfactory fit of the model. The r^2 value was also found to be highly significant (p = 0.001). This equation was utilized in the computation of NPV in the growth simulator.

Estimation of input cost–size relationship for teak trees

The prediction equation developed for working out the cost of thinning/final felling a tree by its diameter value at breast height was,

$$\ln y = \underset{(\pm 0.219)}{-4.017} + \underset{(\pm 0.067)}{2.872} \ln x \qquad (13)$$

where y = input cost (Rs)
x = diameter at breast height (cm)

Mean error sum of squares = 0.308, Adjusted r^2 = 0.814.

The figures in parentheses in Equation (13) are standard errors of the coefficients.

The adjusted r^2 was around 0.81 indicating a satisfactory fit of the model selected. The r^2 value was found to be highly significant (p = 0.001). This cost equation was also utilized in the simulator for the computation of NPV of the cash flows.

Optimum thinning schedule

The summary of optimal density trajectories under each site quality class and interest rate for stands with miscellaneous species is shown in Table 1 and that without miscellaneous species, Table 2. The initial density that maximized the NPV varied from 0.41 for site quality I to 0.21 for site quality IV regardless of interest rate. The rate of increase in initial density required for attaining the optimum was 3% every five years. The optimal rotation age varied from 65 to 40 depending on the interest rate. NPV attained its maximum at the interest rate of 2% and minimum at the interest rate of 5% regardless of site quality class. Similar trends were observed for stands without miscellaneous growth.

Effect of miscellaneous growth

Basically the pattern of results with miscellaneous species was more or less the same as that without miscellaneous species. However, differences occurred in the crop diameter and volume and thus the NPV. An effective comparison was made in this regard. The percentage increase due to the absence of miscellaneous growth centred around 16.30% for crop diameter, 22.90% for MAI in volume and 56.07% for NPV over all site quality classes and interest rates.

DISCUSSION

The present study was largely centred on identifying optimum density management scheme for even-aged teak stands. Since conventional methods based on long-term silvicultural trials would be impractical for the purpose, a solution was sought through simulation studies. A growth simulator was developed based on data from permanent sample plots laid out in different parts of the State and optimum thinning schedules under different site quality classes and interest levels were identified by comparing the NPV of different thinning schedules possible. Information on optimum rotation age was an additional piece of information that came out through simulation trials. Sensitivity of NPV and rotation age to variation in site productivity could also be worked out. The predominant influence of uncontrolled miscellaneous growth was revealed through growth simulation studies, which was found to have profound bearing on the management of teak plantations.

Growth model

Two most relevant points regarding the choice of the growth model used for the study were that the selected model had its base on the unified approach proposed by Zeide (2003) and that it was a whole stand model requiring only stand level information as input variables such as mean diameter, number of trees per unit area and site index. Moreover, the model used modified Reineke's index as a predictor variable, which is a function of both mean diameter and number of trees, and is the most effective measure of the extent of crowdedness in a stand, so far proposed.

One parameter of the growth model of special importance was the index of self-tolerance, which was estimated as 1.28. This index is a measure of the ability of trees to compete with or tolerate conspecifics. Self-tolerance changes markedly with species. The difference in self-tolerance (1.37–0.94) between longleaf pine and the next most self-tolerant species, shortleaf pine, constitutes about 60% of the entire range (1.37– 0.64) of the self-tolerance measure (Zeide 1985). The fact that the index of self-tolerance worked out to 1.28 for teak is an indication of the relatively tolerant nature of the species in pure stands. By the value that is obtained for the said parameter, high mortality should not be caused by slight increases in mean diameter of the stand. This also indirectly reflects on the ecologically adaptive nature of the species. Although physiologically light demanding,

Table 1 Optimal density trajectories under different site quality classes and interest rates (stands with miscellaneous species)

Site quality class	Interest rate (%)	Initial relative density (Proportion)	Rate of change every five years (%)	Rotation age (year)	NPV of cash flows ('000Rs)	Crop diameter (cm)	MAI in volume (m^3ha^{-1})
I	2	0.41	3	65	3677	67.0	8.868
	3	0.41	3	55	2243	62.1	9.094
	4	0.41	3	45	1484	55.5	9.121
	5	0.41	3	40	1039	51.5	9.022
II	2	0.35	3	65	2082	56.7	5.866
	3	0.35	3	55	1253	52.4	6.015
	4	0.35	3	45	819	46.9	6.038
	5	0.35	3	40	565	43.5	5.980
III	2	0.28	3	65	935	45.2	3.418
	3	0.28	3	55	545	41.8	3.509
	4	0.28	3	45	345	37.3	3.533
	5	0.28	3	40	228	34.6	3.509
IV	2	0.21	3	65	229	32.6	1.614
	3	0.21	3	55	111	30.1	1.663
	4	0.21	3	45	55	26.9	1.687
	5	0.21	3	40	22	24.9	1.686

Each row indicates the optimum density trajectory defined by the initial relative density (column 3) and rate of change in initial relative density (column 4) to be made every five years. The terminal values of NPV, crop diameter and MAI in volume at the optimal rotation age are reported against each site quality and discount rate (column 2).

Table 2 Optimal density trajectories under different site quality classes and interest rates (stands without miscellaneous species)

Site quality class	Interest rate (%)	Initial density (Proportion)	Rate of change every five years (%)	Rotation age (year)	NPV of cash flows ('000Rs)	Crop diameter (cm)	MAI in volume (m^3ha^{-1})
I	2	0.41	3	65	5184	78.3	11.072
	3	0.41	3	55	3160	72.4	11.312
	4	0.41	3	45	2087	64.6	11.279
	5	0.41	3	40	1461	59.9	11.106
II	2	0.35	3	65	2957	66.2	7.305
	3	0.35	3	55	1782	61.1	7.459
	4	0.35	3	45	1164	54.5	7.441
	5	0.35	3	40	805	50.5	7.334
III	2	0.28	3	65	1357	52.7	4.238
	3	0.28	3	55	797	48.6	4.330
	4	0.28	3	45	506	43.3	4.329
	5	0.28	3	40	339	40.1	4.276
IV	2	0.21	3	65	373	37.9	1.985
	3	0.21	3	55	194	34.9	2.034
	4	0.21	3	45	105	31.1	2.046
	5	0.21	3	40	55	28.8	2.032

Each row indicates the optimum density trajectory defined by the initial relative density (column 3) and rate of change in initial relative density (column 4) to be made every five years. The terminal values of NPV, crop diameter and MAI in volume at the optimal rotation age are reported against each site quality and discount rate (column 2).

the adaptation in crowded stands could come through elongation of the stems or self-pruning of the branches within permissible density ranges.

Optimization

Finding an optimum density trajectory was done through computer simulation of the stand growth, which was done on deterministic mode. The optimization to be effected required establishing a few other relations like price–size gradient of teak timber, input cost *vs.* tree size relation, which were newly constructed based on records maintained by the Kerala Forest Department. All the optimal density trajectories worked out, pertaining to different site quality or interest levels, involved increasing stand density at a slow rate over the rotation period. The rate of increase to be applied to the initial density varied with only interest rates. The rate at which initial density had to be raised in order to achieve the optimum was the same for any site quality classes. The optimal rotation age though stable over site quality classes varied with interest rates. Higher interest rates suggested lowering of rotation age, which is reasonable from economic point of view. Taking a particular case, with an inflation-free interest rate of 5%, the optimal rotation age to be adopted is 40 years, which is lower than the currently followed spans in Kerala but with lower interest rates, the rotation age jumps to 55 or 65 years. Another interesting finding is that the optimum thinning schedules avoid thinning at five years when the initial planted number is 2500 trees per ha. This may be a consequence of the price structure of teak poles with larger poles fetching larger price at a rate high enough to justify the waiting time.

The optimum thinning schedules showed a wide variation in NPV changing with site quality and interest rate, which is natural. Mammen (2001) had reported NPV for plantations of medium site quality based on records of actual yield. The NPV computed in the present study was based on the cost and price data during 2000–01 whereas the NPV reported by Mammen (2001) was based on the cost and price figures in 1995. Hence, the NPV of present study is not directly comparable with that of Mammen (2001).

Although the thinning schedules actually followed by the Forest Department vary with the regions, one standard for comparison is that offered by the All India Yield Table. It will be informative to make a comparison of the thinning schedules obtained through the present study with that of the yield table. Table 3 shows the reduction in number of trees and change in the density level expected as per the All India Yield Table for teak.

The strategy followed in the yield table is to keep the initial density around 0.4 and to decrease the same by 2% every five years. Although this ensures the stand in fully stocked condition, it does not guarantee maximum NPV, as the construction of yield table was not based on any economic optimization. The optimal density trajectories worked out in the present study suggests retaining the initial density at 0.4 only under site quality I. The initial density is progressively lowered with lower site quality classes. However, the subsequent strategy is to slightly increase the density over the rotation age. Although wisdom of this procedure is not discernible directly, we conclude that the objective function largely determines the stand density management. It is the interplay of volume growth and price of timber that determines the profitability of the plantations rather than any physical impression that may occur in one's mind.

To make yet another comparison, the initial density in the yield table is the same (0.4) in all the site quality classes. This is achieved by carrying out the thinning at five years in higher site quality classes and retaining larger number of trees in lower site quality classes. This trend is continued throughout the growing period and with the result, there would be four times more

Table 3 Number of trees per ha and relative density under different site quality classes as per the All India Yield Table for teak

Age	Number of trees ha^{-1}				Relative density			
	SQ I	SQ II	SQ III	SQ IV	SQ I	SQ II	SQ III	SQ IV
5	1332	1611	2174	–	0.40	0.42	0.45	–
10	632	857	1176	1610	0.38	0.38	0.40	0.42
15	378	531	736	1124	0.35	0.35	0.36	0.38
20	252	373	551	857	0.33	0.33	0.33	0.35
25	185	282	425	687	0.31	0.31	0.31	0.32
30	151	225	353	603	0.31	0.30	0.29	0.31
35	128	193	309	534	0.30	0.30	0.29	0.31
40	114	165	274	479	0.31	0.29	0.29	0.30
45	101	151	249	440	0.30	0.29	0.29	0.29
50	94	136	230	400	0.31	0.29	0.29	0.29
55	89	128	212	371	0.31	0.30	0.29	0.29
60	86	121	200	346	0.32	0.30	0.30	0.29

SQ = Site quality

trees under SQ IV compared with that under SQ I at the end of rotation period. Under the optimal strategies identified presently, there is no thinning at five years and the difference in the number of trees retained in different site quality classes at the end of the rotation period also does not vary much.

Effect of miscellaneous growth

The miscellaneous growth in the plantations was found to have significant effect on the growth of teak trees as its control resulted in about 16% increase in crop diameter and 23% increase in MAI of volume over a rotation period. Consequently, there was an increase of 41, 42, 47 and 95% in NPV for site quality classes I, II, III and IV respectively, averaged over the interest levels considered. In the plots used for the study, the miscellaneous species was dominated by *Terminalia paniculata* (25.53 %), a close associate of teak in natural forests followed by *Bombax ceiba* (24.21 %).

The miscellaneous growth requiring growth conditions identical to the main crop should be exerting a fairly high level of underground competition and its control has proven to be economical. Kerala has presently about 57 855 ha under teak plantations excluding that in wildlife sancturies. The average productivity level is around 3 m^3 ha^{-1} at 60 years at the current level of management practised by the Kerala Forest Department (Nair *et al.* 1997). It could be concluded that effective management of these plantations by adopting optimal stand density levels and weed control measures which are cost effective should go a long way in increasing the productivity and profit from these plantations.

Limitations of the study

In spite of the large sample size (125 measurements of increment) used for the present study, the adjusted r^2 value for the re-estimated diameter increment function was only 0.38 implying that a substantial part of the variation in growth happens on account of factors not included in the model. A major effect not included is the incidence of defoliation by teak defoliator. Teak defoliator has been found to cause depressive influence on growth. Teak defoliator is a migratory pest and its occurrence could not be recorded during the measurement time. Hence the present study indicates average effects regardless of incidence or otherwise of the pest outbreak. In case the effect of teak defoliator is to be included in the model, observations on the incidence of the pest will be required which will enable conditional predictions of tree growth in the presence or absence of attack by the defoliator pest.

The standard errors of some of the parameter estimates were quite high. This is partly due to the low r^2 value (0.38 for the diameter increment function) arising out of the high degree of noise in the growth measurements. The second reason is the correlation between parameter estimates. The correlation coefficients of concern by magnitude were that between b and c_2 (-0.65), between a_2 and b_3 (-0.93) and that between a_1 and b_1 (0.96). It is natural that the parameter b, the index of self tolerance is related to c_2, which indicates density related changes in growth of teak trees. As the correlation is not very high, it can be ignored. The correlations between the intercept and the corresponding exponent parameters: b *vs.* c_2, a_2 *vs.* b_3 partly arise out of the estimation procedure and thus are unavoidable. They were retained in the model because of their essentiality and statistical significance.

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