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KFRI Research Report No. 257

TESTING AN ALTERNATIVE THINNING SCHEDULE FOR TEAK PLANTATIONS BASED ON A SIMULATION MODEL

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An Institution of Kerala State Council for Science, Technology and Environment
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(Final Report of the Research Project No: KFRI 320/1999)

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PROJECT PROPOSAL

1. Project number : KFRI 320/1999

2. Title of the project : Testing an alternative thinning schedule for teak plantations based on a simulation model

3. Objective :
   - (i) To test the validity of a pre-formulated hypothesis that teak stands fully stocked (as per the present norms) at 10 years, do not require further thinning for another 20 years.
   - (ii) To develop growth simulation models using data from semi-permanent sample plots laid out in teak.
   - (iii) To arrive at optimum thinning schedules for teak using growth simulation models.

4. Expected outcome : The most direct output will be information on optimum stand management strategies. The proposed experiment on thinning will be useful in testing certain preformulated hypotheses regarding stand density management in teak.

5. Date of commencement : April 1999

6. Scheduled date of completion : March 2004

7. Funding agency : Kerala Forest Department

8. Project team

   Principal Investigator : K. Jayaraman

   Associate Investigator : N.C. Induchoodan

   Research Fellow : Sunanda. C.

CONTENTS

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ABSTRACT

Through simulation studies with a yield prediction model for teak, Jayaraman (1998) had found that the presently followed thinning schedules based on All India Yield Table for teak are nonoptimal leading to understocked stands. As a corollary of the above finding, it came out that thinning could be delayed in fully stocked stands (as per All India Yield Table for teak) leading to higher yield without unduly sacrificing the diameter growth. A field experiment was planned to test the latter derivation. However, the ultimate objective of the experiment was not 'to recommend' or 'not recommend" delayed thinning based on the results of the experiment. The experiment was only to find out for how long the thinning can be postponed in a fully stocked stand without appreciable reduction in diameter growth. In other words, the refutation of the hypothesis that the present thinning schedules are nonoptimal would only be indicative of the need for an alternative thinning schedule.

The experiment was conducted in fully stocked stands in two sites of different site quality classes in Nilambur. The stands were of age 12 years at Edakkod and 10 years at Valluassery. The trial was laid out in Randomized Complete Block Design with two treatments, viz., the standard as per the All India Yield Table for teak and the proposed schedule based on simulation studies. Under the proposed schedule, the first silvicultural thinning was skipped resulting in around 100 additional trees per ha compared to the plots under standard schedule. The plots were of size 50 m x 50 m with two replications occupying just above 1 ha in each site including border rows. Measurements on girth at breast-height, total height and crown width were made on the trees initially and subsequently at yearly intervals.

The results obtained at the end of three years indicated that the difference in diameter growth between the standard and proposed thinning schedules was statistically nonsignificant. So was the case with the expansion rate of crown width. However, the mean height growth of trees under the higher density of the proposed schedule was significantly higher than that of the standard schedule. The argument is that it shall be possible to realize larger volume later on account of the larger number of trees retained without appreciable reduction in diameter growth due to the crowding. However, it is too early to make any firm conclusions in this regard at this stage. The experiment will need to be continued till a clear indication is obtained. This may take a few more years of annual measurements and analysis.

Attempts were made to develop a growth simulation model for teak so that the performance of stands under different management schemes can be easily studied using the model. The model was developed based on the data gathered from thirty-one permanent sample plots established in teak plantations during 1993-94 by KFRI. These plots belonged to selected age-site quality-stocking classes and were distributed throughout the State. The plots were re-measured during 1997 and 2000. The work of developing growth simulation models was undertaken in collaboration with the University of Arkansas, Monticello, U.S.A. Equations for predicting diameter and volume increments were developed based on Chapman-Richards function.

The model consisted of five modules dealing with the effects of site index, unrestrained growth, aging, density of teak and density of miscellaneous species on the growth of teak. The stand density measure used was based on modified Reineke's index, which allows formation of gaps in the stand with increasing stand age. Further, an impetus module (Zeide, 2002) was also included in the growth equation. The impetus module could indicate changes in growth associated with sudden changes in stand density due to thinning. The parameters of

the equations were estimated using data from the permanent sample plots. Based on the estimated equations, a growth simulator was developed using SAS software and several simulation runs were made to find out the behaviour of stands under various density and site quality levels. Repeated simulation runs indicated that the optimal stand density in terms of modified Reineke's index, for maximizing the cumulative volume over a rotation period is 475. As density is a function of number and diameter, the number of trees will have to be reduced progressively as trees grow in diameter, in order to keep the density level constant at 475.

It was seen that the number of trees required to keep the optimal density at 475 is almost double that of the number prescribed by the existing yield table. Number of trees below 10 years was not reported as it takes time for the young seedlings to attain competition inducing density levels. However, optimal density levels obtained would practically imply planting at a spacing of 1.5 m x 1.5 m (4444 plants/ha) and first silvicultural thinning at 10 years to achieve the desired density levels. In better sites, a silvicultural thinning can be carried out at 5 years to avoid the sudden change in the number of trees.

Additionally, economic analysis with the simulator indicated that optimal rotation age for teak in Kerala is 50 years for all site quality classes. Also, analysis with the growth simulator revealed that understorey species in teak plantations exert a great influence on growth of main crop. By controlling miscellaneous growth, the mean diameter of teak trees at 50 years can be increased by 20% and the mean annual increment in volume at the corresponding age by 30%.

1. INTRODUCTION

Teak (*Tectona grandis* L. f.) is the principal timber tree of peninsular India, Myanmar, Indonesia and Thailand and one of the most valuable timbers in the world. The reputation of teak timber is due to its matchless combination of qualities such as its durability, strength, attractiveness, workability and superior seasoning capacity. It has been widely planted both within its home range and in other tropical regions.

The State of Kerala has the history of growing teak in plantation scale over 150 years. Presently, teak plantations occupy about 76,000 ha which is nearly 50% of the area under forest plantations in the State. Compared to agricultural crops, teak receives very low levels of input in the region. Virtually no post-planting operations take place other than initial tending, periodical thinning and occasional removal of mistletoes. Although the species has come up well in some pockets such as Nilambur, Achencoil and Thenmala, the overall productivity level is low (MAI of 3.1 m^3 ha^{-1} yr^{-1} of timber and smallwood) compared to the potential of 10 m^3 ha^{-1} yr^{-1} as per the All India Yield Table for teak (KFRI, 1997). Since the ban on clearfelling and selection felling from natural forests, plantations have become an important source of teak wood and the demand for the same is expected to remain high in the future.

Stand density management is an important operation in the case of teak plantations as it generates intermittent yields and also allows proper growing space for the residual stand from time to time. The basis of the current prescriptions in this regard in India is the All India Yield Tables for teak derived in 1959 (FRI and Colleges, 1970). Some recent evidences generated through simulation studies indicated a need for rethinking in this line (Jayaraman, 1998). The results of the simulation studies using yield prediction models estimated from a huge set of temporary sample plots in teak plantations indicated that total yield for a rotation age of 60 years is enhanced by retaining trees larger in numbers than that specified by the yield table. Verification of the above finding was suggested, to be accomplished by conducting a field trial.

In spite of over 100 years of research on teak in India, there existed no growth simulation models for teak useful for understanding the stand dynamics under alternative management schemes. In many developed countries, growth simulators are available which can predict the condition of the stand under alternative management schemes and indicate optimum management strategies for each site, given initial stand attributes. Developing growth simulators calls for data from semi-permanent sample plots. An attempt in this direction was made by KFRI by laying out 36 sample plots in teak plantations during 1993-94, in different parts of the State, belonging to different age groups, stocking and site quality classes. These plots were remeasured once in 1997. Subsequent measurements were planned to be taken in these plots, through the present project so as to develop a growth simulation model for teak.

One of the important applications of growth models is that of arriving at optimum thinning schedules using computer simulation methods. An additional objective specified under this project pertains to working out optimum stand density management strategies using growth simulation models.

Past research works on thinning in teak stands have been few, even globally. Some of the significant results of the past are reviewed here before getting into the details of the work accomplished under this project.

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 2,500 to 5,000. After a period of 20 years, natural mortality had reduced these numbers to approximately 1,300 to 1,800 trees per hectare. At the same age, the better sites tend to grow relatively fewer trees than do 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 per cent of that of normally thinned plantations; that the number of trees per ha was 50 to 250 per cent more, and the total basal area per ha 50 to 100 per cent more than under normal conditions of thinning. The total tree volume per ha of the unthinned plots was 20 to 80 per cent more than the total tree volume of the remaining stand and 5 to 25 per cent 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 per cent) 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 the 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. (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.

Venkataramany (1956) gave detailed account of the work and periodic results in the Wynad and Nilambur Divisions in Kerala State. Figures were adduced to show that Craib-type thinnings give rapid diameter increment but less volume than D-grade thinnings, leaving height unaffected.

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 Burma 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. The authors also gave volume tables used in developing the model.

Abayomi *et al.* (1985) reported results of analyses of variance of diameter increment and height increment of 12 teak thinning trials at 6 sites in Nigeria, comparing 4 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 (*Tectona grandis* Linn.) plantations in the Magat Experimental Forest in Philippines. Volume equations and tables were developed for merchantable and sawtimber heights from models chosen by stepwise regression with data from Nueva Vizcaya, Philippines. Merchantable volumes were predicted using an equation with diameter at breast-height and merchantable height from 0.3 m height to 10- or 20-cm top diameter inside bark (respectively total merchantable and saw timber heights) as independent variables.

Subsequent Chapters of this report are organized by way of the objectives of the project just mentioned, i.e., testing the hypothesis on thinning, developing the growth model and working out an optimal thinning schedule based on the growth simulation model.

2. MATERIALS AND METHODS

2.1. Thinning trial

The field trials on thinning schedule were conducted at Nilambur. The trial was to test the proposed thinning schedule against the standard thinning schedule in vogue for teak plantations in Kerala. Several plantations between 10 and 15 years of age around Nilambur were visited and Edakkode 1987 plantation was selected for reasons of adequate stocking, protection and nearness to depot. After preliminary evaluation of site quality, two sets of plots were laid out, each set consisting of 2 plots of size, 50 m x 50 m. The plots were separated by an extra border row in between. Each set of plots was to constitute a block with 2 replications in an overall Randomized Complete Block Design.

The trees in the plots were measured for diameter at breast-height and their relative positions were marked in a stem chart. Both the blocks in Edakkode plantation belonged to site quality I. The number of trees to be retained after thinning under each treatment was worked out based on the age of the stand and the site quality class evaluation done. The number of trees to be retained under the standard thinning schedule came to 530 per ha at 12 years. The corresponding number of trees under the proposed thinning schedule worked out to 632 per ha.

A computer programme was developed to identify the trees to be removed based on the distance between trees and their size, at the same time, avoiding large gaps created through thinning. The thinning was proposed to be done from below in the sense that the trees in lower diameter classes were to be removed first progressively going to upper classes till the required number is met. Also, preference was given to remove deformed and damaged trees from the stand. In the case of overcrowding at any spot, the distance between trees was controlled by the formula suggested by Sagreiya (1956), subject to the overall restriction that the residual number of trees in the plots matches with the prefixed number as per the thinning schedule. For teak, Sagreiya (1956) prescribed selection of the best stems and then giving each of them the optimum growing space, according to the formula $D = 1.5(d+4)$ where D is the diameter of the growing space in feet, and d the diameter of the stem in inches. Accordingly, two adjacent stems of diameter d_1 and d_2 inches are considered as ideally spaced when the distance between them is equal to $1.5\{(d_1 + d_2)/2 + 4\}$ feet.

The thinning was executed as planned in January 2001. Trees of the residual stands were measured for girth at breast-height, total height and crown width. Girth at breast-height and crown width were measured on all the trees. Height was measured using a Blume-Leiss hypsometer on 10 trees within each experimental plot covering the range of diameter values within each plot. The border rows were marked with yellow paint at breast-height. The trees at the periphery were additionally distinguished with red paint on the trunk at 1 m from the ground level.

The above experiment was to be repeated in different site quality classes. One additional site was identified in 1990 Valluassery teak plantation in Nilambur and a second experiment similar to the above was laid out. This site was of site quality II. The number of trees to be retained after thinning under each treatment was worked out based on the age of the stand and the site quality class evaluation done. The number of trees to be retained under the standard thinning schedule came to 728 per ha at 10 years of age. The corresponding number of trees under the proposed thinning schedule worked out to 856 per ha. The positions from which the trees were to be removed were determined through the computer programme, described earlier. Thinning as per the experimental schedule was completed in February 2002.

The experimental layout at the two sites are indicated in Figure 1 and Figure 2. Maps are not to the scale.

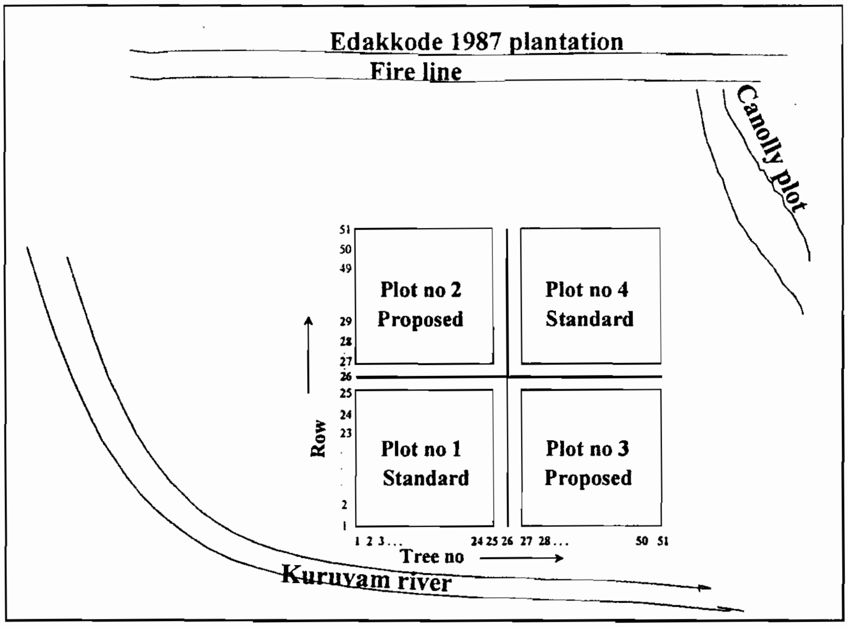


Figure 1. Experimental layout at 1987 Edakkod teak plantation

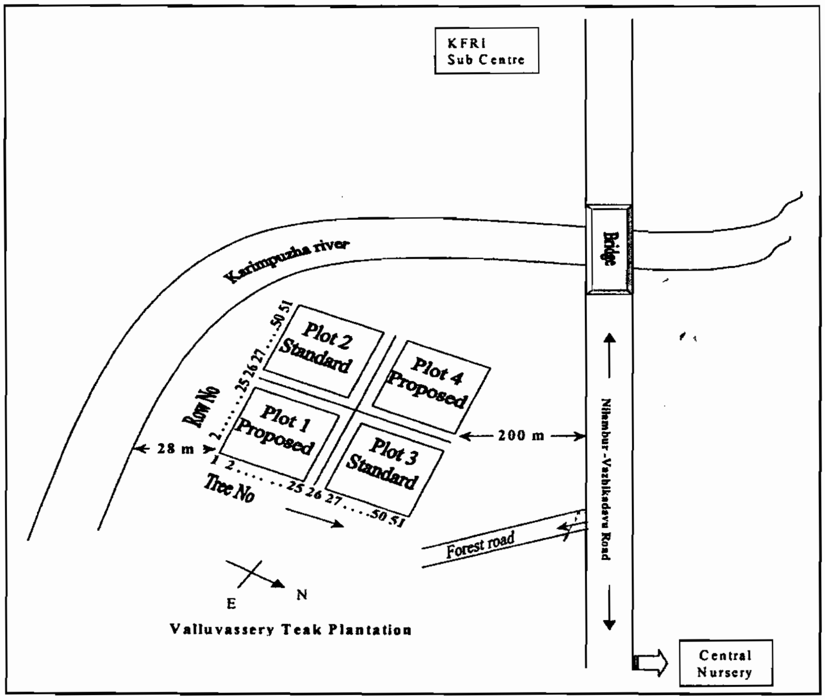


Figure 2. Experimental layout at 1990 Valluassery teak plantation

Search for additional blocks for conducting similar thinning trials in lower site quality classes was made. Although plantations raised in 1987 in Vazhachal, Thodupuzha and Ranni Ranges were visited, no suitable sites could be located for conducting the trial. The site at Vazhachal was abandoned due to problem with elephants. The plantation at Thodupuzha had received a thinning in the previous year and consequently had lower than required stocking. The plantations of the intended age group in Ranni Range were remotely located and so were not considered for the study.

In both the experimental sites, measurements on trees were repeated every year. Girth values were converted to diameter using circular approximation of the cross section of the tree trunk. Mean diameter at breast-height and mean crown diameter for each plot were obtained using quadratic mean of the corresponding individual values. Separate height-diameter relation was established for trees in each treatment at each measurement period. Mean height for each plot was obtained as the mean of the predicted height values. Percentage increase over initial value was computed for each plot for the different variables measured and was subjected to analysis of variance (ANOVA). The ANOVA was carried out based on univariate mixed model, taking treatments as main plots and repeated measurements as subplots. ANOVA was done separately for each site. Analysis based on pooled data over sites was not successful because of missing values for the third year in Valluassery. At the last measurement period, crown length was measured on 10 trees in each plot, to see if the treatments had any effect on this character. Prediction equations were developed for predicting crown length for trees in each treatment and mean crown length was obtained as mean of the predicted values.

2.2. Growth model

A biologically meaningful stand level growth model, which predicts increment in mean tree diameter and volume as a function of stand density was to be developed so that optimal density can be sought analytically and by simulation using the estimated model. Development of the growth model was done in collaboration with the University of Arkansas under a visiting programme of the first author. Zeide (2002) had developed certain process-based models and procedures for projecting diameter and volume growth. For the present case, models proposed by Zeide (2002) were utilized with appropriate modifications to suit the context of the data.

Since the proposed growth model was a function of stand density, a satisfactory measure of density was required first. A proper measure of density should remain constant in equally dense stands, regardless of their diameter. Reineke (1933) had offered such an index based on number of trees and diameter. Reineke's index (S) is given by

$$S = N\left(\frac{D}{25.4}\right)^r \tag{1}$$

where N = Number of trees per ha

D = Quadratic mean diameter of trees in cm

r is a parameter which is taken as 1.6 for all practical purposes.

Reineke's index lumps together two processes of self-thinning *viz.*, increasing average crown size expressed by diameter and diminishing crown closure. Zeide (2002a) further modified this index to describe both processes explicitly. The modified index was

$$S = N\left(\frac{D}{25.4}\right)^{b} e^{(D-25.4)} \qquad (2)$$

However, for use in growth equations, the exponential part of the index was found unnecessary as this aspect could be taken care of by other growth parameters, thus reducing the modified index to a form similar to that of Reineke's index but with a smaller *b* which can be interpreted as a measure of self-tolerance of a species, i.e., the ability of trees to compete with or tolerate conspecifics (Zeide 1985). This ability is measured by the proportion of trees eliminated during period *dt* by a certain increase in average diameter, *dD/Ddt*. Having got a satisfactory measure of stand density, it was possible to set up process-based growth models using the same.

The equation developed was,

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

where Z is the mean annual increment in diameter at breast-height (cm)
H is the top height at the base age of 50 years (m)
D is the quadratic mean diameter of teak (m)
t represents age (year)
S_t is the density of teak and S_m is the density of miscellaneous species including teak coppice.
a_2, b_3, c_2, c_3, p and q are parameters

The model consists of five modules: site index (H^{b_3}), unrestrained growth (D^p), aging (e^{-qt}), density of teak (e^{-S_t/c_2}) and density of miscellaneous species (e^{-S_m/c_3}). Site index as measured by height of trees will have an increasing effect on growth. Diameter represents the size of the tree and growth is generally proportional to the initial size raised to a power. Increasing age acts as a diminishing factor on growth and thus has a negative index. Higher density level of teak or miscellaneous species will have a negative effect on the growth of individual trees. However, higher density levels of teak trees leads to increase in total volume but the effect of miscellaneous species is one-sided.

Further, the following thinning impetus module (Zeide 2002a) was included in Equation (3) in multiplicative mode.

$$impetus = Z(m) = 1 + mMe^{-M} \qquad (4)$$

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

The impetus module could indicate changes in growth associated with sudden changes in stand density due to thinning. When parameter $m > 0$, thinning increases growth of equally dense stands and *vice versa* for $m < 0$. The maximum boost is m/e.

A volume growth model of the following form was also conceived which included the effect of miscellaneous species on growth of teak trees.

$$v' = a_1 b_1 D^{b_1 - 1} Z e^{S_t c_1} e^{S_m c_4} \qquad (5)$$

where v' is mean annual increment in tree volume (m^3)

Z, D, S_t and S_m as defined earlier

a_1, b_1, c_1 and c_4 are parameters

The model was tested utilizing the data obtained from 31 permanent sample plots laid out in teak plantations in different parts of the State of Kerala (Latitude 10.00 N and Longitude 76.25 E), India. The plots were of size 50 m x 50 m except a few which were of size 20 m x 20 m. The plots belonged to age levels varying from 4 to 60 years. The plots were established during 1993-1994 and were remeasured twice during 1997 and 2001. Girth at breast-height (1.37 m above ground) was recorded on all the trees in the plots. Height was measured on a subsample of five trees covering the range of diameters in each plot. Crop diameter was obtained as the quadratic mean diameter of the stand. Top height was computed as the height corresponding to the quadratic mean diameter of the largest 250 trees (by diameter) per hectare as read from a local height-diameter relation developed for each plot. Site index was calculated by using the equation reported by Jayaraman (1998). Volume was computed using the volume prediction equation reconstructed from Chaturvedi (1973).

The mean diameter in the 31 plots ranged from 4.5 to 41.9 cm. The number of trees varied from 76 to 1150 trees ha^{-1} and the basal area from 1.82 to 33.10 m^2 ha^{-1}. The range of site index was from 11.8 to 27.9 m.

The increment in mean diameter was obtained as the difference between quadratic means of diameter after thinning at the current measurement and that before thinning in the succeeding measurement. The increment thus obtained was divided by the interval between measurements to get the mean annual increment. The mean annual volume increment per tree was also obtained in similar lines but the mean volume per tree at any measurement instant was obtained as the arithmetic mean of the predicted volume for individual trees.

2.3. Optimum thinning schedule

Finding an optimum thinning schedule is a matter of finding optimum density first. Since the density is a function of both number of trees and mean diameter, we will need to reduce the number of trees in the stand progressively with increasing mean diameter as the trees grow, which will then constitute an optimum thinning schedule. Zeide (2002) had shown algebraically that the current optimal density index, S_c, defined as the density index at which current volume growth reaches maximum at $c = 1/(1/c_2 - 1/c_1)$. The optimal density thus got would be independent of plantation age, implying that the density, which maximizes the current growth, is the same at any age level. It will also be invariant to diameter, canopy closure, interest rate flows and merchantable limits (Zeide, 2002). However, in addition to species and possibly region, optimal density will change with any factor related to density. Insects, diseases, storms and other disturbances are likely to decrease the optimum because damage caused by these factors escalates at higher densities.

If at each moment, volume growth is maximal at the highest density, then it seems that the sum of volume increments (total volume) must also be the greatest. This reasoning would be true if volume growth was a function of density only. Actually, it is a function of two variables, density and diameter. Diameter also depends on density but not on the current density. As the sum of increments, diameter has been formed by density that existed in the past. To find the optimal value of this long-term density (which is the density that maximizes volume accumulated by the rotation age and, therefore, its mean annual increment), we can calculate standing volume together with volume thinned by a given age for various densities using the estimated density-growth relationship.

In order to find out the long-term optimum, a programme for growth simulation was developed in SAS with diameter as the driving variable. The programme was run for different density levels starting from 0.2 to 1 with a gap of 0.1 and the mean diameter and mean annual increment in accumulated volume were worked out for different age levels. As the change in diameter could occur also due to diameter jump as a consequence of thinning (Zeide 2002a) other than due to growth, the following module for diameter jump was incorporated in the simulation.

$$D_a = D_b (1 + Z/D_b)^{b_4} \tag{6}$$

where D_b and D_a refer to diameter before and after thinning

Z is the diameter increment

b_4 = is a parameter to be estimated.

RESULTS AND DISCUSSION

3.1. Thinning trial

The functional form used for the prediction equations for height and crown length was the following.

$$\mathrm{E}(\ln y) = a + b \ln x \qquad (7)$$

where y is height or crown length as the case may be (m)
x is diameter at breast-height (cm)
a and b are parameters
ln stands natural logarithm
E stands for expectation operator

The estimates of the coefficients are reported in Tables 1 and 2.

Table 1. Estimates of the coefficients of the height-diameter relation under the two treatments in different years for the two sites.

Edakkode

Year	Treatment	$\hat{a}$	$\hat{b}$	MSE	Adj. R^2
Initial	Standard	0.969	0.662	0.006	0.865
	Proposed	0.662	0.769	0.009	0.809
First	Standard	1.075	0.613	0.007	0.824
	Proposed	0.780	0.717	0.012	0.772
Second	Standard	1.189	0.569	0.005	0.859
	Proposed	0.822	0.692	0.012	0.750
Third	Standard	1.220	0.580	0.005	0.849
	Proposed	1.086	0.628	0.006	0.844

Valluassery

Year	Treatment	$\hat{a}$	$\hat{b}$	MSE	Adj. R^2
Initial	Standard	1.665	0.394	0.007	0.633
	Proposed	0.974	0.642	0.020	0.674
First	Standard	1.553	0.447	0.021	0.409
	Proposed	1.000	0.622	0.011	0.790
Second	Standard	1.549	0.465	0.010	0.618
	Proposed	1.011	0.643	0.006	0.883

Table 2. Estimates of the coefficients of the crown length-diameter relation under the two treatments for the two sites (crown length was measured only at the last period).

Site	Treatment	$\hat{a}$	$\hat{b}$	MSE	Adj. R^2
Edakkode	Standard	-0.164	0.902	0.024	0.749
	Proposed	-0.0263	0.857	0.020	0.744
Valluassery	Standard	0.683	0.624	0.025	0.538
	Proposed	0.548	0.660	0.018	0.726

The adjusted R^2 values of the fitted equations were fairly high except in a few cases. The poor relation could partly be due to low accuracy of the instrument used for measuring height. Also, the stands contained irregular gaps in many places, which could influence the relation between height or crown length with diameter at breast-height.

The stand level values of the residual stock in each plot just after thinning are given in Table 3. There was a fair extent of homogeneity among the plots with respect to the initial stand characteristics.

Table 3. Initial stand characteristics (just after thinning) of the experimental plots.

Edakkod

Characteristic	Plot 1	Plot 2	Plot 3	Plot 4
Thinning schedule	Standard	Proposed	Proposed	Standard
Age (year)	12	12	12	12
Number of trees retained	524	632	628	532
Crop diameter (cm)	16.15	14.61	15.59	15.05
Crop height (m)	16.47	15.16	15.92	15.77
Mean crown diameter (m)	3.95	4.13	3.73	4.19
Basal area (m^2 ha^{-1})	10.74	10.59	12.00	9.47

Valluassery

Characteristic	Plot 1	Plot 2	Plot 3	Plot 4
Thinning schedule	Proposed	Standard	Standard	Proposed
Age (year)	10	10	10	10
Number of trees retained	856	728	728	856
Crop diameter (cm)	14.72	15.84	12.75	11.59
Crop height (m)	14.69	15.50	14.37	12.70
Mean crown diameter (m)	3.94	4.04	4.02	3.22
Basal area (m^2 ha^{-1})	14.58	14.36	9.30	9.03

The F values obtained through the analysis of variance of relative growth rates for different characters are reported in Table 4.

Table 4. F values of ANOVA of the relative growth rate (percentage increase over initial value) for the different stand attributes in each site.

Edakkode

	Degrees of freedom	Crop diameter	Crop height	Crown diameter
Block	1	0.71	2.01	16.90
Treatment	1	0.97	0.01	0.04
Year	2	204.6**	746.99**	57.46*
Treatment x year	2	1.91	7.10*	0.18

Valluassery

	Degrees of freedom	Crop diameter	Crop height	Crown diameter
Block	1	10.23	0.004	0.71
Treatment	1	3.79	18.77	11.38
Year	1	702.73**	3632.66**	8.89
Treatment x year	1	2.69	131.12**	0.94

* significant at 5% level, ** significant at 1% level

The Treatment x year interaction was significant only in the case of crop height for both the sites indicating that height growth was not uniform under the two treatments. An examination of the mean percentage increase over initial value (Table 5) indicates that the higher density under the proposed schedule resulted in enhanced height growth by the third year of the experiment. The percentage increase in height was 12.07 under the proposed in contrast to 11.26 under the standard schedule after 3 years in Edakkod. The height growth in the first two years in both the sites did not show any clear trend.

Table 5. Comparison of standard and proposed thinning schedules at ach year after thinning with respect to relative growth rate in different stand attributes.

Edakkod

Stand attribute	Standard schedule Increase over initial value (%)			Proposed schedule Increase over initial value (%)		
	I year	II year	III year	I year	II year	III year
Crop diameter	6.95	11.81	15.43	6.15	9.95	13.17
Crop height	1.26	2.69	11.26	1.94	1.52	12.07
Crown diameter	5.27	14.67	19.56	4.10	14.86	18.29

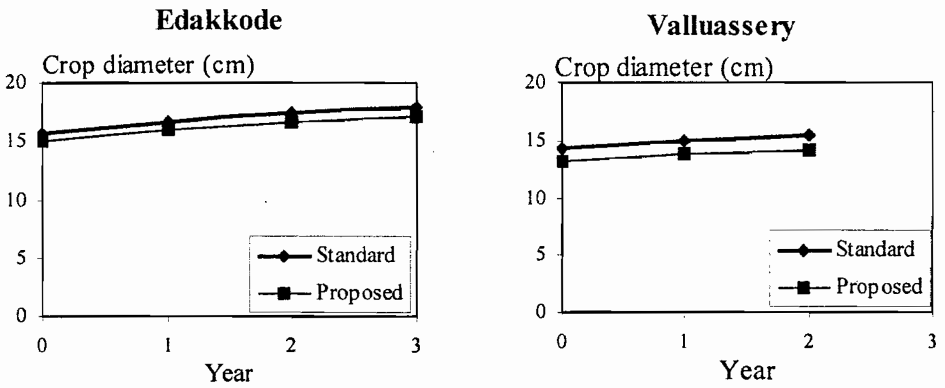
Valluassery

Stand attribute	Standard schedule Increase over initial value (%)		Proposed schedule Increase over initial value (%)	
	I year	II year	I year	II year
Crop diameter	5.01	7.65	5.58	7.91
Crop height	5.67	11.06	0.20	8.11
Crown diameter	-3.19	6.06	8.28	13.00

The figures showing the development of the different stand attributes by their actual status (Figures 3, 4 and 5) gives the impression that the treatments in general have not started acting differently with respect to their effects on the stand attributes. The mean initial values for the stands under the proposed schedules were slightly low which were carried through over the years. No drastic changes due to higher stand density under the proposed schedule were visible. At the end of 3 years in Edakkod and at the end of 2 years at Valluassery, the mean crown length of the trees was lower in the case of proposed schedule compared to that of standard schedule (Table 6). Analysis of variance of variance was not done on these values because of the low degrees of freedom for error.

Table 6. Final status of crown length and basal area under standard and proposed thinning schedules within the period of study.

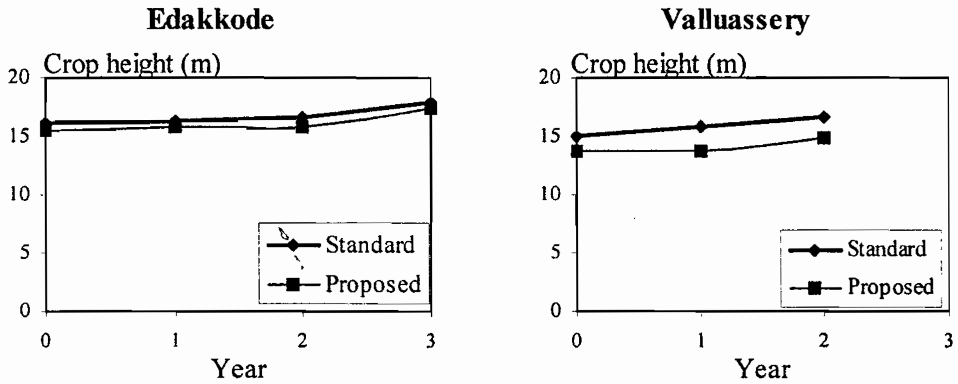
Stand attribute	Edakkode - After 3 years			Valluassery - After 2 years		
	Standard	Proposed	Proposed-Standard	Standard	Proposed	Proposed-Standard
Crown length (m)	11.48	11.03	-0.45	10.83	9.8	-1.03
Basal area (m^2 ha^{-1})	13.44	14.77	1.33	13.69	13.64	-0.05



Edakkode

Valluassery

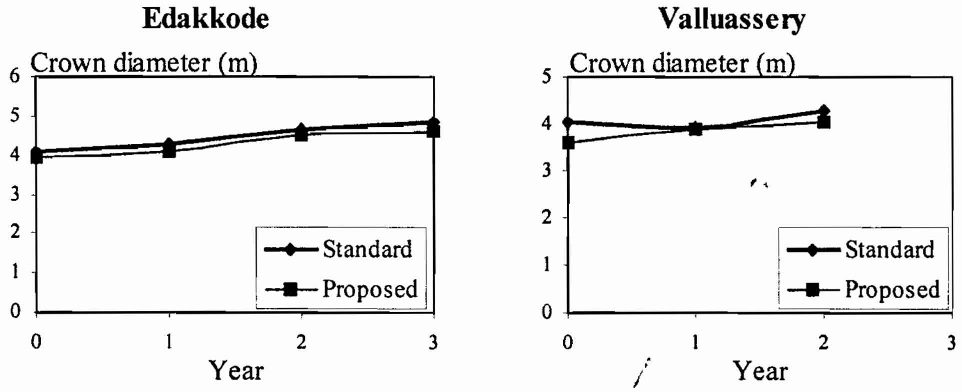
Figure 3. Progress of crop diameter under standard and proposed thinning schedules



Edakkode

Valluassery

Figure 4. Progress of crop height under standard and proposed thinning schedules



Edakkode

Valluassery

Figure 5. Progress of crown diameter under standard and proposed thinning schedules

The contention is that although the higher density may result in slightly reduced diameter growth and enhanced height growth (Table 5), the basal area and volume of the stand will be higher over long periods due to the higher number of trees in the stand. In the present case, the basal area per ha at the end of 3 years in Edakkod and at the end of 2 years in Valluassery did not differ much between the treatments due to the short span of the trial (Table 6).

However, for the time being, the hypothesis that the higher density will not result in appreciable reduction in diameter growth remains un-refuted.

3.2. Growth model

Diameter increment function

The parameters of Equation (3) including the impetus module and Equation (5) were estimated simultaneously using PROC MODEL of SAS, assuming an additive error term. Simultaneous estimation was considered because the endogenous variable Z in Equation (3) appears in the right hand side of Equation (5).

The estimate of parameter p was 0.250 (±0.040). In order to be consistent with certain theoretical expectations on the values of the different parameters involved, the value of b had to be fixed at the initial estimate of 1.25 obtained from the data before other parameters were estimated. The estimate of q was 0.029, which was a function of p and age at inflection point. The estimate of the site index parameter b_3 was 1.09 (±0.26) indicating an almost linear increase in the diameter growth with increase in the site index, keeping other factors constant. As diameter and site index are highly related, a separate module for site index was superfluous but its exclusion reduced the R^2. The parameters c_2 and c_3 were 769 (±379) and 348 (±114) respectively indicating a wide difference in how main crop and miscellaneous species affect the growth of teak trees. The density of teak although has a depressing effect on individual tree growth, it has 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 is one-sided and is very serious as the coefficient $(1/c_3)$ is higher than $(1/c_2)$.

The estimate of impetus parameter was 0.14 (±0.64), nonsgnificant at $P=0.05$, which was probably due to the large gap between thinning and the measurement times. The parameter a_2 was 0.0813 (±0.059). The adjusted R^2 for the re-estimated model was 0.54. The residuals did not show any unsatisfactory pattern when plotted against predicted values of diameter increment.

Volume increment function

Equation (5) when simultaneously estimated with Equation (3), produced the following estimates. The estimates were $a_1 = 0.1263$ (±0.0081), $b_1 = 2.7315$(±0.0732), $c_1 = 3443$(±2666). As the parameter c_4 was nonsignificant, this had been dropped from the model. The parameter c_4 was nonsignificant as the miscellaneous density had no direct effect on volume increment. The miscellaneous species had high influence on diameter growth (Z) but as Z was already present in Equation (5) as a predictor variable, the variable, 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 except for a few outliers but this was ignored because of the high R^2.

Because of the repeated measurements in the sample plots, the residuals of the successive observations could be correlated which may introduce bias in the estimates. However, the observations when ordered by measurements, produced nonsignificant values for Durbin-Watson (DW) statistic for both Equation (3) and Equation (5).

Current Optimum

The optimal density for maximizing current volume growth was found from $S_c = 1/(1/c_2 - 1/c_1)$ as described by Zeide (2002). The value of S_C turned out to be 950. In order to have additional evidence on the value of S_C, Equation (8) was fitted to data on mean diameter and number of trees per ha of teak trees in the three measurement occasions keeping the value of b at 1.25.

$$N = a\left(\frac{D}{25.4}\right)^{b} e^{c(D-25.4)} \tag{8}$$

The estimate of a was 257 (±7) and that of c was 0.000991 (±0.002). Stand density index was computed substituting the estimates of b and c in Equation (2) for 1170 sample plots of the Inventory of Teak Plantations in Kerala-1997 conducted to estimate productivity of teak plantations in Kerala, covering all the age groups available (KFRI 1997). The stand density index ranged from 3 to 1102. The mean of five top ranking values was 911, which was very close to the estimate obtained from c_1 an c_2.

Long-term optimum

In order to find out the long-term optimum, a programme for growth simulation was developed in SAS with diameter as the driving variable. The programme was run for different density levels starting from 0.2 to 1 with a gap of 0.1 and the mean diameter and mean annual increment in accumulated volume were worked out for different age levels. As the change in diameter could occur also due to diameter jump as a consequence of thinning (Zeide 2002a) other than due to growth, the module for diameter jump given in Equation (6) was incorporated in the simulation.

The value for b was set to 1.25 as obtained earlier. The estimate for r came to 0.391 (±0.062). The density of miscellaneous species was set to 60, which was the mean density value for the data set used for estimation of parameters. The mean annual increment in volume was found to attain its maximum at a density level I of about 0.5, where I is S/950, regardless of site quality class. Next, the simulation runs were repeated for all the site quality classes by setting the miscellaneous density to 0. The long-term density was attained again at a density level I of about 0.5 in the absence of miscellaneous species, for all site quality classes. In effect, the long-term stand density index for maximizing cumulative volume of teak was found to be 475.

Economic analysis

Net Present Value (NPV) as shown in Equation (9) was used as a financial criterion to arrive at economic rotation age.

$$V_0 = \sum_{t=0}^{n} C_t/(1+i)^t \tag{9}$$

where V_0 = present value of the cash flows

C_t= cash flow to be received at time t

n = number of periods

i = discount rate

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

$$V_{st} = 1.073 V_{ac}^{0.4147} D^{0.7184} \tag{10}$$

where V_{st} refers to standing volume (m^3 ha^{-1})

V_{ac} refers to accumulated volume (m^3 ha^{-1})

D refers to mean diameter (cm)

The coefficients of Equation (10) were obtained using data from yield table for teak (FRI and Colleges 1970). The fitted model had an R^2 of 0.98. Thinned volume at any age was computed utilizing the successive differences of accumulated thinned volume. These quantities were further divided into quantity of timber and smallwood using Equations (11) and (12).

$$R_{st} = 0.977\left(1 - e^{-0.16D}\right)^{16.078} \tag{11}$$

$$R_{th} = 0.939\left(1 - e^{-0.112D}\right)^{16.848} \tag{12}$$

where R_{st} indicates the proportion of timber in the standing volume

R_{th} indicates the proportion of timber in the thinned volume

D is diameter at breast-height (cm)

The parameters of Equation (11) and (12) were estimated from data of yield table of teak (FRI and Colleges 1970). The R^2 values were 0.99 and 0.96 respectively. Timber refers to round wood with 64 cm or higher girth over bark. Smallwood applies to round wood with girth between 64 and 16 cm girth over bark. Timber and smallwood roughly correspond to logs and poles. The volume figures were multiplied by price per m^3 taken from Mammen (2001). As the price varies with the size category of logs or poles, the median price was taken assuming that the conditional distribution of logs or poles for a given mean diameter of the stand is symmetrical. The median prices were USD 514 per m^3 for timber and USD 172 per m^3 for smallwood. The said prices are realized when the mean diameter of the stand is 55 cm. The constitution of timber and smallwood per m^3 and thus the price per m^3, changes linearly with the diameter. So, the unit price was allowed to change linearly with diameter at any age. Thus the price per m^3 at any age could be obtained by multiplying the unit price at diameter of 55 cm by the ratio of diameter at that age to 55 cm. Net Present Value (NPV) of timber and successive yield of thinning up to any particular age was found out by discounting the value at an inflation free interest rate of 5%.

Examination of the NPV revealed that it attains the maximum around 50 years for all site quality classes. The cost of input was disregarded as the thinning schedule pertains to an ideal strategy of long-term optimal density. More thorough economic analysis may be necessary for practical alternatives.

Effect of understorey species

Miscellaneous species was found to have significant physical effect on growth of teak. In the absence of any miscellaneous species at long-term optimal density, the average diameter at 50 years was about 20 per cent higher than that of stands with miscellaneous species. The corresponding gain in the mean annual increment in volume was around 30 per cent. The miscellaneous species was dominated by *Terminalia paniculata*, a close associate of teak in natural forests.

3.3. Optimum thinning schedule

The present study indicated that current volume growth of teak attains its maximum at a stand density index of 950 but this shall lead to greatly reduced diameter of individual trees and overall yield as well. The optimal long-term density which maximizes the accumulated volume however was found to be around 475. A value of 475 for long-term optimal density may not be directly meaningful to practicing foresters. The number of trees to be retained in unit area in order to keep the density at 475 under different site quality classes is indicated in Table 7, in contrast to the numbers in the yield table for teak. It can be seen that the number of trees required to keep the required density is almost double that of the numbers prescribed by the yield table. Number of trees below 10 years is not reported as it takes time for the young seedlings to attain competition inducing density levels. However, the optimal density levels indicated in Table 7 would practically imply planting at a spacing of 1.5 m x 1.5 m (4444 plants per ha) and first silvicultural thinning at 10 years to achieve the desired density levels. In better sites, a silvicultural thinning can be carried out at 5 years to avoid the sudden change in the number of trees.

Table 7. Number of trees per ha under optimal density in contrast to the numbers in the yield table for teak.

	Optimal density index of 475				Yield table			
Age	SQ I	SQ II	SQ III	SQ IV	SQ I	SQ II	SQ III	SQ IV
10	1217	1634	2352	3795	633	857	1176	1611
15	666	915	1354	2270	378	531	736	1124
20	453	629	943	1612	252	373	551	857
25	345	481	728	1258	185	282	425	687
30	281	394	599	1043	151	225	353	603
35	240	337	514	901	128	193	309	534
40	212	298	456	801	114	166	274	479
45	191	270	413	728	101	151	250	440
50	176	248	381	674	94	136	230	400
55	164	232	357	632	89	128	213	371
60	155	219	338	598	86	121	200	346

A comparison of the effect of keeping the stand density constant at its long-term optimal value over a rotation period of 50 years (with and without miscellaneous species) with that of the existing yield table is furnished in Table 8. A perusal of Table 8 will indicate that the mean annual increment (MAI) at 50 years corresponding to density at its long-term optimal value in the presence of miscellaneous species is lower than the yield table figures. When miscellaneous species is controlled, the MAI and the diameter are higher than the yield table figures. So, it turns out that if the density management is planned to be at its long-term optimal value, it is important to keep off the miscellaneous growth. The data used for generating the yield table were presumably obtained from well-maintained sample plots and the corresponding growth pattern is comparable only with conditions of no weed growth. The economic rotation age worked out based on the model output was fairly comparable with that based on yield table.

Table 8. Comparison of the effect of maintaining plantations at long-term optimal density on diameter and mean annual increment in volume with that of yield table for teak at 50 years. Economic rotation age for each strategy is also indicated.

Site quality	Density level	DBH at 50 years (cm)	MAI at 50 years (m^3 ha^{-1})	Economic rotation age (year)
I	475 t + 60 m	46.3	9.7	50
	475 t	56.2	12.9	50
	Yield table	51.8	10.2	45
II	475 t + 60 m	35.3	6.5	50
	475 t	42.7	8.6	50
	Yield table	37.1	7.3	50
III	475 t + 60 m	25.1	4.0	50
	475 t	30.3	5.2	50
	Yield table	24.6	4.5	65
IV	475 t + 60 m	16.0	2.1	50
	475 t	19.2	2.7	50
	Yield table	16.0	2.2	40

Note : 475t + 60m = Density index of 475 for teak 60 for miscellaneous species.
DBH = Diameter at breast-height, MAI= Mean annual increment

In the analysis phase, the self-tolerance values for teak and miscellaneous species were not found significantly different. However, the miscellaneous species had a greater coefficient in the diameter growth function implying that the competition is mainly for underground resources including soil moisture and nutrients. Removal of miscellaneous growth can bring in multiple benefits. Other than the positive effect on growth on teak trees, local inhabitants would be benefited by the availability of firewood by letting them utilize the same periodically, at no extra cost for cutting. The leaves and branches of small shrubs would add organic matter to the soil as well.

Limitations of the study

The small size of the data (31 plots and 2 remeasurements in 8 years) was probably a limitation of the present study. In order to keep consistency for the important parameter *b* (the exponent *D* in the modified Reineke's index), its value had to be fixed at 1.25 obtained from the diameter increment function, in some subsequent models. The R^2 value for the re-estimated diameter increment function, keeping the inflection point and the parameter *b* fixed, was low (0.54). This could be because diameter growth is very much affected by several extraneous factors. In teak, defoliation by 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. The results of the present study are more general indicating general level of density at which long-term optimum in respect of growth is attained. Despite much effort to obtain data from several sources, no additional data to reconfirm the finding could be obtained.

It is to be noted that keeping density constant at its long-term optimal value need not be the best strategy available. The same may involve frequent thinning as well in order to keep the density constant. Density could be made progressively increasing or decreasing and the consequences in terms of stand structure require a thorough economic analysis, which would be attempted in due course. However, such economic optima would change with change in price levels and over regions.

3. CONCLUSIONS

This study has led to the following conclusions:

1. Higher stand density levels arising out of skipping the first silvicultral thinning around 12 years in teak does not lead to significant reduction in diameter growth in the succeeding few years. Crop height could exhibit higher rate of growth under higher density in the course of three years after thinning.

2. The stand density, which maximizes current volume of teak growth, is as high as 950 in terms of modified Reineke's index but the long-term optimal density worked out to 475.

3. The thinning schedule worked out based on the optimum long-term density level using the growth simulator indicated the need for retaining larger number of trees in the stands when compared to that specified by the All India Yield Table for teak, coupled with control of understorey species to realize higher total yield at the rotation age.

4. At current prices, the economic rotation age for teak in Kerala was found to be 50 years.

5. The mean diameter and mean annual increment in volume at 50 years for stands under long-term optimal density would be higher or on par with the existing yield table values only when the understorey growth is controlled.

6. Understorey species have a great influence on growth of teak trees. By controlling miscellaneous growth, the mean diameter of teak trees at 50 years can be enhanced by 20% and mean annual increment in volume at the corresponding age by 30%.

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