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TESTING AN ALTERNATIVE THINNING SCHEDULE FOR TEAK PLANTATIONS BASED ON A SIMULATION MODEL (Phase II)

(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 2005*
7. Funding agency	:	Kerala Forest Department
8. Project team		
Principal Investigator	:	K. Jayaraman
Associate Investigator	:	N.C. Induchoodan
Research Fellow	:	Sunanda. C.

*The project KFRI 320/99: Testing an alternative thinning schedule for teak plantations based on a simulation model, initiated in 1999 was due for completion in 2004. Some important results of high practical consequence were derived during this period one of which was regarding optimum thinning schedule to be followed for teak plantations in Kerala. A limitation of that study was the small sample size and hence a reconfirmation of the findings using a larger sample was considered desirable. Accordingly, a request was made to extend the project period, which was kindly granted by the Forest Department. During the extended period, the growth simulation model was re-estimated using additional data and optimum thinning schedule was worked out based on the revised model. Additionally, measurements were taken for yet another year in the thinning trials at Nilambur and the pooled data were subjected to analysis. The results obtained in respect of optimal stand density to be maintained in teak plantations and the inference made from observations gathered from the thinning trial during the extended period are presented in this report. The material from the interim report is reproduced here partly in order to keep the continuity and make a full story and hence this may be taken as the final report of the project extending from 1999 to 2005.

During the course of editorial scrutiny, a number of questions were raised regarding the methods and results pertaining to this study. The answers furnished are reproduced in the Appendix of this report for the sake of the readers.

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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 to 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 about 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 four 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. The trees under the standard schedule carrying less number of trees gained more height due to increased space available during the experimental period. Physically, the reduction in diameter growth due to larger number of trees under the proposed schedule was 2.5 per cent in terms of relative growth rate. With a mean initial diameter of 16 cm of the experimental trees, this 2.5 per cent comes to 0.4 cm over 4 years, i.e., a reduction of 1 mm in diameter growth in an year. There is no claim that higher density will not reduce diameter growth. There will be reduction but not appreciable reduction. The results from the thinning trial were only indicative of the nonoptimality of the current thinning schedule in the sense that although higher density may result in slightly reduced diameter growth, the basal area and volume of the stand will be higher over long periods due to the higher number of trees in the stand. Leaving alone the results of the thinning trial, which was only for a short period, actual recommendations on thinning schedules were sought from the results of growth simulation studies conducted separately.

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 clubbed with data from thirty additional plots laid out in 2000 and 2001 and eight plots laid out as part of thinning trials at Nilambur. These plots belonged to selected age-site quality-stocking classes and were distributed throughout the State. The plots were re-measured during 1997, 2000 and 2005. The work of developing growth simulation models was undertaken in collaboration with Dr. Boris Zeide of 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, 2004) 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. Expressed as a ratio of the density level yielding maximum current annual increment (830), the optimal relative density worked out to 0.57.

In the case of teak, density that maximizes cumulative volume serves only as a reference value for comparative purposes. Since price-size gradient is very steep for teak timber, an economic optimum was sought through maximizing the net present value of cash flows. After many trial runs with the simulator, it was found that starting with a relative density level of 0.3 at 5 years and gradually increasing to 0.47 by 50 years is more economical than maintaining a stationary value of 0.57.

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 16 per cent and the mean annual increment in volume at the corresponding age by 25 per cent.

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 per cent 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 1170 temporary sample plots in teak plantations indicated that total yield for a rotation age of 60 years is enhanced by retaining trees larger in number 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. More recently, Bermejo et al. (2004) reported yield tables for teak plantations in Costa Rica based on data from permanent sample plots in the region.

The idea of making this short review was to refer to some important works that had already taken place on thinning in teak plantations. There was no selection of the references as to a particular view regarding suitability of early or delayed thinning. The point to be noted is that other than certain silvicultural considerations, there were no attempts to optimize thinning schedule.

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 and protection from intruders. 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 girth 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 Figures 1 and 2. Maps are not to the scale.

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. A generalized height-diameter relation was established for trees in the experimental blocks including crop diameter and number of trees/ha for each block as additional predictor variables. 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 the difference in the observation periods for the two sites.

Figure 1. Experimental layout at 1987 Edakkod teak plantation

Figure 2. Experimental layout at 1990 Valluassery teak plantation

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 (2004) had developed certain process-based models and procedures for projecting diameter and volume growth. For the present case, models proposed by Zeide (2004) 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 (2005) further modified this index to describe both processes explicitly. The modified index was

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

where b and c are parameters.

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,

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

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 2005) was included in Equation (3) in multiplicative mode.

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

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.

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

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 mainly the data obtained from permanent sample plots laid out in teak plantations in different parts of the State of Kerala. The State of Kerala is situated on the southwestern part of India between 74^0 52' and 77^0 22'E longitudes and between $8^0$18' and $12^0$48'N latitudes. Kerala has an equable climate with the mean daily temperature ranging from 20 to 35^0C. The region receives around 3000 mm of rainfall annually due to the monsoons with a short dry period stretching from December to March. 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. Thirty-one plots were established during 1993-1994 and were remeasured thrice during 1997, 2001 and 2004. Additionally there were growth data at intervals of two to three years from 30 plots laid out in 2000 and 2001 (Jayaraman, 2002). The data collected from the thinning trial laid out at two sites in Nilambur were also utilized for the present study. The thinning trials were at two locations in Nilambur, viz., Edakkod and Valluassery. At each site, there were four plots of size 50 m x 50 m, carrying different levels of stand density. Altogether there were data from 69 plots.

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 less than ten 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 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.

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 (2004) 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, 2004). 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 be 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.

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

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.

In the case of teak, density that maximizes cumulative volume will serve only as a reference value in the density *vs.* growth relationship. Since the price of logs and poles increases steeply with their sizes, large diameter trees have a distinct advantage over small sized trees. Hence identification of optimum thinning schedule is to be based on proper economic analysis.

Net Present Value (NPV) as shown in Equation (7) was used as a criterion for economic analysis.

$$V_0 = \sum_{t=0}^{n} C_t \Big/ (1+i)^t \qquad (7)$$

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,

$$V_{st} = 1.073 V_{ac}^{0.4147} D^{0.7184} \qquad (8)$$

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 (8) 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 (9) and (10).

$$R_{st} = 0.977\left(1 - e^{-0.16D}\right)^{16.078} \quad (9)$$

$$R_{th} = 0.939\left(1 - e^{-0.112D}\right)^{16.848} \quad (10)$$

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 (9) and (10) 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. Jayaraman and Rugmini (1988) had observed that diameter distribution of teak trees corresponded to a symmetrical Weibull distribution. Theoretically, the symmetry of the corresponding distribution of logs and poles from such a stand should be a direct consequence of the symmetry of the diameter distribution of trees. However, this had to be assumed because we have not confirmed the latter by actual felling.

The median prices were Rs 25,690 per m^3 for timber and Rs 8,600 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. Appendix 5 of Mammen (2001) which reports average price of logs and poles of different quality classes formed the basis of the said price-size relationship but for the complications created by subclasses of logs such as A, B, C based on the soundness of logs rather than mid-girth of logs.

The simulator predicts yield from thinning at different years and also final felling for different possible thinning regimes. The volume figures were multiplied by corresponding prices (not constant price per m^3), which generated the cash flows. NPV of the cash flow was computed by discounting and added up to get the total NPV for one particular thinning schedule. 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 per cent.

The cost of input was disregarded for the following reason. When two thinning schedules with the same planting, tending and weeding costs and same land rent are compared, such costs become a common factor in the calculation of NPV and get cancelled while computing the difference of any two NPVs and so, such costs need not be included in the comparison of NPVs. Thus input costs that were common between different thinning schedules could be disregarded for comparative purposes. The common factors include thinning interval kept at 5 years for all the schedules. Universally, density trajectories are ideal lines requiring frequent thinning but deviations can be made depending on the practical situations. Thinning intensity does not qualify fully for a common factor. Its effect had to be disregarded in the absence of information on cost of thinning trees of different diameters. Mammen (2001) had reported cost of thinning by different stages of thinning but the simulator required a continuous function linking cost of thinning to diameter at breast height. However, this lapse was not of any great consequence as the thinning costs come to just around 3 per cent of the revenue from teak plantations on an average (Appendix 6 of Mammen (2001)).

3. RESULTS AND DISCUSSION

3.1. Thinning trial

The equation developed for predicting height was the following.

$$\ln(y) = 0.540 + 0.579 \ln d + 0.0312D + 0.0002303N \qquad (11)$$

where y = Total height (m) of the tree
d = Diameter at breast-height (cm) of the tree
D = Crop diameter (cm)
N = Number of trees per ha

Equation (11) had adjusted R^2 of 0.802 and Mean Square Error (MSE) in the corresponding ANOVA was 0.00089.

The stand level values of the residual stock in each plot just after thinning are given in Table 1. There was a fair extent of homogeneity among the plots with respect to the initial stand characteristics.

Table 1. 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 (no. ha^{-1})	524	632	628	532
Crop diameter (cm)	16.15	14.61	15.59	15.05
Crop height (m)	15.88	14.68	15.70	14.79
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 (no. ha^{-1})	856	728	728	856
Crop diameter (cm)	14.72	15.84	12.75	11.59
Crop height (m)	15.36	16.14	13.09	12.23
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 2.

Table 2. F values of ANOVA of the relative growth rate (percentage increase over initial value) for the different stand attributes in each site.

Edakkode

Source	Degrees of freedom	Crop diameter	Crop height	Crown diameter
Block	1	0.74	0.43	19.17
Treatment	1	1.10	1.64	0.05
Year	3	336.05**	359.3**	53.87*
Treatment x year	3	2.35	4.30	0.09

Valluassery

Source	Degrees of freedom	Crop diameter	Crop height	Crown diameter
Block	1	109.63	157.97	0.17
Treatment	1	7.34	163.75*	4.88
Year	2	223.90**	406.33**	7.50*
Treatment x year	2	0.52	2.72	1.43

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

The treatment x year interaction was nonsignificant for the characteristics in both the sites indicating that differences in the percentage gain over the initial value with respect to any character considered remained stable over years. Treatment differences were significant only in the case of crop height at Valluassery. An examination of the mean percentage increase over initial value (Table 3) indicates that the gain in height is a little more under standard schedule in Valluassery by third year. The trees under the standard schedule could be responding to the larger space available.

Table 3. Comparison of standard and proposed thinning schedules at each year after thinning with respect to relative growth rate in different stand attributes.

Edakkode

Stand attribute	Standard schedule Increase over initial value (%)				Proposed schedule Increase over initial value (%)			
	I yr	II yr	III yr	IV yr	I yr	II yr	III yr	III yr
Crop diameter	6.95	11.81	15.43	18.44	6.15	9.95	13.37	15.89
Crop height	7.41	12.73	16.80	20.16	6.26	10.26	13.72	16.48
Crown diameter	5.27	14.67	19.56	24.96	4.10	14.86	18.29	24.41

Valluassery

Stand attribute	Standard schedule Increase over initial value (%)			Proposed schedule Increase over initial value (%)		
	I yr	II yr	III yr	I yr	II yr	III yr
Crop diameter	5.01	7.65	12.38	5.58	7.91	12.26
Crop height	5.04	7.71	12.47	5.23	7.48	11.53
Crown diameter	-3.19	6.06	5.93	8.28	13.00	11.00

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.

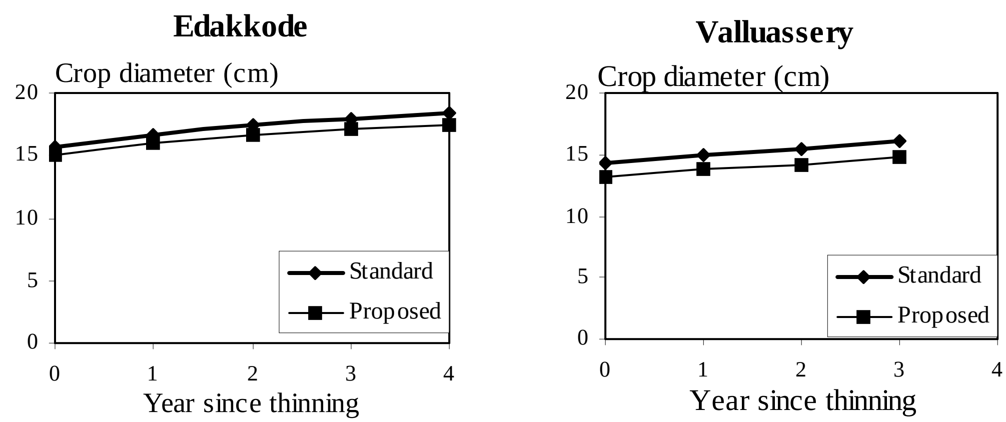

Figure 3. Progress of crop diameter under standard and proposed thinning schedules

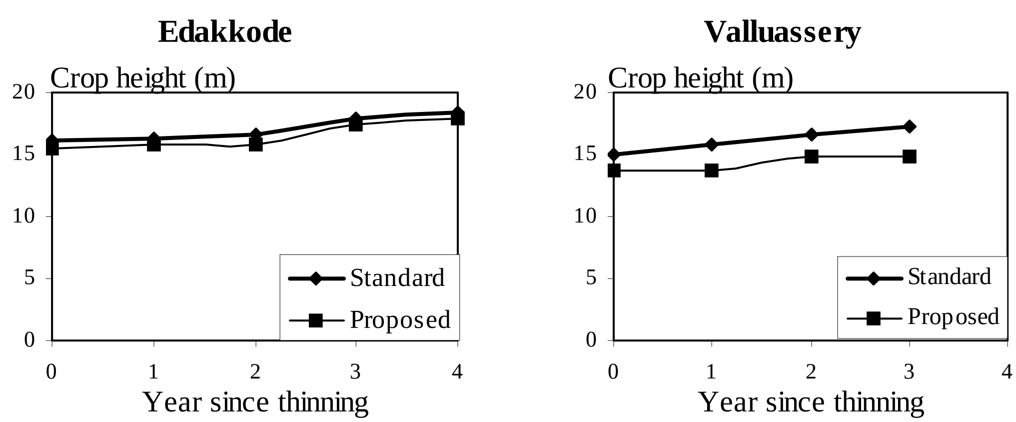

Figure 4. Progress of crop height under standard and proposed thinning schedules

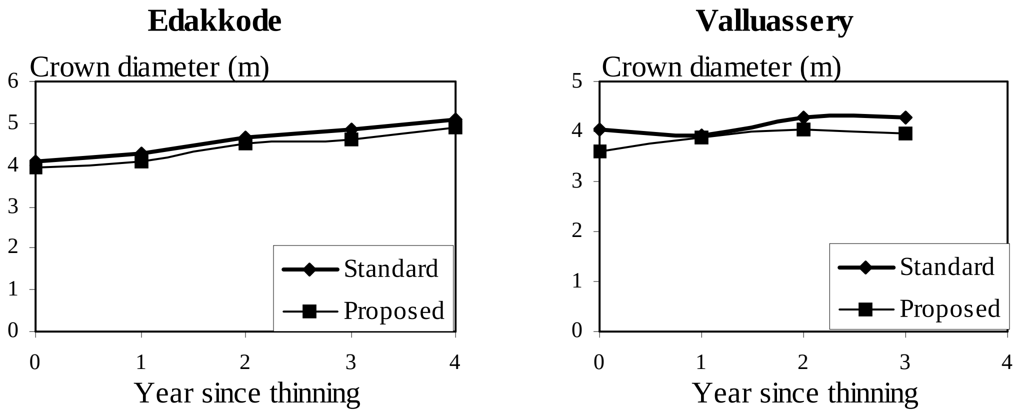

Figure 5**.** Progress of crown diameter under standard and proposed thinning schedules

In physical terms, a difference of 2.5 per cent in the relative growth rate (RGR) of diameter is observed between trees under standard and proposed thinning schedules. With a mean initial diameter of 16 cm of the experimental trees, this 2.5 per cent comes to 0.4 cm over 4 years, i.e., a reduction of 1 mm in diameter growth in an year. Clearly, it was not statistically significant. Thus for the time being, the hypothesis that the higher density will not result in appreciable reduction in diameter growth remains un-refuted. There is no claim that higher density will not reduce diameter growth. The contention is that although the higher density may result in slightly reduced diameter growth, the basal area and volume of the stand will be higher over long periods due to the higher number of trees in the stand. Earlier simulation studies with yield prediction models (Jayaraman 1998) limited such reduction to 10 per cent of the terminal diameter at 60 years and obtained around 30 per cent higher yield over a rotation period by being able to retain larger number of trees in the stand. It is not just diameter but the number of trees also that matters in deciding the profit.

Since the thinning trial was of short duration, the results could not be used for making any direct recommendations. The experiment may need to be continued for knowing for how long thinning at that age can be postponed without appreciable reduction in diameter. However, this does not seem to be necessary as definite recommendations on thinning could be developed through growth simulation studies reported in the following.

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 0.204 (±0.407). The estimate of q obtained was 0.026(±0.005). The age at inflection point worked out to 9 years. The index of self-tolerance b was estimated as 1.31 (±0.911). The estimate of the site index parameter b_3 was 1.0618 (±0.284) indicating an almost linear increase in the diameter growth with increase in the site index, keeping other factors constant. The parameters c_2 and c_3 were 830(±899) and 422 (±258) 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 turned out nonsignificant in trial runs and so was avoided in the final model. The impetus parameter turned out nonsignificant probably due to the large gap between thinning and the measurement times. The parameter a_2 was 0.0752 (±0.0984). The adjusted R^2 for the re-estimated model was 0.36. The residuals did not show any unsatisfactory pattern when plotted against predicted values of diameter increment.

One of the reasons for low R^2 for the diameter increment function is the disturbance created by the teak defoliator pest, incidence of which could not be monitored in the sample plots. Similar is the case of attack by stem borers. For instance, if trees in a sample plot are affected by borers at some point of time, their further growth will be retarded in spite of large initial diameter at the beginning of the growth period whereas the prediction of diameter increment at any stage is largely dependent on the initial size of trees. Measurement error has been another source of disturbance. The paint mark made at breast height on trees in several cases does not stay in tact for three or four years due to termite attack or heavy rains. The soil level at the base of trees either diminishes due to soil erosion or increases due to ant mounds at the base resulting in misidentification of point at which earlier measurement had taken place. Since the stem has a taper, this misidentification causes negative or positive deviation in growth measurement. The third factor for increased noise is the inaccuracy in measurement of site index. We are not sure to what extent the predicted top height at the base age of 50 years could reflect the true productive potential of the site. Variation in management of the plantations and differences in the microclimate over different sample plots other than that accounted by site index, could also have caused much variation in the growth, which were not accounted by the model. This being the case, we can hope to measure or predict only the average effects through the model unless all the factors causing variation are either recorded or eliminated.

Volume increment function

Equation (5) when simultaneously estimated with Equation (3), produced the following estimates. The estimates were a_1= 0.1405(±0.009), b_1=2.7775(±0.075). As the parameters c_1 and c_4 were nonsignificant, they were dropped from the model. These parameters were nonsignificant as either the teak density or the understorey density had no direct effect on volume increment. Both of these variables had high influence on diameter growth (Z) but as Z was already present in Equation (5) 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. 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. The problem of autocorrelation was taken care of by choosing an appropriate method of estimation. 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.

Current Optimum

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 830. In order to have additional evidence on the value of S_C, Equation (12) was fitted to pooled data on mean diameter and number of trees per ha of teak trees in the four measurement occasions keeping the value of b at 1.31.

$$N = a\left(\frac{D}{25.4}\right)^b e^{c(D-25.4)} \tag{12}$$

The estimate of a was 254 (±7.8) and that of c was 0.003054 (±0.0032). 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 2 to 1050. The mean of five top ranking values was 890, which was rather close to the estimate obtained from c_2.

Long-term optimum

In the programme to find long term optimum, the value for b was set to 1.31 as obtained earlier. The estimate for b_4 came to 0.452 (±0.051). The density of miscellaneous species was set to 60, which was the mean density value for the data set used for earlier estimation of parameters. This value was kept unaltered for comparison with the earlier results although additional plots were included in the present data set, The mean annual increment in volume was found to attain its maximum at a density level I between 0.5 and 0.6, where I is S/830, regardless of site quality class. Next, the simulation runs were repeated for all the site quality classes by setting the miscellaneous density to 0. In both the cases, i.e., with and without miscellaneous species, finer analysis within the range of 0.5 to 0.6 indicated that the long-term density was attained at a density level I of about 0.57, for all site quality classes. In effect, the long-term stand density index for maximizing cumulative volume of teak was found to be 475 which was the same value obtained from the earlier exercise using data from 31 permanent sample plots alone. The density that maximizes cumulative volume serves only a reference value in the density growth relationship for comparing with other crops. In teak, this cannot be the basis for any recommendation on thinning or rotation age as the log size-price gradient is very steep. Optimum thinning schedule derived based on economic analysis is reported in section 3.3.

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 16 per cent higher than that of stands with miscellaneous species in any site class. The corresponding gain in the mean annual increment in volume was around 25 per cent. The miscellaneous species was dominated by *Terminalia paniculata*, a close associate of teak in natural forests. These results indicate that in a mixed cropping system involving teak, other components are to so chosen that either they don't compete with teak or they are as valuable or more valuable than teak.

3.3. Optimum thinning schedule

The present study indicated that current volume growth of teak attains its maximum at a stand density index of 830 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. The derivation of the long-term optimal density was made under the assumption that the stands will be maintained under constant density level throughout the growing phase. However, Zeide (2004a) had indicated that stationary density need not be best management strategy and the real problem is to find out the best trajectory of density that minimizes the negative side of density (growth suppression) and capitalizes on its positive side (increased volume). To this end, several trial runs were made with the growth simulator with initial density values changing from 0.2 to 0.6 and progressively changing the density at increasing and decreasing rates. The initial density levels were increased or decreased progressively at the following rates viz., 0.9, 0.95, 1.05 and 1.10 at each lapse of 5 years in the simulation runs. One general finding was that increasing the density would increase the cumulative MAI but result in reduced residual diameter. Reducing the density level over time will produce opposite results. So, the decision on the best strategy to be followed was made based on the NPV. Many trial runs went out of range but after several runs, the best strategy came out which was to start with an initial density level of 0.3 and progressively increase the same by 5 per cent every 5 years. Surprisingly, the NPV values were higher than that obtained by keeping the density stationary at long-term optimum level (0.57). The actual results are given in Table 4 for the case of zero understorey level.

As an additional means of comparison, density values were worked for All India Yield Table for teak. The yield table recommendation was to start with an initial density of around 0.4 and decrease it progressively to 0.31 over a period of 50 years. This strategy was tried with the growth simulator but produced lesser NPV when compared to increasing the density over time.

Table 4. Development of stand attributes under optimal density along with NPV*

Age (year)	Relative density	Number of trees ha^{-1}	Crop diameter (cm)	MAI in volume (m^3 ha^{-1})	NPV of cash flows ('000 Rs)
Site quality I					
5	0.30	1782	5.7	3.170	11
10	0.32	418	17.1	7.977	105
15	0.33	231	27.9	8.349	477
20	0.35	163	37.8	9.226	1017
25	0.36	130	46.8	9.972	1514
30	0.38	111	54.7	10.528	1897
35	0.40	99	61.8	10.912	2157
40	0.42	92	68.0	11.151	2304
45	0.44	87	73.4	11.273	2362
50	0.47	84	78.1	11.301	2354
Site quality II					
5	0.30	2235	4.8	2.577	8
10	0.32	567	13.6	6.037	54
15	0.33	318	21.9	6.035	206
20	0.35	226	29.5	6.536	478
25	0.36	180	36.3	6.990	753
30	0.38	154	42.5	7.333	966
35	0.40	139	47.9	7.569	1108
40	0.42	128	52.6	7.713	1185
45	0.44	122	56.8	7.781	1212
50	0.47	118	60.4	7.788	1204
Site quality III					
5	0.30	2968	3.8	1.989	5
10	0.32	826	10.2	4.281	27
15	0.33	473	16.1	4.046	74
20	0.35	339	21.6	4.269	165
25	0.36	272	26.6	4.501	279
30	0.38	234	31.0	4.682	379
35	0.40	210	34.8	4.805	449
40	0.42	195	38.3	4.877	488
45	0.44	186	41.2	4.905	503
50	0.47	180	43.8	4.899	499
Site quality IV					
5	0.30	4340	2.9	1.406	2
10	0.32	1357	7.0	2.727	12
15	0.33	801	10.8	2.398	25
20	0.35	581	14.3	2.439	43
25	0.36	469	17.5	2.520	66
30	0.38	405	20.3	2.588	90
35	0.40	366	22.8	2.634	110
40	0.42	340	25.0	2.657	124
45	0.44	325	26.9	2.661	132
50	0.47	315	28.6	2.648	133

* The NPV values given in the table are not inclusive of input costs. These values were used only for comparing NPV's of different thinning schedules.

The number of trees to be retained in unit area under different site quality classes in order to keep the relative density at 0.3 at 5 years and changing it by 5 per cent every five years is indicated in Table 5. The number of trees to be retained as per the density standards specified by All India Yield Table for teak for comparable initial diameters is also reported in Table 5. Number of trees below 10 years is not reported as it takes time for the young seedlings to attain competition inducing density levels. The numbers shown under yield table may not match with the numbers reported in yield table because starting values used for diameter are estimated from the data used for the study and not just taken from the yield table. Examination of the NPV also revealed that it attains maximum around 50 years for all site quality classes for stationary optimum density of 0.57. For the optimal density path, NPV got maximized at light slightly less than 50 years.

Table 5. Number of trees per ha under optimal density in contrast to the numbers corresponding to density standards of yield table for teak.

	Optimal density				Yield table			
Age	SQ I	SQ II	SQ III	SQ IV	SQ I	SQ II	SQ III	SQ IV
10	418	567	826	1357	634	857	1245	2037
15	231	318	473	801	315	433	642	1084
20	163	226	339	581	198	274	410	702
25	130	180	272	469	140	194	293	504
30	111	154	234	405	106	148	223	387
35	99	139	210	366	84	118	178	311
40	92	128	195	340	73	102	155	271
45	87	122	186	325	65	91	139	243
50	84	118	180	315	59	83	127	222

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 0.36 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. 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. A host of other extraneous factors other than those included in the model could also cause variation in growth and thereby reduce the predictivity of the model. Hence the present study indicates average effects regardless of other factors affecting growth.

The standard error of some of the parameter estimates were quite high. This is partly due to the low R^2 value (0.36 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 (Table 6). Zeide (2004a) suggested rescaling the growth model using intrinsic units to reduce the number of parameters. Efforts have been initiated to identify values for the intrinsic units (age and size at inflection point) as part of an ongoing project at the Institute.

The optimal density levels indicated refer to only broad strategies of density management in teak plantations at different stages of the crop. For instance, comparison with the numbers of trees as per the yield table standards (Table 5) would show that optimal density levels implies keeping lesser number of trees than the standard in the most active stages of crop growth and vice versa during advanced stages when growth slows down. However, tuning the stand to exact optimal levels may require too frequent thinning that is not practical. The actual economics will depend up on how frequently thinning is undertaken. For instance, one could stop thinning after 40 years for there is very little reduction in number of trees after 40 years in all site quality classes (Table 5).

Table 6. Correlation between parameters of the growth model of Equations (3) and (5).

	b	a_2	b_2	p	q	c_2	c_3	a_1	b_1
b	1.00	0.70	-0.05	0.90	0.55	-0.78	-0.67	-0.18	-0.12
a_2	0.70	1.00	-0.67	0.82	0.67	-0.46	-0.47	0.01	0.05
b_2	-0.05	-0.67	1.00	-0.17	-0.11	-0.23	-0.08	-0.21	-0.21
p	0.90	0.82	-0.17	1.00	0.78	-0.64	-0.57	-0.23	-0.18
q	0.55	0.67	-0.11	0.78	1.00	-0.46	-0.37	-0.11	-0.06
c_2	-0.78	-0.46	-0.23	-0.64	-0.46	1.00	0.75	0.06	-0.01
c_3	-0.67	-0.47	-0.08	-0.57	-0.37	0.75	1.00	0.00	-0.06
a_1	-0.18	0.01	-0.21	-0.23	-0.11	0.06	0.00	1.00	0.96
b_1	-0.12	0.05	-0.21	-0.18	-0.06	-0.01	-0.06	0.96	1.00

4. 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.

2. The stand density, which maximizes current volume of teak growth, is as high as 830 in terms of modified Reineke's index but the long-term stationary optimal density worked out to 475, which is 0.57 in terms of relative density.

3. Starting with a relative density level of 0.3 at 5 years and gradually increasing to 0.47 by 50 years was found more economical than maintaining a stationary value of 0.57. Use of such an optimum thinning schedule results in 6 per cent higher returns, over a rotation period, in terms of net present value when compared to yield table standards.

4. At current prices, the economic rotation age that maximizes net present value of cash flows for teak in Kerala was found to be 50 years.

5. 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 16 per cent and mean annual increment in volume at the corresponding age by 25 per cent.

6. The diameter increment function had low predictivity (adjusted $R^2 = 0.36$) due to a host of extraneous uncontrolled factors that could not be included in the growth model. This being the case, we can hope to measure or predict only the average effects through the model unless all the factor causing variation are either recorded or eliminated. One alternative possible is to localize the predictions through random parameter models, which can be attempted in the future.

7. The whole exercise has finally shown us that the spacing between trees has to be adjusted depending upon the growth rate prevailing at different stages of the crop so as to promote rapid diameter growth and thereby obtain maximum profit.

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APPENDIX
Possible Questions and their Answers

1. Is the economic analysis carried out based on some average price for stem timber and smallwood?

   No; the economic analysis carried out allowed varying price of timber and smallwood based on girth of logs and poles of different categories. The constitution of timber and smallwood per m^3 and thus the price changes linearly with the diameter. So, the unit price was allowed to change linearly with diameter at any age. The price per m^3 at any age could be obtained by multiplying the unit price of diameter of 55 cm by the ratio of diameter at that age to 55 cm. Appendix 5 of Mammen (2001) which reports average price of logs and poles of different quality classes formed the basis of the said price-size relationship but for the complications created by subclasses of logs such as A, B, C based on the soundness of logs rather than mid-girth of logs.

2. The report says (page 26), 'The decision on the best strategy was based on the NPV (Net Present Value)'. How could NPV be used for making a decision on thinning schedule?

   NPV was calculated using the following equation.

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

   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

   The simulator predicts yield from thinning at different years and also final felling for different possible thinning regimes. The volume figures are multiplied by corresponding prices (not constant price per m^3), which generates the cash flows. NPV of the cash flow is computed by discounting and added up to get the total NPV for one particular thinning schedule. It was not a single cash flow table but thousands of different cash flow patterns arising out of different possible thinning schedules under different site quality levels that were being tested by the simulator.

   Increasing density would increase the cumulative MAI but result in reduced residual diameter. Reducing density level over time will produce opposite results. So, the decision on the best strategy to be followed was made based on the NPV.

3. Is not diameter growth of paramount importance in the case of teak? Basal area and stand volume maximization is important for biomass production of pulpwood plantation and not teak.

We raise teak plantations for making profit and not just for creating large diameter trees. Large diameter trees may fetch higher prices but their numbers are also important. We use NPV to avoid all that mess and declare the thinning schedule with the highest NPV as the best, which is just that has been accomplished.

4. If the cost of input is disregarded, how are cash flow tables prepared? If cash flow tables are not prepared, how can NPV be calculated?

   When two thinning schedules with the same planting, tending and weeding costs and same land rent are compared, such costs become a common factor in the calculation of NPV and get cancelled while computing the difference of any two NPVs and so, such costs need not be included in the comparison of NPVs. Thus input costs that were common between different thinning schedules could be disregarded for comparative purposes. The common factors include thinning interval kept at 5 years for all the schedules. Universally, density trajectories are ideal lines requiring frequent thinning but deviations can be made depending on the practical situations. Thinning intensity does not qualify fully for a common factor. Its effect had to be disregarded in the absence of information on cost of thinning of trees of different diameters. Mammen (2001) had reported cost of thinning by different stages of thinning but the simulator required a continuous function linking cost of thinning to diameter at breast height. However, this lapse was not of any great consequence as the thinning costs come to just around 3 per cent of the revenue from teak plantations on an average (Appendix 6 of Mammen (2001)).

5. If total volume is all that matters, why not include the volume of terminalia and other associates of teak, which are timber species too?

   It is not total volume but total profit that matters. In the present case, we talk of pure teak plantations but not of mixed plantations, not even mixed species stands. Also, one conclusion we obtained through the present work is that if any thing is to be grown with teak, it should be as valuable or more valuable than teak.

6. Very detailed distribution of size classes of logs and poles obtained from thinnings in Nilambur is furnished by Mammen (2001). Is there any need to assume symmetrical distribution of logs and poles?

   Mammen (2001) had reported distribution of logs and poles by different stages of thinning like I Mech, II Mech, I Silvi etc, but the logs and poles of any particular thinning were not of same age or site quality. For instance, if the set of plantations from where data on I Mechanical thinning came, contained larger proportion of better plantations, this asymmetry will be reflected in the corresponding distribution of logs and poles. The conditional distribution of logs and poles referred to in the report was with reference to a stand of a particular age and site quality, containing trees growing under uniform conditions. Jayaraman and Rugmini (1988) had observed that diameter distribution of teak trees corresponded to a symmetrical Weibull distribution. Theoretically, the symmetry of the corresponding distribution of logs and poles from such a stand should be a direct consequence of the symmetry of the diameter distribution of trees. However, this had to be assumed because we have not confirmed the latter by actual felling.

7. The thinning trial conducted at Nilambur showed 2.5 per cent reduction in diameter growth by keeping larger number of trees under the proposed thinning schedule. Should we not be concerned about this?

   With a mean initial diameter of 16 cm of the experimental trees, this 2.5 per cent comes to 0.4 cm over 4 years, i.e., a reduction of 1 mm in diameter growth in an year. Clearly, it was not statistically significant. There is no claim that higher density will not reduce diameter growth. There will be reduction but not appreciable reduction. Earlier simulation studies with yield prediction models (Jayaraman 1998) limited such reduction to 10 per cent of the terminal diameter at 60 years and obtained 30 per cent higher yield over a rotation period by being able to retain larger number of trees in the stand. It is not just diameter but the number of trees also that matters in deciding the profit.

8. How are the results from the thinning trial to be compared with that of simulation trials?

   There was some confusion caused by mixing up the results of the thinning trial and that of growth simulation studies. These two studies were entirely different in nature and purpose. The thinning trial conducted was just to evaluate the effect of higher density on diameter growth, i.e., how large or small the effect is. It was not ‘to recommend’ or ‘not to recommend’ delayed thinning *vide* first para of Abstract of the report. We could not have made any recommendation on thinning out of those results of just 4 years. The results showed that there was no appreciable reduction in diameter growth either statistically or physically by retaining 100 additional trees per ha at 12 years of age. We don’t use this result for any other purpose.

   It is from the results of the growth simulation studies that any recommendation on thinning was made. The thinning schedule based on stable relative density 0.57 involved retaining larger number of trees than the Yield Table standards but the strategy of changing density from 0.3 at 5 years to 0.47 at 50 years gave better results. The latter involved retaining lesser number of trees initially when compared to the yield table standards and keeping larger number of trees when the growth slows down. This finding exactly coincides with the silvicultural and physiological requirement of teak trees with growth inflection point below 10 years, other than its role in maximizing the profits.

Additionally, we have to go by the results of the growth simulation studies rather than the earlier simulation studies based on simple yield prediction models, which lacked 'memory'. The term memory here refers to whether the simulation system takes care of the thinning history of the stand or not. Growth models do have memory but not yield prediction models. The results from earlier simulation studies with yield prediction models (Jayaraman 1998) have correspondence with the results obtained now with growth simulation model using stationary density value of 0.57.

9. Does the literature cited support the results of this report?

In the review of literature, all available references were cited regardless of whether they support early or delayed thinning for various reasons, just not to stick to any particular view. Early or delayed thinning was not our concern here but the optimality of thinning schedule. The whole exercise has finally shown us that the spacing between trees has to be adjusted depending upon the growth rate prevailing at different stages of the crop so as to promote rapid diameter growth and thereby obtain maximum profit.

On the whole, it was quite difficult to make sense out of insufficient information available on many aspects involved in this study. There were limitations and the results are still not foolproof but they are the best available at the moment.

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