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Modelling the growth of teak in relation to soil conditions in the Kerala part of the Western Ghats

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CONTENTS

PROJECT PROPOSAL

1. Project number : KFRI 431/2004

2. Title of the project : Modelling the growth of teak in relation to soil conditions in the Kerala part of the Western Ghats

3. Objectives : To evaluate the growth increment of teak stands, in the Kerala part of the Western Ghats, of different age groups belonging to different site quality classes.

   To study the interrelation between the soil properties, foliage nutrient content and the growth of teak.

   To develop a model on growth of teak in relation to soil conditions and leaf nutrient status.

4. Expected outcome : The study will bring out a growth model for teak through which optimum soil conditions and critical nutrient status required for attaining maximum growth at different age levels can be ascertained.

5. Date of commencement : April 2004

6. Scheduled date of completion : March 2007

7. Funding agency : Planning & Economic Affairs Department, Government of Kerala

8. Project team

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ABSTRACT

A study was conducted on modelling the growth of teak in relation to soil conditions from 52 permanent sample plots established in teak plantations in Kerala. The 52 sample plots belonged to different age, site quality and stocking classes were distributed in different parts of Kerala State. The plots were of size 50 m x 50 m, except a few, which were of sizes 40 m x 40 m and 20 m x 20 m. The plots were established during 2000-2001 and re-measured during 2004. Girth at breast-height (1.37 m above ground) was recorded on all the trees in the plots. Height was measured on a sub-sample of less than ten trees covering the range of diameters in each plot. Diameter increment was computed for all the 52 plots. From each of the 52 plots, soil samples were taken from pits at three depth layers *viz*., 0-20, 20-40, 40-60 cm and leaf samples were also collected. The soils were subjected to analysis for determination of particle size separates, bulk density (BD), particle density (PD), water holding capacity (WHC), soil pH, organic carbon (OC), exchange bases (EB), exchange acidity (EA), cation exchange capacity (CEC), base saturation (BS), Total N, available P, K, Na, Ca and Mg. Leaf samples were also analyzed for N, P, K, Ca and Mg contents.

The overall objective of this study was to evaluate alternative model structures useful for characterising the interrelation between soil, foliar nutrient status and growth of plantation teak and select the most suitable model for the purpose. Two major modelling approaches *viz*., empirical and process-based were tried to characterize the interrelation of tree growth *vs* soil properties and tree growth *vs* nutrient status of leaves observed in the sample plots. The relationship between the leaf and soil attributes was studied through canonical correlation analysis.

Under the empirical approach, it was observed that the relationship between tree growth and soil characteristics varied with the soil depth levels. In the 0-20 cm depth level, it was found that there was no significant relationship between soil properties and tree growth. In the 20-40 and 40-60 cm depth levels, the tree growth was significantly influenced by soil pH (acidity). The results showed that with increase in soil pH in both depth levels, there was corresponding increase in the tree diameter growth. In the 20-40 cm depth level, in addition to soil pH, soil bulk density had significant influence on tree growth. It was found that, with the increase in soil bulk

density, there was subsequent decrease in tree diameter growth. Almost 33 per cent of the variation in tree diameter growth was explained by the soil attributes *viz*., soil bulk density and pH in the 20-40 cm depth level.

In all the depth levels, the models obtained through stepwise regression were all linear in nature and no quadratic terms were present. As such, the optimum levels of soil attributes, which maximize the tree growth, could not be determined through canonical analysis. This could be because of the shorter range of soil properties observed under natural conditions.

Under process-based approach, WHC, in the 20-40 cm depth level, turned out as the foremost soil variable significantly influencing tree growth. The adjusted R^2 value for the diameter increment function was 0.55, a reasonable value to expect under uncontrolled conditions. However, this implies that a substantial part of the variation in growth happens on account of factors not included in the model. The results also indicated an almost linear decrease in diameter growth with increase in the soil WHC in 20-40 cm depth level, keeping other factors constant.

The overall result that comes out through the above two modelling approaches is that soil compaction (bulk density) and soil reaction (pH) have much to do with tree growth. Equally important is the soil depth level (20-40 cm), which exerts maximum influence on the growth of trees occupying the site.

In the process-based approach also, the optimum levels of soil attributes, which maximize the tree growth, could not be determined because of restricted range of soil properties in the data set.

The process-based approach is preferable over empirical approach to study soil-tree growth relationship on account of its biological validity.

Study on the relation between leaf nutrient status and tree growth indicated that the growth is influenced by multifarious factors and nutrient composition of leaves alone cannot be considered as a good indicator in this regard.

The interrelationship between the leaf and soil attributes at different soil depth levels was studied separately through canonical correlation analysis. For all the depth levels, leaf Ca had a significant positive influence on soil Ca. For the second and third depth levels (20 - 40 cm and 40 - 60 cm) significant positive correlations were obtained for soil Mg and leaf Ca. In all the three depth levels, the canonical redundancy analysis showed that leaf

nutrient status is greatly influenced by soil attributes. On the whole, canonical correlation analyses revealed intercorrelation exist between leaf and soil characters.

1. INTRODUCTION

Ecosystems by virtue of being multivariate in nature often exhibit intricate relationships between their components. The relationships, being obscure and complex, are many times difficult to be expressed through simplistic models. This investigation was directed to probe on the intricacies of such relationships by taking forest plantation ecosystem as a typical case. More specifically, the study was aimed at developing models for characterising and analysing the interrelation between soil, foliar nutrient status and growth of teak trees in a plantation environment.

In forestry, two major modelling approaches have been used *viz*., top-down and bottom-up approaches. These have been traditionally identified as empirical versus process models. Empirical models are simple with high predictive power, but lack biological realism. Process models, on the other hand, consider the underlying physiological process for the formulation of model structures. Process models though biologically based are poor in their predictive ability and contain too many parameters, values of which are often assumed rather than estimated. More recently, a unified approach has been advocated by Zeide (2004) combining the merits of both the approaches. This study has mainly considered the unified approach for the construction of the models but has been referred as process models.

Teak (*Tectona grandis* Linn. F) is an important plantation species and is one of the most valuable timber species in the tropics where it is grown over 2.25 million ha. In 1995, about 94% of the global teak plantations were in Tropical Asia, with India (44%) and Indonesia (31%) accounting for bulk of the resource. The reputation of teak timber is due to its matchless combination of qualities such as 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 a history of growing teak in plantation scale over 150 years. Presently, teak plantations occupy about 57,855 ha (Prabhu, 2003) which is nearly 50 per cent of the area under forest plantations in the State. Compared to agricultural crops, teak receives very low input levels in the region.

The environmental effect of growing teak in plantation scale especially on its degrading effect on the soils is still debated. The study, thus, gains practical importance by the possibility of deriving useful information on the complex soil-plant milieu of this economically important plantation.

The overall objective of this study was to evaluate alternative model structures useful for characterising the interrelation between soil, foliar nutrient status and growth of plantation teak and select the most suitable model for the purpose. In the model building process, the study would bring out valuable information on soil properties that have a direct bearing on the growth and foliar nutrient status of teak trees, on how the nutrient status of leaves of teak *per se* is related to the growth of teak and also to what extent the nutrient content of leaves and that of soils are related.

Attempts to identify model structures to explain soil-leaf-growth interrelations in teak have been very few in the past. Some of the significant results of the past are reviewed here before getting into the details of the work accomplished under this project.

Hardy *et al.* (1935) stated that the relationship that existed between the plant and its environment was not so simple and factors other than nutrient supply might affect the growth and composition of the plant. Puri (1954) found that there is a seasonal variation in foliar ash, Ca, Mg and Nitrogen in teak.

It was also observed that foliar Ca increased with the advance of the growing season (Bhatia, 1955). On studying the climate, surface geology and vegetation in a number of teak stands, a positive correlation was established between the growth and distribution of teak and soil pH, exchange Ca and Mg and phosphates.

Teak can grow on a variety of soils. The quality of its growth, however, depends on the depth, structure, porosity, drainage and moisture holding capacity of the soil. The best teak growth is obtained in well-drained deep alluvium soils (Seth and Yadav, 1957).

Gagnon (1964) showed that elemental composition of needles in black spruce have relation to the site index or site quality. Hence, to have a comprehensive idea about nutritional status of plantations, one has to consider plantations of different age groups belonging to different site quality classes.

The pattern of nutrient cycling in the plantations has revealed that nutrient deficiencies are essential problems of young and old age trees (Miller, 1984). In tree crops, foliage analysis is reasonably sensitive for detecting nutrient deficiencies and also had the advantage of being directly related to productivity as foliage is the site of photosynthesis (Mead, 1984).

Teak volume was significantly correlated with rainfall, texture, organic matter content and soil pH (Akinsanmi, 1985). Pande and Sharma (1988) observed that, in teak, leaves contribute to a major share of nutrient budget.

A study on the characteristic of teak soils in the tarai region of West Bengal revealed that there is a significant correlation between height and certain chemical properties of surface soils (Singh *et al*., 1990). Teak is characterized by relatively high nutrient requirements and nutrient deficiencies can bring about reduced stand growth but the analysis has been based on simple correlations (Zech, 1990; Zech and Drechsel, 1991).

A study on the relationship between some soil properties and growth of teak revealed that better teak growth was obtained when pH of the soil was moderately acid to near neutral, with medium to very high available P, high to very high exchange Ca, medium to high base saturation and high to very high cation exchange capacity (Chongsuksantikun, 1991).

The relation between soil phosphate and the foliar phosphate contents of teak in West Africa was proved by Glaser and Drechsel (1992). Hernandez *et al*. (1993) noted a positive correlation between foliar K content and teak growth.

As the demand for teak timber is ever increasing, further increase in the area under teak in the public sector is unlikely and productivity of the existing plantations is of utmost importance. One of the ways to achieve this goal is through proper nutrient management of the plantations. In a study on the degradation of tropical rain forests upon replacement with plantations in Andaman and Nicobar Islands in India, Dager *et al.* (1995) concluded that nutrient cycling and water balance were negatively affected by monoculture of commercial teak plantations.

Even though studies were conducted in India on teak nutrition (Kaul *et al.,* 1972, Sharma and Pande, 1989 and Vimal, 1999), the results were by and large inconsistent. Vimal *et al*. (2005) made some attempts in this area but failed to bring out clear indications because of poor sample size and also reported that soil data are inadequate for nutritional assessment and that foliar data are essential to reach firm conclusions. Also, no specific models of soil-leaf-growth interrelations have been found reported in such studies in India. Hence the proposed study takes a new direction.

2. MATERIALS AND METHODS

2.1. Data

2.1.1. Tree growth

The study sites were distributed in the State of Kerala 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 an average of 3000 mm of rainfall annually due to the monsoons with a relatively short dry period stretching from December to March.

An extensive set of growth data had been gathered during 2000-2001 by the Kerala Forest Research Institute from 52 permanent sample plots laid out in teak plantations in different parts of the State of Kerala (Figure 1) as part of a study on stand dynamics of selected forest plantation species of Kerala (Jayaraman, 2002). The details of the sample plots are reported in Table 1. These sample plots were considered for the present study.

The plots were of size 50 m x 50 m, except a few, which were of sizes 40 m x 40 m and 20 m x 20 m. The plots belonged to age levels varying from 5 to 60 years under different site quality classes. Sample plots were established in each of the selected plantations. The selected plots belonged to the age groups *viz*., 0-9, 10-19, 20-29, 30-39 and 40-49 years. The trees in all the above sample plots were re-measured during 2004-05. For locating the trees within each plot for re-measurement, tree position charts of all the plots were prepared by using computer programmes developed in Visual Basic.

Girth at breast-height (1.37 m above ground) was recorded on all the trees in the plots. Height was measured on a sub sample of less than 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.

Table 1. Details of the sample plots

Sl No.	Circle	Division	Range	Name of plantation	Extent (ha)	Year of planting	Site quality
1	South	Achenkovil	Achenkovil	Muthalathodu	11.49	1957	III
2	South	Punalur	Anchal	Kadamankadu	30.35	1948	III
3	South	Punalur	Pathanapuram	Mukkadavu	6.50	1976	III
4	South	Ranni	Ranni	Pampa Valley	10.00	1984	IV
5	South	Ranni	Vadasserikkara	Padayanippara	31.94	1967	IV
6	South	Thenmala	Arienkavu	Thalappara	14.43	1964	III
7	South	Thenmala	Arienkavu	Palaruvi	29.50	1985	IV
8	South	Thenmala	Arienkavu	Karimpinthotam	9.10	1995	II
9	South	Thenmala	Arienkavu	Edapalayam	15.20	1990	III
10	South	Thiruvananthapuram	Kulathupuzha	Mylamood	22.06	1940	IV
11	High Range	Kothamangalam	Kothamangalam	Thattekad	40.89	1956	II
12	High Range	Kothamangalam	Thodupuzha	Valiyakandam	12.85	1957	III
13	High Range	Kothamangalam	Kothamangalam	Thadikulam	25.92	1963	IV
14	High Range	Kothamangalam	Mullaringad	Chattamattom	10.00	1965	IV
15	High Range	Kothamangalam	Kothamangalam	Charupara	104.90	1973	IV
16	High Range	Kothamangalam	Kothamangalam	Avolichal	125.40	1978	II
17	High Range	Kothamangalam	Kothamangalam	Thattekad	52.76	1996	IV
18	High Range	Kottayam	Ayappankovil	Kallar	12.14	1941	IV
19	High Range	Kottayam	Ayappankovil	Ayappankovil	130.50	1967	IV
20	High Range	Munnar	Neriyamangalam	Neriyamangalam	8.82	1952	IV
21	High Range	Munnar	Neriyamangalam	Neendapara	13.60	1984	III
22	Central	Chalakudy	Vellikulangara	Chokkanna	40.20	1954	IV
23	Central	Chalakudy	Pariyaram	Mullapana	200.40	1960	III
24	Central	Malayatoor	Kodanad	Kaprikad B	4.05	1950	IV
25	Central	Malayatoor	Kodanad	Thodakayam	14.60	1983	IV
26	Central	Thrissur	Machad	Kalappara	64.35	1944	IV
27	Central	Thrissur	Machad	Pulippuram	7.68	1942	IV
28	Central	Thrissur	Machad	Pattinikkad	18.22	1943	IV
29	Central	Thrissur	Machad	Palakkathadam	40.47	1953	IV
30	Central	Thrissur	Pattikkad	Kuthiran	45.02	1965	III
31	Central	Thrissur	Pattikkad	Pullamkandom	71.26	1978	IV
32	Central	Vazhachal	Vazhachal	Choozhimeedu	100.00	1973	IV
33	Central	Vazhachal	Vazhachal	Ponjanamkuttu	4.48	1990	III
34	Olavakkode	Mannarkkad	Attappady	Pottikal	19.93	1960	III
35	Olavakkode	Mannarkkad	Mannarkkad	Panakadan	7.89	1960	IV
36	Olavakkode	Nilambur (N)	Nilambur	Valluvassery	29.40	1952	IV
37	Olavakkode	Nilambur (N)	Nilambur	Valluvassery	12.87	1982	IV
38	Olavakkode	Nilambur (N)	Vazhikadavu	Nellikuthu	61.12	1986	III
39	Olavakkode	Nilambur (N)	Nilambur	Valluvassery	55.00	1995	II
40	Olavakkode	Nilambur (N)	Nilambur	Karimkoramanna	7.84	1999	I
41	Olavakkode	Nilambur (S)	Karulai	Sankarankode	81.08	1961	III
42	Olavakkode	Nilambur (S)	Karulai	Poolakkappara	55.14	1969	II
43	Olavakkode	Nilambur (S)	Karulai	Nedumkayam	24.59	1974	IV
44	North	Kannur	Kasaragod	Parappa	19.59	1946	IV
45	North	Kannur	Kasaragod	Parappa	41.93	1958	IV
46	North	Kannur	Kasaragod	Baluvanthadukka	38.00	1999	I
47	North	Wayanad (N)	Tholpetti	Camp road	27.12	1953	III
48	North	Wayanad (N)	Begur	Shanamangalam	66.62	1963	IV
49	North	Wayanad (N)	Begur	Alathur	3.65	1965	II
50	North	Wayanad (N)	Begur	Alathur	6.07	1974	III
51	North	Wayanad (S)	Chedalath	Bhoodanam	50.00	1978	IV
52	North	Wayanad (S)	Chedalath	Padiri north	55.00	1983	III

Note: The dots indicate the location of plots taken from each forest range

Figure 1. Map showing the locations of the study plots

Site index was calculated by using the equation reported by Jayaraman (1998).

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

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

As the sample plots covered a wide range of site conditions and age levels, the data set was considered ideal for developing models. Mean tree characteristics at plot level was used for the model development. Mean diameter was based on quadratic mean of individual tree diameters.

The increment in mean diameter was obtained as the difference between quadratic means of diameter at the current measurement and that in the succeeding measurement. The increment thus obtained was divided by the interval between measurements to get the mean annual increment.

2.1.2. Soil

Three soil pits were dug in each plot and samples collected from 0-20, 20-40, and 40-60 cm layers. The soil samples from each plot were made into a composite sample. The soil samples were air-dried, sieved and subjected to physical and chemical analyses to determine particle size separates, bulk density (BD), particle density (PD), water holding capacity (WHC), soil pH, organic carbon (OC), exchange bases (EB), exchange acidity (EA), cation exchange capacity (CEC), base saturation (BS), Total N, available P, K, Na, Ca and Mg as per standard procedures described in ASA (1965) and Jackson (1958). For the purpose of statistical analyses, properties pertaining to the soils from each layer was considered.

2.1.3. Leaf

Leaf samples were also gathered from ten trees from each plot. For this, 10-20 matured leaves from the middle portion of the tree were collected, oven dried at 70^0C, powdered and kept for analysis. Leaf samples were analysed for N, P, K, Ca and Mg contents as per standard procedures described by Jackson (1958).

2.2. Statistical analysis

Structurally, there are three sets of variables involved in the study, *viz.*, that on growth of teak trees, the corresponding status of soil properties observed in the sample plots and the nutrient status of leaves. The types of analysis carried out for studying the interrelation between the three sets of variables are described below.

2.2.1. Relation between tree growth and soil attributes

The following two major sets of models were tried to characterize the relationships between the sets of variables.

Empirical models

The empirical approach to growth modeling is exemplified by equations selected to maximize fit to the given data set and smooth the data. Their form and parameters have no ecological or mechanical interpretation. A classic example of such models is a polynomial. They are valued for pragmatic reasons and also for convenience of calculation. Parameters of these equations are computed to minimize deviations from data and have no meaning besides serving this practical purpose. It is believed that empirical models are useful in practice but contribute little to our knowledge.

Firstly, a linear regression analysis was done to relate the growth characteristic and the stand features like age of the stand, initial diameter, stand density of teak and miscellaneous species, and site index. In order to find the relation between tree growth and soil attributes through empirical approach, site index was replaced by soil attributes as explained below.

The model relates the growth characteristics to the soil properties through a second order response function of the following form.

$$y = \beta_0 + \sum_{i=1}^{p} \beta_i x_i + \sum_{i=1}^{p} \beta_{ii} x_i^2 + \sum_{i<j}^{p} \beta_{ij} x_i x_j \qquad (2)$$

where, y = growth increment in a mean tree characteristic

x_i's are the set of soil attributes measured in the sample plot

β's are the regression coefficients

p = number of variables

In particular, soil attributes were particle size separates, bulk density, particle density, water holding capacity, soil pH, organic carbon, exchange bases, exchange acidity, N, P, K, Na, Ca and Mg and leaf attributes were N, P, K, Ca and Mg contents.

The function represented in Equation (2) contained additionally age of the stand, mean diameter of trees and stand density as standardizing variables as the measurements on growth increment came from stands of varying age, initial size and density levels. In the regression function, the densities of teak and miscellaneous species were included separately. The density measures were computed as follows.

The density of teak or miscellaneous growth was expressed in terms of modified Reineke's index (Zeide, 2005) given by the following equation

$$S = N\left(\frac{D}{25.4}\right)^{r} \qquad (3)$$

where N = Number of trees per ha
D = Quadratic mean diameter of trees in cm
r is a parameter which was taken as 1.28 (Jayaraman and Rugmini, 2007)

Significant attributes from among the full set of attributes in the second order response function (Equation (2)) were identified through stepwise regression (Montgomery and Peck, 1982). The stepwise regression analysis was carried out after forcing in age, initial size and density in the above function (Equation (2)) other than soil variables. The stepwise procedure was executed using SPSS software package (Norusis, 1988). The stepwise analysis was done separately for each depth level. While doing this analysis, certain variables of the same kind were found significant at two adjacent layers. In order to avoid confusion in drawing inference, one more stepwise analysis was done by combining all soil attributes from all the three depth levels as independent variables along with the forced in variables such as age, initial size and stand density in the function.

Usually to characterise the nature of response surface and to find out the optimum levels of soil attributes and foliar nutrient elements, the resultant equations of stepwise regression are utilized and the levels of soil variables *e.g.*, $x_1, x_2, \ldots, x_p$ which maximize the current growth are identified through canonical analysis (Montgomery, 1991). However, in the present study, no quadratic terms were found significant. As such the optimum levels of soil attributes in the three layers, which maximize the tree growth, could not be determined through canonical analysis. This could be because of the shorter range of soil properties observed under natural conditions. Hence no description on canonical analysis is made here.

Process-based model

Process-based or simply process model is a classical model, which aims not only at a description but also at understanding the underlying cause-and-effect relationships. Although the promise of process models is yet to be realized, they are considered as the major achievement of forest science in the twentieth century.

The basic model structure under this approach was made to correspond with the following model proposed by Jayaraman and Induchudan (2004).

$$y = a_2 H^{b_3} Y^{p} e^{-qt} e^{-S_t/c_2} e^{-S_m/c_3} \tag{4}$$

where y is growth increment in a mean tree characteristic

H is the top height at the base age of 50 years (site index)

Y is the initial value of the mean tree characteristic

t represents age

S_t is the density of teak and S_m is the density of miscellaneous species including teak coppice as defined in Equation (3).

$a_2, b_3, c_2, c_3,$ p and q are parameters

For inclusion of soil variables in the above model, the site index was replaced by significant soil variables as determined through a regression of site index on soil variables. The significant soil variables were selected through stepwise regression analysis by considering site index as dependent variable and soil attributes as independent variables. For relating site index with soil attributes, the stepwise analyses (log linear regression analysis) were done separately for each depth level. An additional stepwise analysis was also done by combining the soil attributes from all the three depth levels. The site index was then replaced with the significant soil attributes retaining the same structural form as of site index in Equation (4) but one component for each soil variable like $S_1^{b_3}$, $S_2^{b_4}$ etc. The parameters of Equation (4) were then estimated using ordinary least squares executed through PROC MODEL of SAS (1993), assuming an additive error term. In the SAS programme, the parameter q was constrained by the following relation, $q = \ln(1/(1\text{-}p))/t_\$$ where $t_\$$ is the age at inflection point. The age at inflection point, $t_{\$}$, worked out using stump analysis on 57 trees, was 8 years (Rugmini and Jayaraman, 2006).

2.2.2. Relation between tree growth and nutrient status of leaves

The relation between tree growth and nutrient status of leaves was studied in similar lines as that used for relating tree growth with soil attributes.

2.2.3. Relation between soil attributes and nutrient status of leaves

The relation between the nutrient status of leaves and soil properties was studied through canonical correlation analysis (Rao, 1973). It is a procedure, which finds a linear combination of the original variables from each set called a canonical variable such that the correlation between the first two canonical variables is maximised. The correlation between the two canonical variables is called first canonical correlation. The procedure continues by finding a second set of canonical variables uncorrelated with the first pair that produces the second highest correlation coefficient. The process of constructing the canonical variables continues until the number of pairs of canonical variables equal to number of variables in the smallest group. Each canonical variable is uncorrelated with all other canonical variables of either set except for one corresponding canonical variable in the opposite set. Canonical redundancy analysis was also used to examine how well the original variables can be predicted from the canonical variables. This analysis was done using CANCORR procedure of SAS (1993) software.

3. RESULTS

The plots were located in sites of different site quality classes and age groups. The distribution of the plots over site quality/age classes is shown in Table 2. Plantations of site quality classes I and II were generally not very frequent in the area sampled.

Table 2. Distribution of sample plots in different age and site quality classes

Age	Site quality classes				Total
	I	II	III	IV	
	Top height (m)				
	36-30	30-24	24-18	18-12	
0- 9	2	2	-	1	5
10-19	-	-	4	5	9
20-29	-	1	2	5	8
30-39	-	2	2	5	9
40-49	-	1	6	6	13
50-59	-	-	1	5	6
≥ 60	-	-	-	2	2
Total	2	6	15	29	52

The mean diameter in the 52 plots ranged from 2.48 cm to 45.83 cm. The number of trees varied from 80 to 2088 trees ha^{-1} and the basal area from 0.49 to 30.03 m^{2} ha^{-1}. The range of site index was from 6.67 to 36.62 m. The mean height in the 52 plots ranged from 4.48 cm to 25.98 cm. The ranges of different tree, soil and leaf characteristics measured in this study are reported in Tables 3 and 4.

Table 3. Range of foliar nutrient status and tree growth parameters

	Minimum	Maximum	Mean	Standard deviation
Girth at breast-height (cm)	7.79	143.97	73.15	32.61
Height (m)	4.48	25.98	15.64	5.00
N (%)	1.25	3.22	2.21	0.43
P (%)	0.26	0.80	0.51	0.14
K (%)	0.23	1.76	0.90	0.38
Ca (%)	1.01	6.90	2.42	1.12
Mg (%)	0.42	1.20	0.69	0.15

Table 4. Range of soil properties in the three depth levels

Soil properties	Depth level (cm)												Unit
	0-20				20-40				40-60				
	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD	
Gravel	0.5	49.5	12.29	10.12	0.5	49.5	16.43	12	2	47	16.94	12.17	%
Sand	72	92	83.15	4.49	65	89	80.11	5.1512	8.8	91	78.02	11.01	%
Silt	2	13	8.75	2.37	5	15	9.71	2.208	4	16	10.02	2.55	%
Clay	4	16	8.1	2.62	5	22	10.17	3.57	5	19	10.44	3.2	%
PD	2.07	2.73	2.38	0.14	2	2.65	2.37	0.149	2.01	2.61	2.37	0.14	g/cc
BD	0.84	1.17	1.03	0.07	0.80	1.16	1.01	0.156	0.81	1.18	1.03	0.08	g/cc
WHC	35.67	63.14	46.53	6.8	34.22	61.64	47.76	7.23	34.64	62.74	47.87	6.49	%
pH	4.61	6.67	5.54	0.42	4.85	6.19	5.41	0.36	4.85	6.2	5.4	0.33	
OC	0.59	3.31	1.65	0.57	0.06	2.05	1.08	0.39	0.37	1.8	0.87	0.3	%
BS	58.14	94.85	76.74	8.01	56.6	90.33	76.49	7.88	61.22	89.7	78.18	7.27	%
EA	1.90	11.5	5.03	1.89	2.1	8.1	4.73	1.36	1.9	7.8	4.28	1.29	me/100g
EB	8	35	17.12	4.96	6	28	16.23	5.04	7	32	16.21	5.29	me/100g
CEC	12.80	36.90	22.14	5.17	10.6	34.10	20.96	5.14	11.4	36.1	20.49	5.45	me/100g
Na	8.30	21.6	12.19	2.81	6.9	22.6	13.12	3.07	8.6	23.9	14.01	3.41	ppm
N	308.00	1046.2	672.08	197.53	246	1046	571.12	161.7	4.71	923	530.19	169.41	ppm
P	0.04	15.33	4.99	2.82	0.13	9.21	4.25	2.56	0.13	9.68	3.50	2.36	ppm
K	2.10	21.7	10.24	5.71	1.2	17.6	6.43	4.07	1.1	14	5.53	3.23	ppm
Av. Ca	0.02	0.16	0.05	0.04	0.004	0.54	0.05	0.08	0.004	0.28	0.04	0.06	%
Av. Mg	0.003	0.06	0.02	0.01	0.004	0.04	0.02	0.01	0.002	0.0576	0.02	0.01	%

n = 52

3.1. Relation between tree growth and soil attributes

3.1.1. Empirical models

Linear regression equation relating quadratic mean annual increment in diameter and the stand features like age of the stand, initial diameter, stand density of teak and miscellaneous, and site index was of the following form,

$$\begin{array}{l} y = 0.724 - 0.007\,x_1 + 0.007\,x_2 - 0.0002\,x_3 - 0.0014\,x_4 + 0.015\,x_5 \\ \quad\;\; (0.147)\quad (0.004)\quad (0.657)\quad (0.000)\quad (0.000)\quad (0.007) \end{array} \tag{5}$$

where, y = Mean annual increment in diameter (cm)
x_1 = Age (years)
x_2 = Initial diameter (cm)
x_3 = Stand density of miscellaneous species
x_4 = Stand density of teak
x_5 = Site index

The values in the parentheses are standard errors of the coefficients. Zero values for standard errors are only a consequence of number of digits displayed.

The adjusted R^2 was 0.333. All the regression coefficients of the above equation except that of initial diameter and stand density of miscellaneous species were found highly significant, indicating that age of the stand, site index and stand density of teak had significant influence on the tree growth.

To find out the nature of relationship between tree growth and soil attributes, mean annual increment in tree diameter was considered as an index of growth. As measurements on growth increment come from stands of varying age, initial size and density, these variables were included in the stepwise analysis along with the soil attributes. The resultant equations of the stepwise regression with respect to soil properties at three depth levels separately and also by considering soil properties from all depth levels together (combined) are given in Table 5.

In the first depth level *viz*., 0-20 cm layer, the resultant equation had an adjusted R^2 value of 0.278. No soil properties were found related to tree growth. The model is linear and no quadratic terms and interaction terms are present.

The equation fitted with respect to soil properties in 20-40 cm layer, had an adjusted R^2 value of 0.607. Bulk density and pH in soils had significant influence on tree growth. However, the absence of quadratic terms in the model indicates a linear surface. Soil bulk density had a linear effect with negative coefficient, whereas soil pH had a linear effect with positive coefficient. The negative coefficient of bulk density indicates that with decreasing bulk density in the soil, diameter growth is increased. The positive coefficient of pH indicates that with increasing pH in the soil, diameter growth also increased.

In the third depth level (40-60cm layer), the model had an adjusted R^2 value of 0.324. Soil pH alone had significant influence on tree growth in this particular depth level. Also, it had a linear effect with positive coefficient. No quadratic or interaction terms were present in the model.

Table 5. Relation between tree growth and soil attributes

Depth level (cm)	The resultant equation of the stepwise regression	Adjusted R^2 value
0 - 20	$y = 0.898 - 0.0101\, x_1 + 0.568\, x_2 - 0.000181\, x_3 - 0.00122\, x_4$ (0.129) (0.004) (0.630) (0.000) (0.000)	0.278
20 - 40	$y = -0.469 - 0.010\, x_1 + 0.810\, x_2 - 0.000023\, x_3 - 0.00110\, x_4 - 1.098\, x_{28} + 0.430\, x_{30}$ (0.465) (0.003) (0.482) (0.000) (0.000) (0.208) (0.089)	0.607
40 - 60	$y = -0.393 - 0.009\, x_1 + 0.371\, x_2 - 0.00014\, x_3 - 0.00136\, x_4 + 0.242\, x_{48}$ (0.642) (0.004) (0.617) (0.000) (0.000) (0.118)	0.324
Combined	$y = -0.472 - 0.010\, x_1 + 0.812\, x_2 - 0.000024\, x_3 - 0.001 x_4 - 1.101\, x_{28} + 0.432\, x_{30}$ (0.466) (0.003) (0.483) (0.000) (0.000) (0.208) (0.089)	0.608

where, x_{28} = Bulk density in 20-40 cm depth level
x_{30} = pH in 20-40 cm depth level
x_{48} = pH in 40- 60 cm depth level
y, x_1, x_2, x_3 and x_4 are defined earlier

The values in the parentheses are standard errors of the coefficients

The equation fitted with respect to properties of soils in all layers (0-20, 20-40 and 40-60 cm layer) taken together, had the same structure and adjusted R^2 value (0.608) as obtained in 20-40 cm depth level equation. Bulk density and pH in soils belonging to 20-40 cm layer have significant influence on tree growth. However, the absence of quadratic terms in the model indicates a linear surface. Soil bulk density, belonging to 20-40 cm depth level, had a linear effect with negative coefficient, whereas soil pH in 20-40 cm depth level had a linear effect with positive coefficient.

In all the above equations, no quadratic terms were present. As such, the optimum levels of soil attributes in the three layers, which maximise the tree growth, could not be determined.

The equation fitted to soil properties in the 20-40 cm layer and that of combined set from all layers had higher adjusted R^2 values when compared to that of Equation (5). The results showed that by replacing the site index with the soil parameters *viz*., BD and pH in the 20-40 cm depth level, the value of the adjusted R^2 changed from 0.33 to 0.61.

3.1.2. Process-based model

In the SAS programme used for estimation of parameters of Equation (4), the parameter q was constrained by the following relation, $q = \ln(1/(1\text{-}p))/t_\$$

where $t_{\$}$ is the age at inflection point. The age at inflection point, $t_{\$}$, worked out using stump analysis on 57 trees was 8 years (Rugmini and Jayaraman, 2006). The estimate of parameter p was 0.179 (±0.0357). The estimate of q worked out to 0.025 $(q = \ln(1/(1\text{-}p))/t_{\$})$. The index of self-tolerance b was fixed as 1.2773 (Jayaraman and Rugmini, 2007).

The estimate of the site index parameter was 0.646943 (±0.2395), indicating a less than proportionate increase in the diameter growth with increase in the site index, keeping other factors constant. The site index parameter and the parameter p were highly significant. The parameters c_2 and c_3 were 374 (±148) and 412 (±216) respectively. The density of teak although has a depressive 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 could be very serious if the reciprocal of its value is large. In the present case, the effect of the latter was moderate.

The parameter a_2 was 0.338674 (±0.2391). The adjusted R^2 for the model was 0.5025. The residuals did not show any unsatisfactory pattern when plotted against predicted values of diameter increment.

The resultant equations of the stepwise regression involving site index as dependent variable and soil variables as independent variables in the logarithmic scale, at three depth levels separately and also by taking soil properties from all layers (combined) are given in Table 6.

Table 6. Relation between site index and soil attributes in the log scale

Depth level (cm)	The resultant equation of the stepwise regression	Adjusted R^2 value
0-20	ln x_5 = 3.251 + 0.145 ln x_{19} (0.189) (0.058)	0.096
20-40	ln x_5 = 6.729 - 1.081 ln x_{29} + 0.136 ln x_{40} (1.016) (0.262) (0.061)	0.291
40-60	ln x_5 = 2.658 + 0.141 ln x_{59} (0.061) (0.047)	0.140
Combined	ln x_5 = 6.729 - 1.081 ln x_{29} + 0.136 ln x_{40} (1.016) (0.262) (0.061)	0.291

where, x_5 = Site index

x_{19} = Ca (%) in 0-20 cm depth level

x_{29} = WHC (%) in 20-40 cm depth level
x_{40} = K (ppm) in 20-40 cm depth level
x_{59} = P (ppm) in 40-60 cm depth level

The values in the parentheses are standard errors of the coefficients

For the first depth level (0-20 cm), the resultant model had a very low adjusted R^2 value of 0.096. The site index was significantly influenced by soil Ca content. The result showed that with the increase in the soil Ca, there was corresponding increase in site index.

In the second depth level (20-40 cm), the site index was significantly influenced by K and WHC of soils. The model had an adjusted R^2 value of 0.291, which is greater than that of the surface and deeper layers (0-20 and 40-60 cm depth levels). It is noted that with increase in K, site index increased and vice versa with WHC.

In the last depth level (40-60 cm), the model had an adjusted R^2 value of 0.140. Here also, the site index was significantly influenced by soil P. The indication was that with the increase in soil P, the site index increased.

The equation fitted with respect to properties of soils from all layers (0-20, 20-40 and 40-60 cm depth level) taken together, had the same form and adjusted R^2 value (0.291) as obtained in the case of 20-40 cm depth level. The results indicated that, of the 18 soil properties at each of the three depth levels, WHC and K at 20-40 cm depth level had significant influence on site index. Hence WHC and K in 20-40 cm depth level were considered for replacing top height in the process-based model (Equation (4)).

The process-based model was fitted after replacing top height by significant soil attributes *viz*., WHC and K in 20-40 cm depth level, in Equation (4). However, since the estimate of the soil K parameter was found nonsignificant within the process model setup, the same was avoided in the final model and the parameters were re-estimated following the same procedure mentioned earlier. Thus the final model was of the following form.

$$y = a_2\, x_{29}^{b_3}\, Y^{p} e^{-qt} e^{-S_t/c_2} e^{-S_m/c_3} \tag{6}$$

where, y is growth increment in a mean tree characteristic
x_{29} is WHC (%) in 20-40 cm depth level
Y is the initial value of the mean tree diameter (m)
t represents age (years)

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 estimate of parameter p was 0.1989 (±0.0347). The estimate of q worked out to 0.028 ($q = \ln(1/(1\text{-}p))/t_{\$}$). The estimate of the soil WHC parameter, b_3, was -1.14823 (±0.5253), indicating an almost linear decrease in the diameter growth with increase in the soil WHC in 20-40 cm depth level, keeping other factors constant. The estimate of the parameters *viz.*, soil WHC and p were highly significant.

The parameters c_2 and c_3 were 388 (±136) and 430 (±247). The parameter a_2 was 188.0103 (±377.6). The adjusted R^2 for the model was 0.5475. The residuals did not show any unsatisfactory pattern when plotted against predicted values of diameter increment.

The results showed that by replacing the site index with the soil parameter WHC in 20-40 cm depth level, the value of the adjusted R^2 had changed from 0.5025 to 0.5475.

In the process-based approach also, the optimum levels of soil attributes, which maximize the tree growth, could not be determined because of restricted range of soil variables.

3.2. Relation between tree growth and nutrient status of leaves

The resultant equation with respect to nutrient status of leaves obtained through regression, following methods similar to that used with soil variables was the following.

$$\begin{array}{lllll} y = 0.900 & -\ 0.010\,x_1 & +\ 0.570\,x_2 & -\ 0.0001\,x_3 & -\ 0.001\,x_4 \\ \quad (0.129) & (0.004) & (0.631) & (0.000) & (0.000) \end{array} \qquad (7)$$

where, y = Mean annual increment in diameter (cm)
x_1 = Age (years)
x_2 = Initial diameter (cm)
x_3 = Stand density of miscellaneous species
x_4 = Stand density of teak

The values in the parentheses are standard errors of the coefficients, zeroes appearing because of display limits.

The model had an adjusted R^2 value of 0.279. No leaf attribute was found significantly related to tree growth. Hence no empirical relation between tree growth and nutrient status of leaves could be established.

Further no leaf attribute was found significantly related to site index and no process model including nutrient status of leaves could be fitted.

On the whole, the results indicate that one-time assessment of nutrient levels in leaves as a whole gives no indication of the growth attained in the subsequent years.

3.3. Relation between soil attributes and nutrient status of leaves

Canonical correlation analysis was used for analysing the relationship between leaf variables and soil variables. This procedure was applied to all the three data sets belonging to the three soil depth levels.

Soils in the 0 - 20 cm depth level

The simple linear correlation coefficients between the leaf and soil attributes in the 0-20 cm layer are given in Table 7.

Table 7. Coefficients of correlations between the leaf attributes and the soil attributes in the 0-20 cm depth level

Soil attributes	Leaf attributes				
	N	P	K	Ca	Mg
Gravel	0.0432	-0.1899	0.0189	-0.0888	0.1782
Sand	0.1124	0.1193	0.2460	-0.2197	-0.1127
Silt	-0.0983	-0.0729	-0.3262	0.3182	0.1772
PD	-0.1655	-0.1475	-0.1910	0.1945	-0.1222
BD	-0.2815	-0.0117	-0.2729	0.3924	-0.0293
WHC	0.2560	-0.0672	0.3184	-0.3732	0.1705
EA	-0.3616	0.0459	-0.1363	0.3132	0.0082
EB	-0.0809	-0.3352	-0.3121	0.0822	0.0685
BS	-0.2146	-0.4702	-0.4852	0.1061	-0.1839
CEC	0.1959	-0.0679	-0.0101	-0.1538	0.0719
pH	0.0143	0.1818	-0.0118	0.1466	0.1802
OC	0.0858	0.1497	-0.0138	0.0831	0.1991
Total N	-0.1378	0.1679	0.0049	0.2498	0.0758
Av. Ca	-0.3510	0.1694	-0.2468	0.6537	0.0485
Av. Mg	-0.2753	0.2361	-0.0750	0.2715	-0.0747
Na	-0.1166	-0.0067	-0.0162	0.3539	0.0161
K	0.0148	-0.1167	0.0451	0.0183	0.0635
P	0.1206	0.2304	0.0428	0.1810	0.2235

The correlation is low or moderate between many variables. The largest correlation coefficient, 0.6537 was between leaf Ca and soil Ca and the correlation was positive. Also soil base saturation had significant negative effect on leaf K and P.

The canonical correlations between foliar and soil attributes are reported in Table 8. The likelihood ratio test revealed that the first two of these correlations are significant. The corresponding canonical variates accounted for about 78 per cent of the total variability in the variables measured on leaves.

Table 8. Eigen values and canonical correlation between leaf and soil variables in the 0-20 cm depth level

No	Eigen value	Canonical correlation	Proportion of variance	Cumulative proportion
1	3.5481	0.8832	0.5016	0.5016
2	1.9398	0.8123	0.2743	0.7759
3	0.8282	0.6731	0.1171	0.8930
4	0.5180	0.5842	0.0732	0.9662
5	0.2388	0.4390	0.0338	1.0000

The standardised canonical coefficients for the leaf attributes and correlation between the leaf attributes and their two significant canonical variables are given in Table 9. The first canonical variable for leaf was a linear combination mainly of leaf Ca. Leaf Ca had positive correlations with the first leaf canonical variable. The second leaf canonical variable was a function of leaf K, which showed positive correlation with the second canonical variable.

Table 9. Standardized canonical coefficients for the leaf attributes and correlation between the leaf attributes and their two significant canonical variables

Leaf attributes	Canonical coefficients		Correlations	
	Leaf 1	Leaf 2	Leaf 1	Leaf 2
N	-0.5807	-0.4721	-0.4847	0.3998
P	0.4859	0.0798	0.2304	0.5830
K	0.1395	1.1825	-0.3182	0.8956
Ca	0.7627	0.1219	0.8535	-0.2310
Mg	0.0002	0.3124	0.0799	0.3566

The standardised canonical coefficients for the soil attributes and correlations between the soil attributes and their significant canonical variables are presented in Table 10. The first soil canonical variable was mainly a function of Ca as judged by its correlation with the different soil variables. The second soil canonical variable was a linear combination of base saturation only showing high correlation with the corresponding soil properties.

Table 10. Standardized canonical coefficients for the soil attributes and correlation between the soil attributes and their two significant canonical variables (soils in the 0-20 cm depth level)

Soil attributes	Canonical coefficients		Correlations	
	Soil 1	Soil 2	Soil 1	Soil 2
Gravel	0.0914	0.3502	-0.2066	0.0389
Sand	0.1779	-0.0223	-0.1591	0.2282
Silt	0.0747	-0.6071	0.2478	-0.3090
PD	0.0989	-0.0093	0.1654	-0.2141
BD	0.3260	0.3511	0.4743	-0.1872
WHC	0.1578	0.7361	-0.4772	0.3176
EA	0.6740	0.0680	0.5119	0.0665
EB	-0.4889	-0.6843	-0.1095	-0.4015
BS	0.2128	-0.4265	-0.1026	-0.6825
CEC	-18.0132	-18.4488	-0.3005	-0.1307
pH	-52.2675	-49.7003	0.2154	0.0837
OC	53.8556	52.0514	0.0956	0.0337
Total N	0.9700	0.0171	0.3995	0.1704
Av. Ca	1.0095	0.3770	0.8494	-0.0219
Av.Mg	-0.1181	-0.0794	0.5335	0.0861
Na	0.1298	0.2513	0.3760	0.1028
K	-0.3778	0.0859	-0.0510	0.0727
P	0.0168	0.3001	0.2106	0.1280

The canonical redundancy analysis showed that 37 per cent of the variance of the leaf attributes was explained by the first two soil canonical variables while 14 per cent of the variance of soil attributes was explained by the first two leaf canonical variables (Table 11).

Table 11. Standardized variance of the leaf and soil attributes explained by the opposite canonical variables (soils in the 0-20 cm depth level)

Canonical variable	Standardized variance of leaf		Standardized variance of soil	
	Proportion	Cumulative proportion	Proportion	Cumulative proportion
1	0.1754	0.1754	0.1038	0.1038
2	0.1956	0.3710	0.0387	0.1425
3	0.0858	0.4569	0.0187	0.1612
4	0.0487	0.5056	0.0180	0.1792
5	0.0282	0.5338	0.0072	0.1864

The squared multiple correlations between the leaf attributes and the two significant canonical variables of the soil characters are given in Table 12. The first soil canonical variable, which was a linear function of soil Ca, had some predictive power for leaf Ca. The second canonical variable for soil, which was mainly a linear function of base saturation, had some predictive power for leaf K and leaf Ca.

Table 12. Squared multiple correlations between the leaf attributes and the two significant canonical variables of the soil attributes (0-20 cm depth level)

Leaf attributes	Canonical variables	
	Soil 1	Soil 2
N	0.1833	0.2887
P	0.0414	0.2657
K	0.0790	0.6082
Ca	0.5684	0.6036
Mg	0.0050	0.0889

The squared multiple correlations between the soil characters and the two significant canonical variables of the leaf characters are given in Table 13. The first canonical variable for leaf, which was a linear function of leaf Ca, was a good predictor of soil Ca. The second leaf canonical variable, which was a linear combination of leaf K and leaf P, had some predictive power for soil Ca.

Table 13. Squared multiple correlations between the soil attributes and the two significant canonical variables of the leaf attributes (0-20 cm depth level)

Soil attributes	Canonical variables	
	Leaf 1	Leaf 2
Gravel	0.0333	0.0343
Sand	0.0198	0.0541
Silt	0.0479	0.1109
PD	0.0213	0.0516
BD	0.1755	0.1986
WHC	0.1777	0.2442
EA	0.2044	0.2074
EB	0.0094	0.1157
BS	0.0082	0.3156
CEC	0.0704	0.0817
pH	0.0362	0.0408
OC	0.0071	0.0079
Total N	0.1245	0.1437
Av. Ca	0.5629	0.5632
Av.Mg	0.2221	0.2270
Na	0.1103	0.1173
K	0.0020	0.0055
P	0.0346	0.0454

The canonical redundancy analysis showed that the variations in leaf attributes were greatly influenced by soil attributes while the variation in soil attributes was less influenced by the leaf attributes.

Soils in the 20 - 40 cm depth level

The simple linear correlation coefficients between the leaf and soil attributes at 20-40 cm layer are given in Table 14.

The correlation is low or moderate between many variables. The largest correlation coefficient, 0.4992 was between leaf Ca and soil Mg and the correlation was positive. The positive relationship between leaf Ca and soil Ca was also significant. Soil WHC had a negative influence on the leaf Ca.

Table 14. Coefficients of correlations between the leaf attributes and the soil attributes in the 20-40 cm depth level

Soil attributes	Leaf attributes				
	N	P	K	Ca	Mg
Gravel	0.0934	-0.0766	0.0184	-0.1005	0.2522
Sand	0.0977	0.1832	0.2931	-0.2244	-0.0949
Silt	-0.1094	-0.0801	-0.3374	0.2438	0.1014
PD	-0.3584	-0.3182	-0.3755	0.3011	-0.2255
BD	-0.2388	0.1765	-0.0739	0.2744	0.0139
WHC	0.2901	-0.1369	0.3613	-0.4420	0.1606
EA	-0.4218	0.1498	-0.1911	0.3356	-0.0554
EB	0.1662	-0.0537	-0.0307	-0.1753	0.0688
BS	-0.1004	-0.2999	-0.3328	-0.0078	-0.1057
CEC	0.3416	-0.0804	0.0446	-0.2906	0.0904
pH	0.0256	0.1617	-0.0101	0.0832	0.1615
OC	0.1150	0.1373	0.0019	0.0050	0.1820
Total N	-0.1967	0.1646	-0.0639	0.3148	0.0777
Av. Ca	-0.3256	0.2285	-0.2220	0.4262	0.1024
Av. Mg	-0.2015	0.2922	-0.2159	0.4992	0.1448
Na	-0.2324	-0.0748	-0.3157	0.4237	0.0918
K	0.1045	0.0426	0.0423	0.0414	0.0567
P	-0.1598	0.1901	-0.0946	0.2626	-0.1815

The canonical correlations between foliar and soil attributes are reported in Table 15. The likelihood ratio test revealed that the first one of these correlations was significant. The corresponding canonical variate accounted for about 52 per cent of the total variability in the variables measured on leaves.

Table 15. Eigen values and canonical correlation between leaf and soil variables in the 20-40 cm depth level

No	Eigen value	Canonical correlation	Proportion of variance	Cumulative proportion
1	2.4882	0.4460	0.5171	0.5171
2	1.3361	0.7563	0.2777	0.7947
3	0.4728	0.5666	0.0983	0.8930
4	0.3470	0.5075	0.0721	0.9651
5	0.1679	0.3791	0.0349	1.0000

The standardised canonical coefficients for the leaf attributes and correlation between the leaf attributes and the single significant canonical variable are given in Table 16. The canonical variable for leaf was a linear combination of leaf Ca, leaf N and leaf K.

Leaf Ca had positive correlation with the leaf canonical variable, whereas leaf N and K had negative correlations with the leaf canonical variable.

Table 16. Standardized canonical coefficients for the leaf attributes and correlation between the leaf attributes and the single significant canonical variable (20-40 cm depth level)

Leaf attributes	Canonical coefficients	Correlations
	Leaf 1	Leaf 1
N	-0.4795	-0.5506
P	0.6918	0.2005
K	-0.3948	-0.5475
Ca	0.4819	0.7903
Mg	-0.0315	-0.0104

The standardized canonical coefficients for the soil attributes and correlations between the soil attributes and the significant canonical variable are presented in Table 17. The soil canonical variable was a linear combination of Mg, Ca, WHC and EA. The properties Mg, Ca and EA had positive correlation with the canonical variable. Water holding capacity had a negative correlation with the soil canonical variable. This showed that the nutrient status and exchange acidity had positive correlation, while the physical property *viz*., WHC had negative correlation with the soil canonical variable.

Table 17. Standardized canonical coefficients for the soil attributes and correlation between the soil attributes and the significant canonical variables (20-40 cm depth level)

Soil attributes	Canonical coefficients	Correlations
	Soil 1	Soil 1
Gravel	0.0004	-0.1911
Sand	0.0867	-0.1669
Silt	0.2332	0.2895
PD	-0.2311	0.2986
BD	0.3360	0.4707
WHC	-0.3390	-0.7038
EA	0.3905	0.6450
EB	-0.2871	-0.2265
BS	0.2981	-0.0336
CEC	0.9471	-0.4498
pH	-1.0608	0.1641
OC	0.0000	0.0423
Total N	1.2255	0.4531
Av. Ca	0.2321	0.7151
Av.Mg	0.0265	0.7341
Na	0.2893	0.4565
K	-0.0312	-0.0227
P	0.0872	0.4472

The canonical redundancy analysis showed that 18 per cent of the variance of the leaf attributes was explained by the first soil canonical variable while 13 per cent of the variance of soil attributes was explained by the first leaf canonical variable (Table 18).

Table 18. Standardized variance of the leaf and soil attributes explained by the opposite canonical variables (20-40 cm depth level)

Canonical variable	Standardized variance of leaf		Standardized variance of soil	
	Proportion	Cumulative proportion	Proportion	Cumulative proportion
1	0.1809	0.1809	0.1315	0.1315
2	0.0936	0.2744	0.0389	0.1704
3	0.0814	0.3558	0.0215	0.1919
4	0.0341	0.3899	0.0089	0.2008
5	0.0283	0.4182	0.0115	0.2123

The squared multiple correlations between the leaf attributes and the significant canonical variable of the soil characters are given in Table 19. The soil canonical variable, which was a linear combination of Mg, Ca, WHC and EA, had some predictive power for leaf Ca.

Table 19. Squared multiple correlations between the leaf attributes and the significant canonical variable of the soil attributes (20-40 cm depth level)

Leaf attributes	Canonical variable
	Soil 1
N	0.2163
P	0.0287
K	0.2138
Ca	0.4455
Mg	0.0001

The squared multiple correlations between the soil characters and the single significant canonical variable of the leaf characters are given in Table 20. The leaf canonical variable, which was a linear combination of leaf Ca, leaf N and leaf K, is a good predictor of soil Mg, Ca and WHC.

The redundancy analysis showed that variation in leaf characters was reasonably related to the soil canonical variables but less so when the reverse relation was considered.

Table 20. Squared multiple correlations between the soil attributes and the significant canonical variable of the leaf attributes (20-40 cm depth level)

Soil attributes	Canonical variable
	Leaf 1
Gravel	0.0261
Sand	0.0199
Silt	0.0598
PD	0.0636
BD	0.1580
WHC	0.3534
EA	0.2967
EB	0.0368
BS	0.0008
CEC	0.1443
pH	0.0192
OC	0.0013
Total N	0.1464
Av. Ca	0.3647
Av. Mg	0.3844
Na	0.1487
K	0.0004
P	0.1426

Soils in the 40 - 60 cm depth level

The simple linear correlation coefficients between the leaf and soil attributes at 40-60 cm layer are given in Table 21.

The correlation is low or moderate between many variables. The largest correlation coefficient, 0.5140 was between leaf Ca and soil Mg and the correlation was positive. Significant positive correlations were seen between soil Ca and leaf Ca and significant negative correlation was seen between soil WHC and leaf Ca.

The canonical correlations between foliar and soil attributes are reported in Table 22. The likelihood ratio test revealed that the first two of these correlations were significant. The corresponding canonical variates accounted for about 70 per cent of the total variability in the variables measured on leaves.

Table 21. Coefficients of correlations between the leaf attributes and soil attributes in the 40-60 cm depth level

Soil attributes	Leaf attributes				
	N	P	K	Ca	Mg
Gravel	-0.2205	-0.1926	-0.1999	-0.0766	0.1339
Sand	0.1671	0.2082	0.0892	0.0172	0.1295
Silt	-0.1474	0.0599	-0.2054	0.2174	0.0710
PD	-0.0910	-0.0032	-0.1586	0.2213	-0.2059
BD	-0.2017	0.1817	-0.1717	0.3646	-0.0545
WHC	0.2635	0.0324	0.3916	-0.4729	0.2790
EA	-0.3976	0.1656	-0.1814	0.3240	-0.0182
EB	0.1930	0.0056	-0.0058	-0.1808	0.0795
BS	0.2384	-0.1235	-0.0781	-0.0792	0.0035
CEC	0.2725	-0.0587	0.0778	-0.3377	0.0061
pH	0.0058	0.2683	0.0079	0.0654	0.1733
OC	0.0697	0.2457	0.0264	-0.0173	0.1688
Total N	-0.1596	0.2318	-0.0614	0.3390	0.1669
Av. Ca	-0.3477	0.2287	-0.2140	0.4068	0.0325
Av.Mg	-0.2891	0.2322	-0.2063	0.5140	0.0438
Na	-0.2632	0.0776	0.0735	0.1179	-0.2192
K	0.1130	0.0817	0.0738	0.0574	0.0538
P	-0.1744	0.2907	-0.1834	0.2597	-0.3295

Table 22. Eigen values and canonical correlation between leaf and soil variables in the 40-60 cm depth level

No	Eigen value	Canonical correlation	Proportion of variance	Cumulative proportion
1	2.5105	0.8457	0.3694	0.3694
2	2.2405	0.8315	0.3296	0.6990
3	1.0708	0.7191	0.1575	0.8565
4	0.5625	0.6000	0.0828	0.9393
5	0.4126	0.5405	0.0607	1.0000

The standardised canonical coefficients for the leaf attributes and correlation between the leaf attributes and their two significant canonical variables are given in Table 23. The first canonical variable for leaf was a linear combination of leaf Ca and leaf K. Leaf Ca had positive correlations with the first leaf canonical variable and leaf K had negative correlation with the first leaf canonical variable.

The second leaf canonical variable was a function of leaf P and leaf N. Leaf P had positive correlation with the second canonical variable and leaf N had negative correlation with the second canonical variable.

Table 23. Standardized canonical coefficients for the leaf attributes and correlation between the leaf attributes and their two significant canonical variables (40–60 cm depth level)

Leaf attributes	Canonical coefficients		Correlations	
	Leaf 1	Leaf 2	Leaf 1	Leaf 2
N	-0.1271	-1.2151	-0.3592	-0.3314
P	0.8290	0.6965	0.3223	0.3719
K	-0.6057	0.3054	-0.4592	0.2456
Ca	0.4613	-0.5649	0.6659	-0.2553
Mg	-0.3770	0.5346	-0.2702	0.2225

The standardized canonical coefficients for the soil attributes and correlations between the soil attributes and their significant canonical variables are presented in Table 24. The first soil canonical variable was a linear combination of soil P, Mg, WHC, Ca, BD, exchange acidity and N.

The second soil canonical variable was a linear combination of base saturation and exchange acidity. Exchange acidity had a positive correlation with the second canonical variable, whereas base saturation had a negative correlation with the second canonical variable.

The canonical redundancy analysis showed that 20 per cent of the variance of the leaf attributes was explained by the first two soil canonical variables while 17 per cent of the variance of soil attributes was explained by the first two leaf canonical variables (Table 25).

The squared multiple correlations between the leaf attributes and the two significant canonical variables of the soil characters are given in Table 26. The first soil canonical variable, which is a linear combination of soil P, Mg, WHC, Ca, BD, exchange acidity and N, had some predictive power for leaf Ca. The second canonical variable for soil, which is a linear combination of base saturation and exchange acidity, had some predictive power for leaf Ca.

Table 24. Standardized canonical coefficients for the soil attributes and correlation between the soil attributes and their two significant canonical variables (40–60 cm depth level)

Soil attributes	Canonical coefficients		Correlations	
	Soil 1	Soil 2	Soil 1	Soil 2
Gravel	0.0128	0.2978	-0.1140	0.2256
Sand	-1.2456	1.7089	0.0667	0.0346
Silt	-0.2000	0.7792	0.3150	0.0881
PD	0.4100	-0.2518	0.3367	-0.2107
BD	0.3724	0.4984	0.5545	0.1011
WHC	-0.2069	0.8840	-0.6707	0.2867
EA	0.0678	0.6309	0.5370	0.4213
EB	-0.1609	-0.0422	-0.1534	-0.1054
BS	-0.4144	-0.2323	-0.1457	-0.4244
CEC	86.5300	-77.8005	-0.3412	-0.1854
pH	355.8806	-321.9650	0.2149	0.2861
OC	-365.7990	330.9046	0.1268	0.2338
Total N	-1.0730	0.8296	0.4057	0.2818
Av. Ca	-0.4089	0.9850	0.6371	0.3657
Av.Mg	0.4367	-1.0485	0.6797	0.2203
Na	0.0932	0.1281	0.2250	0.2556
K	-0.1188	0.0190	0.0176	-0.0740
P	0.4670	0.1524	0.7311	0.0428

Table 25. Standardized variance of the leaf and soil attributes explained by the opposite canonical variables (40–60 cm depth level)

Canonical variable	Standardized variance of leaf		Standardized variance of soil	
	Proportion	Cumulative proportion	Proportion	Cumulative proportion
1	0.1373	0.1373	0.1238	0.1238
2	0.0585	0.1959	0.0411	0.1650
3	0.0699	0.2658	0.0273	0.1922
4	0.0665	0.3323	0.0224	0.2147
5	0.1178	0.4501	0.0117	0.2264

Table 26. Squared multiple correlations between the leaf attributes and the two significant canonical variables of the soil attributes (40–60 cm depth level)

Leaf attributes	Canonical variables	
	Soil 1	Soil 2
N	0.0923	0.1682
P	0.0743	0.1699
K	0.1508	0.1925
Ca	0.3171	0.3622
Mg	0.0522	0.0864

The squared multiple correlations between the soil characters and the two significant canonical variables of the leaf characters are given in Table 27. The first canonical variable for leaf, which was a linear combination of leaf Ca and leaf K, is a better predictor of soil P. The second leaf canonical variable is a function of leaf P had some predictive power for soil P, Ca and WHC.

Table 27. Squared multiple correlations between the soil attributes and the two significant canonical variables of the leaf attributes (40–60 cm depth level)

Soil attributes	Canonical variables	
	Leaf 1	Leaf 2
Gravel	0.0093	0.0445
Sand	0.0032	0.0040
Silt	0.0710	0.0763
PD	0.0811	0.1118
BD	0.2199	0.2270
WHC	0.3217	0.3786
EA	0.2062	0.3289
EB	0.0168	0.0245
BS	0.0152	0.1397
CEC	0.0832	0.1070
pH	0.0330	0.0896
OC	0.0115	0.0493
Total N	0.1177	0.1726
Av. Ca	0.2903	0.3827
Av. Mg	0.3304	0.3639
Na	0.0362	0.0814
K	0.0002	0.0040
P	0.3822	0.3835

4. DISCUSSION

In the present study, two major modelling approaches *viz*., empirical and process-based have been used to characterize the interrelation of tree growth *vs* soil and tree growth *vs* foliar nutrient status. Empirical approach is based on the response surface methodology propounded by Box and Draper (1987), which essentially tries to approximate an unknown response-input relation, by a quadratic function in the independent variables. Reduction in the number of predictor variables was achieved through stepwise procedure. The process model on the other hand is based on well-structured biologically valid functions and parameters, although some variable selection procedure was required for such models in the present case. The relationship between the leaf and soil attributes was studied through canonical correlation analysis. The implications, importance and limitations of the results are discussed below.

The relation between tree growth and soil attributes

Empirical model

For the first depth level (0-20 cm), it was found that there was no significant relationship between soil properties and tree growth. This may be due to plantation activities, and especially during taungya cultivation, the soils in the surface layer would have been eroded and the soils in the sub surface layer exposed. The penetration of roots and the availability of nutrients in the sub surface layer would not be similar to those in the surface layer. This shows the necessity of soil amendments in the exposed sub surface layer.

In 20-40 and 40-60 cm depth levels, the tree growth was significantly influenced by soil pH (acidity). The results showed that with increase in soil pH in both depth levels, there was corresponding increase in the tree diameter growth. In the 20-40 cm depth level, with the increase in soil bulk density, there was subsequent decrease in tree diameter growth. This clearly indicates that the soil compaction and soil reaction affects the growth of trees.

For the combined set *i.e.*, when properties of soils in all layers (0-20, 20-40 and 40-60 cm layer) were taken together, bulk density and soil pH in the 20-40 cm layer showed significant influence on tree diameter growth. The results agree with those of Bhatia (1955) and Akinsanmi (1985). In young teak plantations, because of plantation activities, this phenomenon will be very prominent and hence ameliorative measures such as control of soil and water erosion, soil amendments etc., will be required in such teak plantations.

In all the depth levels, no quadratic terms showed up in the model. As such, the optimum levels of soil attributes, which maximize the tree growth, could not be determined through canonical analysis. This could be because of the shorter range of soil properties observed under natural conditions.

In the empirical growth model, by replacing the site index with the soil parameters *viz*., BD and pH in 20-40 cm depth level, the value of the adjusted R^2 increased from 0.333 to 0.608. This could be due to the simple fact that soil variables are more accurately measured than site index.

Process-based model

The basic model structure used in the study corresponds to the model proposed by Jayaraman and Induchudan (2004). Site index in the model was replaced by significant soil attributes identified through stepwise regression analysis relating site index and soil attributes.

In the 20-40 cm layer, WHC and K of soils significantly influenced the site index. The model had an adjusted R^2 value of 0.291, which is greater than that of the surface and deeper layers (0-20 and 40-60 cm depth levels). The results were such that with the increase in K, site index increased, but with the increase in WHC, site index decreased. Alexander *et al*. (1987) in a statewide study on teak plantations had noted that 31% of the variation in top height was accounted by soil variables *viz*., gravel, sand, pH, EA and EB.

In the process-based model, WHC in 20- 40 cm depth level was turned out to be significant, whereas the estimate of the soil K parameter was found nonsignificant. The adjusted R^2 value for the diameter increment function was 0.55, a reasonable value to expect under uncontrolled conditions. The results also indicated an almost linear decrease in the diameter growth with increase in the soil WHC in 20-40 cm depth level, keeping other factors constant.

By replacing the site index with the soil parameters *viz.*, WHC in the 20-40 cm depth level in the growth model, the value of the adjusted R^2 changed from 0.5025 to 0.5475.

The empirical approach had showed the contribution of bulk density and pH in 20-40 cm layer in tree growth whereas the process-based approach identified WHC at the same depth level as the major soil variables significantly influencing tree growth. Admittedly, although soil K has relation with site index, this need not be shown up in the model for diameter growth.

It is of interest to note that bulk density and pH in 20-40 cm layer came out as influential variable in the empirical approach but WHC in 20-40 cm layer was shown to be important in the process-based approach. Some disparity in such results could occur due to the scale used for the analysis. The selection of specific variables could also be easily affected by the modeling approach but the overall message that comes out through the analysis is that soil compaction (bulk density) which in turn controls the water holding capacity and soil reaction (pH) has much to do with tree growth. Equally important is the soil depth level (20-40 cm), which exerts maximum influence on the growth of trees occupying the site.

The results showed that by replacing the site index with the soil parameter WHC in 20-40 cm depth level, the value of the adjusted R^2 changed from 0.5025 to 0.5475, leaving still a dominant portion of the variation in diameter growth unexplained by the model. This indicates that the growth attained during any time interval is affected by a large number of extraneous factors other than soil or stand variables and also that such factors could either mask or vitiate the effect of soil variables on growth.

The optimum levels of soil attributes, which maximize the tree growth, could not be determined due to restricted range of soil properties. This happened as a natural consequence of the absence of sites belonging to I and II site quality classes for several age classes.

The present study was conducted in teak plantations widely distributed all over the state. No deliberate attempts were made to control the status of soils and leaf attributes. The natural variation was left uncontrolled, except for the effect of age. The range of variation found in the values of each characteristic in a given depth level is an important factor to be considered while judging the significance of their effect on tree growth. In many instances, the range of variation was found to be small. Even when an element has significant effect, the chance of getting it masked by uncontrolled factors related to microclimate and inter-tree competition is high in a study like this. Hence, many variables which might have influenced the tree growth may not appear in the final equation of the stepwise regression. Also, in some cases, by sheer chance, some variables may accidentally get included in the final equation even when they have no significance on tree growth, although chances of such occurrence are low. Additionally, when there is high intercorrelation among the regressor variables, the stepwise regression is likely to exclude many variables from the final model considering them as redundant. In spite of the limitations, certain broad indications were obtained by the use of the procedures.

Finally, an important limitation of this approach was that the tree growth, which is a manifestation of long years of complex interactions with soils and climate, need not show good relationship with current soil fertility attributes or leaf nutrient status like in agricultural crops. Nevertheless, the observation that almost 33 per cent of the variation in tree growth could be explained by soil properties (bulk density and pH) belonging to sub surface layer; and also almost 29 per cent of variation in the site index could be explained by the soil nutrient (K) levels, are quite notable.

Relation between tree growth and nutrient status of leaves

The regression analysis for relating diameter growth and leaf nutrient attributes indicated that tree diameter growth was not significantly related to leaf nutrients. This may be due to the fact that the growth is influenced by multifarious factors and nutrient composition of leaves alone cannot be considered as a good indicator in this regard.

The relation between soil attributes and nutrient status of leaves

In the first depth level (0-20 cm), the simple linear correlation between leaf characters and the soil characters was low or moderate in many cases. Highest correlation was between leaf Ca and soil Ca and the correlation was positive. Also, soil base saturation had significant negative effect on leaf K and P.

The first soil canonical variable, a function of Ca was highly correlated with the first leaf canonical variable represented by leaf Ca alone. Soil Ca had significant positive effect on leaf Ca. The second soil and leaf canonical variables suggest that leaf K and P is significantly influenced by soil BS.

Teak being calcicole, the requirement of the tree with respect to calcium is more and is manifested in the leaves.

The canonical redundancy analysis showed that 37 per cent variations in leaf attributes are influenced by soil attributes, which is physiologically justifiable. At the same time, 14 per cent variation in soil characters was found influenced by the leaf characters. This could be due to the fact that, leaf fall and litter decomposition depends on several extraneous factors and hence, the strength of this relationship is very weak. In the plantations, it is observed that most of the feeding roots are concentrated in the surface layer and hence the absorption of nutrients from this layer will be more when compared to other layers. Thus, per cent contribution of soil variables affecting leaf properties is relatively higher in this layer.

In the second depth level (20-40 cm), there was a significant positive correlation between soil Mg and leaf Ca concentrations. The positive relationship between leaf Ca and soil Ca was also significant.

The soil and leaf canonical variables in this depth level indicated that leaf Ca, N and K status are significantly influenced by soil Mg, Ca, WHC and EA. The redundancy analysis showed that in this depth level, only 18 per cent of variation in leaf characters is explained by the soil canonical variable and 13 per cent of variance in soil characters is explained by the leaf canonical variable.

In 40-60 cm depth level, the simple linear correlation between two sets of variables was low in many cases. However, significant positive correlations were seen between soil Mg and leaf Ca, soil Ca and leaf Ca and significant negative correlation was observed between soil WHC and leaf Ca.

The first soil and leaf canonical variables advocate that leaf Ca and K concentration is significantly influenced by soil P, Mg, WHC, Ca, BD, EA and N. The second soil and leaf canonical variables imply that leaf P and N concentration is significantly influenced by soil BS and EA.

The canonical redundancy analysis showed that 20 per cent variation in the leaf attributes was explained by the first two soil canonical variables while 17 per cent variation in soil attributes was explained by the first two leaf canonical variables.

The soil and leaf variables found significant in each depth level and their percent contribution are reported in the Table 28 in summary form.

Table 28. Summary of canonical correlation analysis in each depth level

Soil depth level (cm)	Soil variables affecting leaf properties	Percent contribution of soil attributes	Leaf variables affecting soil properties	Percent contribution of leaf attributes
0-20	Ca and BS	37	P, K and Ca	14
20-40	Mg, Ca, WHC and EA	18	Ca, N and K	13
40-60	P, Mg, WHC, Ca, BD, EA, N, BS and EA	20	Ca, K, P and N	17

On the whole, the canonical correlation analysis revealed the significant intercorrelations existing between leaf and soil attributes. Besides, this analysis has shown that the leaf nutrient content influences the soil attributes to a great extent due to effect of litter fall and nutrient return to soil. This is supportive of the fact that teak returns more nutrients than it retains and, therefore, is more efficient in recycling the nutrients (George and Varghese, 1992).

5. CONCLUSIONS

The study conducted on modelling the growth of teak in relation to soil conditions from 52 permanent sample plots distributed in different parts of Kerala led to the following conclusions:

1. In the empirical approach, the relation between tree growth and soil characteristics varied with the soil depth levels. Almost 33 per cent of the variation in tree diameter growth was explained by the soil attributes *viz*., soil bulk density and pH in the 20-40 cm depth level. This clearly indicates that the soil compaction and soil reaction affect the growth of trees. In young teak plantations, this phenomenon was very prominent and ameliorative measures such as control of soil and water erosion, soil amendments etc., are required. The models obtained through stepwise regression were all linear in nature and no quadratic terms were present. In all the three depth levels, the optimum levels of soil attributes, which maximize the tree diameter growth, were not attained within the range of the data.
2. In the process-based approach, WHC in the 20-40 cm depth level was identified as the major soil variable significantly influencing tree growth. The optimum levels of soil attributes, which maximize the tree growth, could not be determined because of the shorter range of soil properties observed under natural conditions.
3. The results obtained from both the approaches indicated that soil compaction (bulk density) and soil reaction (pH) exerts a major influence on tree growth.
4. Study on the relation between leaf nutrient status and tree growth indicated that the growth is influenced by multifarious factors and nutrient composition of leaves alone cannot be considered as a good indicator in this regard.
5. In all the three depth levels, the canonical redundancy analysis showed that leaf nutrient status is deeply influenced by soil attributes.
6. The process-based approach is preferable over empirical approach to study soil-tree growth relationship on account of its biological validity.

7. REFERENCES

A S A.1965. *Methods of Analysis*. Parts 1 & 2. C.A. Black *et al*. American Society of Agronomy, Madison, Wisconsin, USA. 1572p.

Akinsanmi, F.A. 1985. Effects of rainfall and some edaphic factors on teak growth in Southwestern Nigeria. *Journal of Tropical Forest Science*, 1: 44 –52.

Alexander T. G., Sankar S., Balagopalan M. and Thomas P. T. 1987. Soils in teak plantations of different site quality. KFRI Research Report. 45, Kerala Forest Research Institute, Peechi. 17 p.

Bhatia, K.K. 1955. Foliar Ca of teak. *Journal of Indian Botanical Society*, 34: 227-234.

Box, G.E.P. and Draper, N.R. 1987. *Empirical Model Building and Response Surface.* John Wiley & Sons, Inc. New York, NY, USA. 669 p.

Chaturvedi, A.N. 1973. General standard volume tables and height-diameter relationship for teak (*Tectona grandis*). Indian Forest Records (NS). Silviculture, Vol. 12, No. 8, Manager of Publications, Delhi. 8p.

Chongsuksantikun, P. and Tantiraphan, W. 1991. Study on the relationship between some soil properties and growth of *Tectona grandis*. *Van saran*, 49:38-41.

Dager, J.C., Mongia, A.D. and Singh, N.T. 1995. Degradation of tropical rain forest soils upon replacement with plantations and arable crops in Andaman and Nicobar Islands in India. *Tropical Ecology*, 36(1): 89-101.

Gagnon, J.D. 1964. Relationship between site index and foliar nitrogen at two crown levels for mature black spruce. *Forestry*, 29(1): 22-28.

George, M. and Varghese, G. 1992. Nutrient cycling in Tectona grandis plantation. *Journal of Tropical Forestry*, 8(2): 127-133.

Glaser, B. and Drechsel, P. 1992. Relation between ‘available’ soil phosphate and the foliar phosphate contents of *Tectona grandis* (teak) in West Africa. *Zeitschrift- fur- pflanenernahrung-und-Bodenkunde*, 155: 115-119.

Hardy, F.M.C., Donal, J.A. and Rodriduez, G. 1935. Leaf analysis as a means of diagnosing nutrient requirements of tropical orchard crops. *Journal of Agricultural Science*, 25: 620-627.

Hernandez, R., Torres, A., Marquez, O. and Franco, W. 1993. Foliar nutrient content and growth in teak plantations in Ticoporo Venezuela.(Spanish). *Turrialba*, 43: 11-15.

Jackson, M.L. 1958. *Soil Chemical Analysis*. Prentice Hall Inc., USA. 428p.

Jayamadhavan, A. 1996*. Nutrient deficiency diagnosis in Tectona grandis* L.F. M. sc Thesis. College of Forestry, KAU, Thrissur, Kerala.

Jayaraman, K. 1998. Structural Dynamics of Teak Stands in Kerala. KFRI Research Report No. 141. Kerala Forest Research Institute, Peechi, Kerala. 28p.

Jayaraman, K. 2002. Stand dynamics of selected forest plantation species of Kerala. KFRI Research Report No. 233, Kerala Forest Research Institute, Peechi, 26p.

Jayaraman, K. and Induchudan, N.C. 2004. Testing an Alternative Thinning Schedule for Teak Plantations based on a Simulation Model. KFRI Research Report No. 257, Kerala Forest Research Institute, Peechi, Kerala. 23p.

Jayaraman, K. and Lappi, J. 2001. Estimation of height-diameter curves through multilevel models with special reference to even-aged teak stands. *Forest Ecology and Management*, 142: 152-162.

Jayaraman, K. and Rugmini, P. 2007. A growth simulation model for even-aged teak stands and its applications in plantation management. (Submitted for publication in *Journal of Tropical Forest Science*).

Kaul, O.N., Gupta, A.C. and Negi, J.D.S. 1972. Diagnosis of mineral deficiencies in teak (*Tectona grandis*) seedlings. *Indian Forester*, 98(3): 173-177.

Mead, D.J. 1984. Diagnosis of nutrient deficiencies in plantation Ecosystems. In: Nutrition of Plantation Forests. Academic Press, London, 53-78.

Miller, H.G. 1984. Dynamics of nutrient cycling in plantation ecosystems. In: *Nutrition of Plantation Forests*. Academic Press, London, 259-291.

Montgomery, D.C.1991. *Design and Analysis of Experiments*. Third edition. John Wiley and Sons, New York, 549p.

Montogomery, D.C. and Peck, E.A. 1982. *Introduction to Linear Regression Analysis.* John Wiley and Sons, New York, 504p.

Norusis, M.J. 1988. SPSS/PC + Advanced Statistics Version 2.0 for the IBM PC/XT//AT and PS/2. SPSS Inc. Chicago**.**

Pande, P.K. and Sharma, S.C. 1988. Litter nutrient dynamics of some plantations at New Forest, Dehra Dun. *Journal of Tropical Forestry*, 4(4): 339-349.

Prabhu, N. 2003. Teak in Kerala, India: Past, Present and Future. Pp. 54 – 62 in Bhat, K. M. *et al*. (Eds.) *Quality Timber Products of Teak from Sustainable Forest Management. Proceedings of the International Tropical Timber Organization*. 2-5 December 2003, Kerala Forest Research Institute, Peechi, Kerala, India.

Puri, G.S. 1954. Foliar constituents in some tree species of *Shorea Robusta* Forests of the Siwaliks, U.P. *Indian Forester*, 4: 339-349.

Rao, C.R., 1973. *Linear Statistical Inference and its Applications*. Second edition, Wiley Eastern Pvt. Ltd., New Delhi, 625p.

Reineke, L.H. 1933. Perfecting a stand-density index for even-aged forests. *Journal of Agricultural Research,* 46: 538-540.

Rugmini, P. and Jayaraman, K.2006. Intrinsic units of growth for teak trees. (Submitted for publication in *Trees - Structure and Function*)

SAS. 1993. SAS/ETS® User's Guide. Version 6, Second Edition, SAS institute Inc., SAS Campus Drive, Cary, NC 27513, U.S.A. 507-684.

Seth, S.K. and Yadav, J.S.P. 1957. Country report from India on silviculture and management of teak. FAO teak sub commission, Baddung FAO/TSC 57/7, 21p.

Sharma, S.C. and Pande, P.K.1989. Patterns of litter nutrient concentration in some plantation eco-system. *Forest Ecology and Management*, 29:151-163.

Singh, P., Das, P.K., Nath, S and Banerjee, S.K. 1990. Characteristics of teak (*Tectona grandis*) growing soils in the tarai region of West Bengal. *Van Vigyan,* 28(1/2): 6-15.

Vimal, M. 1999. Soil-plant nutritional status of *Tectona grandis* L.f. in relation to age and site quality. M.Sc Thesis , Kerala Agricultural University, Thrissur, Kerala, India, 90p.

Vimal, M., Sudhakara, K., Jayaraman, K. and Sunanda, C. 2005. Effect of soil-leaf nutritional factors on the productivity of Teak (Tectona grandis L.F.) in Kerala State, India. In: Proceedings of the paper presented in International Conference on Quality Timber Products of Teak from Sustainable Forest Management, 2-5 December 2003, Kerala Forest Research Institute, Peechi, India,. 530-539.

Zech, W. 1990. Mineral deficiencies in forest plantations of North-Luzon, Philippines. *Tropical Ecology*, 31(1): 22-31.

Zech, W and Drechsel, P. 1991. Relationships between growth, mineral nutrition and site factors of teak (*Tectona grandis*) plantations in the rainforest zone of Liberia. *Forest Ecology and Management*, 41(1&2): 221-235.

Zeide, B. 2004. Optimal stand density: a solution. *Canadian Journal of Forest Research*, 34: 846-854.

Zeide, B. 2005. How to measure stand density. *Tree - Structure and Function*, 19(1): 1-14.