SOIL - PLANT NUTRITIONAL STATUS OF *Tectona grandis* L.f. IN RELATION TO AGE AND SITE QUALITY

By
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THESIS

Submitted in partial fulfilment of the requirement for the degree of

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DECLARATION

I hereby declare that this thesis entitled "SOIL-PLANT NUTRITIONAL STATUS OF *Tectona grandis* L.f. IN RELATION TO AGE AND SITE QUALITY" is a bonafide record of research work done by me during the course of research and that this thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title of any other University or Society.

Vellanikkara
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CERTIFICATE

Certified that this thesis entitled "SOIL-PLANT NUTRITIONAL STATUS OF *Tectona grandis* L.f. IN RELATION TO AGE AND SITE QUALITY" is a record of research work done independently by **Sri. Vimal, M.** under my guidance and supervision and that it has not previously formed the basis for the award of any degree, fellowship or associateship to him.

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VIMAL, M.

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Introduction

INTRODUCTION

Teak (*Tectona grandis* L.f.) belonging to the family Verbenaceae is the most important timber tree species of South and South-east Asia. It is a large deciduous tree indigenous to India. Endowed with the characteristic of most versatile use, teak is extensively used in ship building, house construction, bridge and wharf, furniture and for most of the common purposes for which wood is used (Champion and Griffith, 1960).

In Kerala teak has been raised as plantations since 1844. The major expansion in area under teak in the State occurred during the period 1960-1980. As a result, nearly 50 per cent of the area under forest plantations in the State is occupied by teak. The Kerala Forest Department has about 78,000 ha. of teak plantations at present (KFRI, 1992). Since the demand for teak timber is ever increasing and further increase in the area under teak in the public sector is unlikely, productivity of the existing plantations is of utmost importance. This calls for effective plantation management including a reduction in the rotation age of the species. One of the ways to achieve this goal is through proper nutrient management of the plantations.

A knowledge of importance and deficiencies of different nutrient elements is a pre-requisite in any plant nutrition programme. Teak is characterised by relatively high nutrient requirements (Zech and Drechsel, 1991). They also reported that nutrient deficiencies can bring about reduced stand growth in teak.

The pattern of nutrient cycling in the plantations has revealed that nutrient deficiencies are essentially problems of youth and old age trees (Miller, 1984). 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 qualities.

In tree crops, foliage analysis is reasonably sensitive for detecting nutrient deficiencies and also has the advantage of being directly related to productivity as foliage is the site of photosynthesis (Mead, 1984). Also, in teak, leaves contribute to a major share of the nutrient budget (Pande and Sharma, 1988).

Soil testing helps to predict deficiencies, stand growth and amount of fertilizers to be applied (Mead, 1984). If nutrient supply is inadequate, deficiency symptoms may appear. But in many cases, especially when growth rate is high, the plant gets adjusted to the nutrient situation and deficiency symptoms will become transient (Ingestad, 1982).

Nutritional diagnosis studies have been very much limited in tropical tree crops. Very few studies were conducted in India on teak nutrition and the results are by and large inconsistent. An assessment of nutritional factors limiting the productivity of teak plantations will give lot of insight into better management strategy of future plantations. So the basic objective of the present study is to identify and assess the nutritional factors limiting productivity of teak plantations of different age groups belonging to different site qualities and to recommend possible corrective measures. The study also aimed to findout the influence of nutrient status of soil and leaf on the tree growth as represented through volume and current annual increment in basal area per tree. Another objective was to find out the influence of soil characteristics like pH, organic carbon and nutrient content on foliar nutrient concentration of teak belonging to different age groups and site qualities spread throughout the State of Kerala.

Review of Literature

REVIEW OF LITERATURE

Judicious management of nutrition is a powerful tool to ensure increased productivity of forest plantations. During the past decades demands for forest products have drastically increased and natural forest resources mainly in the tropics have been steadily depleted. This emphasises the need for increased forest productivity and the importance of nutrient management of forest plantations. Very few works are seen to be carried out on the mineral nutritional aspects of tropical forest tree species. There is very little information, especially in tropics, about the complex long term relationship between soil nutrient status and nutrient availability on the one hand and tree nutrition as well as tree growth on the other. Despite its immense popularity and commercial importance, nutritional aspects of teak have seldom been studied. This calls for a better understanding of teak's nutrient management.

2.1 Role of mineral nutrient elements on plant growth and development

2.1.1 Nitrogen

Nitrogen is usually the fourth most abundant element in plants following carbon, oxygen and hydrogen. Nitrogen containing compounds constitute 5 to 30 per cent of the dry weight of plants (Kramer and Kozlowski, 1960). As a constituent of protein, enzyme and chlorophyll, N is involved in all processes associated with protoplasm, enzymic reactions and photosynthesis (Gauch, 1972). It plays an important role in the synthesis of protein, chlorophyll and nucleic acids and is also associated with cell division and cell enlargement (Pandey and Sinha, 1972). N as nitrate ion is involved in the initiation of the activity of nitrate reductase enzyme (Ferrari and Verner, 1969). Nitrogen has a major role in maintaining the phytochrome balance in plants. It favoures the synthesis of cytokinins in root meristems (Marschner, 1982).

2.1.2 Phosphorus

Phosphorus, one of the quantitatively prominent nutrient elements occurs in both organic and inorganic forms and is translocated readily in both forms (Kramer and Kozlowski, 1960). It promotes healthy root growth and fruit ripening by helping translocation of carbohydrates (Pandey and Sinha, 1972).

Being a constituent of coenzymes NAD, NADP and ATP, P plays an important role in the oxidation, reduction and energy transfer reactions of cell metabolism (Epstein, 1978; Jain, 1981).

As a constituent of nucleoproteins, P is involved in the unique portion of protoplasm concerned with the cell division and the transfer of hereditary characteristics by the chromosomes (Gauch, 1972). It is a constituent of phospolipids. P is concerned with H+ transfers that occur as steps in the Kreb's cycle, glycolysis and the pentose cycle (Mc Elroy and Glass, 1952).

P is known to be involved in photosynthesis in connection with phosphorylation of various intermediates in CO_2 assimilation.

Marschner (1982) found that P favoured the movement of cytokinins from roots to other parts of plants and hence, its deficiency resulted a decline in cytokinin content of tissues.

2.1.3 Potassium

Potassium is the only monovalent cation essential for all higher plants (Reed, 1942). Although the relatively high requirement of K by most plants has been reported, isolation of K containing compound from plants has not yet become possible (Evans and Sorger, 1966). K appears to be completely watersoluble in plants. The principal role of K is that of an activator of numerous enzymes. K is involved in starch synthesis. During K deficiency, lack of starch synthesis could be the result of reduced energy supply since K is necessary for glycolysis, oxidative phosphorylation, photophosphorylation and for adenine synthesis (Evans and Sorger, 1966). It also plays a role in the translocation of photosynthates from leaves to other portions of plants (Hartt, 1969).

Capron *et al.* (1982) noted that though K activated synthesis of chlorophyll, an increased partitioning of K to the chloroplast in K deficient plants was the major reason for substantial reduction in photosynthetic rates during the initial stages of deficiency of this element. K was reported to have direct influence on cell division and higher cell number (Boringer and Schacherer, 1982). It is found that low K resulted in reduced transport of cytokinins from roots but enhanced ABA export to grains which caused accelerated senescence (Marschner, 1982). A particular concentration of K is necessary to maintain the osmotic pressure and turgidity of cells.

2.1.4 Calcium

The concentration of Ca in the dry weight of plants can vary over a wide range of about 0.1 to 2.5 per cent but, as it has low mobility and can't be readily redistributed from older to new leaves, the higher concentrations are probably greater than the metabolic requirement. Ca is the major cation of the middle lamella of cell walls, of which calcium pectate is a principle constituent. Hence it has an important bearing on the mechanical strength of tissues (Tagawa and Bonner, 1957). Ca is essential for the formation of cell membrane systems on which functional integrity and cellular metabolism are dependent (Marinos, 1962).

A definite role of Ca in N metabolism was indicated by Paulsen and Harper (1968). Ca is involved in intracellular transport of nitrate. Ca is essential for the growth and development of roots (Rios and Pearson, 1964). Calcium provides a base for the neutralization of organic acids and is essential for counteraction of metal toxicity (Pandey and Sinha, 1972). Ca plays a role in the binding of nucleic acids with protein and nitrate assimilation. Ca is an essential constituent of α-amylase, a starch digesting enzyme (Salisburry and Ross, 1977).

Calcium ion itself is reported to be inactive, its activity being modified through a homologous class of Ca binding proteins. Calmodulin is one among such proteins that controls numerous key enzyme systems and cellular processes. The Ca-calmodulin complex bind the calmodulin dependent enzymes like NAD kinase thus turning them as active enzymes (Anderson and Cormier, 1978). It is reported that root development had an exponential course at higher levels of Ca and was enhanced with increase in its concentration (Emanuelson, 1984).

2.1.5 Magnesium

The concentration of Mg in the dry matter of plants is variable, but generally lower than calcium. Unlike Ca, magnesium is mobile and large proportion of the total magnesium is associated with organic anions.

Magnesium is a specific constituent of chlorophyll (Magnesium porphyrin), in which one atom of Mg is bound to four pyrrole rings. Thus Mg plays a key role in photosynthesis. Mg also plays a major role numerous enzyme reactions. Because of its role as a cofactor of enzymes that act on phosphorylated substrates, the distribution of Mg in plants is often similar to that of phosphorus.

Mg is a constituent of chromosomes and plays a significant role in protein synthesis (Agarwala and Sharma, 1976). It acts as a carrier of P and helps in the solubilization of P (Ananthanarayana and Rao, 1979). Magnesium is also involved in the synthesis of fats and carbohydrate metabolism.

2.1.6 Iron

The functions and physiological effects of iron in plants depend on changes in its oxidation sate between Fe (ii) and Fe (iii) and the formation of complexes with organic and inorganic ligands.

Fe stored in leaves as a ferric phospho protein, phytoferritin, serves as a reserve for developing plastids and hence for photosynthesis (Hyde, 1963).

Fe is a constituent of iron porphyrin (haemes), enzymes such as catalase, peroxidase and cytochrome oxidase. There are also non-haeme iron proteins including ferredoxins and mitochondrial iron enzymes which play roles in electron transport (Burris, 1966). Fe also appears to be essential for chlorophyll synthesis (Bogorad, 1966) but it is not a part of chlorophyll. It functions in photosynthesis, nitrate and nitrite reductions (Betts and Hewltt, 1966) and in nitrogen fixation. Iron is reported to act as an activator of nitrate reductase and aconitase (Salisbury and Rose 1977).

2.1.7 Manganese

Manganese is absorbed from solution as Mn (ii) ion and translocated to the shoots primarily as free ion. Although its content in plant dry matter is typically 50 μg/g, it can approach 1000 μg/g in some plants growing on acid soils (Labanauskas, 1966). Manganese, like magnesium, can act as a cofactor of many enzymes that act on phosphorylated substrates. Some of the enzyme reactions in the tricarboxylic acid cycle, notably de carboxylases and dehydrogenases, are also activated by Mn, but as manganese can be substituted by Mg, the relative importance of these two ions is uncertain.

The main role identified for Mn is the one it plays in the evolution of oxygen in photosynthesis. Mn is present in the chloroplasts in a complex which oxidizes water to produce molecular oxygen, hydrogen ions and electrons (Saliskury and Ross, 1977).

Mn when present at high concentration in the medium may induce Fe deficiency in plants (Pandey and Sinha, 1972). It plays an important role in glycolysis and Krebs' cycle and hence in it's absence glucose accumulates. Mn is also essential for chlorophyll synthesis. It plays a role in regulating the levels of auxin in plant tissues by activating the auxin oxidase system.

2.1.8 Zinc

Zinc is absorbed as Zn (ii) and translocated to the shoots primarily as the free ion. It is known to be an essential constituent of only three plant enzymes, namely carbonic anhydrase, alcohol dehydrogenase and superoxide dismutase (Vallee and Wacker, 1976). However, studies of Zinc requiring enzymes isolated from other organisms, and also with Zn deficient plants, suggests that it is specifically required for many other plant enzymes including additional dehydrogenases, DNA and RNA nucleotidyltransferases and some peptidases and proteinases.

It has long been known that Zn has a marked effect on the level of auxin (Skoog, 1940). There is uncertainty about where Zn is involved in the synthesis of auxin, but it appears to be required in the synthesis of intermediates in the metabolic path way, through tryptophan to auxin.

Deficiency of Zn severely depresses the production of protein in meristematic tissue resulting in accumulation of amino acids and amides (Kitagishi and Obata, 1986).

There is some evidence that the synthesis of protein, which is mediated by RNA, is regulated by the concentration of Zinc. With citrus it has been found that the levels of both RNA and protein were lower in Zinc deficient than in healthy leaves (Kessler and Monselise 1959).

2.2 Diagnostic methods for detecting nutritional deficiencies and disorders

Diagnosis implies determination of the nutrient status of the site or trees. Diagnosis is a prerequisite to make sound decisions for management of plantations and hence profitable use of fertilizers. In some situations, it may be sufficient to know which nutrient or nutrients are limiting growth but more often, it is important to know how severe the deficiency is and also to predict the response to offered quantities of nutrients (Mead, 1984). A tree or a stand may suffer from nutritional disturbance if the supply of one or more nutrients is either too low or too high for optimum growth. Disturbance caused by excess of nutrients is rare in plantations; common case is insufficient nutrient supply (Drechsel and Zech, 1993).

Diagnosis can be done by several methods which include Visual Symptoms, Plant Tissue Analyses, Soil Analyses and Biological Assessments. In each of the broad categories many variants have been tried and some have proved more useful than others in certain situations. All have their limitations. In investigating new problems, it is prudent to use a range of techniques, and in general faster progress is made this way than by relying on a single technique (Gentle and Humphreys, 1968).

2.3 Soil analysis

Soil analysis is an important tool in forest nutrition research. The soil testing for diagnosis of nutrient deficiencies has received less attention than foliar analysis in forestry (Mead, 1984). The major successes have been with soil phosphorus studies (Pritchett, 1979).

Nutritional problems are in many cases only symptoms of unfavourable soil conditions like acidity, salinity, shallowness, stagnating water, low organic matter, low nutrient adsorption or high nutrient fixation, low available water capacity etc. The advantage of soil over tissue analyses is that nutrient supply of soils can be measured before establishing a plantation. The aims of soil testing are to determine the relative adequacies of nutrients available to plant so as to predict the onset of a deficiency, or to predict stand growth and also to provide guidance on the amount of fertilizer to be applied. Soil testing aims at assessing the nutrient status of soil through quick chemical tests. These tests determines the potential of the soil to supply nutrients to plants.

As growth is a function of soil and environmental factors, the soil test alone can't be an absolute predictor of plant growth. According to Pushpadas and Ahammed (1980) though routine soil testing gives some idea about the total quantity of available nutrients in the soil, it fails to give adequate information on the rate at which these nutrients would become available to rubber (*Hevea braziliensis*) crops. It also does not take into account the availability of organic form of nutrients such as phosphorus. Sometimes the nutrients present in the soil may not become available to the plant because of the adverse physico chemical or bio chemical properties of soil which may not be evident from routine soil testing.

The value of soil analysis in predicting the nutritional disturbances of forest stands is limited due to the discrepancy between the physiological and temporal complex system of nutrient uptake processes and the laboratory soil extraction methods. The latter have generally been developed and verified in agriculture, where it is more easy to analyse the nutrient uptake by whole-plant-analysis. It will be impossible to analysis the really available fraction of specific nutrient in the soil for a relevant lifetime of a tree beyond the seedling stage (Drechsel and Zech, 1993).

The limitations of soil testing could be overcome by foliar diagnosis.

2.4 Foliar analysis

The rationale behind plant tissue analysis is that the concentration or contents of nutrients or other extracts within a specified plant part reflects the nutritional status of the plant and thus its growth potential. The techniques are intented to give a direct measure of the nutrients that the plant has derived from the soil, rather than measuring the supply of nutrients in the soil itself (Mead, 1984).

In tree crops, foliage analysis has been shown to be reasonably sensitive for detecting deficiencies and also has the advantage of being directly related to productivity as foliage is the site of photosynthesis. The nutrient status of a tree seems to be reflected best by the chemical composition of its foliage (Drechsel and Zech, 1993).

Foliar diagnostic technique was first developed by Lagatu and Maume (1926) in France. They defined foliar diagnosis as the assessment of chemical status, at a given point in time, of suitably selected leaves. This technique was first used for robusta coffee in Ivory coast (Loue, 1951).

The capacity of the leaf to variation in composition makes it sensitive to variation in the medium and the leaf analysis has practical advantages with perennial plants. The nutrient content of a leaf is not static but subject to changes with various factors, both external and internal. For practical convenience a period when the leaf nutrient content is relatively stable is chosen for sampling and related to the performance of the plant in quality and quantity. The position of leaf, part of leaf, and form of nutrient to be estimated are all standardised.

Wadleigh (1949) remarks that, for any given combination of environmental factors, within a plant tissue, there is an optimum content of mineral nutrients for maximum plant growth and deviation from this affects it. This is the strong basis on which plant analysis as a diagnostic tool stands.

The nutrient requirement of certain crops particularly temperate and subtropical fruit crops have been formulated using this technique (Smith, 1962).

2.5 Foliar analysis Vs Soil analysis

Foliar analysis is a method of establishing the levels of nutrients below which plants show deficiency symptoms and nutrient values associated with optimum growth and yield. It is used as a guide to the nutritional status of the plant. Analysis of the soil, on the other hand, provides information only on the amount of nutrient available at a given moment, not on the amount actually taken up by the crop.

Hardy *et al.* (1935) stated that the relationship that existed between the plant and its environment was not simple, and factors other than nutrient supply might affect the growth and composition of the plant.

Schroo (1960), compared the results of soil analysis with those obtained from leaf analysis and used it as a guide to the nutritional demands of young cocoa. He observed closest relationship between soil phosphorus and magnesium with that of leaves and also found that agreement between leaf and soil nitrogen, potassium and calcium was less satisfactory.

Leverington *et al.* (1962) could not find any consistent relationship between leaf potassium status of sugarcane and the amount of potassium for the maximum yield. They concluded that unless potassium is very deficient, soil analysis is more reliable than leaf analysis for assessing potassium requirement of sugarcane.

Leaf composition in apple, raspberry and black current was related to nutrient elements in soil by Jones (1963). The soil and leaf analysis showed in general a relationship between macro nutrients in the top soil and those in the leaves.

Soil and tissue tests for predicting olive yield in Turkey were examined by Fox *et al.* (1964). Leaf nutrient levels were found to be better correlated with yield. In the case of deep loam soils, with a root range several meters deep, more accurate information on the nutrient status of Cox's orange apple trees is obtained from plants than from soil analysis (Leferre, 1965). In an experiment with four year old cocoa plants, Acquaya *et al.* (1965) observed positive correlation between soil exchangeable potassium and leaf potassium. Verliere (1965) also found that the growth rate of cocoa was significantly correlated with soil phosphorus.

Ollagnier and Giller (1965) compared foliar diagnosis with soil analysis in determining the phosphorus and potassium requirement of groundnut and foliar nutrient levels were better correlated with yield than soil nutrient levels.

Champion (1966) opined that foliar diagnosis and soil analysis are both necessary in judging fertilizer requirement of banana.

Ruer (1966) found that soil analysis was less sensitive than foliar analysis for detecting nitrogen and magnesium deficiency in cultivated palms.

Wessel (1970) reported that nitrogen content of soil was indicative of the nitrogen availability to cocoa plant and that leaf nitrogen could only be used in detecting the deficiency of nitrogen in the soil. He found a positive relationship between soil and leaf phosphorus. He concluded that soil and leaf analysis are having limited value for assessing the nitrogen requirement of cocoa, butcan fairly determine the phosphorus requirement of the crop.

Soil tests are suggested by many for monitoring the nutrient requirement of young plants. With regard to NPK nutrition of one year old apple trees, soil analysis gave better results but with two year old trees foliar analysis was better (Klossowski and Czynczyk, 1974). In pineapple, a pre-plant soil analysis would be significant to indicate the phosphorus and potassium requirements (Plessis and Koens, 1983). Hanson (1987) and Hancock and Nelson (1988) suggested soil test for monitoring the potassium status of young blueberry plants.

Annie (1982) reported that the foliar diagnosis of cocoa plant indicated a good relationship between the soil nutrient status and leaf nutrient status. She has also obtained positive correlation between soil test values and leaf nutrient concentration in the order of magnesium followed by Ca, N, K and least by P.

Primary positive correlation between soil nutrients and leaf nutrients was observed in a nutrient survey of strawberry in Norway and Sweden (Sakshaug, 1982). Significant positive correlation between potassium values in the soil and in the leaf samples was most frequent.

Although strong relationship between soil nutrients and leaf nutrients was observed in many crops, little or no correlation was observed between soil and leaf nutrients in some crops. There was no significant correlation between soil and leaf nutrients with respect to nitrogen, phosphorus and potassium in mango (Bopaiah and Srivastava, 1984). In the case of blueberry, weak correlations were noted between soil and leaf nutrient levels of P, K, Ca and Mg (Hanson, 1987; Hancock and Nelson, 1988).

Amir Husni and Miller (1991) after studying soil and foliar nutrient composition and their influence on accumulated basal area in Malaysian tropical rain forest reserves concluded that soil data are inadequate for nutritional assessments and that foliar data are essential to reach firm conclusions.

2.6 Index tissue for nutrient diagnosis

Index tissue can be defined as the tissue that can be used to follow the levels of each factor as the crop grows (Clements, 1980). Such a tissue must reflect in a high degree of correlation, the levels within the whole plant, for as the absorption and utilization of any factor vary, such variations should be reflected by the index tissue.

The leaf is the centre for physiological activity of plants. It is the site where mineral nutrients are converted in to structurally and metabolically active components along with the products of photosynthesis. Consequently, any deficiency or toxicity usually drastically affects the concerned enzyme activity. Nutrient deficiency and toxicity is usually expressed by the leaves and thus leaves form an ideal plant part for nutritional diagnosis.

Rogers *et al.* (1955) showed that leaf was sensitive or even more sensitive than any other plant part for determining the nutrient status of strawberry.

The index tissues are standardised for a large number of crops. Reddy *et al.* (1988) carried out studies to identify and select N, P and K index tissue in papaya by determining their concentrations in petioles at different stages of maturity. Mathew (1990) identified the first group of leaves (leaf 1 and 2 near inflorescence) as ideal for diagnostic purpose in relation to N and K in cashew. Jose *et al.* (1991) suggested regression models to predict yield in coconut with an accuracy of 86.2 per cent utilizing the N, P and K contents of the leaf lamina of tenth leaf.

Jayamadhavan (1996) found that the second leaf rank from the bottom canopy was ideal for collecting leaf samples for determining N, P and K content in teak.

2.7 Factors influencing foliar nutrient levels

Important factors which influence foliar nutrient levels are discussed by Van den Driessche (1974), Lambert (1984), Mead (1984) and Weetman and Wells (1990). In summary, the most important are time of sampling during the vegetation period, age of the foliage and crown position (Drechsel and Zech, 1993).

Several studies show that over the vegetation period in most species foliar concentrations of highly mobile nutrients, like N, P and K, decreases, partly due to increasing dry weight of the foliage, while elements which are less mobile in the phloem, like Ca, Si, Mn or Fe are accumulated in the leaves. Differences of nutrient levels over the season may be over 100 to 1000 per cent in several nutrients. Tree species retaining their foliage for more than two years show peak levels of N, P and K in the first and second year, followed by decreases of as much as 50 per cent for (2) 3-6 year old foliage (Weetman and Wells, 1990).

With increasing shading from upper to lower and outer to inner crown, the concentrations of such nutrients as N and P decrease, while those of Ca and Al increase. Intensity and variability of concentration changes as well as the behaviour of elements depend on the species. Studies in these lines were carried out on several tropical species, like *Eucalyptus deglupta* (Lamb, 1976) and *Gmelina arborea* (Evans, 1979). A summary of observations is listed by Weetmann and Wells (1990).

Even on the same soil, quite different foliar levels would be found in trees of different age (Lambert, 1984) or provenance or the same trees from year to year (Vanden Driessche, 1974). Regular controlled fires could reduce foliar N and increase foliar P (O'Connell *et al.*, 1981). Also flowering and fruiting needs nutrients, which will be transferred from other organs like foliage. Hence there are many limitations to the use of tissue analysis. Inspite of these problems, its use in forestry is expanding, since the only alternative is expensive diagnostic fertilization (Drechsel and Zech, 1993).

2.8 Interpretation of soil and foliar data

Several approaches have been used to interpret foliar analysis data from forest stands (Weetman and Wells, 1990; Mead, 1984), which include interpretation without reference data, evaluation of soil and foliar data by correlation analysis, the critical level approach and the DRIS system.

2.8.1 The critical level approach

The most common method of diagnosing mineral nutrient problems is determining critical nutrient concentration. The critical level of a nutrient is defined as the level below which a response to fertilizer might be expected. Some times this is defined as the optimum point on the curve of nutrient level Vs. growth or alternatively beyond which there is a significant decline in growth (Ulrich and Hills, 1967).

The critical level between latent deficiency and optimum supply, which is considered as the foliar nutrient concentration at which yield attains 90 per cent of the possible maximum is the common accepted one (Van den Driessche, 1974), although it is only well established in interpretation of foliar analysis in temperate and subtropical agriculture, for pasture crops, fruit trees, coffee etc (Reuter and Robinson, 1986).

The critical concentration of different nutrient elements for different crops have been worked out by several research workers.

In tea, critical nutrient concentration on third leaves in various varieties was reported to be 4.6 to 3.6 per cent by Lin (1963). Akhmetov and Bairamov (1968) have suggested that optimal N, P and K content assuring best harvest would be 4.5 to 4.8 per cent, 0.5 to 0.6 per cent and 2.2 to 2.4 per cent respectively.

In oil palm, K content below 1 per cent in dry matter indicated K deficiency (Ochs, 1965).

Gugeon (1947) found that a concentration of 2.3 per cent nitrogen on dry matter basis indicates healthy condition in apple while 1.5 per cent N denotes deficiency.

In cocao, critical concentrations of N, P and K on dry matter basis were found to be 2.32, 0.22 and 0.19 per cent respectively (Mc Donald, 1934).

Sen *et al.* (1947) reported intermediate composition of 2.52 per cent, 0.17 per cent and 0.64 per cent of N, P and K as 3.07 to 3.34 per cent, above 0.25 per cent and 1.11 per cent respectively for rubber.

For coconut N, P, K, Ca and Mg values were found to be 1.7 per cent, below 0.1 per cent, 0.45 per cent, 0.5 per cent and 0.35 per cent respectively (Prevot and Ollagnier, 1957).

Under tropical conditions, optimum and 90 per cent critical levels could be established only in fertilized pot cultures or industrial plantations, where optimum yield is known, since the typical case of tropical plantations is suboptimal growth (Drechsel and Zech, 1993). Due to anatomical and physiological characteristics, there can be large differences in optimal and critical values for different species or biotypes even under same site conditions. Until now such data have been published only for some subtropical species (Richards and Bevege, 1969; Bevege and Richards, 1971). Besides nutrient concentrations, optimal or critical nutrient ratios could also give valuable informations (Schonau, 1984).

2.9 Nutrition of plantations in the tropics

There are two important considerations in plantation development related to land use: the increased wood production will have to come from a decreasing land area and many new ventures in plantations will be largely, confined to land systems needing rehabilitation (Leslie, 1980).

Nutritional problems have confronted many plantation development programmes. Of the fifteen mineral elements known to be essential for the normal growth of higher plants, deficiencies of all except Mo, Co, Se, Na and Cl have been reported to occur in forest tree plantations (Nambiar, 1984). As hardwood plantations of trees such as eucalyptus extend, there will be a parallel increase in problems of nutrient management.

Plantations of *Pinus radiata* in Australia have suffered from extensive deficiencies of N, P, S, Cu, Zn and B and successful establishment of pine plantations was essentially dependent on the correction of P and Zn deficiency and more recently the need for relatively large inputs of N to achieve high growth rates has received wide recognition (Nambiar, 1984). Extensive nutritional problems have been reported also from Newzealand, South Africa and USA.

Responses to the correction of nutrient deficiencies have been often spectacular. Waring (1980) reported that biomass of *P. radiata* increased from 20.9 to 79.5 t/ha with P and 175 t/ha with P and N, 7 years after applying fertilizers to transplanted seedlings in Australia. Cromer and Williams (1982) showed that the net primary production of *Eucalyptus globulus* between ages 6 and 9.5 years increased from 7.2 to 15.4 t/ha/yr as a result of N and P fertilization; accompanied by substantial increase in stand diameter and height.

Eucalyptus grandis plantations in South Africa managed over a 6 to 22 year rotation showed 30 to 39 per cent increase in wood volume as a result of fertilization in extensive areas (Schultz, 1976).

There is much evidence of responses to forest fertilizers by relatively slow growing species in cold environments and also in older stands. Miller and Miller (1976) reported that net primary production of 36 year old *Pinus nigra* in Scotland increased from 8 to 25 t/ha with N fertilization. Many of the forest stands in Northern hemisphere are considered to be nitrogen deficient (Nambiar, 1984).

Most nutrition research in forestry has been conducted in developed countries in temperate climate. However, substantial forest plantations are among the most urgent needs in the developing tropical and sub tropical countries throughout the world.

Nutritional research on tropical tree species aimed at optimizing production and sustaining it over several rotations seems to be limiting. In teak, opportunities for increasing productivity in a short rotation age is thought of and proper nutritional study is a pre-requisite for achieving the goal.

Materials and Methods

MATERIALS AND METHODS

An investigation to identify and assess the nutritional factors limiting productivity of teak plantations of different age groups belonging to different site quality classes in Kerala was carried out at the College of Forestry, KAU, Vellanikkara during 1994-1996. The nature of relation between tree growth and the soil/leaf nutrient status, the nature of relation between current annual increment in basal area per tree and the soil/leaf nutrient status and correlation between leaf attributes and soil attributes were investigated in this study.

3.1 Location

The field work was conducted in different teak plantations of Kerala Forest Department spread throughout the State. The area falls under north latitude between 8° 18' and 12° 48' and East longitude between 74° 52' and 77° 22'. The average annual rainfall is 3000 mm. Climate is warm and humid. The soils are predominantly lateritic.

3.2 Selection of different sites

Sample plots of size 50 m x 50 m belonging to different age groups and site quality classes retained as semi-permanent sample plots by Kerala Forest Research Institute, Peechi were utilized for the study. Twenty plots were selected for this study and the name and other details of plantations are given in Table 1. The locations are also given in Fig. 1. The selected plots belonged to the following age groups viz., 0-9, 10-19, 20-29, 30-39 and 40-49 years.

3.3 Selection of trees

Fifteen representative trees were selected from each plot such that they included trees having maximum and minimum, average and intermediate gbh (girth at breast height) levels. The height and gbh of all the selected trees were measured using clinometer and tape respectively.

3.4 Collection of leaf samples

Leaf samples were collected from the fifteen selected trees of each plot during the months of September to November as per the procedure standardised by Jayamadhavan (1994) . The second leaf rank from the bottom canopy was collected for the analysis. They were oven dried (70°C) and powdered using grinder and stored in polythene bags till analysis.

3.5 Collection of soil samples

Representative soil samples were taken from 0-30 cm depth at a lateral distance of 1 m from the base of each of these trees. The soil samples were collected from three points and mixed to get the representative sample for each tree. Soil and leaf samples were collected simultaneously. Collected soil samples were air dried and sieved through 2 mm mesh and stored in polythene bags till analysis.

3.6 Analytical method

3.6.1 Plant analysis

Leaf samples were analysed for N, P, K, Ca, Mg, Fe, Mn and Zn concentration.

Table 1 Details of plantations selected

No.	Division	Range	Name of the plantation	Year planted	Age	Site quality
1	Chalakudy	Pariyaram	Vettukuzhy	1985	9	1
2	North Wayanad	Begur	Alathur	1981	14	1
3	South Wayanad	Chedalath	Bhoodanam	1978	17	2
4	South Wayanad	Chedalath	Ciyambam	1978	17	2
5	Konni	Naduvathu-muzhy	Karippanthodu	1971	24	1
6	Nilambur South	Karulai	Nedumkayam	1974	21	2
7	Kothamangalam	Kothaman-galam	Charupara	1973	22	2
8	Vazhachal	Vazhachal	Choozhimedu	1971	23	3
9	Thrissur	Peechi	Kuthiran	1965	30	2
10	Mannarkad	Mannarkad	Panankadam	1960	35	2
11	Kothamangalam	Thodupuzha	Valiyakandam	1956	39	2
12	Kothamangalam	Kothaman-galam	Thadikulam	1963	32	3
13	Thrissur	Peechi	Pothundy	1958	36	3
14	Wynad (WL)	Tholpetti	Camproad	1953	42	2
15	Munnar	Neryaman-galam	Neryamangala m	1952	43	2
16	Konni	Konni	Inchapara	1946	49	2
17	Thrissur	Machad	Palakathadom	1953	42	3
18	Kozhikode	Peruvanna-muzhi	Panikkottoor	1951	44	3
19	Punalur	Anchal	Kadamankadu	1948	47	4
20	Kannur	Kasargod	Parappa	1946	48	4

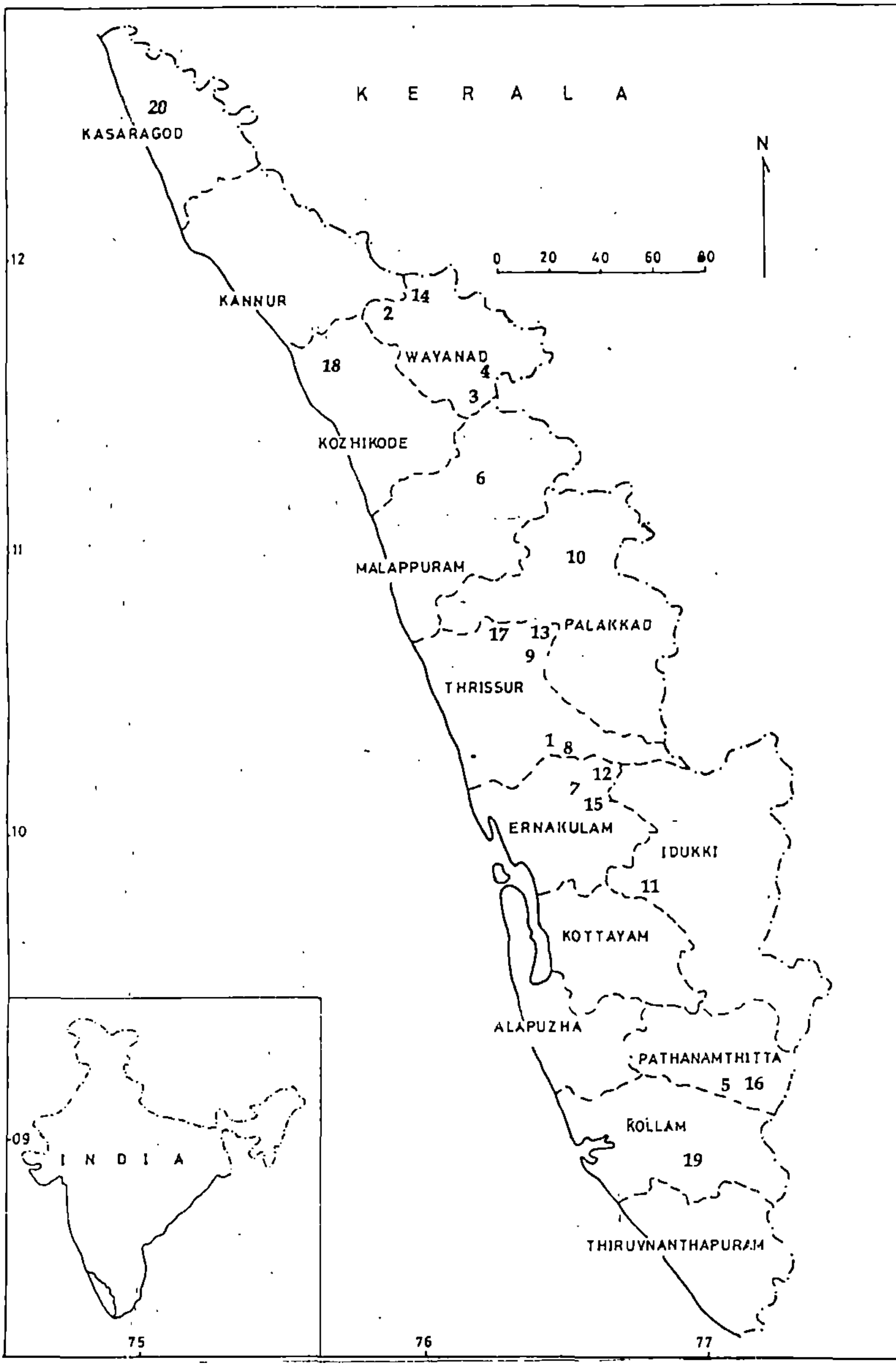

Fig.1. Map of Kerala showing the locations of plots

Legend numbers represent the name of the plantations described in Table 1.

Nitrogen was estimated by modified Kjeldahl's method (Jackson, 1973). Determination of other nutrients was done after digestion with 10:3 nitric acid, perchloric acid mixtures. Concentration of P in the digest was determined by the Vanadomolybdate yellow colour method and K was estimated using flamephotometer (Jackson, 1973). Concentration of Ca, Mg, Fe, Mn and Zn in the digest were estimated using an atomic absorption spectrophotometer (Perkin Elmer, USA). LaCl was used to overcome interferences in estimating Ca and Mg. The analytical procedures employed and their references are given in Table 2.

3.6.2 Soil analysis

Soil samples, representative of each tree were analysed for pH, organic carbon, available P, total N and exchangeable K, Ca, Mg, Fe and Zn. Organic carbon was estimated titrimetrically by Walkley-Black method, available P extracted using Bray-I extractant and estimated by reduced molybdate blue colour method and exchangeable K by extraction with neutral normal ammonium acetate and estimation by Flamephotometry. Exchangeable Fe and Zn were estimated by extraction with 0.1 N HCl and estimated by AAS. Concentration of Ca, Mg, Fe and Zn were estimated using an atomic absorption spectrophotometer (Perkin Elmer, USA). To avoid interferences while estimating Ca and Mg, LaCl was used. The analytical procedures and their references are given in Table 3.

Table 2 Details of the methods followed in leaf analysis

Nutrient	Digestion procedure	Method of estimation	Instrument used	Reference
Nitrogen	H_2SO_4 digestion	Distillation and Titration	Titrimetric	Jackson (1973)
Phosphorus	10:3 HNO_3 diacid digestion	Vanadomolybdate yellow colour method	Spectro photometer	"
Potassium	"	Direct reading	Flame photometer	"
Calcium	"	"	AAS	
Magnesium	"	"	"	
Iron	"	"	"	
Manganese	"	"	"	
Zinc	"	"	"	

Table 3 Details of the methods followed in soil analysis

Soil characteristic	Extractant used	Method of estimation	Instrument used	Reference
pH	1 : 2.5 soil water ratio	Direct reading	pH meter	Jackson (1973)
Organic carbon	-	Walkley-Black	Titrimetric	"
Available P	Bray I	Molybdenum blue estimation	Spectro photometer	"
Available K	N.Normal ammonium acetate	Direct reading	Flame photometer	"
Exchangeable Ca	"	"	AAS	
Exchangeable Mg	"	"	"	
Exchangeable Fe	0.1 N Hcl	"	"	
Exchangeable Zn	"	"	"	

3.7 Statistical analysis

3.7.1 Relation between tree growth and soil attributes and foliar nutrient status

One of the objectives of the analysis was to find out the nature of the relation between tree growth and the soil and foliar nutrient status. Tree volume, considered as an expression of growth, was computed for individual sample trees using the prediction equation reported by Chaturvedi (1973).

$$V = 0.1217 + 0.2257\ D^2H \qquad (3,\ 1)$$

where,

V = Volume of timber and small wood from the tree (m^3)

D = Diameter at breast-height of the tree (m)

H = Total height of the tree (m)

Since the trees were of different age gradations, the effect due to age had to be eliminated first before regressing the volume on soil and foliar nutrient status directly. For this purpose, an equation of the following form was fitted first and the residuals were obtained.

$$\ln\ V = a + b\ X \qquad (3,\ 2)$$

where,

V is as defined earlier

X = Age of the tree (year)

ln indicates natural logarithm

`a' and `b' are constants

The residuals of the above equation were then regressed on the soil and leaf attributes separately using the following model.

$$y = \beta_0 + \sum_{i=1}^{p} \beta_i x_i + \sum_{i=1}^{p} \beta_{ii} x_i^2 + \sum_{i<j}^{p} \beta_{ij} x_i x_j \qquad (3, 3)$$

where,

y = Residuals from the volume-age equation

x_i's are the set of soil or leaf attributes as the case may be

ß's are the regression coefficients

P = number of variables

In particular, the soil attributes were pH, organic carbon and concentrations of N, P, K, Ca, Mg, Fe and Zn and the leaf attributes were concentrations of N, P, K, Ca, Mg, Fe, Mn and Zn.

Significant attributes from among the full set of attributes in the second order response function of (3, 3) were identified through stepwise regression (Montgomery and Peck 1991). The step-wise procedure was executed using SPSS software (Norusis, 1988). Before fitting the equation (3, 3), the whole set of 300 trees was divided into three age groups as <= 20 years, > 20 and <= 40 years and >40 years. These groups were formed based on the major differences found with respect to the pattern of relative growth rate in these age groups as computed from the All India Yield Table (Fig.2 in results) for teak (Anon, 1970). There were 60 trees in the first age group, 135 trees in the second age group and 105 trees in the last age group. Stepwise regression was carried out by taking the volume as dependent variable for each age group separately. The resultant equations of stepwise regression were utilized to characterise the nature of response surface and to find out the optimum levels of soil attributes and foliar nutrient elements. The levels of $x_1, x_2, \ldots, x_p$ which maximize the predicted response were identified through the following equation (Montgomery, 1991).

$$x_0 = -\frac{1}{2} B^{-1} b \tag{3, 4}$$

Where `b' is a (pxl) vector of the first-order regression coefficients and B is (p x p) matrix whose main diagonal elements are pure quadratic coefficients (β_{ii}) and whose offdiagonal elements are one-half the mixed quadratic coefficients (β_{ij}, $i \neq j$) i.e.,

$$b = \begin{bmatrix} \beta_1 \\ \beta_2 \\ \cdot \\ \cdot \\ \beta_p \end{bmatrix} \qquad B = \begin{bmatrix} \beta_{11} & \beta_{12}/2 & \ldots & \beta_{1p}/2 \\ & \beta_{22} & \ldots & \beta_{2p}/2 \\ & & & \cdot \\ & & & \cdot \\ & & \cdot & \beta_{pp} \end{bmatrix}$$

The predicted response at the stationary point is given by the following equation.

$$\hat{Y}_0 = \beta_0 + \frac{1}{2} x'_0 b \tag{3, 5}$$

To characterise the response surface, it was necessary to express the fitted model (3) in canonical form.

$$\hat{Y} = \hat{Y}_0 + \lambda_1 w_1^2 + \lambda_2 w_2^2 + \ldots + \lambda_p w_p^2 \tag{3, 6}$$

Where w_i's are the transformed independent variables and the $\{\lambda_i\}$ are the eigenvalues or characteristic roots of matrix B.

The nature of the response surface can be determined from the stationary point and the sign and magnitude of the λ_i's. Suppose that the stationary point is within the region of exploration for fitting the second-order model. If the $\{\lambda_i\}$ are all positive, then x_o is a point of minimum response. If the $\{\lambda_i\}$ are all negative, then x_o is a point of maximum response and if the $\{\lambda_i\}$ have different signs, then x_o is a saddle point of minimum response.

3.7.2 Relation between CAI in basal area per tree and soil attributes and foliar nutrient status

Analysis was done to find out the nature of relationship between current annual increment (CAI) in basal area per tree of each plot and the corresponding soil and leaf attributes. Basal area (BA) per tree in each plot was calculated using the equation:

$$\text{BA per tree} = \frac{\text{Basal area per plot}}{\text{Number of trees in the plot}}$$

CAI is calculated using the formula.

$$\text{CAI} = \frac{BA_2 - BA_1}{A_2 - A_1}$$

where,

BA_1 = Basal area per tree at the time of first measurement

BA_2 = Basal area per tree at the time of second measurement

A_1 = Age of the tree at the time of first measurement

A_2 = Age of the tree at the time of second measurement

The first measurement on the trees were taken in 1992-94. The second measurement was taken in 1997 (Jayaraman, 1998).

CAI per tree was computed at the plot level because records of increments of individual trees could not be obtained.

CAIs in basal area per tree were regressed on the different measurements made on soil and leaves along with age and initial basal area per ha included as independent variables in the regression model (3, 3) using SPSS software. Age and initial basal area per ha were included in the model, so as to eliminate their influences from the effects of soil/leaf variables on the CAI. Significant variables from the soil/leaf variables in the second order response function were identified through stepwise regression. The resultant equations of stepwise regression were utilized to characterise the nature of response surface and to find out the optimum levels of soil/leaf attributes as described in section 3.7.1.

3.7.3 Canonical correlation analysis

For analysing the relationship between the two sets of variables (eight leaf variables and nine soil variables), a technique called canonical correlation analysis was used. It is a procedure which finds a linear combination from each set called a canonical variable such that the correlation between the first two canonical variables is maximized. 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 equals to the 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 (Rao, 1973).

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 software (Anonymous, 1994).

Results

RESULTS

The results of the study on the soil-plant nutritional status of *Tectona grandis* L.f. in relation to age and site quality are presented in this Chapter.

4.1 Relation between tree growth and soil attributes and foliar nutrient status

To find out the nature of relationship between tree growth and the soil attributes and foliar nutrient status, the tree volume was considered as an index of growth. The whole set of 300 trees was grouped into three age groups as < = 20 years, >20 and < = 40 years and >40 years. These groups were formed based on the major differences found in the pattern of relative growth rate in these age groups as computed from the All India Yield Table for teak (Fig.2).

Since the trees were of different age gradations, the effect due to age had to be eliminated first before regressing the volume on soil attributes and leaf nutrient status directly. The volume-age equation fitted was the following:

$$\ln V = \underset{(0.1014)}{-1.743} + \underset{(0.0030)}{0.0251\ A} \qquad (4,\ 1)$$

where,

In V = Natural logarithm of volume of timber and small wood from the tree (m^3)
A = Age of the tree (year)

The values in parentheses are standard errors of the coefficients. The adjusted R^2 to the above equation was 0.1886.

The residuals of the above equation were then regressed on the different fertility attributes of soil and nutrient status of leaves separately using equation (3, 3) described in materials and methods. The results are presented in the following sections.

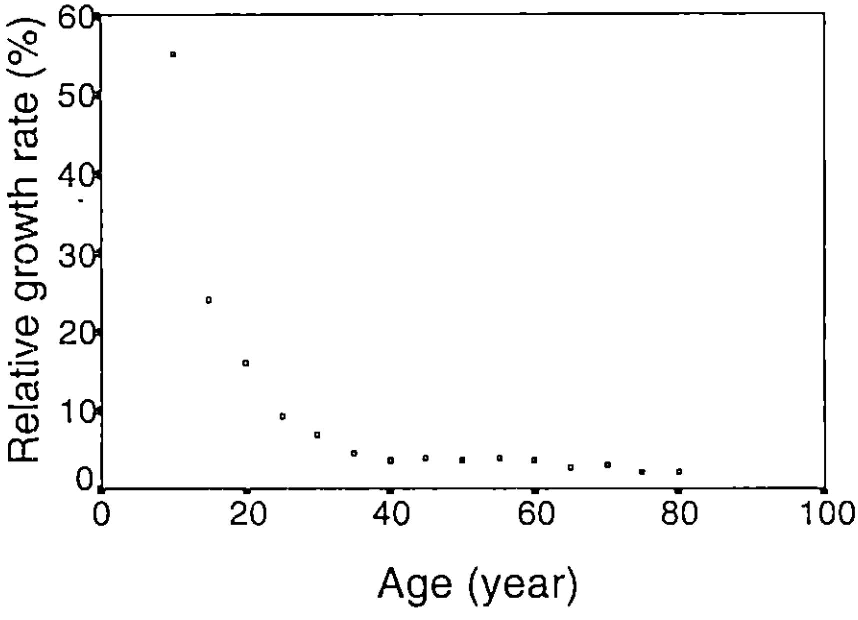

Fig.2. Relative growth rate in percentage at different years of age for Teak

4.1.1 Relation between tree growth and nutrient status of leaves

The resultant equations of the stepwise regression with respect to nutrient status of leaves of trees belonging to the three age groups are given in Table 4.

For the first age group (< = 20 years), the resultant model was linear and had an adjusted R^2 value of 0.1089. The nitrogen is the only element found to be related to volume growth. The negative coefficient of nitrogen indicates that the higher the volume growth, lesser the nitrogen concentration in leaf which could be explained on the basis of dilution effect.

For the trees having age > 20 and age < = 40, the model had an adjusted R^2 value of 0.2977. The absence of quadratic terms in the model indicates a linear surface subjected to interactions between nitrogen and calcium, phosphorus and calcium and magnesium and iron in the leaf. The first two interactions had positive coefficients while interaction between magnesium and iron had a negative coefficient.

The equation fitted with respect to nutrient status in leaf of trees having age > 40 years, through stepwise regression had an adjusted R^2 value of 0.3213. The model is linear and no quadratic terms are present. Phosphorus had a linear effect on the model. Also the interaction between nitrogen and calcium, nitrogen and magnesium and phosphorus and zinc contribute to the linear surface. The interaction between nitrogen and magnesium had a negative coefficient while others had positive coefficients.

The critical nutrient concentrations with respect to tree volume do not seem to be attained by the levels of nutrients available in the present data set.

Table 4 Relation between tree growth and nutrient status of leaves

Age group	The resultant equation of the stepwise regression	Adjusted R^2 value
<=20 years	$y = 0.8277 - 0.4736\, x_1$ (0.3302) (0.1652)	0.1089
> 20 and <= 40 years	$y = -1.0045 + 0.2604\, x_1x_4 + 0.3113\, x_2x_4$ (0.3066) (0.0642) (0.1517) $- 0.0055\, x_5x_7$ (0.0013)	0.2977
> 40 years	$y = -3.6101 + 5.5133\, x_2 + 0.4917\, x_1x_4$ (0.6427) (2.4672) (0.9097) $- 1.2684\, x_1 x_5 + 0.1223\, x_2x_6$ (0.4772) (0.0681)	0.3213

where,
y = residuals from the volume-age equation
x_1 = leaf nitrogen
x_2 = leaf phosphorus
x_4 = leaf calcium
x_5 = leaf magnesium
x_6 = leaf zinc
x_7 = leaf iron

The values in the parantheses are standard errors of the coefficients

4.1.2 Relation between tree growth and soil attributes

The resultant equations of the stepwise regression with respect to fertility attributes in soils under trees belonging to the three age group were given in Table 5.

In the first age group (age $< =$ 20 years), the resultant equation had an adjusted R^2 value of 0.4731. The model is linear and no quadratic terms are present. The linear surface is subjected to interactions between phosphorus and potassium, phosphorus and magnesium, calcium and iron and zinc and soil pH. Zinc had also a linear effect having a positive coefficient. The interaction coefficients of phosphorus and magnesium and zinc and soil pH were negative while others had positive coefficients.

The equation fitted with respect to nutrient status in soils of trees having age $>$ 20 and age $< =$ 40 years, had an adjusted R^2 value of 0.3476. Many components of the nutrient status in soils have significant influence on the volume growth of trees. However, the absence of quadratic terms in the model indicates a linear surface. Soil calcium had a linear effect with a positive coefficient. The linear surface was also subjected to interactions between nitrogen and zinc, phosphorus and organic carbon, magnesium and zinc and iron and organic carbon. The interaction between magnesium and zinc and iron and organic carbon were having negative coefficients while the other two had positive coefficients.

For the third age group (age $>$ 40 years), the model had an adjusted R^2 value of 0.4997. The equation had one linear term (phosphorus), three interactions terms

Table 5 Relation between tree growth and nutrient status of soil

Age group	The resultant equation of the stepwise regression	Adjusted R^2 value
< =20 years	$y = 0.0383 + 0.5526\, x_6 + 2.2434\, x_2x_3$ (0.2200) (0.2236) (0.6719) $- 2.2142\, x_2x_5 + 0.0194\, x_4x_7 - 0.1283\, x_6x_9$ (0.9718) (0.0038) (0.0432)	0.4731
> 20 and < =40 years	$y = - 0.8121 + 7.7064\, x_4 + 1.2953\, x_1x_6$ (0.2132) (2.0081) (0.3407) $+ 0.0075\, x_2x_8 - 15.8635\, x_5x_6 - 0.0040\, x_7x_8$ (0.0033) (6.4587) (0.0018) $- 0.0055\, x_5x_7$ (0.0013)	0.3476
> 40 years	$y = - 6.2031 + 0.5546\, x_2 + 40.1271\, x_1x_4$ (0.9900) (0.0854) (7.6566) $- 1.9066\, x_1x_6 - 0.0104\, x_2^2 + 0.0483\, x_8x_9$ (0.4042) (0.0019) (0.0224)	0.4997

where,

y	=	residuals from the volume-age equation
x_1	=	soil nitrogen
x_2	=	soil phosphorus
x_3	=	soil potassium
x_4	=	soil calcium
x_5	=	soil magnesium
x_6	=	soil zinc
x_7	=	soil iron
x_8	=	organic carbon
x_9	=	soil pH

The values in the parantheses are standard errors of the coefficients and a quadratic term. The interaction terms include interactions between nitrogen and calcium, nitrogen and zinc and organic carbon and pH. Phosphorus had a quadratic term in the equation. Exploration of the surface through the canonical form revealed the existence of a saddle point on the surface. But the point of maximal response of the phosphorus axis was attained. As there is no interaction term of phosphorus with the other variables in the model, the maximal response of phosphorus is predicted at 26.66 ppm, using differential equation.

4.2 Relation between CAI in basal area per tree and soil attributes and foliar nutrient status

Current annual increment in basal area per tree in different plots was regressed on the different measurements made on soil/leaves along with age and initial basal area per ha using a second order polynomial model. Significant variables from the leaf/soil variables in the second order response function were identified through stepwise regression.

4.2.1 Relation between CAI in basal area per tree and nutrient status of leaves

The equation fitted with respect to nutrient status in leaves, through stepwise regression was:

$$y = \underset{(0.0022)}{0.0084} - \underset{(0.00004)}{0.00003\, x_1} + \underset{(0.0132)}{0.0330\, x_{10}} - \underset{(0.000002)}{0.000006\, x_2 x_8} - \underset{(0.0002)}{0.0005\, x_6 x_7}$$

where,

y = CAI in basal area per tree

x_1 = age in year

x_2 = leaf nitrogen

x_6 = leaf magnesium

x_7 = leaf zinc

x_8 = leaf iron

x_{10} = initial basal area per ha.

The model had an adjusted R^2 value of 0.4441. The absence of quadratic terms in the model indicates a linear surface subjected to interaction between nitrogen and iron and between magnesium and zinc. Both these interactions had negative coefficients. Age and basal area also had a linear effect on the model.

4.2.2 Relation between CAI in basal area per tree and soil attributes

The fitted equation with respect to nutrient status of soils, through stepwise regression was:

$$y = \underset{(0.0039)}{0.0122} - \underset{(0.0001)}{0.0004}\,x_1 + \underset{(0.0126)}{0.0534}\,x_{11} + \underset{(0.0004)}{0.0013}\,x_1x_2 - \underset{(0.0032)}{0.0076}\,x_2x_{10}$$

where,

y = CAI in basal area per tree

x_1 = age in years

x_2 = soil nitrogen

x_{10} = soil pH

x_{11} = initial basal area per ha

The adjusted R^2 value is 0.5618. Here also the model is linear and no quadratic term is present. The interaction between age and nitrogen and nitrogen and soil pH contribute to the linear surface. The age and initial basal area were also linear terms.

4.3 Canonical correlation analysis

This technique 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 age groups identified.

4.3.1 For age < = 20 years

The simple linear correlation coefficients between the leaf and soil attributes are given in Table 6. The correlation is low or moderate between many sets of variables. The largest correlation coefficient, 0.7922 was between leaf K and soil organic carbon and the correlation was positive. The correlation coefficients between leaf N and soil organic carbon was 0.6816, followed by 0.6536 between leaf Mn and soil organic carbon. Both these correlations were positive in nature. Also, the correlation coefficients between leaf Mn and soil N, leaf Fe and soil P, leaf Mg and soil P, leaf K and soil P, leaf Ca and soil K, leaf Ca and soil Ca, leaf Ca and soil Mg, leaf Ca and soil Zn, leaf Mg and soil Fe, leaf P and soil Fe, leaf P and soil organic carbon, leaf Ca and soil organic carbon, leaf Mg and soil organic carbon, leaf Fe and soil organic carbon and leaf Mg and soil pH were found to be significant.

The canonical correlations between foliar and soil attributes are reported in Table 7. The likelihood ratio test revealed that the first three of these correlations are significant. The corresponding canonical variates account for about 92 per cent of the total variability in the variables measured on leaves.

The standardised canonical coefficients for the leaf attributes and correlation between the leaf attributes and their three significant canonical variables are given in Table 8. The first canonical variable for leaf is a linear combination mainly of leaf K, leaf N, leaf Mn, leaf Fe and leaf Ca. Leaf Mn, leaf Fe and leaf Ca had positive correlations with the first leaf canonical variable while the other two had negative

Table 6 Coefficients of correlations between the leaf attributes and the soil attributes (age < =20 years)

Leaf	Soil								
	N	P	K	CA	MG	ZN	FE	OC	PH
N	0.1100	-0.3941	0.3172	0.0578	0.1123	-0.0714	-0.1325	0.6818*	-0.1430
P	0.1338	0.0080	0.1675	0.1921	0.1563	0.1567	0.3021*	0.2583*	0.0455
K	0.1582	-0.4342*	-0.2200	0.1315	0.1305	-0.1385	-0.1817	0.7922*	-0.1013
CA	-0.1100	0.0259	0.5228*	0.3345*	0.3748	0.3321*	0.2137	-0.4408*	0.0806
MG	-0.1944	-0.4068*	0.0307	0.0674	0.1478	0.3670	0.3318*	0.3106*	0.2996*
ZN	-0.0793	-0.1401	-0.1204	0.2123	0.0804	-0.1469	-0.1760	0.2238	0.1004
FE	-0.0839	0.2966*	0.2462	-0.0925	-0.1328	0.0840	0.0877	-0.5164*	-0.0088
MN	-0.3545*	0.3920	0.2243	-0.0986	-0.0933	0.0993	0.0511	-0.6536*	0.1523

Note: * indicates correlation coefficients significant at P = 0.05 with n = 105 pairs of observation

Table 7 Eigen values and canonical correlation between leaf and soil variables

No.	Eigen value	Canonical correlation	Proportion of variance	Cumulative proportion
1	7.6804	0.9406	0.6014	0.6014
2	2.8713	0.8612	0.2248	0.8263
3	1.1497	0.7313	0.0900	0.9163
4	0.6429	0.6256	0.0503	0.9667
5	0.2216	0.4259	0.0174	0.9840
6	0.1444	0.3555	0.0113	0.9953
7	0.0449	0.2074	0.0035	0.9988
8	0.0148	0.1207	0.0012	1.0000

Table 8 Standardized canonical coefficients for the leaf attributes and correlation between the leaf attributes and their three significant canonical variables

Leaf attributes	Canonical coefficients			Correlations		
	Leaf 1	Leaf 2	Leaf 3	Leaf 1	Leaf 2	Leaf 3
N	-0.1733	0.0025	0.5564	-0.8483	-0.0887	0.0999
P	0.0082	0.0847	0.6022	0.3062	0.3996	0.3095
K	-0.5949	0.5961	-0.6797	-0.9678	-0.0166	-0.1097
CA	-0.0116	1.5279	-0.1879	0.7732	0.5804	0.0165
MG	-0.0301	-0.1955	0.8898	-0.3652	-0.1153	0.6195
ZN	-0.0193	-0.0823	-0.3641	-0.2271	0.0008	-0.3630
FE	0.0552	-0.1667	0.0738	0.5966	0.0138	-0.1006
MN	0.2687	-0.7163	-0.0857	0.8736	-0.0967	-0.1232

correlations. The second leaf canonical variable is a function of leaf Ca which has a positive correlation with the second canonical variable. The third leaf canonical variable is mainly a function of leaf Mg and has also a positive correlation with the third canonical variable.

The standardized canonical coefficients for the soil attributes and correlations between the soil attributes and their significant canonical variables are presented in Table 9. The first soil canonical variable is mainly a function of organic carbon. It has a negative correlation with the first canonical variable. The second soil canonical variable is a linear combination mainly of soil Mg, soil Ca, soil K and soil P. Soil P has a negative correlation with the second canonical variable while others have positive correlations. Soil Fe and soil Zn have positive correlation with the third soil canonical variable and this variable is a function of these two characters.

The canonical redundancy analysis showed that 50 per cent of the variance of the leaf attributes is explained by the first three soil canonical variables while 37 per cent of the variance of soil attributes is explained by the first three leaf canonical variables (Table 10).

The squared multiple correlations between the leaf attributes and the three significant canonical variables of the soil characters are given in Table 11. The first soil canonical variable, which is mainly a function of organic carbon has some predictive power for leaf K, leaf N, leaf Mn and leaf Ca. The second canonical variable for soil, which is a linear combination mainly of soil Mg, soil Ca, soil K and soil P has some predictive power for leaf K, leaf Ca, leaf Mn and leaf N.

Table 9 Standardized canonical coefficients for the leaf attributes and correlation between the soil attributes and their three significant canonical variables

Soil attributes	Canonical coefficients			Correlations		
	Soil 1	Soil 2	Soil 3	Soil 1	Soil 2	Soil 3
N	-0.2228	0.4515	0.2239	-0.2162	0.2906	-0.0889
P	1.3193	0.1039	0.1695	0.4921	-0.5343	-0.3515
K	-0.0778	0.2447	-0.5755	0.2726	0.5611	0.0625
Ca	0.4436	0.3489	-0.8001	-0.1364	0.7679	-0.0274
MG	0.5617	0.7273	0.7960	-0.1473	0.8330	0.1339
ZN	0.2687	-0.2353	0.4041	0.1226	0.3403	0.6346
FE	0.2806	0.2055	0.9150	0.1520	0.1647	0.7562
OC	-0.4618	-0.1699	0.0866	-0.8550	0.2945	-0.0260
PH	-0.0301	-0.1211	0.1356	0.1134	-0.1032	0.3010

Table 10 Standardized variance of the leaf and soil attributes explained by the opposite canonical variables

Canonical variable	Standardised variance of leaf		Standardised variance of soil	
	Proposition	Cumulative proportion	Proportion	Cumulative proportion
1	0.4100	0.4100	0.1166	0.1166
2	0.0489	0.4589	0.1820	0.2986
3	0.0440	0.5030	0.0725	0.3711
4	0.0356	0.5386	0.0429	0.4299
6	0.0106	0.5671	0.0142	0.4440
7	0.0021	0.5692	0.0011	0.4451
8	0.0010	0.5702	0.0019	0.4469

Table 11 Squared multiple correlations between the leaf attributes and the three significant canonical variables of the soil attributes

Leaf attributes	Canonical variables		
	Soil 1	Soil 2	Soil 3
N	0.6367	0.6425	0.6479
P	0.1319	0.2506	0.3016
K	0.8287	0.8289	0.8353
CA	0.5290	0.7788	0.7790
MG	0.1180	0.1278	0.3331
ZN	0.0457	0.0457	0.1161
FE	0.3150	0.3151	0.3205
MN	0.6752	0.6822	0.6903

The squared multiple correlations between the soil characters and the three significant canonical variables of the leaf characters are given in Table 12. The first canonical variable of leaf characters which is a linear combination mainly of K, Mn, N, Fe and Ca is a good predictor of soil organic carbon. The second canonical variable of leaf which is mainly a function of Ca had some predictive power for organic carbon, soil Mg, soil Ca and soil P. The third leaf canonical variable which is a function of Mg was having some predictive power for soil Mg, soil organic carbon, soil P and soil Ca.

4.3.2 For age > 20 and age < = 40

The simple linear correlation coefficients between the leaf and soil attributes coming under this age group are presented in Table 13. The correlation was low in most cases or moderate between many sets of variables. The highest correlation coefficient value of 0.5703 was between leaf Mg and soil Mg which were positively correlated. The correlation coefficient between leaf Ca and soil Ca was 0.5410 and were positively correlated. The leaf K and soil P were positively correlated with a coefficient of 0.5242. The correlation between leaf Fe and soil N, soil P with leaf N, P, K and Mg, soil K with leaf P and Fe, soil Ca with leaf N, P, K, Ca, Mg and Fe, soil Mg with leaf K, Ca, Mg, Zn and Fe, soil Zn with leaf Zn, soil Fe with leaf P and Ca, soil organic carbon with leaf P, K and Fe and soil pH with leaf Ca were found to be significant.

Table 12 Squared multiple correlations between the soil attributes and the three significant canonical variables of the leaf attributes

Soil attributes	Canonical variables		
	Leaf 1	Leaf 2	Leaf 3
N	0.0413	0.1040	0.1082
P	0.2143	0.4260	0.4921
K	0.0657	0.2993	0.3014
CA	0.0165	0.4538	0.4542
MG	0.0192	0.5339	0.5435
ZN	0.0133	0.0992	0.3146
FE	0.0205	0.0406	0.3464
OC	0.6468	0.7112	0.7115
PH	0.0114	0.0193	0.0677

Table 13 Coefficients of correlations between the leaf attributes and the soil attributes (age < =20 and age < =40 years)

Leaf	Soil								
	N	P	K	CA	MG	ZN	FE	OC	PH
N	0.0154	0.3444*	-0.0638	-0.2938*	-0.3731	0.0653	0.0464	-0.0273	-0.0239
P	-0.1210	0.3057*	0.3220*	0.4297*	0.1692	0.0004	-0.1938*	-0.0104	0.0959
K	-0.1638	0.5242*	0.1774	-0.2158*	-0.4036	-0.0321	-0.0370	-0.2264*	0.0609
CA	-0.1313	0.0762	0.1460	0.5410*	0.4242*	0.0810	-0.2306*	-0.1357	0.2333
MG	0.0319	-0.4463*	0.0686	0.4631*	0.5703*	-0.0096	-0.0567	0.1567	0.0176
ZN	0.1519	-0.0823	-0.1762	-0.1598	-0.2334*	-0.2538*	0.0676	-0.0404	0.1662
FE	-0.2644*	0.4500	-0.2641*	-0.2841*	-0.4303*	-0.0108	0.1595	-0.3126*	-0.0718
MN	-0.1763	-0.1360	-0.1802	0.0273	0.0979	0.0474	0.1070	-0.1573	-0.1177

Note: * *indicates correlation coefficients significant at P = 0.05 with n = 135 pairs of observations*

The canonical correlations between leaf and soil variables along with eigen values are given in Table 14. The likelihood ratio test suggests that the first two correlations are significant. The first two canonical variables accounted for about 70 per cent of the total variability in the leaf nutrient status.

The standardised canonical coefficients for the leaf attributes and the correlations between the leaf attributes and their two significant canonical variables are given in Table 15. The first canonical variable was a linear combination mainly of leaf Mg, leaf K and leaf N. Leaf Mg had a negative correlation with first canonical variables while leaf K and leaf N had positive correlations. The second leaf canonical variable was a function of leaf P and leaf Ca. Both these characters had positive correlation with the second leaf variable.

The standardized canonical coefficients for the soil attributes and correlations between the soil attributes and their significant canonical variables are reported in Table 16. The first soil canonical variable was mainly a linear combination of soil Mg, soil P and soil Ca. Soil Mg and soil Ca had a negative correlation while the soil P had a positive correlation with the first soil canonical variable. The second soil canonical variable was a function of soil Ca and soil P in which both these characters had positive correlation with the second canonical variable.

The canonical redundancy analysis showed that about 25 per cent of the variance of the leaf characters is explained by the first two soil canonical variables and 19 per cent of the variance of the soil characters is explained by the first two leaf canonical variables (Table 17).

Table 14 Eigen values and canonical correlation between leaf and soil attributes

No.	Eigen value	Canonical correlation	Proportion of variance	Cumulative proportion
1	1.4500	0.7693	0.4420	0.4420
2	0.8601	0.6800	0.2622	0.7042
3	0.3726	0.5210	0.1136	0.8178
4	0.2734	0.4634	0.0834	0.9012
5	0.1836	0.3939	0.0560	0.9571
6	0.1109	0.3160	0.0338	0.9910
7	0.0274	0.1632	0.0083	0.9993
8	0.0023	0.0478	0.0007	1.0000

Table 15 Standardized canonical coefficients for the leaf attributes and correlation between the leaf attributes and their significant canonical variables

Leaf attributes	Canonical coefficient		Correlations	
	Leaf 1	Leaf 2	Leaf 1	Leaf 2
N	0.1533	0.0940	0.5951	-0.0503
P	-0.1238	0.7167	0.0248	0.8794
K	0.4826	0.0434	0.8154	0.2822
A	0.1099	0.5765	-0.3630	0.6770
MG	-0.5139	-0.2230	-0.8980	0.1301
ZN	0.0753	-0.0575	0.2076	-0.0888
FE	0.1992	-0.1356	0.4736	-0.0661
MN	0.0540	0.0984	-0.2438	-0.1336

Table 16 Standardized canonical coefficients for the soil attributes and correlations between the soil attributes and their significant canonical variables

Soil attributes	Canonical coefficient		Correlations	
	Soil 1	Soil 2	Soil 1	Soil 2
N	0.1268	-0.1299	-0.1862	-0.2433
P	0.4789	0.3912	0.6784	0.5717
K	0.1925	0.0745	-0.0765	0.4846
CA	-0.2217	1.3155	-0.5824	0.7795
MG	-0.6504	-0.6302	-0.8025	0.3932
ZN	-0.0381	-0.1890	-0.0134	0.1097
FE	-0.1031	0.1408	0.0776	-0.3991
OC	-0.1832	0.1080	-0.3657	-0.1526
PH	0.0989	0.0885	0.0290	0.2769

Table 17 Standardized variances of the leaf and soil attributes explained by the opposite canonical variables

Canonical variables	Standardized variance of leaf		Standardized variance of soil	
	Proportion	Cumulative proportion	Proportion	Cumulative proportion
1	0.1690	0.1690	0.1068	0.1068
2	0.0787	0.2477	0.0850	0.1918
3	0.0282	0.2758	0.0245	0.2163
4	0.0220	0.2979	0.0301	0.2464
5	0.0189	0.3168	0.0131	0.2596
6	0.0074	0.3242	0.0105	0.2701
7	0.0021	0.3264	0.0014	0.2714
8	0.0001	0.3265	0.0002	0.2716

The squared multiple correlations between the leaf attributes and the significant canonical variables of the soil attributes are given in Table 18. The first canonical variable of the soil which is mainly a linear combination of soil Mg, P and Ca had some predictive power for leaf Mg and K. The second soil canonical variable which is a function of soil Ca and P had predictive power for leaf Mg, K and P.

The squared multiple correlations between the soil attributes and significant variables of the leaf attributes are presented in Table 19. The first leaf canonical variable which is a function of Mg, K and N had some predictive power for soil Mg, Ca and P. The second canonical variable for leaf which is a linear combination mainly of P and Ca had some predictive power for soil Ca, Mg and P.

4.3.3 For age > 40 years

The simple linear correlation coefficients between the leaf and soil attributes for the age group are reported in Table 20. The correlation is moderate or low between many sets of variables. The highest correlation coefficient 0.7397 was between leaf K and soil P. It was followed by the correlation between leaf K and soil Fe, the coefficient being 0.6523. In both cases the direction of correlation was positive. Significant correlation was also observed between soil N and leaf Fe, soil P and leaf N, soil P and leaf Zn, soil K and leaf K, soil K and leaf Ca, soil K and leaf Fe, soil Ca and leaf P, soil Ca and leaf Ca, soil Mg and leaf P, soil Zn and leaf P, soil Zn and leaf K, soil Zn and leaf Ca, soil Zn and leaf Zn, soil Fe and leaf N, soil Fe and leaf Mg, soil Fe and leaf Zn. Organic carbon and leaf P, organic carbon and leaf Ca, soil pH and leaf K, soil pH and leaf Mg and soil pH and leaf Fe.

Table 18 Squared multiple correlations between the leaf attributes and the significant canonical variables of the soil attributes

Leaf attributes	Canonical variables	
	Soil 1	Soil 2
N	0.2096	0.2108
P	0.0004	0.3580
K	0.3935	0.4303
CA	0.0780	0.2899
MG	0.4773	0.4851
ZN	0.0255	0.0291
FE	0.1328	0.1348
MN	0.0352	0.0434

Table 19 Squared multiple correlations between the soil attributes and the significant canonical variables of the leaf attributes

Soil attributes	Canonical variables	
	Leaf 1	Leaf 2
N	0.0205	0.0479
P	0.2724	0.4235
K	0.0035	0.1121
CA	0.2007	0.4817
MG	0.3811	0.4526
ZN	0.0001	0.0057
FE	0.0036	0.0772
OC	0.0791	0.0899
PH	0.0005	0.0359

Table 20 Coefficients of correlations between the leaf attributes and the soil attributes (age > =40 years)

Leaf	Soil								
	N	P	K	CA	MG	ZN	FE	OC	PH
N	-0.1495	0.4313*	0.1121	-0.0670	-0.0915	0.1862	0.3197*	-0.1157	0.0574
P	-0.2504*	0.0858	-0.1457	-0.2786*	-0.3214	-0.2203*	-0.0920	-0.2884*	-0.1019
K	-0.1414	0.7397*	0.3568*	0.0678	-0.1414	0.4345*	0.6523*	-0.0538	0.2121*
CA	0.1879	0.0699	0.3356*	0.3639*	0.1734	0.2253*	0.1105	0.2813*	0.1870
MG	-0.1751	-0.1848	0.1296	0.0972	0.1721	-0.0458	-0.2044*	0.0484	0.2009*
ZN	-0.1328	0.3398*	0.0191	-0.0418	-0.0450	0.2763*	0.2780*	-0.1291	-0.1793
FE	-0.3661*	-0.0934	0.2972*	0.1852	0.1099	0.0364	-0.1633	-0.1625	0.2698*
MN	0.0230	-0.0508	0.1524	0.0850	0.1110	0.0608	-0.0281	0.0597	-0.0839

Note: * indicates correlation coefficients significant at P = 0.05 with n = 105 pairs of observation

The canonical correlations between leaf and soil attributes are reported in Table 21. The significance of each canonical correlation against zero was tested using likelihood ratio test. It revealed that the first three of these correlations were significant. The corresponding canonical variate accounted for about 90 per cent of the total variability in the attributes measured on leaves.

The standardized canonical coefficients for the leaf attributes and correlation between the leaf attributes and their three significant canonical variables are given in Table 22. The first canonical variable for leaf was mainly a linear combination of leaf Fe, leaf K and leaf Mg. The leaf K had a positive correlation with the first canonical variable while the other two had negative correlations. The second leaf canonical variable was a function of leaf K, which had positive correlation with the second leaf canonical variable. The third leaf canonical variable was a function of leaf Zn and leaf Ca. The leaf Zn had a positive correlation with the third leaf canonical variable.

The standardized canonical coefficients for the soil attributes and correlation between the soil attributes and their three significant canonical variables are reported in Table 23. The first soil canonical variable was a function of soil P and soil Fe and these two characters had positive correlation with the first soil canonical variable. The second canonical variable for soil was a linear combination mainly of soil K, soil P, soil Zn, soil Fe and soil pH. All these character had positive correlation with the second soil canonical variable. The third soil canonical variable was a function of organic carbon and soil N. Both these characters had negative correlation with the third soil canonical variable.

Table 21 Eigen values and canonical correlation between leaf and soil attributes

No.	Eigen value	Canonical correlation	Proportion of Eigen variance	Cumulative proportion
1	2.5288	0.8465	0.4286	0.4286
2	2.0996	0.8230	0.3559	0.7845
3	0.6757	0.6350	0.1145	0.8990
4	0.2909	0.4747	0.0493	0.9483
5	0.1537	0.3650	0.0261	0.9744
6	0.1051	0.3083	0.0178	0.9922
7	0.0456	0.2087	0.0077	0.9999
8	0.0005	0.0222	0.0001	1.0000

Table 22 Standardized canonical coefficients for the leaf attributes and correlation between the leaf attributes and their significant canonical variables

Leaf attributes	Canonical coefficients			Correlations		
	Leaf 1	Leaf 2	Leaf 3	Leaf 1	Leaf 2	Leaf 3
N	0.0732	0.2684	-0.0514	0.4030	0.2997	0.3537
P	0.0818	-0.2260	0.1712	0.0565	-0.0357	0.3484
K	0.4054	0.7967	-0.0478	0.6629	0.5876	0.1568
CA	0.3850	0.2784	-0.8240	-0.0724	0.2730	-0.6087
MG	-0.3008	0.3568	0.2072	-0.5782	0.2096	-0.0656
ZN	0.1129	0.1025	0.7380	0.3537	0.1927	0.6709
FE	0.6761	0.5760	0.1654	-0.7691	0.4789	-0.0356
MN	0.0563	-0.0628	0.2001	-0.1548	0.0483	-0.0560

Table 23 Standardized canonical coefficients for the soil attributes and correlation between the soil attributes and their three significant canonical variables

Soil attributes	Canonical coefficients			Correlations		
	Soil 1	Soil 2	Soil 3	Soil 1	Soil 2	Soil 3
N	1.1078	-0.7067	-0.8096	0.3189	-0.4037	-0.5882
P	0.8948	0.5753	0.4608	0.6138	0.7575	0.1361
K	-0.3263	0.1850	-0.6656	0.0484	0.7905	0.3209
MG	-0.0202	0.0466	0.5267	-0.1753	0.1176	-0.2262
ZN	-0.0443	0.2556	0.7051	0.3353	0.6534	-0.0647
FE	0.3078	-0.3965	-0.3377	0.6196	0.6322	-0.0382
OC	-0.3982	0.3306	0.0274	0.1980	-0.0707	-0.6187
PH	-0.0512	0.2140	-0.4474	-0.1346	0.5753	-0.3898

The standardized variances of the leaf and soil attributes explained by the opposite canonical variables is given in Table 24. It shows that 27 per cent of the variance of the leaf characters is explained by the first three soil canonical variables and about 35 per cent of the variance of the soil characters is explained by the first three leaf canonical variables.

The squared multiple correlations between the leaf attributes and the significant canonical variables of the soil attributes are given in Table 25. It indicated that the first soil canonical variable which was mainly a function of soil P and Fe had some predictive power for leaf Fe and K. The second soil canonical variable, a function of soil K, P, Zn, Fe and pH had some predictive power for leaf K and Fe. The third canonical variable for soil which was a function of soil N and organic carbon had some predictive power for leaf K and Fe.

The squared multiple correlations between the soil attributes and the significant canonical variables of the leaf attributes are reported in Table 26. The first leaf canonical variable, mainly a linear combination of leaf Fe, K and Mg had some predictive power for soil Fe and P. The second leaf canonical variable which was a function of leaf K had some predictive power for soil P and Fe. The third leaf canonical variable which was mainly a function of leaf Zn and Ca had some predictive power for soil P and Fe.

Table 24 Standardized variances of the leaf and soil attributes explained by the opposite canonical variables

Canonical variables	Standardized variance of leaf		Standardized variance of soil	
	Proportion	Cumulative proportion	Proportion	Cumulative proportion
1	0.1509	0.1509	0.0847	0.0847
2	0.0697	0.2207	0.2033	0.2880
3	0.0555	0.2761	0.0582	0.3462
4	0.0211	0.2972	0.0288	0.3749
5	0.0175	0.3147	0.0128	0.3877
6	0.0116	0.3263	0.0024	0.3901
7	0.0035	0.3297	0.0042	0.3943
8	0.0001	0.3298	0.0000	0.3943

Table 25 Squared multiple correlations between the leaf attributes and the significant canonical variables of the soil attributes

Leaf attributes	Canonical variables		
	Soil 1	Soil 2	Soil 3
N	0.1164	0.1772	0.2277
P	0.0023	0.0032	0.0521
K	0.3149	0.5487	0.5587
CA	0.0038	0.0542	0.2036
MG	0.2395	0.2693	0.2710
ZN	0.0896	0.1148	0.2963
FE	0.4239	0.5792	0.5797
MN	0.0172	0.0188	0.0200

Table 26 Squared multiple correlations between the soil attributes and the significant canonical variables of the leaf attributes

Soil attributes	Canonical variables		
	Leaf 1	Leaf 2	Leaf 3
N	0.0729	0.1833	0.3228
P	0.2700	0.6587	0.6662
K	0.0017	0.4249	0.4664
CA	0.0002	0.1104	0.2068
MG	0.0220	0.0314	0.0520
ZN	0.0797	0.3688	0.3705
FE	0.2751	0.5458	0.5464
OC	0.0281	0.0315	0.1859
PH	0.0130	0.2372	0.2984

4.4 Statistical parameters of tree, soil and leaf characteristics

The statistical parameters of different tree, soil and leaf characteristics measured in this study are reported in Tables 27 and 28. These Tables contains range, mean and standard deviation values for each of the characteristics belonging to different age groups. Initial and final basal areas and current annual increments for the plots are also given in Table 29.

Table 27 Statistical parameters of soil fertility attributes and height and girth of trees for the three age groups of teak

27a. For age < =20 years (Number of trees observed = 60)

Variable	Minimum	Maximum	Mean	Standard deviation	Unit
N	0.08	0.32	0.22	0.04	%
P	7.00	48.00	19.22	15.15	$\mu g\ g^{-1}$
K	0.0081	0.0356	0.02	0.01	%
Ca	0.023	0.315	0.19	0.09	%
Mg	0.005	0.025	0.02	0.00	%
Fe	13.070	288.46	136.64	118.08	$\mu g\ g^{-1}$
Zn	0.770	15.46	7.11	4.73	$\mu g\ g^{-1}$
OC	0.90	5.70	3.48	1.04	%
pH	4.8	5.7	4.14	0.16	
Height	1.20	18.30	13.06	3.23	m
Girth	9.00	97.00	57.91	22.31	cm

27b. For age > 20 and age < =40 years (Number of trees observed = 135)

Variable	Minimum	Maximum	Mean	Standard. deviation	Unit
N	0.07	0.36	0.22	0.06	%
P	6.00	37.00	14.59	7.06	$\mu g\ g^{-1}$
K	0.0019	0.0413	0.01	0.01	%
Ca	0.007	0.318	0.08	0.06	%
Mg	0.001	0.027	0.01	0.01	%
Fe	5.88	46.04	19.34	8.49	$\mu g\ g^{-1}$
Zn	0.34	18.96	1.99	1.94	$\mu g\ g^{-1}$
OC	0.84	5.88	3.54	1.16	%
pH	3.5	5.6	4.95	0.32	
Height	2.80	28.50	16.71	5.97	m
Girth	21.00	155.00	79.53	30.69	cm

27c. For >40 years (Number of trees observed = 105)

Variable	Minimum	Maximum	Mean	Standard. deviation	Unit
N	0.08	0.41	0.24	0.08	%
P	8.00	40.00	15.61	9.13	$\mu g\ g^{-1}$
K	0.0069	0.0469	0.02	0.01	%
Ca	0.017	0.206	0.10	0.06	%
Mg	0.004	0.026	0.02	0.01	%
Fe	7.23	199.25	32.83	38.02	$\mu g\ g^{-1}$
Zn	0.390	6.890	2.09	1.40	$\mu g\ g^{-1}$
OC	1.20	5.94	3.43	1.22	%
pH	3.9	5.7	4.91	0.39	
Height	2.60	31.10	19.78	6.53	m
Girth	31.00	200.00	95.68	37.26	cm

Table 28 Statistical parameters of leaf nutrient concentrations and height and girth of trees for the three age groups of teak

28a. For age < =20 years (Number of trees observed = 60)

Variable	Minimum	Maximum	Mean	Standard. deviation	Unit
N	1.23	3.05	1.95	0.45	%
P	0.1613	0.2737	0.22	0.03	%
K	0.450	2.300	1.27	0.59	%
Ca	1.840	5.647	3.37	0.92	%
Mg	0.258	0.660	0.44	0.09	%
Fe	59.00	360.00	178.22	79.55	$\mu g\ g^{-1}$
Zn	10.00	45.00	20.62	6.88	$\mu g\ g^{-1}$
Mn	15.00	99.00	50.88	19.26	$\mu g\ g^{-1}$
Height	1.20	18.30	13.06	3.23	m
Girth	9.00	97.00	57.91	22.31	cm

28b. For age > 20 and age < =40 years (Number of trees observed = 135)

Variable	Minimum	Maximum	Mean	Standard. deviation	Unit
N	1.04	2.51	1:56	0.28	%
P	0.0750	0.5737	0.23	0.10	%
K	0.100	2.050	0.66	0.40	%
Ca	1.728	6.785	3.59	1.04	%
Mg	0.198	1.198	0.52	0.15	%
Fe	54.00	569.00	222.74	100.73	$\mu g\ g^{-1}$
Zn	7.00	34.00	17.47	5.53	$\mu g\ g^{-1}$
Mn	21.00	147.00	67.82	26.03	$\mu g\ g^{-1}$
Height	2.80	28.50	16.71	5.97	m
Girth	21.00	155.00	79.53	30.69	cm

28c. For age >40 years (Number of trees observed = 105)

Variable	Minimum	Maximum	Mean	Standard. deviation	Unit
N	0.95	2.52	1.66	0.30	%
P	0.1275	0.3563	0.21	0.05	%
K	0.200	2.050	0.79	0.43	%
Ca	2.297	5.675	3.66	0.74	%
Mg	0.203	0.875	0.50	0.14	%
Fe	84.00	902.00	244.58	166.70	$\mu g\ g^{-1}$
Zn	7.00	42.00	20.25	6.56	$\mu g\ g^{-1}$
Mn	29.00	148.00	59.23	21.62	$\mu g\ g^{-1}$
Height	2.60	31.10	19.78	6.53	m
Girth	31.00	200.00	95.68	37.26	cm

Table 29 Initial and final basal areas and current annual increments for different plots

Sl. No.	Plantation Name	Date of first measurements	Date of second measurement	BA1	BA2	STOCK1	STOCK2	AGE	CAI
1	Vettukuzhy	09-Mar-1993	13-Feb-1997	11.43	8.52	1409	384	4.0	0.0035
2	Alathur			-	-	-	-	-	-
3	Bhoodanam	20-Apr-1993	26-Mar-1997	9.78	13.25	616	620	4.0	.0014
4	Ciyambam	26-Mar-1994	25-Mar-1997	13.92	17.03	1044	860	4.0	.0016
5	Karippanthode	-	-	-	-	-	-	-	-
6	Neduumkayam	27-Mar-1993	07-Feb-1997	7.43	8.00	400	324	4.0	.0015
7	Charupara	25-Feb-1994	04-Apr-1997	14.08	15.27	716	640	3.0	.0014
8	Choozhimedu	05-Mar-1993	11-Feb-1997	6.25	6.85	360	280	4.0	.0018
9	Kuthiran	01-Apr-1993	24-Jan-1997	14.77	10.58	400	176	4.0	.0058
10	Panakadan	24-Mar-1994	12-Mar-1997	17.30	18.92	272	272	4.0	.0015
11	Valiyakandam	14-Mar-1994	07-Apr-1997	15.63	17.88	176	184	3.0	.0028
12	Thadikulam	23-Feb-1994	05-Apr-1997	9.90	11.13	292	288	3.0	.0015
13	Pothundi	31-Mar-1993	22-Jan-1997	10.84	10.82	184	169	4.0	.0013
14	Camproad	22-Apr-1993	27-Mar-1997	15.21	13.85	128	100	4.0	.0049
15	Neriyamangalam	27-Feb-1994	06-Apr-1997	22.20	22.68	188	180	3.0	.0026
16	Inchappara	24-Mar-1993	23-Mar-1997	8.22	10.11	92	84	4.0	.0078
17	Palakkathadom	18-Mar-1993	28-Jan-1997	11.24	12.17	208	216	4.0	.0006
18	Panikkottor	27-Mar-1994	19-Apr-1997	15.57	15.09	272	264	3.0	.0000
19	Kadamankadu	10-Mar-1993	22-Feb-1997	8.33	8.69	332	316	4.0	.0006
20	Parappa	10-Apr-1993	17-Apr-1997	6.04	5.70	356	256	4.0	.0013

Discussion

DISCUSSION

5.1.1 Relation between tree growth and nutrient status of leaves

For the first age group (< =20 years), the resultant model was linear and had a very low adjusted R^2 value of 0.1089. The leaf nitrogen concentration had a very meager effect on the tree volume. The negative coefficient of the nitrogen indicates that with increasing volume growth, nitrogen concentration in the leaves decreased which could be explained on the basis of dilution effect. So there is scope for getting more volume growth by applying nitrogen fertilizers. This was the age group where relative growth rate was maximum and hence one expects maximum influence of leaf nutrient status on growth of the tree. But the result does not show such influences by any element. At this phase of plantation development, the canopy is open and no distinctive microclimate and soil environment are developed. So the effect of other factors like soil physical properties, moisture availability and temperature might have masked the effect of leaf attributes on tree growth. Also the range of variation for all the macro elements and for most microelements was very narrow.

For the second age group, the tree volume was significantly influenced by leaf nutrient concentrations of N, P, Ca, Mg and Fe. Here the model was linear and had a higher adjusted R^2 value of 0.2977 compared to the first age group. The results show that with the increase in the volume growth of tree, there was a corresponding increase in the leaf nutrient concentrations of N, P and Ca. The interaction between Mg and

Fe in leaf had a negative effect on tree growth. No quadratic terms were present in the resultant equation.

For the last age group, the model had an adjusted R^2 value of 0.3213. The model was linear and no quadratic terms were present. The phosphorus content in the leaf had a positive linear effect on tree volume indicating higher tree volume with increase in leaf phosphorus. Also there was significant positive interaction between nitrogen and calcium and also between phosphorus and zinc.

In all the three age groups, the critical nutrient concentrations with respect to tree volume do not seem to be attained by the levels of nutrients available in the present data set. Jayamadhavan (1996) also reported that the critical nutrient levels for N, P and K could not be determined for the four site quality classes of teak plantation of Nilambur, since the basal area and volume increased with increasing foliar nutrient concentrations.

Also, from the results, it can be seen that the adjusted R^2 values increase from first age group to third age group. A possible explanation here could be that larger volume of a tree compared to that of its counterparts in lower age group would have been a result of continued better nourishment over a longer time span. Thus it is just natural that the leaf nutrient status of such trees reflect the higher attainment in the physical dimensions.

5.1.2 Relation between tree growth and soil fertility attributes

For the first age group, the resultant model had an adjusted R^2 value of 0.4731. The result indicated that Zn in the soil is linearly related to the tree volume. Also the interaction between soil phosphorus and potassium and also the interaction between calcium and iron were positive indicating the synergistic rather than antagonistic effects of these sets of elements on tree volume.

For the second age group, the model contained no quadratic terms. The adjusted R^2 value was 0.3476. The result indicated that calcium in the soil had a significant positive effect on tree volume. In this age group coefficient of variation of soil characters was very small in most of the cases.

In the last age group, the model had an adjusted R^2 value of 0.4997. The interaction between organic carbon and pH of the soil had a positive effect on tree volume. Soil phosphorus had a quadratic term in the model. Exploration of response surface through canonical form revealed the existence of a saddle point on the surface. But the point of maximal response was attained in the phosphorus axis. As there was no interaction term of phosphorus with other nutrients in the model, using differential equation, the point of maximal response for phosphorus was predicted at P=26.66 ppm. Comparing soils under teak plantations and natural forests of Madhya Pradesh, Choubey *et al.* (1987) reported that phosphorus under teak plantations is higher than natural forests and also values tended to increase with the age of plantations.

The present study was conducted on teak plantations widely distributed all over the state. No deliberate attempts were made to control the status of soil 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 characteristics in a given age group 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 accidently get included in the final equation even when they have no significant effect on tree growth, although chances of such occurrence are low. Additionally, when there is high intercorrelation among the regression variables, the stepwise regression is likely to exclude many variables from the final model considering them as redundant. In spite of the limitation, certain broad indications are sure to be 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 soil and climate need not show good relationship with current soil fertility attributes or leaf nutrient status like in agricultural crops. The use of volume prediction equation would have also brought in some error in the assessment of volume. Nevertheless, the observation that almost 50 per cent of the variation in tree volumes in the older age group could be explained by soil nutrient levels is something remarkable.

5.2 Relation between CAI in basal area per tree and soil attributes and foliar nutrient status

Current annual increment in basal area per tree was computed through stand level values because records of increment of individual trees could not be obtained. Since the height of all trees in the plots was not known, basal area was taken as an index of growth in this case.

In the case of relationship between CAI in basal area per tree and nutrient status of leaves, the model had an adjusted R^2 value of 0.4441. The model was linear and no quadratic terms were present in the model. The interaction between nitrogen and iron and also that between magnesium and zinc had negative effects on the CAI in basal area per tree.

Relation between CAI in basal area per tree and nutrient status of soil also followed a linear model, the adjusted R^2 value being 0.5618. The result revealed that interaction between age and soil nitrogen had a positive effect of CAI indicating that for any fixed age level, variation in CAI is positively related to soil nitrogen. This may also imply that effect of soil nitrogen on CAI need not remain the same at all age levels. Alternatively, age related change in CAI is positively modified by the level of soil nitrogen. The interaction between nitrogen and pH was negative.

5.3 Canonical correlation analysis

For analysing the relationship between the eight leaf variables and nine soil variables, canonical correlation analysis was used. This procedure was applied to all the three data sets belonging to different age groups.

5.3.1 For age $<=20$ years

The simple linear correlation between leaf characters and the soil characters was low or moderate in many cases.

Soil organic carbon had a significant influence on many of the leaf nutrient concentrations. Highest correlation was between organic carbon and leaf potassium. The soil is derived from ancient crystalline rocks of archean age rich in potassium.

Availability of this element to plant increases under the influence of organic acids liberated during decomposition of organic matter. This may be the reason to get a good correlation between organic carbon and leaf potassium.

Organic carbon also had significant influence on leaf nitrogen. Organic matter is the major source of soil nitrogen. Mineralization of organic matter leads to availability of soil nitrogen and plant takes up these easily available nitrogen and hence with increase in soil organic carbon, leaf nitrogen also increases.

Significant positive correlation was also seen between soil calcium and leaf calcium contents.

The first soil canonical variable, a function of organic carbon is highly correlated with the first leaf canonical variable represented mainly by leaf nitrogen, potassium, iron and manganese. Organic carbon had significant negative effect on leaf iron and manganese concentrations. The Fe and Mn forms complexes with organic acids and thus their availability may get reduced when organic carbon is more in the soil. The second soil and leaf canonical variables suggest that leaf Ca concentration is significantly influenced by availability of Ca and Mg in the soil. The third canonical variable for soil and leaf indicates that leaf Mg concentration is influenced by soil Zn and Fe contents.

The canonical redundancy analysis showed that the variations in leaf attributes are greatly influenced by soil fertility attributes while the variation in soil characters is less influenced by the leaf characters. As this is a initial stage of plantation development this fact holds true.

5.3.2 For age >20 and age <=40 years

The low value of simple linear correlation coefficients indicates low correlation between many leaf and soil attributes. In this age group also there was a significant positive correlation between soil and leaf calcium concentrations. The positive relationship between leaf magnesium and soil magnesium was also significant. In this case also soil organic carbon had a negative influence on the iron concentration in the leaves.

The first canonical variables show that Ca and Mg in soil had positive correlation with leaf Mg content. The second canonical variables indicate strong positive interactions between soil Ca and leaf Ca and soil P and leaf P.

The redundancy analysis shows that in this age group also variation in leaf characters are well explained by the soil canonical variables and variance in soil characters are less explained by the leaf canonical variables.

The first soil canonical variable which was mainly a function of soil Mg had some predictive power for leaf Mg concentration.

5.3.3 For age >40 years

The simple linear correlation between two sets of variables was low in many cases. Significant positive correlations were seen between soil K and leaf K, soil Ca and leaf Ca and soil Zn and leaf Zn.

The canonical redundancy analysis for this age group shows that 27 per cent of the variation of leaf attributes is explained by the first three soil canonical variables and about 35 per cent of the variance of the soil attributes is explained by the first three leaf canonical variables. In this case it is clear that leaf attributes are having greater say in variance in the soil attributes.

On the whole, the canonical correlation analysis revealed the significant inter-correlations existing between leaf and soil attributes.

Also this analysis shows that as the age of the plantation increases and canopy closure occurs, the leaf nutrient contents influence the soil fertility attributes to a greater 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).

Summary

SUMMARY

The study `soil-plant nutritional status of *Tectona grandis* L.f. in relation to age and site quality' was carried with the basic objective of identifying and assessing the nutritional factors limiting productivity of teak plantations of different age groups belonging to different site classes and to recommend possible corrective measurers. The study was conducted at College of Forestry, Vellanikkara during 1994-96. The nature of relation between tree growth and the soil/leaf nutrient status, the nature of relation between current annual increment in basal area per tree and soil/leaf nutrient status and correlation between leaf attributes and soil attributes were investigated in this study.

The field work was conducted in different teak plantations of Kerala Forest Department stretching throughout the state. The chemical analysis involved in this study was conducted at different colleges of Kerala Agricultural University main campus, Vellanikkara.

The salient findings of the present investigations are summarised below:

The relation between leaf nutrient status and tree volume was feeble in all the three age groups. The obtained models through stepwise regression were all linear in nature and no quadratic terms were present in the models. In all the three age groups, the critical nutrient concentrations with respect to tree volume do not seem to be attained by the levels of nutrients available in the present data set. It indicates that volume of tree could be increased further by adequate supply of the appropriate nutrient elements.

The relation between tree growth and nutrient status of soil was stronger compared to the relation between the growth and nutrient status of leaves. For the first two age group selected, the models were linear in nature. For the older plantations (Age >40 years), almost 50 per cent of the variation in tree volume was explained by the soil nutrient levels. For this age group soil phosphorus had a quadratic term in the model and the point of maximal response for phosphorus was predicted at P = 26.66 ppm.

The relationship between CAI in basal area per tree and nutrient status of leaves was also linear. The relationship between CAI in basal area per tree and nutrient status of soil revealed that for any fixed age level, variation in CAI is positively correlated to soil nitrogen. This may also imply that effect of soil nitrogen on CAI need not remain same at all age levels. Alternatively, age related change in CAI is positively modified by the level of soil nitrogen.

To find out the relationship between the leaf attributes and soil attributes canonical correlation analysis was used.

For the younger age group (age <=20 years) soil organic carbon had a significant positive influence on leaf nitrogen and potassium. Also organic carbon had significant negative effect on leaf Fe and Mg concentrations.

Significant positive correlation was seen between leaf Ca and soil Ca for all the age groups. For the last age group (age >40 years) significant positive correlations were obtained for soil K and leaf K and also between soil Zn and leaf Zn.

On the whole canonical correlation analysis reveals the significant inter-correlation existing between leaf and soil characters. Also this analysis shows that as the age of the plantation increases and canopy closure occurs, the leaf nutrient content influences the soil fertility attributes to greater extent due to the effect of litter fall.

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SOIL - PLANT NUTRITIONAL STATUS OF *Tectona grandis* L.f. IN RELATION TO AGE AND SITE QUALITY

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ABSTRACT OF THE THESIS

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ABSTRACT

A study was conducted at College of Forestry, Vellanikkara, KAU, during the period 1994-1996 to identify and assess the nutritional factors limiting productivity of teak plantations, of different age groups belonging to different site qualities, spread through out the State of Kerala. The study was aimed to find out the influence of nutrient status of soil and leaf on the growth as represented through volume and current annual increment in basal area per tree. Another objective was to find out the influence of soil characteristics like pH, organic carbon and nutrient contents on foliar nutrient concentration of teak. The leaf samples were analysed for N, P, K, Ca, Mg, Fe, Mn and Zn concentrations. The soil samples were analysed for pH, organic carbon, available P, total N and exchangeable K, Ca, Mg, Fe and Zn. The whole set of 300 trees was divided into three age groups as $<=$ 20 years, $>$ 20 and $<=$ 40 years and $>$ 40 years and stepwise regression was carried out by taking volume as dependent variable for each group separately. The resultant equations in stepwise regression were utilized to characterize the nature of response surface and to find the optimum levels of soil attributes and foliar nutrient elements. For analysing the relationship between soil attributes and foliar nutrient concentrations a technique called canonical correlation analysis was used.

The relation between leaf nutrient status and tree volume was feeble in all the three age groups. In all the three age groups, the critical nutrient concentrations with respect to tree volume do not seem to be attained by the levels of nutrients available in the present data set, indicating a increase in tree volume by adequate supply of the appropriate nutrient elements.

The relation between tree growth and nutrient status of soil was stronger compared to the relation between the tree growth and nutrient status of soil. For the first two age group selected, the models were linear in nature. For the older plantations (Age >40 years), almost 50 per cent of the variation in tree volume was explained by the soil nutrient levels. For this age group soil phosphorus had a quadratic term in the model and the point of maximal response for phosphorus was predicted at P = 26.66 ppm.

The relationship between current annual increment in basal area per tree and nutrient status of leaves and soil was also linear. Age related change in current annual increment is positively modified by the level of soil nitrogen.

To find out the relationship between the leaf attributes and soil attributes canonical correlation analysis was used. For the younger age group (age < = 20 years) soil organic carbon had a significant positive influence on leaf nitrogen and leaf potassium concentrations while it had a negative effect on leaf Fe and leaf Mg concentrations. Also significant positive correlation was seen between leaf Ca and soil Ca for all the age groups.

The canonical correlation analysis showed that as the age of the plantations increases and the canopy closure occurs, the leaf nutrient contents influence the soil fertility attributes to a greater extend due to the effect of litter fall.